LIGHTING STRATEGIES FOR NIGHTTIME CONSTRUCTION AND MAINTENANCE ACTIVITIES ON ROADWAYS

by

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Dedicated to my family members for their unwavering support in my pursuit of becoming a better person and a professional engineer, to the Peruvian Government for providing me with this once-in-a-lifetime opportunity to study at one of the most prestigious universities in the United States and the world, to Purdue University for providing me a world-class education, and to the National University of Engineering, Peru for educating and equipping me with the engineering foundation necessary to solve and address complex engineering problems.

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ABSTRACT

Over the last two decades, an increasing number of highway construction and maintenance projects in the United States have been completed at night to avoid or mitigate traffic congestion delays. Working at night entails several advantages, including lower traffic volumes at night, reduced impact on local businesses, more freedom for lane closures, longer possible work hours, lower pollution, cooler temperatures for equipment and material, and fewer overall crashes due to lower traffic volumes at night. Although nighttime roadway operations may minimize traffic disruptions, there are several safety concerns for motorists passing by and for workers in the nighttime work zone. For instance, just in 2019, there were 842 work zone fatalities reported in the United States, with 48% of these being associated with fatalities on night shifts. Additionally, 70% of these fatalities involved drivers/occupants under the age of 50. Moreover, improper lighting arrangements or excessive lighting levels produced by temporary lighting systems installed at the job site could cause harmful levels of glare for the traveling public and workers leading to an increase level of hazards and crashes in the vicinity of the work zone.

To address the issue of glare, very few studies have been conducted to evaluate and quantify glare at work zones. Most of these studies were limited to the determination of disability glare levels of lighting systems (balloon lights and light towers) with a metal-halide type light source by using the veiling luminance ratio ($V_{L\ ratio}$) as a criterion for limiting disability glare. However, deeper evaluation of the effects of driver's age on the veiling luminance ratio, and the use of energy-efficient lighting systems which employ light-emitting diode (LED) type light sources were not performed.

This thesis focuses on determining and evaluating disability glare on nighttime work zones as a step towards developing appropriate lighting strategies for improving the safety of workers and motorists during nighttime highway construction and maintenance projects. Disability glare is the glare that impairs our vision of objects without necessarily causing discomfort and it can be evaluated using the veiling luminance ratio ($V_{L\ ratio}$). In this study, disability glare values were determined by using lighting data (vertical illuminance and pavement luminance measurements) from testing 49 lighting arrangements. Two LED balloon lights, a metal-halide light tower, and an LED light tower were utilized for the field lighting experiments. The disability glare level

evaluation examines the effects of mounting height, power output, rotation angle, and aiming angle of luminaires on the veiling luminance ratio values (which is a criterion for limiting disability glare).

The analysis of the disability glare values revealed four major findings regarding the roles played by the mounting height, power output, lighting system orientation, aiming angles of luminaries, and driver's age on disability glare levels as follows: (i) an increase in mounting heights of both balloon lights and light towers resulted in lower veiling luminance ratio values (or disability glare); (ii) compared to the "perpendicular" and "away" orientations, orienting the light towers in a "towards" direction (45 degrees) significantly increases the disability glare levels of the lighting arrangement; (iii) increasing the tilt angles of luminaires of the portable light towers resulted in an increase in veiling luminance ratio values; (iv) for balloon lights, at observers ages over 50, $V_{L\ ratio}$ values were found to be greater than the maximum recommended; (v) for LED light towers oriented towards the traffic, at driver's ages over 40, $V_{L\ ratio}$ values exceed the Illuminating Engineering Society (IES) recommended value; and (vi) for metal-halide light towers oriented towards the traffic, at driver's ages over 50, $V_{L\ ratio}$ values exceed the IES recommended value. The results from this research study can provide State Transportation Agencies (STAs) and roadway contractors with a means to improve glare control strategies for nighttime work.

1. INTRODUCTION

In 2019, 842 work zone fatalities were reported in the United States by the National Highway Traffic Safety Administration. Of these work zone fatalities, 403 (or 48%) were linked to fatalities that occurred during night shifts. Moreover, 70% of these fatalities represent drivers/occupants under age 49 (NHTSA, 2019). State transportation agencies have paid close attention to these work zone statistics to assess safety concerns associated with nighttime operations.

In the last two decades, an increasing number of roadway construction and maintenance projects have been performed at night in the United States in order to reduce or avoid traffic congestion on high-volume highways, minimize inconvenience to motorists, provide work crews with less traffic to protect against, and meet project deadlines (El-Rayes et al., 2003). Working at night has several advantages, including reduced traffic congestion, motorist delays, and extended working hours (Shepard & Cottrell, 1986). Although nighttime roadway operations may minimize traffic disruptions, several safety concerns exist. Cottrell (1999) reported that limited visibility, driver impairment, inadequate lighting, and lack of maintenance of traffic control devices are common issues that affect workers' and motorists' safety in night work zones.

Lighting affects nearly every aspect of nighttime highway operations. The reduction of the lighting levels in the work zone can directly impact the safety of workers and motorists (Mostafavi et al., 2012). Improper lighting arrangements or excessive lighting levels at nighttime work zones could cause harmful glare levels for the traveling public and workers (Rebholz et al., 2004). Glare is the sensation of annoyance, discomfort, or loss of visual performance and visibility when the luminance experienced in the visual field is significantly greater than what the observer's eyes are adapted to (El-Rayes et al., 2003; Ellis et al., 2003; Odeh, 2010). Glare produced by lighting systems on a work zone is regarded as one of the primary lighting issues during nighttime highway operations because it increases levels of hazards and crashes in the vicinity of the work zone (Hancher & Taylor, 2001; El-Rayes et al., 2003). Minimizing glare during nighttime highway operations can improve the safety of workers and the traveling public.

1.1 Background and Research Motivation

Between 2018 and 2019, fatalities in work zones increased by 11%, and the number of work zone fatalities at night increased by nearly 9% (NHTSA, 2019; FHWA, 2021). These statistics indicate that work zone safety at night is a growing concern for highway safety. State transportation agencies (STAs) are looking for ways to improve work zone lighting and glare control strategies for motorists and workers alike. Very few studies have been conducted in the past to evaluate glare at work zones, and these studies did not consider the effect(s) of the different ages of motorists and workers, on the calculation of veiling luminance ratio values (a criterion for limiting glare). Prior studies also focused on the evaluation of disability glare levels produced by more traditional lighting sources such as metal-halide. Moreover, the recommendations resulting from these studies regarding glare control strategies were only partially adopted by a few State Transportation Agencies (STAs). Thus, additional research of objective quantification and evaluation of disability glare levels produced by temporary lighting systems is needed to strengthen and support the State's work zone lighting strategies, particularly those that employ light-emitting diode (LED) sources.

In September 2020, the Indiana Department of Transportation (INDOT) began a study through the Joint Transportation Research Program (JTRP) of INDOT and Purdue University to investigate factors that contribute to worker injuries and crashes in work zones by comparing the characteristics of highway operations at night and during the day. The study's objectives were: (i) identification of the safety issues of nighttime operations on roadways; (ii) determination of the factors that contribute to worker injuries and crashes during daytime and nighttime work zone operations; and (ii) formulation of recommendations regarding which work zone alternative provides a higher level of safety for work crews and roadway users and under what conditions.

This thesis focuses on determining and evaluating disability glare on nighttime work zones as a step towards developing appropriate lighting strategies for improving the safety of workers and motorists during nighttime highway construction and maintenance projects. Disability glare impairs our vision of objects without necessarily causing discomfort (Vos, 2003). By quantifying and evaluating disability glare in nighttime work zones, resident engineers and contractors can resolve disagreements over acceptable or objectionable glare levels. This study will provide a detailed disability glare determination procedure, a set of recommended disability glare levels, and practical recommendations to minimize disability glare levels experienced by drive-by motorists

when passing through work zones. STAs could adopt these recommendations in developing appropriate work zone lighting policies.

1.2 Problem Statement

Excessive lighting levels or inadequate lighting arrangements in work zones cause glare for the traveling public and workers on the job site. Motorists passing near a nighttime construction/maintenance work zone may experience difficulty adjusting to the sudden changes in lighting levels as they travel from a relatively dark roadway environment to a bright work zone environment. Similarly, direct and bright light sources on the work zone may impair the vision of equipment operators and workers. Additionally, an inefficient lighting arrangement in the work zone may cause complaints about light trespass from people upset by unwanted light entering their windows or intruding upon their property.

To overcome the inherently limited visibility that nighttime highway operations represent, proper and sufficient lighting should be provided to workers to perform work while minimizing disability glare for traveling public passing near the work zone. By determining the veiling luminance ratio values (a criterion for limiting disability glare) for different lighting configurations, lighting strategies were developed to maximize the safety of workers and motorists and nighttime operations efficiency.

1.3 Research Questions

A state-of-the-art literature review was conducted to examine previous research and current practices related to disability glare produced by light sources on work zone lighting for highways. The state-of-the-art showed that glare on work zones was primarily determined by analyzing drivers' perceptions of glare rather than using objective metrics such as the veiling luminance ratio, which measures disability glare. Additionally, the state-of-the-practice showed that minimal information regarding recommendations for avoiding or minimizing glare on work zones is available for practitioners.

Using the veiling luminance ratio metric for determining disability glare on work zones involves performing vertical illuminance and pavement luminance measurements. These measurements of illuminance and luminance serve as inputs to calculate the veiling luminance

ratio (or disability glare). They are typically measured using instruments such as illuminance meters and luminance meters, respectively. Measuring illuminance and luminance may pose some challenges. For instance, vertical and pavement luminance measurements may vary from one lighting system type to another, from different mounting heights of lamps (or fixtures) and different tilt angles of the lighting fixtures. So, considering these challenges and implications of determining disability glare on work zones, the thesis addresses the following research questions:

1. What are the effects of lighting systems' mounting height, electrical power output (wattage), and motorists' age on veiling luminance ratios for light-emitting diode (LED) balloon lights?
2. What are the effects of lighting systems' mounting height, orientation, aiming angles of luminaries, and motorists' age on veiling luminance ratios for metal-halide (MH) and light-emitting diode (LED) light towers?
3. Under what ranges of motorists' age and lighting configurations (lighting type, orientation, aiming angles, mounting height, and electrical power) can disability glare be minimized or avoided in nighttime work zones?

1.4 Research Framework

This study aims to provide practical recommendations to state transportation agencies and roadway contractors regarding optimal lighting arrangements that alleviate and control disability glare levels experienced by passing motorists and workers on nighttime highway work zones. To accomplish this goal, two main research objectives were defined as follows:

1. Develop an objective procedure to determine disability glare for nighttime roadway work zones through the calculation of the veiling luminance ratio ($V_{L\ ratio}$) which is employ for quantifying and limiting disability glare, and it is defined as the maximum veiling luminance divided by the average luminance of the road surface.
2. Evaluate and compare the effects of the lighting type, orientation, aiming angles, mounting height, equipment power output, and motorists' age on the values of veiling luminance ratio (or disability glare) for different lighting arrangements.

3. Provide practical recommendations regarding optimal lighting arrangements that alleviate, and control disability glare levels experienced by passing motorists and workers on nighttime highway work zones.

1.5 Research Methodology

To accomplish the research's objectives, a research methodology was designed and divided into five research tasks, as illustrated in Figure 1.1. These tasks are described as follows:

1. Conducting a comprehensive state-of-the-art literature review and a state-of-the-practice review. The state-of-the-art review assesses previous research that studied glare produced by various lighting systems (e.g., portable light towers, balloon lights, nite-lite systems) on controlled work zone environments. Similarly, the state-of-the-practice review examines the current practices, standards, and guidelines to understand how disability glare is determined and how negative impacts of glare on both workers and the traveling public can be minimized on nighttime highway operations.
2. Conducting survey of work zone lighting strategies and lighting systems used in nighttime construction and maintenance projects on roadways. A survey questionnaire was developed as part of the study titled "Alternative Strategies for Roadway Work Zone Safety and Productivity" sponsored by the Joint Transportation Research Program/Indiana Department of Transportation (JTRP)/INDOT and Purdue University and deployed to roadway contractors to obtain their perspectives regarding nighttime highway operations, and to gain insight about lighting systems used in practice.
3. Conducting formal interviews with safety officers associated with roadway construction projects in Indiana to determine common lighting systems on nighttime work zones and strategies employed to reduce or avoid glare at work zones.
4. Conducting field experiments using various lighting arrangements. The field experiments were conducted on a simulated work zone lane closure to measure vertical illuminance and pavement luminance for four lighting systems: two LED balloon lights, a single metal-halide light tower, and a single LED light tower. These measurements were taken from inside of a car to simulate glare experienced by nighttime drivers traveling along the construction work zone and were later used to determine the veiling luminance ratio. The

setup parameters of the lighting systems evaluated during the experiments were the mounting heights, rotation angles (or orientations), aiming angles of lighting fixtures, and electrical power outputs.

5. Performing descriptive and statistical analysis of the data collected. This task employs the Factorial Analysis of Variance (ANOVA) to explore the influence of the dependent variables (mounting height, orientation, tilt angle of luminaries, lighting type, and wattage) or factors on a single dependent variable (veiling luminance ratio). Compared to a one-way ANOVA, a Factorial ANOVA uses two or more independent variables with two or more categories to predict the change in a single dependent variable (Mertler et al., 2021).

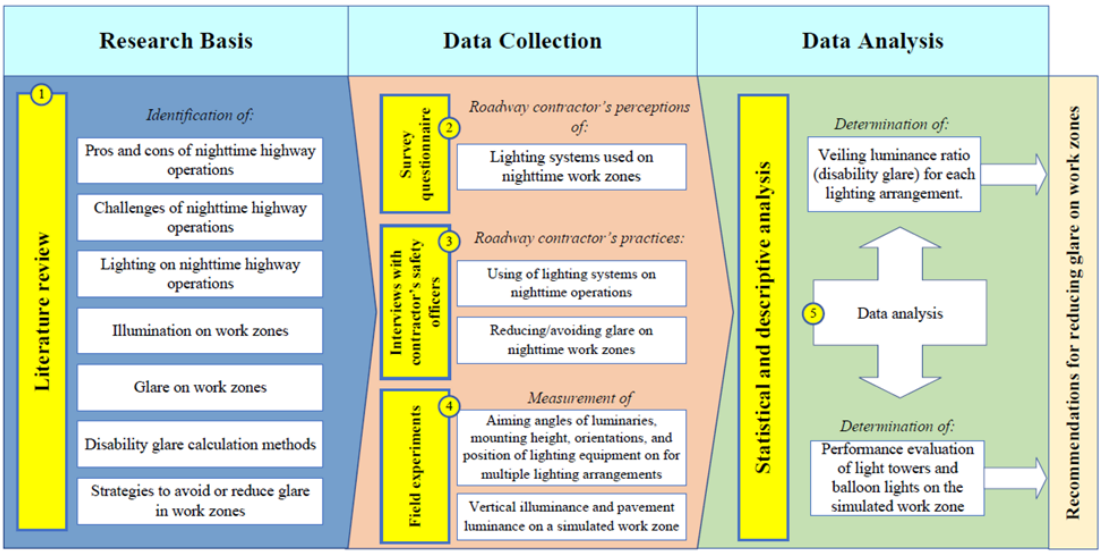


Figure 1.1. Research methodology.

1.6 Thesis Organization

This thesis is organized into five chapters. Chapter 2 describes the state-of-the-art literature and state-of-the-art practice review of current research studies, standards, and guidelines on determining disability glare and reducing its adverse effects on nighttime roadway operations for both workers and the traveling public. Chapter 3 discusses the research framework for determining disability glare in nighttime construction/maintenance projects and describes the steps for the field lighting experiments and measurements to be performed during the data collection process. Chapter 4 provides the disability glare levels calculated from each of the lighting arrangements

tested during the field experiments. It also includes two analyses: (1) Factorial Analysis of Variance (ANOVA) of the tested parameters of the lighting systems (mounting height, orientations, tilt angles, and electrical power) to determine their effects on disability glare levels; and (2) an analysis of the effects of changing the motorists' age on disability glare levels. Finally, Chapter 5 summarizes the study research, its contributions and limitations, and recommendations for future work.

2. LITERATURE REVIEW

The frequency of nighttime construction and maintenance operations in the United States has increased during the last two decades, especially in major cities, as State Transportation Agencies (STAs) strive to limit traffic on roadways during peak times and reduce inconvenience to the public. Although nighttime operations on roadways may minimize traffic disruptions, there are several safety concerns when undertaking nighttime roadway operations. Limited visibility, driver impairment, inadequate lighting, and lack of maintenance of traffic control devices are common issues that affect workers' and motorists' safety in night work zones (Cottrell, 1999). As nighttime operations continue to become more common, state transportation agencies and contractors must be aware of the safety, quality, and productivity implications of these operations. Several state transportation agencies and contractors have implemented standard practices to ensure roadway users' and work crews' safety. These practices include adequate lighting, appropriate personal protective equipment, traffic control, motorist assistance programs, and on-site law enforcement programs. This chapter will discuss the following themes: (1) common factors influencing nighttime operations; (2) lighting terminology; (3) review of past and ongoing research studies regarding work zone lighting and glare; (4) review of standards and guidelines for determining disability glare and recommendations for minimizing harmful levels of glare in nighttime roadway operations.

2.1 Nighttime Highway Work Zones: Advantages and Disadvantages

Performing construction and maintenance operations at night has positive and negative impacts on workers and motorists/road users. While some of these impacts are well-known, others have not been sufficiently investigated in prior research. This section provides a general overview of both advantages and disadvantages as observed in practice, reported in studies, or viewed by State Transportation Agencies (STAs), and the traveling public. In addition to obvious advantages of nighttime operations, such as lower traffic congestion, reduced impact on local businesses, more freedom for lane closures, longer possible work hours, lower pollution, cooler temperatures for equipment and material, and fewer overall crashes due to lower traffic volumes, there are certain disadvantages. Many complex issues, including safety, productivity, and quality, poorer visibility,

higher worker accident rates, higher traffic accident rates, noise disruption, construction nuisances, possibly quality issues, and light pollution, are associated with nighttime operations (Ellis & Kumar, 1993; Elrahman & Perry, 1998; Al-Kaisy & Nassar, 2005; Elrahman, 2008). Table 2.1 summarizes key traffic-related, construction-related, economic, social, and environmental factors that impact the safety, productivity, and quality of nighttime construction and maintenance operations.

2.2 Decision to Work at Nighttime on Highway Work Zones: Current Practice

Nighttime construction is being used increasingly by STAs and other highway agencies to conduct highway maintenance and construction projects. However, the literature review shows that few uniform guidelines or procedures currently exist to assist in deciding when to employ nighttime operations for highway construction and maintenance projects.

Prior research studies indicate that several factors influence roadway construction and maintenance projects performed at night. These factors can be categorized as traffic, construction, economic, economic, and social-related factors (Elrahman & Perry, 1998; Elrahman, 2008). Traffic and construction-related factors are closely related to the operations on and off the work zone. For instance, traffic-related factors address issues of congestion, safety, and traffic control of nighttime operations, while construction-related factors focus on the quality and productivity of the works. Another critical factor is lighting because it affects nearly every aspect of nighttime work. For instance, reduced lighting on the work zone can directly impact the safety of work crews and motorists. The absence of natural lighting reduces the visibility and awareness of work crews, may decrease productivity, and increases project costs due to additional lighting expenses, worker premiums and overtime payments, and placement of additional traffic control devices (Mostafavi et al., 2012). Abraham et al. (2007) categorized factors affecting safety in nighttime operations as uncontrollable and controllable. Uncontrollable factors, such as driver impairments (i.e., drowsy or drunk driving) and worker fatigue, can endanger the work crew's safety.

On the other hand, controllable factors, such as adequate lighting for workers' visibility, and traffic work zone set-up for intrusions of motorists, can minimize unsafe conditions on nighttime job sites. Several studies have been done since 1990 describing distinct factors related with nighttime work and have provided recommendations to enhance work zone safety of roadway

operations performed at night. The decision to conduct nighttime highway construction and maintenance projects varies from State to State and largely depend on how much traffic can be allowed to back up, what the public will tolerate, and the characteristics of the highway system (for instance, the road geometry characteristics) in question (Ellis & Kumar, 1993).

Table 2.1. Advantages and Disadvantages of Nighttime Highway Work Zones.

Traffic-related factors	Advantages	Disadvantages
Congestion	• There is a significant decrease in traffic congestion and work-related delays and stops (Hancher & Taylor, 2001). • Roadway operations scheduled at night reduce or avoid the adverse effects of work zones' traffic congestion and traveling public delays (Al-Kaisy & Nassar, 2005; Elrahman, 2008).	
Safety	• Lower levels of traffic tend to keep work zone crash rates low (Park et al. 2002; Elrahman 2008) • Workers are more aware of hazards at night, and they tend to be more conscious of nighttime safety procedures and practices. (Elrahman 2008)	• Poor visibility, inadequate lighting, worker fatigue, and impaired drivers increase accident risks at nighttime work zones (Rebholz et al., 2004). • Inherent work zone restrictions such as delimited areas, distraction/lack of visibility of drivers due to ongoing operations, and lack of familiarity with traffic control along the work zone increase the traffic accident rates (Rebholz et al., 2004). • Less traffic at night encourages motorists to speed, resulting in high risk and severity of traffic accidents (Elrahman & Perry, 1998; Rebholz et al., 2004). • Glare can be dangerous to motorists and annoying to residents in the vicinity of the nighttime operations (Elrahman & Perry, 1998; Elrahman, 2008).
Traffic Control	• There is increased flexibility and expeditious movement of traffic through the work zone due to lower traffic interference and improved level of service (Elrahman & Perry, 1998; Rebholz et al., 2004; Elrahman, 2008).	• The need for improved traffic control strategies at work zones might add additional cost and time to projects (Rebholz et al., 2004; Elrahman, 2008) • Placing and removing traffic control devices and lighting systems are complex, and if they cannot be removed by the end of the night shifts, opening lanes for traffic may become dangerous to motorists (Elrahman, 2008).

Table 2.1. continued

Construction-related factors	Advantages	Disadvantages
Quality	• A high level of work quality can be achieved as during the day when adequate illuminance levels are provided at the work zone (Elrahman, 2008; Ogunrinde et al., 2020). • Enhanced working conditions in high-temperature zones due to cooler nighttime temperatures (Shepard & Cottrell, 1986).	
Productivity	• Reduced traffic interference and longer work shifts affect nighttime construction productivity and efficiency (Hancher & Taylor, 2001; Elrahman, 2008). • Material delivery (concrete or asphalt) are likely to be more efficient at night (Ellis, 2001).	• Productivity is slightly impacted during nighttime operations due to reduced visibility on the work zone (Al-Kaisy & Nassar, 2005). • Communication between field and office personnel may be difficult during nighttime operations (Hancher & Taylor, 2001; Elrahman, 2008).
Equipment Repair		• Additional effort should be put to develop contingency plans for dealing with the breakdown of major piece of equipment during nighttime hours (Hancher & Taylor, 2001).
Work Operations	• The possibility of having both daytime and nighttime shifts may reduce the project duration (Elrahman, 2008).	• Scheduling field and office personnel may be more challenging at night. State and local policies may restrict nighttime operations. Nighttime operations may also be restricted by unions and material suppliers (Hancher & Taylor, 2001; Elrahman, 2008).
Economic Factors	Advantages	Disadvantages
Business Cost	• Businesses near work zones with low traffic volume may experience reduced economic impacts during nighttime shifts (Douglas & Park, 2003).	• Trucking and shipping companies that rely heavily on nighttime services may be harmed, as nighttime roadway operations may cause travel times to be extended (Elrahman, 2008).
User Cost	• There may be significant economic benefits of users' travel time and vehicle operating costs produced by nighttime work due to less traffic disruption (Holguín-Veras et al., 2003).	

Table 2.1. continued

Economic Factors	Advantages	Disadvantages
Construction Cost	• Selecting an appropriate work zone type can reduce traffic interference and increase operational efficiency (Elrahman & Perry, 1998).	• Nighttime operations may be more expensive, in part because of overtime charges, night premium pay, lighting expenses, and enhanced traffic control costs (Al-Kaisy & Nassar, 2005; Mostafavi et al., 2012)
Social and Environmental factors	Advantages	Disadvantages
Driver Condition		• Concerns over driver fatigue, impaired drivers, and drivers unfamiliar with the work zone layout increase at night (Higa & Kim, 2013).
Worker Health	• The health of workers may be affected positively by lower exposure to automotive emissions caused by decreased congestion (Elrahman, 2008).	• There are concerns about possible declines in worker attention and overall health due to disrupting the body's natural circadian rhythms (Shane et al., 2012). • Workers frequently perceive that travel speeds are faster at night and that their safety is put at risk during nighttime operations (Elrahman, 2008) • Workers' quality of life may be affected due to reduced social- and family-interaction opportunities (Shane et al., 2012).
Noise, Vibration, Light Pollution, Fuel Consumption, and Air Quality	• Nuisances can be mitigated by proper planning and administration of nighttime operations (Shane et al., 2012). • Public participation enables identifying and resolving potential problems before they become major issues (Schexnayder, 2011). • Less fuel is burned by cars since idling is reduced due to lower congestion (Elrahman, 2008).	• Nighttime work may cause noise, vibration, light, and other disturbances to neighboring communities (Schexnayder, 2011).

In 1990, the University of Washington surveyed State Highway Agencies and contractors to investigate the relative importance of different factors when roadway construction work needs to be performed at night and examine the primary concerns of using a nighttime construction schedule (Hinze & Carlisle, 1990). Twelve factors influencing the decision to require nighttime work were identified. The survey results indicated that traffic congestion is the most important factor, followed by safety, while the project's cost is relatively minor. The survey also assessed the respondents' perceptions of the effectiveness of traffic control devices during nighttime operations on a 7-point scale. Lighting was deemed the most effective method of providing safety to workers and motorists during total and partial road closures, followed by signs and sequential arrow boards, as shown in Table 2.2.

Table 2.2. Importance of traffic control devices on nighttime construction projects (Hinze & Carlisle, 1990).

Traffic Control Device	Total Road Closure	Partial Road Closure
Lighting	6.39	6.59
Signs	6.24	6.41
Sequential Arrow Board	6.06	6.41
Physical Barriers	5.94	6.09
Changing Message Sign	5.76	5.91
Safety Vests	5.48	6.32
Reflectorized Cones	5.31	5.91
Police Patrol	5.06	5.65
Flaggers	3.94	4.91

In 2000, The Kentucky Transportation Cabinet (KyTC) surveyed several state transportation agencies, Kentucky highway contractors, and resident engineers to determine nighttime construction practices, the factors that influence the decision to work at night, the impact that nighttime work has on the project's schedule, cost, and safety, and the impact that nighttime work has on the quality and productivity of specific construction activities (Hancher & Taylor, 2001). Survey results indicated that high daytime traffic level is the primary consideration in selecting nighttime operations for highway projects among the participants. The authors also reported that quality, lighting, and safety as common problems encountered at nighttime work zones between the three groups, as shown in Table 2.3. They stressed the importance of carefully selecting lighting

systems for activities occurring on or near the roadway to minimize glare for both workers and motorists.

Table 2.3. Top five issues encountered at nighttime work zones (Hancher & Taylor, 2001).

State Transportation Agencies	Contractor	KyTC resident engineers
1. Quality	1. Quality	1. Safety
2. Lighting	2. Lighting	2. Lighting
3. Safety	3. Safety	3. Quality
4. Productivity	4. Equipment maintenance	4. Employee morale
5. Public irritation	5. Productivity	5. Traffic control

As part of developing a model to improve the decision-making process concerning daytime versus nighttime construction and maintenance operations, the Oregon Department of Transportation (ODOT) personnel surveyed employees from ODOT, roadway contractors, and other state transportation agencies' personnel involved in nighttime construction and maintenance projects to rate and rank relevant factors that influence the decision to undertake nighttime projects (Park et al., 2002). The survey included 19 factors identified through the literature review. These factors were rated on a 7-point scale and ranked from 1 to 19 regarding the importance of the decision-making process. As shown in Table 2.4, the survey results indicated that safety, traffic control, and congestion were the most important factors influencing the decision to undertake nighttime roadway operations. Similarly, air quality and fuel consumption were rated as the least important. Lighting was rated 4th in the level of importance and ranked 8th out of 19 factors.

Table 2.4. Relevant factors in the decision-making process concerning daytime vs. nighttime roadway operations (Park et al., 2002).

Factor	Average Rating – Scale (1-7)	Factor	Average Ranking – Scale (1-19)
Safety	6.44	Safety	1.90
Traffic control	6.07	Traffic control	3.94
Congestion	5.98	Congestion	5.06
Lighting	5.84	Quality	6.18
Quality	5.40	Productivity	7.54
Public relations	5.32	Worker condition	7.61

Table 2.4. continued

Factor	Average Rating – Scale (1-7)	Factor	Average Ranking – Scale (1-19)
Worker condition	5.19	Driver condition	8.05
Productivity	5.11	Lighting	8.93
Driver condition	5.07	Public relations	9.62
Scheduling	5.04	Construction cost	9.74
Accident cost	4.94	Scheduling	10.53
Construction cost	4.92	Noise	11.23
Noise	4.70	Accident cost	11.44
Communication supervision	4.64	User cost	12.21
User cost	4.57	Communication supervision	12.34
Availability of material and equipment	4.52	Maintenance cost	13.39
Maintenance costs	4.46	Availability of material and equipment	13.54
Air quality	3.27	Air quality	14.89
Fuel consumption	2.89	Fuel consumption	16.12

2.3 Lighting Requirements for Nighttime Highway Work Zones

Prior research has identified lighting as a critical factor when planning nighttime roadway construction operations. Work zone lighting affects the work zone safety, the quality of constructed product or facility, the productivity of work crews, and worker morale (Bryden & Mace, 2002b). Work zone lighting also influences traffic control, safety, and human factors (Ellis & Kumar, 1993; Al-Kaisy & Nassar, 2005). This section provides a general overview of key terms related to work zone lighting. While the requirements for fixed roadway lighting are distinct from those for the work zone lighting, there are some similarities in the design criteria, procedures, and variables used, necessitating a discussion of roadway lighting in this section.

2.3.1 Illuminance

Illuminance is the density of luminous flux (time rate of light flow) that falls upon a surface area and is measured in lumens/ft^2 (or lumens/m^2) or foot-candle (or lux). Illuminance can be

measured using an illuminance meter (or a light-sensitive cell), as shown in Figure 2.1. The surface orientation can be either horizontal or vertical, and therefore, illuminance can be classified as horizontal illuminance or vertical illuminance (Shane et al. 2012; IES 2018). Illuminance is affected mainly by the number and the intensity of the light sources and the distance between light source(s) and the surface area (El-Rayes et al., 2003; Ellis et al., 2003). Appropriate illuminance levels should be provided in work zones to ensure adequate lighting conditions for nighttime operations. Minimum illuminance levels covering most highway- and bridge-related nighttime works range from 54 to 216 lx. These recommended illuminance values are intended to satisfy safety requirements and provide a guide for efficient visual performance (Ellis et al., 2003).

Figure 2.1. Digital illuminance meter (Minolta Konica, 2012).

2.3.2 Light Uniformity

Uniformity evaluates the suitability of lighting arrangements in nighttime work zones and quantifies how light is distributed evenly across the target (Finley et al., 2013). As shown in Equation (2.1), light uniformity is calculated as the ratio between the average illuminance (E_{avg}) and the minimum illuminance (E_{min}) over the relevant area (El-Rayes & Hyari, 2005a). Acceptable values of uniformity ratio specified in existing lighting standards range from 10:1 to 2:1, with 5:1 generally considered suitable for construction activities (Ellis et al., 2003). The maximum ratios of light uniformity should not be exceeded to ensure that light is uniformly distributed over the nighttime work zone.

$$Uniformity\ ratio = \frac{E_{avg}}{E_{min}} \tag{2.1}$$

2.3.3 Luminance

The amount of lighting available for nighttime operations can also be measured through the luminance. Luminance is the amount of luminous flux (light) reflected by a surface and is the light that is used to see an object. The luminance of a surface is determined by the direction from which light strikes it, the direction from which it is viewed, and the surface's reflective properties. For instance, the light reflected by the road surface is termed pavement luminance or roadway luminance. Luminance is measured using a luminance meter as illustrated in Figure 2.2 in candelas/m^2 (cd/m^2) (Ellis et al. 2003; Shane et al. 2012; IES 2018). There are two types of luminance that are relevant in the construction of work zones on roadways: veiling luminance and pavement luminance.

Veiling luminance is produced when scattered light within the eye, caused by high-intensity light sources in the field of view, tends to superimpose a luminous haze on the retina. The effect is similar to looking at the scene through a luminous veil. The luminance of this "veil" on the retina is added to both the task and background luminance, diminishing the contrast between objects and their surroundings. A typical example of veiling luminance is attempting to see beyond oncoming headlights at night.

Pavement luminance provides the motorist with the information necessary to evaluate the visual scene. The luminance of roadway surface ahead of the motorist should satisfy three conditions: (1) an average luminance sufficient to adapt the driver's vision to existing road surface; (2) a minimum illuminance level sufficient to ensure adequate visibility of any object on or near the roadway; and (3) a light uniformity level sufficient to maintain continuity within the visual scene to ensure comfort by eliminating the driver's need for frequent and rapid eye movements. The pavement or roadway luminance is the luminous intensity per unit projected area reflecting off (or emitted from) the roadway surface toward an observer (IES, 2018). Pavement luminance depends on (1) the quantity of light reaching the road surface, (2) the reflection characteristics of the road surface, (3) the angle from which the light strikes the road surface, and (4) the location of the observer (El-Rayes et al., 2003).

Figure 2.2. Digital luminance meter (Minolta Konica, 2015)

Pavement surfaces reflecting light towards the observer may be classified into three groups: (1) ideal specular surface, (2) perfectly diffuse surface, and (3) mixed reflection (see Figure 2.3). The ideal specular surface reflects all the light incident on a point at an angle of reflection equal to the angle of incidence. For instance, light reflected by mirrors and highly polished metal surfaces. On the other hand, a perfectly diffuse surface, regardless of the angle of incidence, reflects light as a cosine function of the angle from normal. A perfectly diffuse surface would appear equally bright to an observer from any viewing angle. Diffuse surfaces include white mat-finished paper or walls finished with flat white paint at incident angles close to zero degrees. However, most surfaces encountered in our daily life fall between the ideal specular and the ideal diffuse surfaces and exhibit characteristics of mixed reflection (King, 1973). For instance, road surfaces do not reflect light diffusely but semi-specularly which means that a portion of the light is reflected secularly and the other portion diffusely (IES, 2018).

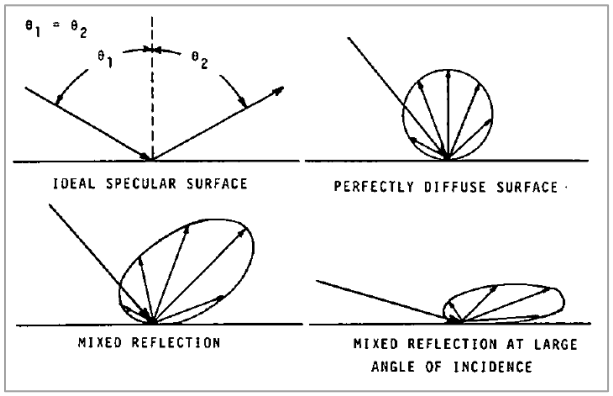


Figure 2.3. Surfaces reflecting light towards the observer (King, 1973).

The calculation of pavement luminance requires information regarding the directional surface reflectance characteristics of the pavement. Thus, the Illumination Engineering Society of North America (IES, 2018) has classified pavement surfaces into four categories based on the reflectance characteristics (Q_0) and the specularity of the pavement, as shown in Table 2.5. For instance, concrete surfaces (R1) show higher reflectance (or Q_0 values) than asphalt surfaces, R2 through R4.

Table 2.5. The Road Surface Classifications (IES, 2018).

Class	Q_0	Description	Mode of Reflectance
R1	0.10	Portland cement concrete road surface. Asphalt road surface with a minimum of 12 percent of the aggregates composed of artificial brightener (e.g., Synopal) aggregates. (Examples: labradorite, quartzite)	Mostly diffuse
R2	0.07	Asphalt road surface with an aggregate composed of a minimum 60 percent gravel (size greater than 1cm). Asphalt road surface with 10 to 15 percent artificial brightener in aggregate mix. (Not normally used in North America)	Mixed (diffuse and specular)
R3	0.07	Asphalt road surface (regular and carpet seal) with dark aggregates (e.g., trap rock, blast furnace slag); rough texture after some months of use (typical highways).	Slightly Specular
R4	0.08	Asphalt road surface with very smooth texture	Mostly Specular

2.3.4 Glare

Glare is the sensation of annoyance, discomfort or loss of visual performance and visibility when the luminance experienced in the visual field is significantly greater than what the observer's eyes are adapted to (El-Rayes et al., 2003; Ellis et al., 2003; Odeh, 2010), as illustrated in Figure 2.4. Glare is determined by the veiling luminance ratio ($V_{L\ ratio}$), which is the maximum veiling luminance divided by the average luminance of the road surface (IES, 2018). The rationale behind using the veiling luminance ratio rather than using an absolute value of veiling luminance is due to the perception of glare is dependent on the amount of veiling luminance reaching the observer's eye, and on the lighting level at which the observer's eyes are adapted before being exposed to that amount of glare (Odeh, 2010). The veiling luminance is a function of the illuminance produced by the glare source, measured at the vertical plane of the observer's eye (vertical illuminance), and

the glare angle, the angle between the object being viewed and the center of glare source (Mace et al., 2001).

Figure 2.4. Example of glare (IES, 2018).

Glare can be classified into two types: disability glare and discomfort glare. Disability glare impairs our vision of objects without necessarily causing discomfort (Vos, 2003). Disability glare occurs due to light scattering within the eye, effectively reducing contrast and, consequently, object visibility (Bryden & Mace, 2002b). The effect is like looking through a luminous veil or attempting to see through approaching headlights at night. Disability glare is based on three factors: (1) illuminance on the eye from the glare source, (2) glare angle between the directions of the glare source and the direction of viewing, and (3) observer's age (Mace et al., 2001).

In contrast, discomfort glare is a term that refers to a bright light that, due to its size and luminance, causes a quantifiable amount of subjective discomfort or annoyance (Mace et al., 2001). This type of glare can increase blink rate to tears and pain but does not reduce visibility. While the disturbing effect on disability glare is a matter of masking by straight light, the disturbing effect on discomfort glare is distraction (Vos, 2003; IES, 2018). Discomfort glare is affected by three major factors: (1) location of glare source relative to the line of sight; (2) luminance of the background; and (3) luminance and size of the glare source leading to illuminance at the observer's eye (Mace et al., 2001). When an observer views a very bright light source such as a sunlit beach or a snow field, it may be perceived as discomfort glare; however, it is an entirely different phenomenon. This phenomenon is defined as dazzling glare, and it is functional protection against

retinal over-exposure, something that may lead to temporary or even permanent blindness due to retinal burn (Vos, 2003).

2.3.5 Light Trespass

Light trespass or obtrusive lighting is defined by three correlated elements: spill light, glare, and sky glow (Lutkevich et al., 2012). Spill light or stray light is the amount of light that leaves a specific site and enters another site. For instance, nighttime lighting on work zones may cause complaints about light trespass from people upset by unwanted light entering their windows or intruding upon their property, as shown in Figure 2.5.

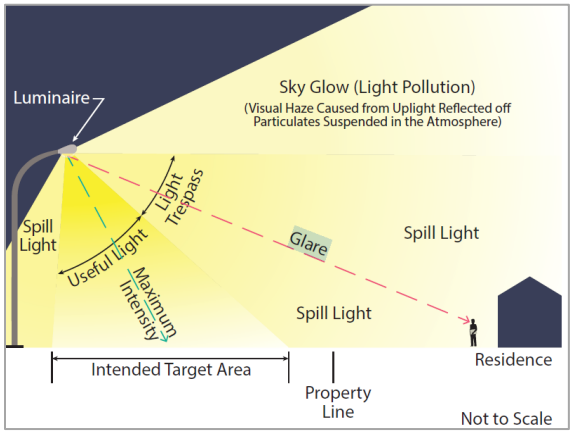


Figure 2.5. Elements of Light Trespass (IES, 2018).

Spill light can be controlled by taking the measurement of vertical illuminance at the property boundary line or the edge of the road allowance (IES, 2018). Sky glow is a term that refers to the increased sky brightness caused by electric light scattering into the atmosphere, most notably from outdoor lighting in urban areas. The IES recommends maximum initial light trespass levels within given areas of brightness in terms of vertical illuminance. The vertical illuminance values should range from 0.5 to 15 lx in lighting zones (LZ-0) to (LZ-4), as shown in Table 2.6, to avoid/reduce light trespass.

Table 2.6. Recommended Maximum Initial Vertical Illuminance Light Trespass from Exterior Lighting , Based on Lighting Zone (IES, 2018).

Lighting Zone (LZ)	Recommended Uses or Areas	Maximum Initial Vertical Illuminance, lx (fc)*
LZ-0	Areas in which permanent lighting is not expected and when used, is limited in the amount of lighting and the period of operation. It includes wilderness areas, parks, and preserves, and undeveloped rural areas.	0.5 (0.05)
LZ-1	Areas that desire low ambient lighting levels. It includes rural and residential areas. It includes rural and residential areas.	1.0 (0.1)
LZ-2	Areas with moderately high lighting levels. It includes commercial business districts and high density or mixed-use residential districts.	3.0 (0.3)
LZ-3	Areas with moderately high lighting levels. It includes large cities' business districts.	8.0 (0.7)
LZ-4	Areas of very high ambient lighting levels. It includes high intensity business or industrial zone districts.	15.0 (1.4)

Note: (*) Maximum at any point in the vertical plane of the property line.

2.3.6 Visibility

Visibility was cited as the primary concern when working at night (Al-Kaisy & Nassar, 2005). The primary goal of any lighting design is to create an environment in which people can perform effectively, efficiently, and comfortably through their sense of vision. When designing a lighting system for nighttime roadway operations, it is crucial that workers are visible to the motorists who travel through the work zone. Visibility and visual perception of the observer are greatly affected by factors such as contrast sensitivity, visual acuity, glare, and age.

Contrast sensitivity refers to the eye's ability to distinguish between objects, visual tasks, and backgrounds of varying luminance (IES, 2018). If the object's luminance is greater than the background, it is said to have positive contrast, but if the object's luminance is less than the background, it is said to have negative contrast (See Figure 2.6). Increased luminance levels increase object's contrast. With increased contrast sensitivity, the eye can distinguish objects or visual tasks that have a low contrast against their background. On the contrary, task visibility may fall below the threshold when contrast is extremely low, making it unlikely that the task will be

seen. Threshold contrast is calculated using the probability of detecting an object 50% of the time (Lutkevich et al., 2012). Contrast is calculated using Equation (2.2).

$$C = \frac{L_t - L_b}{L_b} \tag{2.2}$$

where

C = contrast.

L_t = luminance of the target or object to be seen (in candela per square meters; cd/m^2).

L_b = luminance of the target's or object's background (in candela per square meters; cd/m^2).

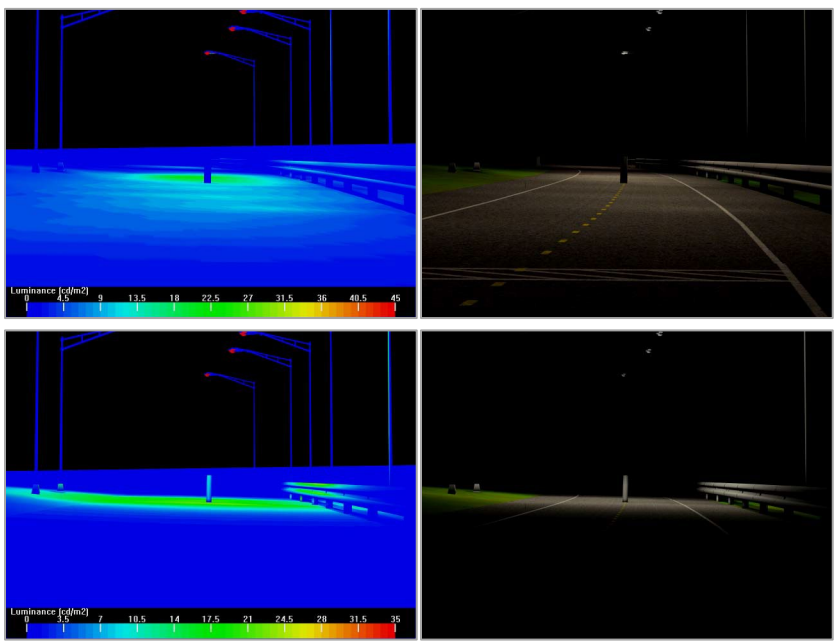


Figure 2.6. Contrast Sensitivity (negative contrast in the top two images and positive images in the bottom two images) (Lutkevich et al., 2012).

Visual acuity is a metric that indicates an individual's ability to distinguish detail under specific conditions. It is affected, by contrast, both luminance and spectral. Since large objects have a lower contrast threshold than small objects of equal luminance, they are easier to see. Color rendition-enhanced light sources increase color contrast and make small objects easier to distinguish from their backgrounds (IES, 2018). Non-uniformities in the observer's field of view, particularly those caused by bright sources, influence the eye's adaptation level. For instance, when an equipment operator's scan moves from well-lit nearby tasks to more distant tasks with little or no lighting in a construction work zone, the adaptation level is constantly changing; this

phenomenon is called *transient adaptation*. Transient adaptation is the phenomenon of decreased visibility after viewing a luminance that is greater or less than that of the task (Ellis et al., 2003). With age, contrast sensitivity decreases, and the eye's sensitivity to blue light decreases. Also, with age, the sensitivity to glare increases. While younger individuals have little difficulty distinguishing details in the vicinity of a glare source, older individuals face significant difficulties. Both visual functions exhibit a significant decrease in sensitivity after the observer's age of 40 (Mace et al., 2001; Vos, 2003).

2.4 Safety Issues of Work Zone Lighting

Inadequate lighting on roadway work zones increases the probability of accidents. The most obvious incidents on nighttime operations are safety-related. They include vehicle intrusions into work zones, workers struck by intruding vehicles, workers struck by construction equipment, and intrusion into operational lanes (Shane et al., 2012). "Struck-by" events occurring on and off the work area because of poor lighting conditions are the major cause of worker accidents (Arditi & Shi, 2003). Poor lighting conditions impede workers from seeing other workers on-site and may hinder their abilities to operate equipment safely. Similarly, inadequate lighting conditions and arrangements cause glare to motorists when passing the work zone and may impair their visibility (Rebholz et al., 2004).

2.4.1 Causes of Glare on Nighttime Highway Work Zones

Glare is one of the major issues related to nighttime highway work zone lighting. Glare can be produced by (1) fixed road lighting, (2) vehicles' headlights, and (3) construction and lighting equipment on the work zone (Ellis et al., 2003; IES, 2018).

Roadway lighting is a significant source of glare for drivers and motorists. Glare from roadway lighting has a greater effect as the luminance of the glare source increases, the luminance of the pavement decreases, and the glare angle between the light source and the observer's line of sight decreases (Mace et al. 2001; IES 2018). Three factors affect the glare angle and its effect on the overall level of glare perceived by drivers: the distance between the driver and the light source, the light source's mounting height in relation to the observer's height, and the light's aiming (Bryden & Mace, 2002a). Glare is intensified in urban and semi-urban areas with roadway lighting

because roadway or street lighting increases the pavement luminance value. On the other hand, rural areas often lack or have no roadway lighting, and glare creates a unique condition as a result of the abrupt transition from a dark environment to a well-lit one and then back to darkness as one passes through a work zone (Ellis et al., 2003).

Vehicle headlights are also another major cause of glare in nighttime driving. Factors that affect the levels of glare caused by vehicles headlight include the intensity of the headlights, glare angle, background luminance, size of the glare source, glare source luminance, driver age, and other reflective surfaces (Mace et al., 2001). The closer the observer is to approaching headlights, the greater the illuminance levels, consequently, the more glare. Glare angle is dependent on the distance between opposing and observer vehicles, the road geometry, and the offset of opposing vehicle paths. In general, the glare angle is smallest when the opposing vehicle is the furthest away, which results in low illumination. However, the glare angle becomes large enough to mitigate the glare effect when the opposing vehicle approaches, and the illumination increase significantly. The luminance of the background is typically determined by pavement luminance. For instance, concrete pavements are more reflective than asphalt pavements and thus have a higher luminance; however, pavement reflectivity is affected by wear and other factors (Mace et al. 2001; Adrian and Jobanputra 2005).

Nighttime construction work zones can also cause glare. Several factors affect glare levels in and around the work zone, including the type and wattage of the lighting equipment, the location of the lighting equipment in the work zone, the offset distance respecting motorists and working crews, the aiming angle of the luminaires, and the mounting height of the luminaires (El-Rayes et al. 2003; Ellis et al. 2003; El-Rayes and Hyari 2005a).

2.4.2 Glare Calculations

A few prior studies have reported various methodologies to measure, quantify, and calculate disability and discomfort glare. The following subsections will describe the methods used to quantify and measure disability and discomfort glare.

Disability Glare Calculation

The most common formula for calculating disability glare resulted from several studies made by Holladay in 1926. Later, Stiles et al. (1934) confirmed and extended Holladay's studies. The initial Holladay formula did not consider driver's age and is also limited to an angular range of one degree up to 30 degrees (Vos, 2003). In 1990, IJspeert et al. determined that the value of the coefficient "k", which accounted for the observer's age, increases sharply beyond 70 years of age. The Illuminating Engineering Society (IES, 2018) suggests using the initial Stiles-Halladay formula in combinations with the aging factor "*k*" for determining disability glare for a point glare source. Equations (2.3), (2.4), and (2.5) show the calculation of the veiling luminance (L_v) due to one single light source, glare angle, and aging factor, respectively.

$$L_v = k * \frac{E_{glare}}{\theta^n} \tag{2.3}$$

where

L_v = veiling luminance from one individual luminaire.

E_{glare} = illuminance upon the eye by the (small) glare source.

θ = glare angle, between the directions of the glare source and the direction of viewing. With L_v and E in compatible units (candela/m^2 and lux, respectively) and θ in degrees, as shown in Figure 2.7.

n = variable dependent on the glare angle θ.

$$n = 2.3 - 0.7 \log_{10} \theta \quad for\ \theta < 2°;\ n = 2 \quad for\ \theta \geq 2° \tag{2.4}$$

k = aging factor. The aging factor k has a value of 10 for a 25-year-old-observer. It is important to point out, that the coefficient "*k*" increases with observer's age, as shown in Equation (2.5). For instance, a sharp increase of the calculated veiling luminance is noted for observer's age beyond 70.

$$k = 10\left[1 + \left(\frac{Age}{70}\right)^4\right] \tag{2.5}$$

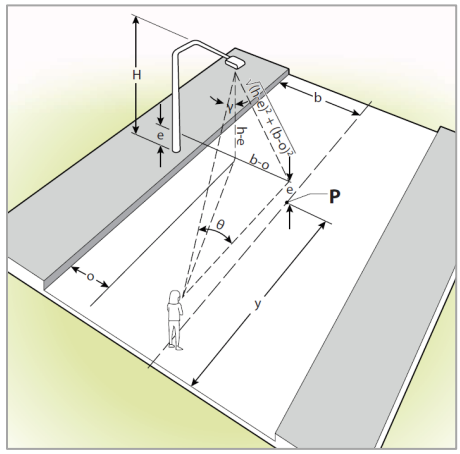


Figure 2.7. Geometric relationships for calculating veiling luminance (IES, 2018).

The International Commission on Illumination, abbreviated as CIE from its French title Commission Internationale de l'Eclairage (CIE, 2002), set up a committee to update the Stiles-Holladay equation. The results were three disabling glare equations that are an extension of the classic Stiles-Holladay equation which considers the effect of age and the effect of ocular pigmentation (Vos, 2003). The first formula is the CIE Age-adjusted Stiles-Holladay Disability Glare Equation (2.6), in the glare angle between 1° < θ < 30° and n = 2.

$$\left[\frac{L_{veil}}{E_{glare}}\right]_{Age-adjusted\ Stiles-Holladay} = 10\left[1+\left(\frac{Age}{70}\right)^4\right]*\frac{1}{\theta^2} \tag{2.6}$$

where

L_{veil} = the veiling luminance (in cd/m^2)

E_{glare} = illuminance at the observer's eye (in lx)

Age = the observer's age (in years)

θ = the angle between the line of sight and the glare source (in degrees)

The second formula is the CIE Small Angle Disability Glare Equation (2.7) that accounts for glare angles relative down to about 0.1 degree (i.e., down to where the domain of refractive errors starts and occurs when the eye is unable to bend and focus light appropriately onto the retina). The validity domain is 0.1° < θ < 30° and $n = 2.3 - 0.7\log_{10}\theta$; $for\ \theta < 2°$.

$$\left[\frac{L_{veil}}{E_{glare}}\right]_{small\ angle} = \frac{10}{\theta^3} + \left[1 + \left(\frac{Age}{62.5}\right)^4\right] * \frac{5}{\theta^2} \tag{2.7}$$

The third formula is the CIE General Disability Glare Equation (2.8) with full range validity domain of glare angle $0.1° < \theta < 100°$.

$$\left[\frac{L_{veil}}{E_{glare}}\right]_{general} = \frac{10}{\theta^3} + \left[1 + \left(\frac{Age}{62.5}\right)^4\right] * \left[\frac{5}{\theta^2} + 0.1\frac{p}{\theta}\right] + 0.025p \tag{2.8}$$

where

p = the eye pigmentation factor, which ranges from 0 to 1.2. The p values of 0, 0.5, 1.0, and 1.2 are for black, brown, light blue, and very light blue eye colors, respectively. This equation describes the fanning out effect caused by eye color differences greater than about 30°. At large glare angles, the light blue color of the eye reflects more disability glare.

An alternative method to determining disability glare is the Threshold Increment (TI). The CIE mainly uses this method for roadway lighting calculations. As mentioned in Section 2.3.6, when the contrast between an object and its background is said to be at threshold, the probability of detection is 50 percent. If a glare source is added, visibility will drop below the threshold. The contrast must be increased to revert to the 50 percent probability condition threshold. The magnitude of the contrast increase is a measure of disability glare. The threshold increment describes the percentage increase in threshold luminance due to the addition of a glare source as, shown in Equation (2.9). In other words, it indicates how much brighter an object must be in percentage terms to be seen in the same condition with or without a glare source present (IES, 2018). Figure 2.8 shows the TI in percent as a function of the veiling luminance and the average pavement luminance for an object subtending 8 inches of arc.

$$TI = 60.275\left(\frac{L_v}{L^{0.862}}\right) \tag{2.9}$$

where

TI = Threshold Increment in percentage (%)

L = Average pavement luminance (in cd/m^2)

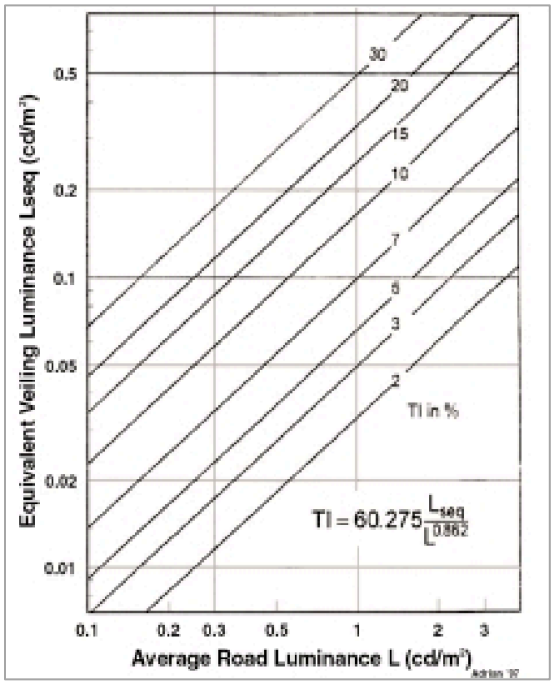


Figure 2.8. Threshold Increments for different levels of veiling luminance and pavement luminance (Adrian & Schreuder, 1970).

Discomfort Glare Calculation

The most popular method to measure discomfort glare was originated in the automotive industry. Discomfort glare was measured using a subjective scale developed by de Boer & Schreuder (1967). This method employs a nine-point scale with qualifiers at the odd points, as shown in Table 2.7.

Table 2.7. The De Boer nine-point scale for discomfort glare.

Glare mark	Glare appraisal
9	Unnoticeable
7	Satisfactory
5	Just acceptable
3	Disturbing
1	Unbearable

Schmidt-Clausen & Bindels (1974) continued and improved the work made by Boer and Schreuder. These researchers developed a mathematical equation that predicts the mean of de Boer rating of a light source using (1) adaptation luminance, (2) illuminance directed toward the

observer's eye; and (3) the angle between the observer's line of sight and the glare source (glare angle), as shown in Equation (2.10).

$$W = 5.0 - 2.0LOG \frac{E_i}{0.003 * \left(1 + \sqrt{\frac{L_a}{0.04}}\right) * \theta_i^{0.46}} \tag{2.10}$$

where

W = mean of the deBoer's scale (1 to 9).

L_a = adaptation luminance (in candela per square meter).

E_i = illumination directed toward the observer's eye from the *i*th source (in lx).

θ_i = glare angle between observer's line of sight and the *i*th source (minutes of arc).

Olson & Sivak (1984) conducted a study to collect discomfort ratings in a realistic scenario when two cars meet to determine whether the Schmidt-Clausen & Bindels' equation applied to these conditions. The researchers discovered that the mean ratings were more comfortable by one or two scale intervals than predicted. Similarly, Porter et al. (2005) evaluated the applicability of the Schmidt-Clausen & Bindels' equation using the mean discomfort ratings obtained from eleven vision enhancement systems (VES) that combined high intensive discharge (HID), ultraviolet A (UV-A), and halogen lamps in driving scenarios with oncoming glare. The researchers concluded that the average de Boer rating in a realistic driving environment could be reasonably predicted using one of the variations of the Schmidt-Clausen & Bindels' equation calculated by the linear regressions to the VES data. The Schmidt-Clausen & Bindels' equation variations are shown in Equations (2.11) and (2.12). Equation (2.11) is based on the maximum illumination experienced, and Equation (2.12) one is based on the last illumination experienced.

$$W = 6.79 - 2.0LOG \frac{E_{max}}{0.003 * \left(1 + \sqrt{\frac{L_a}{0.04}}\right) * \theta_{max}^{0.46}} \tag{2.11}$$

where

W = mean of the deBoer's scale (1 to 9).

E_{max} = maximum illumination level directed toward the observer's eye from the headlamps (in lx).

θ_{max} = glare angle between observer's line of sight and the headlamps at a location where maximum illumination occurs (minutes of arc).

L_a = adaptation luminance (in cd/m^2).

$$W = 6.61 - 2.08LOG \frac{E_{last}}{0.003 * \left(1 + \sqrt{\frac{L_a}{0.04}}\right) * \theta_{last}^{0.46}} \tag{2.12}$$

where

W = mean of the deBoer's scale.

E_{last} = last level of illumination directed toward the observer's eye from the headlamps (in lx).

θ_{last} = glare angle between observer's line of sight and last location (minutes of arc).

L_a = adaptation luminance (in candela per square meter).

Van Bommel & De Boer (1980) investigated discomfort glare for roadway lighting in both static and dynamic models that the CIE accepted as the Glare Control Mark formula (CIE, 1976 & 1995) as shown in Equation (2.13). Glare Control Mark (G) is based on the installation characteristics (number of luminaries per kilometer, reduced mounting height of luminaires, color, and directional radiation pattern of light sources), projected area of the luminaires, the intensity in the direction of an approaching vehicle driver, and the average road luminance (L_{av}).

$$G = 13.84 - 3.3 \log I_{80} + 1.3 \left(\log \frac{I_{80}}{I_{88}}\right)^{0.5} - 0.08 \log \frac{I_{80}}{I_{88}} + 1.29 \log F + C + 0.97 \log L_{av} + 4.41 \log h' - 1.46 \log p \tag{2.13}$$

where

G = glare evaluated on a nine-point scale.

I_{80} = the luminous intensity of a luminaire emitted in a direction with an angle of 80˚ with respect to the downward vertical (cd).

I_{88} = the luminous intensity of a luminaire emitted in a direction with an angle of 88˚ with respect to the downward vertical (cd).

F = the area of the projected light-emitting surface of the luminaire in the direction of 76˚ with respect to the downward vertical in the road axis parallel meridian plane (m^2).

C = a color factor. C=0.4 for low-pressure sodium lamps and C=0 for other light sources.

L_{av} = the average road surface luminance (cd/m^2).

h' = the reduced mounting height of the luminaires (the actual mounting height minus 1.5 m, which represents the eye height of the observer) (m).

p = the number of luminaires per km.

This formula is applicable to installations of one or two luminaire(s) rows along the road axis direction that exceed 300 meters, and is valid within the ranges specified below:

1. $50 < I_{80} < 7000$ (in candelas; cd)
2. $1 < I_{80}/I_{88} < 50$
3. $.007 < F < 0.4$ (in square meters; m^2)
4. $.03 < L_{av} < 7$ (in candela per square meters; cd/m^2)
5. $5 < h' < 20$ (in meters; m)
6. $20 < p < 100$

Vos (2003) expressed the Glare Control Mark (GM) in a condensed form as shown in Equation (2.14). Glare Control Mark (GM) diminishes with discomfort and is evaluated using the following scale: GM = 1: bad, GM = 3: inadequate, GM = 5: fair, GM = 7: good, GM = 9: excellent.

$$GM = F + 1.29logA_{14} - 3.31logI_{10} + 0.97logL_{rd} \quad (2.14)$$

where

F = a value which is determined by the installation characteristics (number of light points per km, suspension height, color, and directional radiation pattern.

A_{14} = is the projected area of the luminaires (m^2) visible at 14˚ below the horizontal.

I_{10} = the intensity (cd) in the direction of an approaching car driver at 10˚ below the horizontal line of view.

L_{rd} = the average road luminance (cd/m^2).

The International Commission on Illumination (L'Èclairage, 1994) developed a method for evaluating glare for outdoor sports lighting and area lighting applications. This system can be used to assess the glare rating of existing installations and to forecast the glare rating during the design stage of new installations. The Glare Rating (GR) calculation grid indicates the amount of glare experienced by the observer at each point in the grid based on the veiling luminance produced

by the luminaires and the surrounding environment (ground plane only). The observer's gaze determines it as he or she examines each point on a horizontal illuminance grid. Glare ratings are applied to horizontal grids of points below eye level and are commonly used in outdoor areas and sports lighting applications, as illustrated in Figure 2.9.

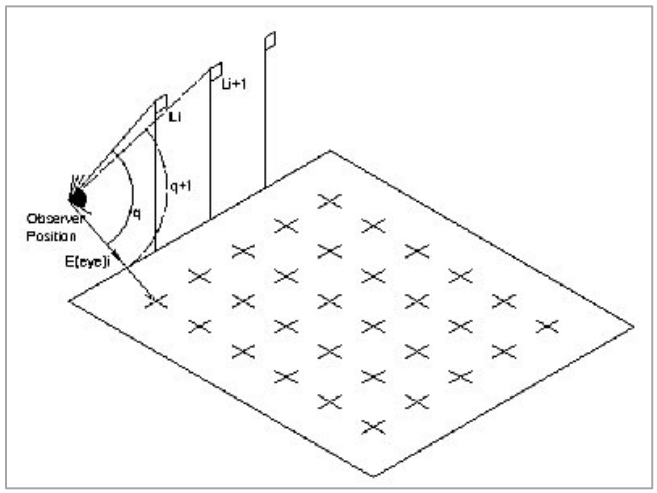


Figure 2.9. Glare rating grid and observer position (Lighting Analysts Inc., 2021).

The glare rating (GR) is given by Equation (2.15). where L_{VL} defined as the veiling luminance on the observer's eye produced by the luminaires for one single point, and L_{VE} is defined as the veiling luminance produced by the environment.

$$GR = 27 + 24\log\left(\frac{L_{VL}}{{L_{VE}}^{0.9}}\right) \tag{2.15}$$

Veiling luminance produced by the luminaires is given by Equation (2.16) where i is the current luminaire being considered, n is the total number of luminaires in the job site, $E_{(eye)i}$ is the illuminance produced on the observer's eye in a plane perpendicular to the line of sight and produced by the ith light source, and q_i defined as the angle between the observer's line of sight and the direction of light.

$$L_{VL} = 10\sum_{i=1}^{n}\frac{E_{(eye)_i}}{(q_i)^2} \tag{2.16}$$

Veiling luminance produced by the environment is given by Equation (2.17), where ρ is the reflectance of the area assuming diffuse reflection, Ω_0 is the unity solid angle in steradians, and $E_{hor,av}$ as average horizontal area illuminance (ground plane).

$$L_{VE} = 0.035 * \left[\frac{E_{hor,av} * \rho}{(\pi * \Omega_0)}\right] \tag{2.17}$$

Glare control Mark (G) and Glare rating (GR) are related through Equation (2.18). The higher the value of the G marker, the better the glare restriction provided by the installation. The glare assessment scale visualizes the differences in glare rating values.

$$GR = (10 - G) * 10 \tag{2.18}$$

2.5 Recent and Ongoing Research for Determining and Evaluating Glare in Work Zones

Several studies have been done to determine disability glare at nighttime work zones. Hyari and El-Rayes (2006) conducted a series of field experiments at the Advanced Transportation Research and Engineering Laboratory (ATREL) in Illinois to identify practical and adequate lighting arrangements for nighttime work zones and assess their compliance with existing standards and lighting design criteria mandated by several State Transportation Agencies. For the field tests, two distinct activity areas were chosen. A short two-lane area (7m x 30m) required the installation of two light towers, while a larger two-lane area (7m x 75m) required the installation of at least three light towers. Each light tower was equipped with four 1,000-watt metal halide luminaires and had a vertical extension of 7.8 meters. These experiments examined five parameters (1) the distance between light towers, (2) the offset distance between the light tower and the work zone's edge, (3) the mounting height of luminaires, (4) the aiming angle of luminaires, and (5) the luminaire's rotation angle. Twenty-five (25) lighting arrangements resulted from combining these parameters. The work zone areas were divided into grids of equally spaced points (3 m). During the field experiments, researchers found that only four lighting combinations were found to be practical to set up on-site and successful in satisfying the specified lighting performance criteria. Measurements of veiling luminance and pavement luminance were made following the IES recommendations. The findings indicated that when the distance between light towers was reduced

from 30 to 20 meters, the aiming angles of the four luminaires were reduced from 20° to 0°, and the mounting height was maintained at 7.8 meters, glare levels decreased (veiling luminance ratios decreased from 0.11 to 0.04), and when the luminaires' aiming angle was increased from 20° to 45° and varying the rotation angle of one of the luminaires in the two exterior tower, glare levels increased (veiling luminance ratios were up from 0.12 to 0.2).

Odeh et al. (2009) also conducted field tests to determine and quantify disability glare and lighting performance induced by light towers at nighttime work zones. An experimental lighting design of a simulated work zone at the Illinois Center for Transportation (ICT) sought mainly to analyze the effect of the mounting height of the light tower (H), the aiming angle of the luminaires (AA), and the rotation angle (RA) on glare levels produced by light towers. A two-lane segment (405 m) without street lighting was selected to simulate a typical lane closure work zone. Fourteen (14) different lighting arrangements were set up using a typical metal-halide light tower equipped with four 1,000-W luminaires. Lighting parameters were set up as follows: mounting height (H) of 5 and 8 meters, rotation angle (RA) at 0, 20, and 45 degrees, aiming angle (AA) at 0, 20, and 45 degrees, and the light tower was placed in the middle of the closed lane. Disability glare was determined by the veiling luminance ratio and measured on a grid of equally spaced points of 5 meters within both lanes. In two cases, the veiling luminance ratios exceeded the recommended 0.4 limits for the IES's roadway lighting design. Disability glare levels increased as motorists approached the light tower and reached a peak between 10 and 25 meters from the light tower, and it decreased steadily as the mounting height increased. For instance, when RA was 0° and AA was 45°, disability glare at the first line of sight was reduced by 64% when the mounting height was increased from 5 to 8.5 m, as shown in Figure 2.10. The increase of aiming angle (AA) of luminaries from 0° to 20° and 45° caused a significant increase in glare experienced by motorists. Furthermore, the results indicated that the effect of the RA on the veiling luminance ratio was dependent on the AA of luminaries. The study was limited to analyzing a conventional metal halide light tower.

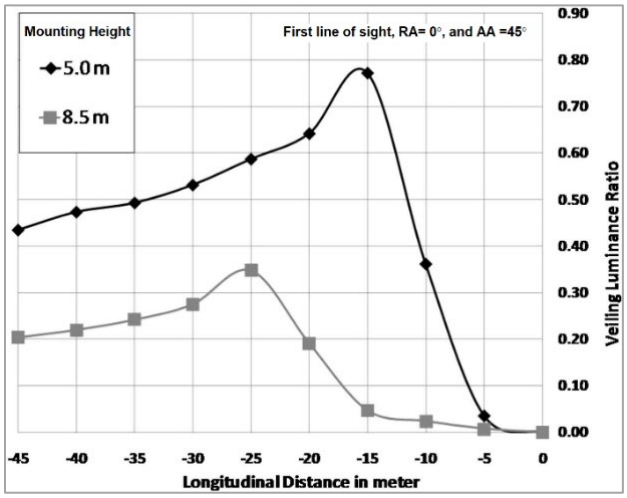


Figure 2.10. Impact of mounting height on veiling luminance ratio (Odeh et al., 2009).

In 2011, Hassan et al. complemented the study made by Odeh et al. (2009) by conducting a field study to determine the light and glare characteristics of two balloon lighting systems and comparing them with a conventional light tower. The field tests took place at the Louisiana State University (LSU) Petroleum Engineering Research Laboratory. The measurements of pavement luminance and vertical illuminance were conducted also on a simulated work zone using a predefined experimental grid and taken from inside a car and along two lines of sight, the first located at one-quarter of lane width (0.95 m from the edge of the closed lane) and the second located at three-quarters of lane width (2.8 m). The existing surface was categorized as type R1, as shown inTable 2.5. Three lighting systems were tested: two balloon lights with a wattage of 1,000-W and light output of 115,000 and 112,000 lumens, respectively, and one light tower with four 1,000-W floodlights and a luminous flux of 110,000 lumens. Balloon lights were extended up to 5.4-m height and for the light tower up to 9-m height. Fourteen lighting arrangements were evaluated by combining the type of lighting system, mounting height, aiming angle (25, 35, and 45 degrees), distance of the lighting system from the lane edge, and the number of luminaires used. One additional arrangement was tested in the absence of any light source on the site to account for inferences caused by external and moonlight. The illuminances measured for this case were subtracted from those measured for each experimental case. The major findings on this study were as follows: (1) when light towers and balloon lights were mounted at the same height, the light tower produced more glare; (2) the glare experienced by motorists increases gradually as they approach the light source, reaches a peak, and then diminishes to a negligible level at the light

source, as illustrated in Figure 2.11; and (3) increasing the mounting height and decreasing the aiming angle of the luminaires reduces glare but also reduces the coverage distance available for construction activities.

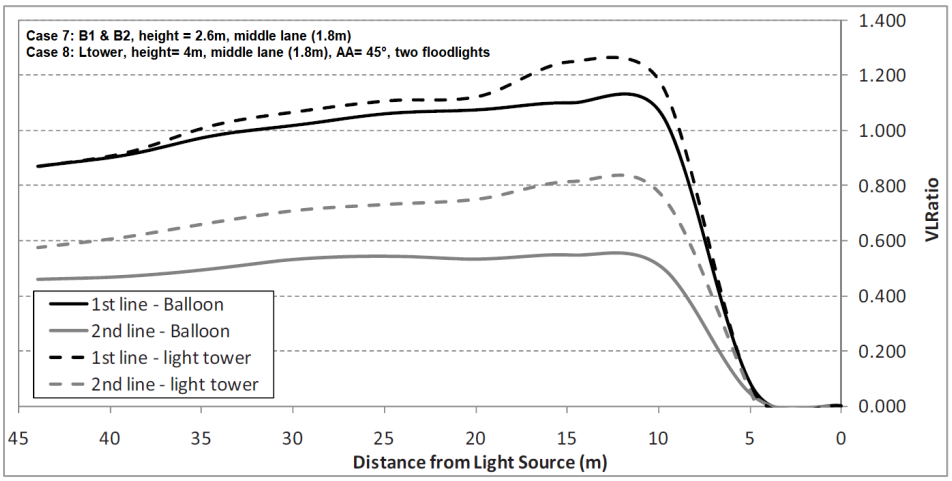


Figure 2.11. Veiling luminance ratio for two balloon lights and a light tower (Hassan et al., 2011).

Very few research studies have been done to evaluate discomfort glare in realistic settings. Bullough et al. (2014) conducted a study to evaluate the relative visual performance of workers under different work zone light levels. The visual performance assessment included several scenarios representative of visual tasks performed by workers (ages from 20 to 60 years) in roadway work zones. The scenarios ranged from small targets (a keyhole viewed from a distance of 3 ft) to medium-sized targets (a hand tool located 10 ft ahead on the ground while walking toward it) and large targets (a truck located 100ft away). The range of light levels used in the analyses was from 3 to 300 lux.

The Relative Visual Performance (RVP) model was used to determine the speed and accuracy of visual processing as a function of background luminance, luminance contrast, target size, and observer age. RVP values range from zero near the threshold to greater than one. RPV > 1 indicates near-maximum visual processing speed and accuracy, and RVP = 0 represents the threshold for visual identification. An RPV ≥ 0.8 is desirable for consistent visibility unaffected by minor changes in light level, contrast, or size. The Bullough et al. (2014) study indicated that (1) illumination levels of at least 10 lx would be sufficient to maintain a good level of visual

performance (RPV ≥ 0.8) for most visual tasks performed by most workers, but for older workers (60-years and older), illumination levels lower than 10 lux can result in these tasks being invisible; (2) when a glare illuminance of 20 lux is present at a visual angle of 20° off-axis, low-contrast objects viewed by workers between 20 to 60 years old become invisible at the lowest work zone lighting illuminance (3 lux), while the smallest low-contrast object falls below the visual threshold for older workers (60-years and older) even at illuminance levels as low as 10 lux; and (3) for the older workers (60-year-olds and older), a light level of 30 lx would maintain suprathreshold visibility of the lowest-contrast small objects (See Figures 2.12 and 2.13).

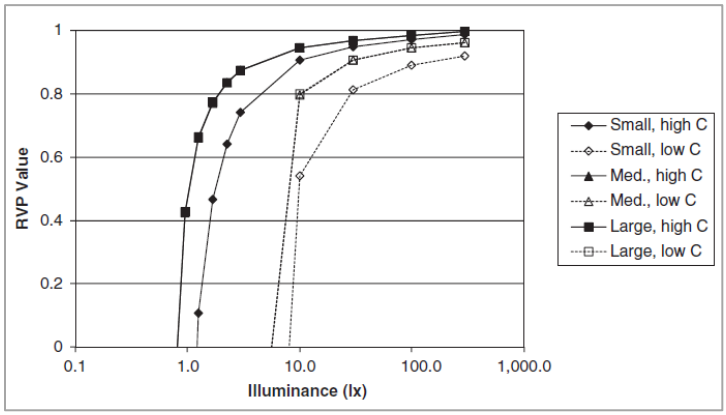


Figure 2.12. RPV Values (task sizes and contrast), 20- to 60-year-old worker, glare of 20 lx (Bullough et al., 2014).

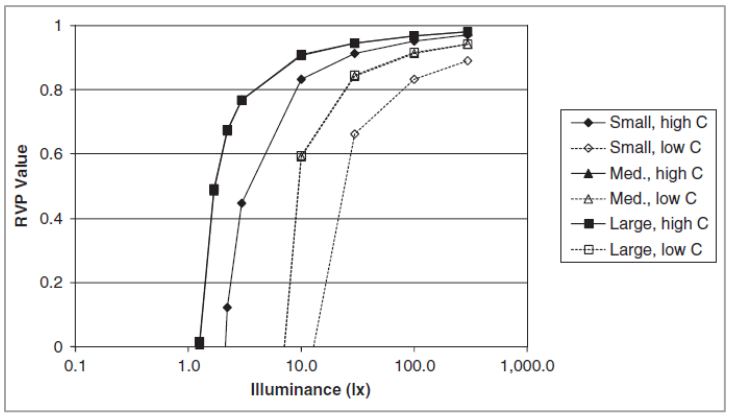
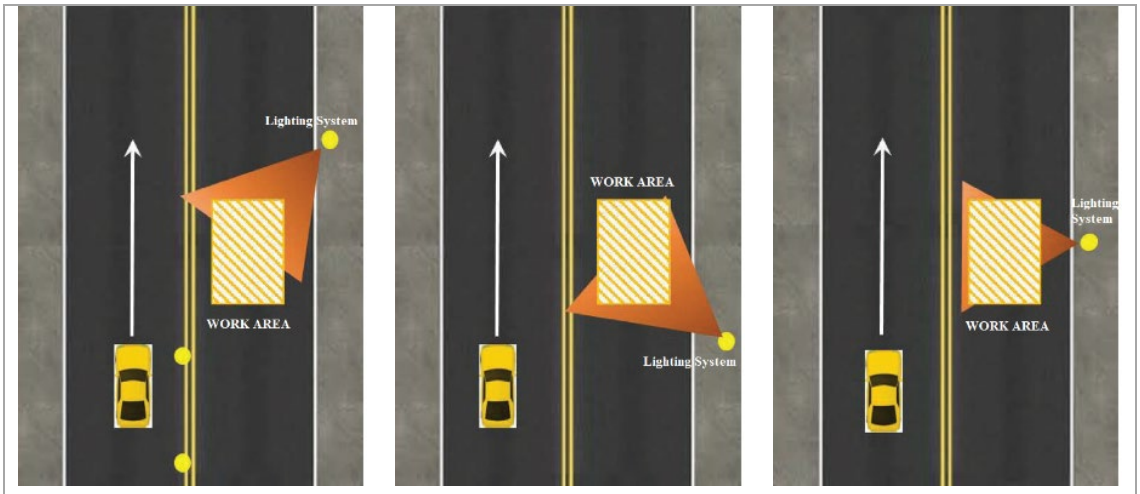


Figure 2.13. RPV Values (task sizes and contrast), 60+ years worker, glare of 20 lx (Bullough et al., 2014).

Bhagavathula and Gibbons (2017) conducted a study to evaluate the effect of light tower type and their orientation on driver visual performance and understand drivers' perceptions in terms of visibility and glare. The perceptions of drivers' visibility and glare were explored using a questionnaire. Twenty-four (24) participants (divided into two groups: those aged 60 or more and those aged 18 to 35) were asked to fill out the questionnaire after driving through a simulated work zone lane closure (10m. x 3m.) illuminated with 108 lux at the Virginia Smart Road (speed limit 55mph). Multiple lighting arrangements were tested with three lighting systems: (i) a metal halide portable light tower with four 1,000-W luminaires (440,000 lumens), (ii) a metal-halide balloon light with four 1,000-W luminaries enclosed within a balloon, which diffuses the light, and (iii) a newer LED light tower, with six LED luminaries (240,000 lumens). Light towers were mounted at 6.09 m (20 ft). Also, three orientations or rotation angles were selected for the field tests: (1) "toward" oncoming traffic; (2) "away" from oncoming traffic; and (3) "perpendicular" to traffic, as shown in Figure 2.14. Using a Likert scale (1- Strongly agree, 2- Disagree, 3-Neutral, 4- Agree, and 5- Strongly Agree), the participants were asked to provide their perceptions of glare in two statements: (1) the current lighting conditions caused glare while driving through the work zone, and (2) the glare from the current lighting conditions affected their ability to detect the worker.



(a) "towards" (b) "away" (c) "perpendicular"

Figure 2.14. Lighting system orientations used for illuminance characterization (Bhagavathula et al., 2017).

Six distinct linear mix models (LMMs) were used to evaluate the lighting system's effect on visibility and glare for each light tower orientation. The LMM statistical results for glare indicated that the primary effects of light type, light orientation, and their two-way interaction were all significant. The glare rating was dependent on both the type of light and its orientation, as illustrated in Figure 2.15. The mean glare rating for the LED light tower was less than “neutral,” and the balloon light was greater than “neutral” in all three orientations. Both the balloon light and metal halide light tower had mean glare ratings greater than “neutral” in the towards orientation. Also, the effect of light type was significant for each of the three orientations. The glare ratings were significantly different when the three lighting systems were viewed perpendicularly; the balloon light had the highest glare rating, while the LED light tower had the lowest. Similarly, in “toward” orientation, metal halide had the highest mean glare ratings, while the LED light tower had the lowest. Finally, the balloon light produced the most glare in the "away" orientation, while the LED light tower produced the least.

Despite the study’s findings regarding detection distance and participants’ perceptions of visibility and glare, the study had several limitations. First, only a 60° aiming angle of luminaires was used for light towers. In addition, only one lighting system was used to illuminate the work area; and only one visual detection task (detecting the worker position within the work zone) was included in the experiment.

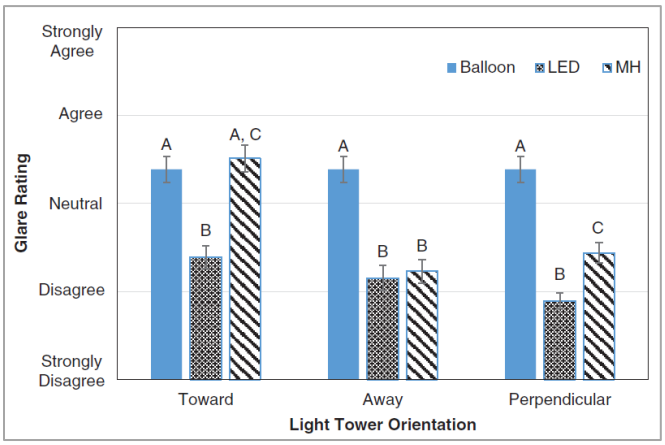


Figure 2.15. In light towers, higher ratings are associated with higher glare. Uppercase letters denote groupings based on significant ($p < .05$) paired comparisons of light tower types with respect to each orientation (Bhagavathula et al., 2017).

To address the limitations of the 2017 study, Bhagavathula and Gibbons (2018) conducted a follow-up study to objectively evaluate the effects of mounting heights, offset distances, and the number of light towers in the work zone on drivers' visual performance and discomfort glare. Similar to the 2017 study, twenty-four participants (divided into two groups: those aged 60 or more and those aged 18 to 35) drove through a simulated lane closure on the Virginia Smart Road (speed limit 55mph). Participants rated the discomfort glare levels produced by portable light towers and under various lighting configurations (mounting height, offset distance, and the number of light towers) through a 0 to 6 rating scale (0 indicated "no discomfort glare" to 6 indicated "glare intolerable"), as described in Table 2.8. Three lighting systems were used on the field tests: (i) a metal halide light tower with four 1,000-W (440,000 lumens) luminaires, (ii) a balloon light with four 1,000-W metal halide luminaires (440,000 lumens) enclosed within a balloon, which diffuses the light, and (iii) a smaller balloon light with an 800-W LED luminaire (84,000 lumens). Also, three different mounting heights were tested on these lighting systems (15, 20, and 25 ft), as well as three different offset distances (0 ft – light tower in the lane, 10 ft – light tower in the shoulder, and 20 ft – light tower off the shoulder). Fifteen lighting arrangements in total resulted from combining light tower type, mounting height, offset distances, and the number of lighting equipment. They were merged into one variable called "light tower orientation." Nine of these arrangements were designed by combining the three mounting heights and three offset distances of the 4000-W balloon light; three arrangements were possible due to the three mounting heights of the 4,000-W metal halide light tower and the 60° aiming angle of the luminaires; two lighting configurations were used for the 800-W LED balloon light, which was mounted at the height of 15 feet and placed in the center of the closed lane; and a single control condition without a light system (unlit zone).

Table 2.8. Discomfort Glare Scale Rating (Bhagavathula & Gibbons, 2018).

Description	Rating
No discomfort glare	0
Glare between non-existent and noticeable	1
Glare noticeable	2
Glare between noticeable and disagreeable	3
Glare disagreeable	4
Glare between disagreeable and intolerable	5
Glare intolerable	6

A linear mix model (LMM) was used to evaluate the effects of light tower orientation on discomfort glare ratings. The results from the LMM analysis indicated that the main effect of light tower orientation was significant, and the two-way interaction between age and "light tower orientation" was also significant. The effect of "light tower orientation" on discomfort glare is shown in Figure 2.16. The study demonstrated that increased offset distances and mounting heights resulted in lower discomfort glare ratings. For instance, the 4,000-W metal halide light tower mounted at 20 and 25 ft. had significantly lower discomfort glare ratings (ratings around 2) than the 800-W LED balloon light mounted at 15 ft (ratings greater than 3). Also, the findings indicated that up to two 800-W light towers could be mounted on construction equipment without impairing drivers' discomfort glare ratings. When the 4,000-W metal halide light tower was mounted at a 20-ft, drivers of ages 18-35 listed this configuration with lower glare ratings than those aged 60 or higher. The results reflect drivers' glare ratings in ideal conditions and lighting performance decrements are expected in real-work zone conditions. These findings are applicable only to work zones on limited-access highways with no other source of roadway lighting available other than portable lighting systems. The presence of roadway lighting may reduce drivers' perceptions of glare because of their increased adaptation level.

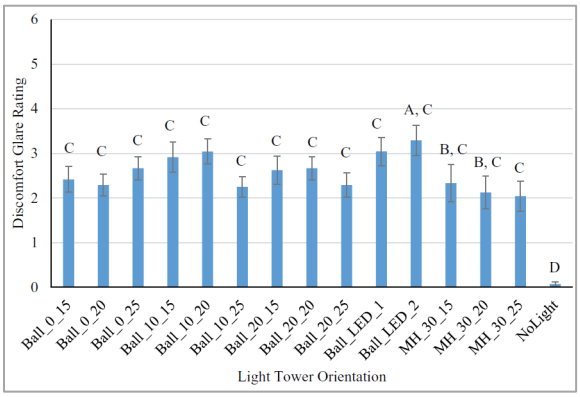


Figure 2.16. Effect of "light tower orientation" on discomfort glare rating. Uppercase letters indicate significant ($p < .05$) post hoc groupings of light tower types within each mounting height (Bhagavathula & Gibbons, 2018).

Based on the results obtained from previous studies regarding the evaluation of disability glare produced by commonly used lighting systems such as balloon lights and light towers at nighttime workzones, researchers have provided practical recommendations to State

Transportation Agencies (STAs) and roadway contractors about reducing and controlling harmful levels of glare to workers and motorists. Most of these recommendations were adopted and implemented by some state transportation agencies as work zone lighting standards and specifications for nighttime construction and maintenance projects. These work zone lighting standards and specifications are discussed in the next section.

2.6 Work Zone Lighting Standards

This section summarizes ongoing practices adopted by the State Transportation Agencies in the US and other professional organizations regarding recommended light levels and glare reduction or avoidance in nighttime work zones.

2.6.1 State Transportation Agencies (STAs)

Lighting standards of nine State Transportation Agencies (STAs) were explored to obtain work zone lighting requirements and specifications for nighttime operations. Among the nine STAs explored, some of them corresponded to Indiana's neighboring States while others corresponded to those States that have strong experience in transportation research. Most of the work zone lighting provisions are typically found in the State Manual on Uniform Traffic Control Devices (MUTCD, 2009) or within the MUTCD State supplement(s). Of the nine STAs, only five has developed detailed provisions regarding work zone lighting that include: (1) minimum illuminance levels for a variety of work zone tasks and uniformity ratio values; (2) if lighting plans are required before commencement of nighttime operations; and (3) glare control measurements. These states are Illinois, Michigan, New York, Virginia, and Oregon. Across all the nine STAs, values of minimum illuminance levels by type of work zone activity are provided in the work zone lighting provisions. Three out of nine STAs required submitting a nighttime lighting plan before any operation begins, and six STAs provided glare control recommendations.

Table 2.9 summarizes the general illumination guidelines outlined by the STAs in this group. Most of the glare control recommendations presented in these guidelines are supported by prior research. For instance, the recommendations for controlling and reducing harmful glare levels on nighttime operations suggested by the Illinois Department of Transportation were based on studies performed by Odeh et al. (2009).

Table 2.9. Summary of State Transportation Agency Work Zone Lighting Recommendations.

State	Minimum Average Illuminance Levels fc (lx)	Lighting Plan required	Glare addressed	Recommendations to reduce or avoid glare
Illinois (IDOT, 2019)	• 5 fc (54 lx) through the work area. • 10 fc (108 lx) – vertical illuminance measured at 1 ft (300 mm) out from the flagger's chest.	No	Yes	• Lighting systems employing flood, spot, or stadium luminaires shall be aimed downward at the work area and rotated outward by no more than 30° from the nadir (straight down) • Balloon lights shall be installed at a minimum height of 12 ft (3.6 m) above the roadway. • Headlights of construction vehicle and equipment shall not be used within the work zone except as allowed for specific construction operations, and shall not be used when facing oncoming traffic
Indiana (INDOT, 2011)	• 5 fc (54 lx) – for general activities • 10 fc (108 lx) – for activities around equipment • 20 fc (216 lx) - for tasks requiring high levels of precision and extreme care (e.g., signalization)	No	No	• Not specified
Missouri (MoDOT, 2021)	• 0.6 fc (6.5 lx) – overhead lighting shall be provided in areas significant to traffic guidance within the work zone (e.g., transitions, ingress and egress areas, equipment crossing, intersections, and temporary signals) • 5 fc (54 lx) – for general activities and flagger stations • 10 fc (108 lx) – for activities around equipment • 20 fc (216 lx) - for tasks requiring high levels of precision and extreme care (e.g., signalization)	Yes	No	• Not specified

Table 2.9. continued

State	Minimum Average Illuminance Levels fc (lx)	Lighting Plan required	Glare addressed	Recommendations to reduce or avoid glare
Michigan (MDOT, 2010)	• 5 fc (54 lx) throughout the entire area of operation where workers may pass through on foot or are present but are not performing construction work • 10 (108 lx) on a jobsite where construction work is performed	Yes	Yes	• Design and operate the lighting system in such a way that it does not create glare that would obstruct traffic, workers, or inspection personnel. • Aim flood, spot, or stadium type luminaries downward at the work and rotated outward no greater than 30 degrees from nadir (straight down). • Position balloon lights at least 12 feet above the roadway.
Ohio, Kentucky, & Wisconsin (OhioDOT, 2005; MUTCD, 2009; WisDOT, 2017)	• 5 fc (54 lx) for general activities • 10 fc (108 lx) – for activities around equipment • 20 fc (216 lx) – for tasks requiring high levels of precision and extreme care	No	No	• Not specified
Virginia (VDOT, 2019)	• 5 fc (50 lx) – general construction activities and flagger stations. • 20 fc (216 lx)- tasks requiring high levels of precision (e.g., signalization).	No	Yes	• Elimination of potential glare shall be determined by driving through and observing the floodlit area from each direction on all approaching roadways at night and on a regular basis throughout each shift. If it is not possible to eliminate glare, non-glare lighting devices such as non-glare air-filled lighting devices or anti-glare shields shall be considered.
Oregon (ODOT, 2021)	• 5 fc (50 lx) – through the workspace and flagging stations (light output of less than 2,500 watts).	No	Yes	• Temporary glare shields and glare screens are installed along the top of the concrete barrier between opposing traffic lanes to prevent opposing headlight glare from impairing driver visibility. • Low-density polyethylene (LDPE) plastic glare screens that extend approximately 24 inches above the top of the barrier area allowed.

Table 2.9. continued

State	Minimum Average Illuminance Levels fc (lx)	Lighting Plan required	Glare addressed	Recommendations to reduce or avoid glare
New York (NYDOT, 2021)	• Level I – 5 fc. For areas of general construction operations (e.g., work zone traffic control set-up and operations, staging, excavation, cleaning and sweeping, etc.) • Level II – 10 fc (flagging stations, asphalt paving, milling, etc.) • Level III – 20 fc (pavement crack filling, pavement patching/repairs, installation of signal equipment, and other tasks involving fine details) • Max. Uniformity ratio 5:1	Yes	Yes	• Tower-mounted luminaires should be installed parallel or perpendicular to the roadway • Aiming angle of luminaires shall not exceed 45°. • No luminaires with a luminous intensity greater than 20,000 candelas at an angle of 72° above the vertical shall be permitted. • When a tower is in use, it shall be extended to its full working height to minimize glare and provide uniform illumination. • When necessary, the contractor shall install shields, visors, or louvers on luminaires to reduce objectionable levels of glare.
California (Caltrans, 2020)	• 3 fc (32 lx) – general construction area • 5fc (54 lx) – outdoor active construction areas (e.g., concrete placement, excavation, loading platforms, etc.) • 10 fc (108 lx) - general construction plant and shops (e.g., batch plants, screening plants, etc.) and nighttime highway construction work. • 30 fc (324 lx) – first aid stations.	No	Yes	• No person shall install, maintain, or display, on or near any highway, any light of any color with a brilliance that impairs the vision of highway drivers (California Vehicle Code 21466.5).

2.6.2 Other Professional Organizations

Several agencies at the federal and State levels have also investigated factors affecting nighttime operations. The work zone lighting guidelines developed by these agencies as described in this section.

National Cooperative Highway Research Program (NCHRP)

Ellis et al. (2003) conducted a study to develop illumination guidelines for nighttime highway construction. The study developed guidelines for work zone illumination and recommended illuminance values for typical construction and maintenance activities performed at night. The most common construction and maintenance activities these State Transportation Agencies performed at night included asphalt concrete pavement of intersections, the in-situ concrete construction of bridge decks, excavation, filling, embankment construction, milling repaving, and marking of limited-access highways.

The researchers adapted illumination guidelines from other industries (e.g., automotive, iron and steel, petrochemical, and pulp and paper) to the specific needs of nighttime construction and maintenance projects. Table 2.10 provides the three illumination categories, which specify minimum illuminance levels of 54 lx (5 fc), 108 lx (10 fc), and 216 lx (20 fc) for specific tasks and cover most highway construction and maintenance operations. Additionally, the authors suggested recommendations to reduce and control glare at nighttime work zones, as shown in Table 2.11, based on four factors: light beam spread, light's mounting height, location, and aiming angles of luminaires. First, the vertical beam spread is a potential source of glare, and for the majority of highway construction applications, the spread should be as narrow as possible. Second, the determination of mounting height is key in controlling glare; the accepted principle for determining the minimum glare-producing mounting height is that the angle formed by the horizontal work surface and a line drawn through the luminaire and a point one-third the distance across the work zone should not be less than 30 degrees. (See Figure 2.17).

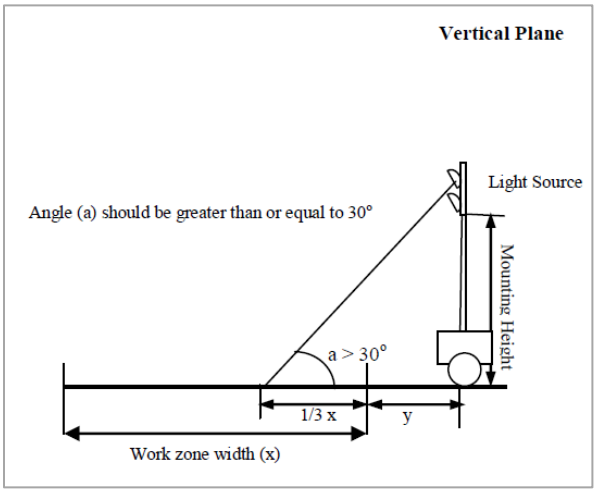


Figure 2.17. Mounting Height of Luminaries (Ellis et al., 2003).

Third and fourth, glare can be mitigated by removing luminaires from motorists' and workers' normal sightlines. Whether luminaires are placed out of normal sightlines or critical viewing angles for motorists and workers is determined by the selected pole location and the actual luminaire aiming. Generally, luminaires should be aimed so that a line drawn from the luminaire beam axis intersects normal lines of sight at an angle of between 45 and 135 degrees in the horizontal; angles greater than 135 degrees should be avoided. Lastly, aiming of luminaires, the angle formed by the nadir and the center of the luminaire beam spread should not exceed 60 degrees as a rule for aiming. Another critical factor to consider when minimizing glare is light intensity at angles greater than 72 degrees from vertical. The most effective countermeasures to reduce or avoid glare are the adequate aiming of the luminaires and the use of glare control shading hardware.

Table 2.10. Summary of Illumination Categories (Ellis et al., 2003).

Category	Min. Illuminance Level lx (fc)	Average Uniformity Ratio L_{avg}/L_{min}	Maximum Uniformity Ratio L_{max}/L_{min}	Recommended For	Example of Activities
I	54 lx (5 fc)	5:1	10:1	General illumination of the job site.	• Excavation • Sweeping • Movement in the general area and movement area between tasks
II	108 lx (10 fc)	5:1	10:1	Illumination of tasks being performed and around equipment.	• Paving • Milling • Concrete work • Around construction equipment
III	216 lx (20 fc)	5:1	10:1	Illuminance on tasks that require extreme caution and attention, high accuracy, and fine finish.	• Crack and pothole filling • Signalization works • Maintenance of electrical connections (Incl. lighting)

Table 2.11. Glare Control Recommendations (Ellis et al., 2003).

Glare control factor	Recommended glare control
Beam Spread	• Select the vertical and horizontal beam spreads to minimize light spillage. • Consider using cutoff luminaires.
Mounting Height	• Coordinate minimum mounting heights with a source lumen.
Location	• Luminaire beam axis crosses normal line of sight between 45° and 90°.
Aiming	• Angle between main beam axis and nadir less than 60°. • Intensity at angles greater than 72° from the vertical less than 20,000 candela.
Supplemental Hardware	• Visors, louvers, shields, screens, barriers

Illuminating Engineering Society (IES)

The Illuminating Engineering Society (IES, 2018) has published guidance on evaluating the requirements for lighting the roadway to ensure visibility for road users passing through or adjacent to the work area. This guidance considers the impact on drivers of glare produced by lighting within the work zone area since disability glare can be debilitating and quickly cause driver confusion. Work zone lighting incorporates the roadway street lighting design's purpose, which aims to assist motorists in detecting obstacles within and beyond the range of the vehicles headlights, providing adequate visibility for pedestrians and cyclists, and aiding in visual search tasks on and adjacent to the street.

The work zone lighting design considers four parameters: (1) visual task in a given environment; (2) glare, light trespass, and sky glow issues; (3) impact of headlights; and (4) spectral content of luminaires in order to achieve effects of color in the environment of the project. The IES (2018) recommends three distinct evaluation methods for assessing various aspects of continuous highway, street, and work zone lighting design: (i) luminance; (ii) illuminance; and (3) small target visibility (STV). The luminance method of roadway lighting design establishes the perceived "brightness" of the road by measuring the amount of light reflected from the pavement in the driver's direction. The illuminance method determines the amount of light incident on the roadway surface or vertical surfaces by the roadway lighting system. Surfaces have varying reflectance characteristics; different illuminance levels are required for each standard roadway surface type. The small target visibility (STV) method of design is based on the visibility levels of an array of small targets on the roadway, and it considers the following factors: (1) luminance of the targets and the immediate backgrounds; (2) the adaptation level of the adjacent surroundings; and (3) disability glare.

According to the IES recommended practice (IES, 2018), work zone lighting can negatively affect the visual performance of all road users traveling through or near the work zone. Thus, lighting systems impact on the work area affects the driver's visual performance. For instance, inappropriate placement of high-intensity lighting systems can create disability glare and reduce visibility. Also, light trespassing into travel lanes can have a detrimental effect on the uniformity of the lighting design in travel lanes. To address this safety issue, the IES recommends average values of luminance and light uniformity, and maximum values for veiling luminance ratio based on practical experience and consensus among lighting experts (See Table 2.12). The IES

guidance also recommends that veiling luminance ratio values should never be greater than 0.3 ($L_{v,max}/L_{avg}$) and indicates that glare experienced by drivers because of work zone lighting can be mitigated by: (1) not aiming lights "upstream" toward oncoming traffic; (2) ensuring that neither the light source nor any reflector in the optical system is directly visible to the driver; and (3) increasing the illumination levels for the travel lanes.

Moreover, IES indicates that, generally, transition lighting is not required for work zones, as light levels should not exceed those design values illustrated in Table 2.12. Transition lighting shall be used in two conditions. When the light levels in the work zone travel lanes are greater than 3 times the light levels outside the work zone, transition lighting should be installed, using the guidance for departure zone lighting found in Toll Plazas; and (2) when the roadway is not illuminated beyond the work zone, transition lighting should be installed when the average illuminance level in the travel lanes within the work zone is greater than 0.9 fc (10 lx). Finally, the IES recommended practice (IES, 2018) contains recommendations for lighting travel lanes in long-duration work zones, as shown in Table 2.13. Long-duration work zones are construction or maintenance areas occupied for more than three nights.

Table 2.12. Lighting Design Criteria for Highways and Streets (IES, 2018).

Road Classification	Pedestrian Activity Classification	Average Luminance L_{avg} (candelas/m^2)	Average Uniformity Ratio L_{avg}/L_{min}	Maximum Uniformity Ratio L_{max}/L_{min}	Maximum Veiling Luminance Ratio $L_{v,max}/L_{avg}$
Freeway Class A		0.6	3.5	6.0	0.3
Freeway Class B		0.4	3.5	6.0	0.3
Expressway		1.0	3.0	5.0	0.3
Major	High	1.2	3.0	5.0	0.3
	Medium	0.9	3.0	5.0	0.3
	Low	0.6	3.5	6.0	0.3
Collector	High	0.8	3.0	5.0	0.4
	Medium	0.6	3.5	6.0	0.4
	Low	0.4	4.0	8.0	0.4
Local	High	0.6	6.0	10.0	0.4
	Medium	0.5	6.0	10.0	0.4
	Low	0.3	6.0	10.0	0.4

L_{avg}: Maintained average pavement luminance
L_{min}: Minimum pavement luminance
$L_{v,max}$: Maximum veiling luminance

Table 2.13. Recommendations for Lighting Travel Lanes in Long-Duration Work Zones (IES, 2018).

Highway Type	Activity	Existing Lighting	Lighting Required	Maintain Lighting	Provide Lighting (*)
Rural Highway	No ongoing work at night	No	No	N/A	No
		Yes	Yes	Yes	N/A
	Work ongoing at night	No	Yes	N/A	Yes
		Yes	Yes	Yes	N/A
Urban Streets	No ongoing work at night	No	No	N/A	No
		Yes	Yes	Yes	N/A
	No ongoing work at night, major diversions in alignment	No	Yes	N/A	Yes
	Work ongoing at night	Yes	Yes	Yes	N/A
		No	Yes	N/A	Yes
Urban Highway	No ongoing work at night	No	No	N/A	No
		Yes	Yes	Yes	N/A
	No ongoing work at night but major diversions in alignment	No	Yes	N/A	Yes
	Work ongoing at night	No	Yes	N/A	Yes
		Yes	Yes	Yes	N/A

(*) Lighting should meet the values established in Table 2.12.

International Commission of Illumination (CIE)

The International Commission on Illumination (CIE) has published several recommendations for lighting external work areas, including building sites that address illuminance levels, uniformity, and glare (L'Èclairage, 2010). The CIE defined three lighting classes (M, C, and P). The "M" lighting classes are intended for drivers of motorized vehicles on traffic routes and are classified in six levels (M1 to M6). The application of these classes is conditional on the geometry of the relevant area and traffic and time-related conditions. The appropriate lighting-class must be chosen based on the road's function, the design speed, the overall layout, the volume and composition of traffic, and the surrounding environment. The lighting criteria used are the maintained average road surface luminance (Lav), the overall (U_0) and longitudinal (U_1) uniformity of the luminance, and the threshold increment (f_{TI}). Table 2.14 shows the recommended values for the lighting classes M1 to M6.

The "C" lighting classes are intended for conflict areas. Conflict areas occur when vehicle streams intersect or run into areas frequented by pedestrians, cyclists, or other road users or when the road geometry changes, such as a reduction in the number of lanes or a reduction in the width

of the roadway lane. For conflict areas, luminance is the recommended lighting design criteria. The lighting classes C0 to C5 are defined by the lighting criteria given for each class in Table 2.15. The "P" lighting classes are intended for pedestrians and cyclists on pathways, bikeways, and other road segments that exist independently or alongside the roadway of a traffic route and for residential streets, pedestrian streets, and parking lots. The lighting classes P1 to P6 are defined by the lighting criteria given for each class in Table 2.16

Furthermore, the CIE recommended values for illuminance vary by task, as did the prior studies in highway work zone lighting, for uniformity ratios and glare rating vary by task. The CIE recommendations provided in Table 2.17 are generally consistent with the recommendations provided by the the National Cooperative Highway Research Program (NCHRP) Report 498, *Illumination Guidelines for Nighttime Highway Work* regarding work zone lighting.

Table 2.14. Lighting classes for motorized traffic, based on road surface luminance (L'Èclairage, 2010).

Lighting Class	Road Surface				Threshold Increment
	Dry			Wet (*)	
	L_{av} in cd/m^2	U_0	U_1	U_0	f_{TI}
M1	2.0	0.40	0.70	0.15	10
M2	1.5	0.40	0.70	0.15	10
M3	1.0	0.40	0.60	0.15	15
M4	0.75	0.40	0.60	0.15	15
M5	0.50	0.35	0.40	0.15	15
M6	0.30	0.35	0.40	0.15	20

(*) Applicable in addition to dry condition, where road surfaces are wet for a substantial part of the hours of darkness and appropriate road surface reflectance data are available

Table 2.15. Lighting classes for conflict areas (L'Èclairage, 2010).

Lighting Class	Average Illuminance over whole of used surface E in lux	Uniformity of Illuminance U_0	Threshold Increment f_{TI} in % (*)	
			High and moderate speed	Low and very low speed
C0	50	0.40	10	15
C1	30	0.40	10	15
C2	20	0.40	10	15
C3	15	0.40	15	20
C4	10	0.40	15	20
C5	7.5	0.40	15	25

(*) Applicable where visual tasks usually considered for the lighting of roads for motorized traffic

Table 2.16. Lighting classes for pedestrian and low speed traffic areas (L'Èclairage, 2010).

Lighting Class	Average Horizontal Illuminance $E_{h,avg}$ in lux (lx)	Minimum Horizontal Illuminance $E_{h,min}$ in lux (lx)	Additional requirement if facial recognition is necessary	
			Minimum Vertical Illuminance $E_{v,min}$ in lux (lx)	Minimum Semi-cylindrical Illuminance $E_{sc,min}$ in lux (lx)
P1	15	3.0	5.0	3.0
P2	10	2.0	3.0	2.0
P3	7.5	1.5	2.5	1.5
P4	5.0	1.0	1.5	1.0
P5	3.0	0.6	1.0	0.6
P6	2.0	0.4	0.6	0.4

Table 2.17. CIE Recommended Illuminance, Uniformity Ratio, and Glare Rating values (L'Èclairage, 1998).

Area to be Lit	Operation Performed	Minimum Maintained Average Horizontal Illuminance (lx)	Minimum Uniformity Ratio Level		Maximum Glare Rating (GR)
			Minimum/ Average	Maximum/ Minimum	
Work Area or Task	Very rough work	20	0, 25	8	55
	Rough work	50	0, 40	5	50
	Accurate work	100	0, 40	5	45
	Fine work	200	0, 50	3	45
Traffic Areas	Pedestrian passage, vehicle turning, loading, and unloading points	50	0, 40	5	50
Safety and Security	General lighting on building site	50	0, 40	5	50

2.7 Chapter Summary

This chapter discussed the following themes: (1) the benefits and challenges of performing nighttime operations on roadways, (2) common factors influencing nighttime operations; (3) key lighting terminology; (4) the review of safety challenges regarding work zone lighting and glare control on roadways, (5) the review of past and ongoing research studies regarding work zone lighting, disability glare, and discomfort glare; and (6) the review of standards and guidelines for determining disability glare and recommendations for minimizing harmful levels of glare in nighttime roadway operations.

As part of the review of past and ongoing research studies regarding work zone lighting and glare, a detailed assessment of two types of glare: disability glare and discomfort glare on motorists and workers during nighttime roadway construction and maintenance operations, was also investigated. Disability glare was determined using the veiling luminance ratio, a value for limiting glare; this value requires the input of vertical and pavement luminance measurements. Discomfort glare was analyzed by prior researchers through the assessment of driver perceptions of glare. In both cases, glare was determined through field experiments conducted in a controlled work zone environment using typical lighting systems for nighttime operations. In the past, very few studies were conducted to evaluate disability and discomfort glare at work zones, and the recommendations formulated from these studies were only partially adopted by a few State Transportation Agencies (STAs) for reducing and controlling harmful levels of glare to workers and motorists. Thus, additional research on the objective quantification and evaluation of disability glare levels in nighttime work zones is needed to strengthen the work zone lighting provisions of State Transportation Agencies, and to formulate a detailed procedure for quantifying and evaluating disability glare produced by commonly used lighting systems in nighttime work zones.

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3. RESEARCH METHODOLOGY

Chapter 2 discussed prior studies that examined disability glare on nighttime roadway operations and described how glare is determined using measurements of vertical illuminance and pavement luminance of the lighting equipment placed at roadway work zones at night. This chapter summarizes the methods used in this research study to determine disability glare on nighttime roadway construction and maintenance projects. Chapter 3 is divided into four sections. The first section of this study describes the results of a survey deployed to roadway contractors to assess their perceptions of lighting systems used on nighttime highway work zones. The second section describes the key insights regarding lighting challenges in highway work zones extracted from interviews with the Safety Officers from companies linked with the Indiana Constructors Inc. (ICI). The third section describes a detailed procedure used to measure vertical illuminance and pavement luminance and calculate the values of veiling luminance ratio (or disability glare). The last section includes a descriptive and statistical analysis of the calculated veiling luminance ratio from the different lighting system types. The content in this chapter will provide researchers, State Transportation Agencies (STAs) engineers, and roadway contractors an understanding of how disability glare produced by temporary lighting systems can be determined in nighttime work zones. It will also assist them in developing strategies to reduce glare and by doing so, to prevent accidents/crashes for the traveling public driving through work zones.

The research methodology consisted of five steps. The first step was the literature review; this step allowed the identification of the advantages and disadvantages of nighttime highway operations, the challenges associated of performing nighttime operations, the recent and ongoing research regarding disability and discomfort glare, the methods used for determining disability glare on work zones, and the work zone lighting and glare controls strategies used in nighttime work zones. The steps two, three, and four constituted the data collection phase, which was accomplished by implementing and deploying a survey questionnaire to roadway contractors, conducting interviews with contractor's safety officers, and conducting field experiments to measure vertical illuminance and pavement luminance. The last step in the methodology was the

analysis of the data collected. Figure 3.1 shows the sequence of the research process and the instruments used in each step of the methodology.

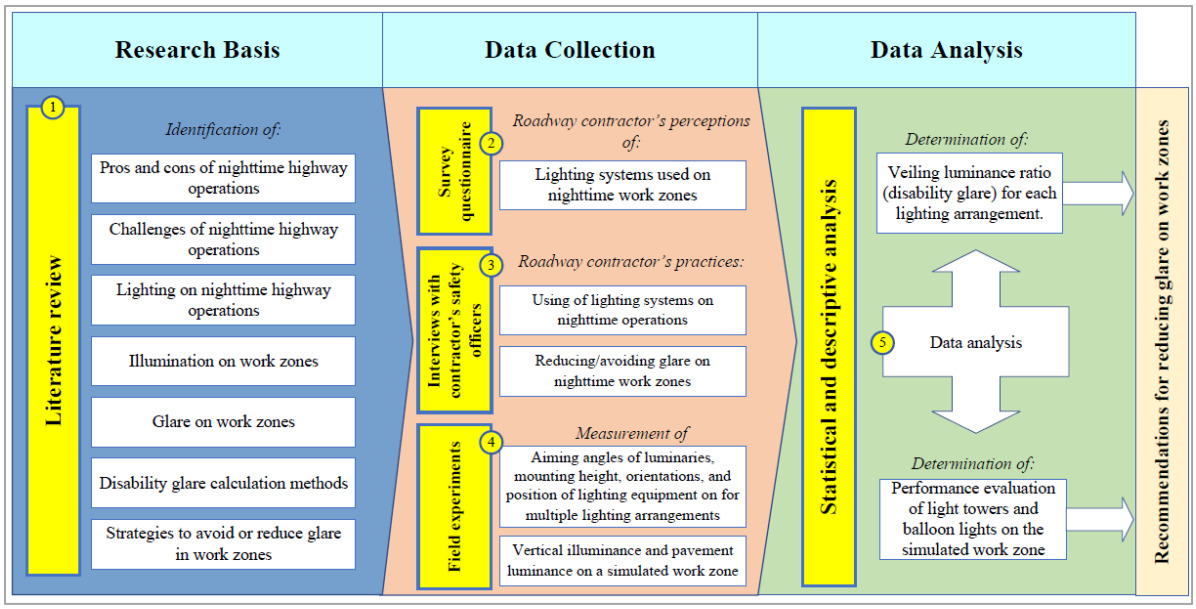


Figure 3.1. Research methodology.

3.1 Identification of Lighting Systems Used on Nighttime Highway Work Zones in Indiana

Lighting systems are critical components for nighttime roadway operations. Knowing the perceptions of roadway contractors regarding lighting systems used on nighttime highway work zones in Indiana was critical for this research study because it assists selecting appropriate lighting equipment that will be used to perform measurements of vertical illuminance and pavement luminance to determine disability glare in work zones. Towards this goal, a survey was used to gather data related to roadway contractors' perspectives regarding their experiences on nighttime construction and maintenance operations on roadways. The survey was deployed as part of the INDOT/JTRP SPR 4542 project aimed to identify the safety challenges with nighttime operations on roadways and to determine the factors that contribute to worker injuries and crashes during daytime and nighttime work zone operations.

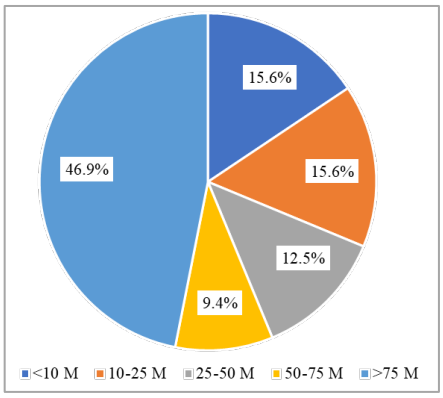
3.1.1 Development and Deployment of Survey Questionnaire

The JTRP/SPR 4542 survey questionnaire was designed to gather data related to roadway contractors' perspectives regarding their experiences on nighttime operations. The online questionnaire (APPENDIX A) was prepared, tested, and deployed using the Purdue Qualtrics platform. The questionnaire was organized into four sections. The first section sought information about the contractor's experiences performing nighttime operations. The second section addressed lighting systems, while the third section addressed traffic control strategies/devices used in roadway construction operations. The contractor's perceptions on the costs of nighttime work, the productivity of work crews, and the quality of the constructed/repaired roadway were included in the final section of part of the questionnaire. Before deploying the survey to the roadway contractors, a Research Exemption Request was filed with Purdue University's Committee on the Use of Human Research Subjects, also known as the Institutional Review Board (IRB). The research exemption was appropriate because the research protocol did not exceed the minimal risk, the subjects' participation in the online survey was voluntary, and the release of the data would not harm the subjects. The approved IRB-2021-924 exemption form is provided in APPENDIX B. The survey questionnaire was deployed among members of the Indiana Constructors Inc. (ICI), on June 11, 2021, after receipt of approval by Purdue's Institutional Review Board (IRB). It was available online until July 31, 2021. ICI is an organization that groups companies dedicated to the highway, heavy, and utility construction industry in Indiana. This section will discuss the second part of the JTRP/SPR 4542 survey questionnaire regarding lighting systems used on nighttime highway work zones in Indiana.

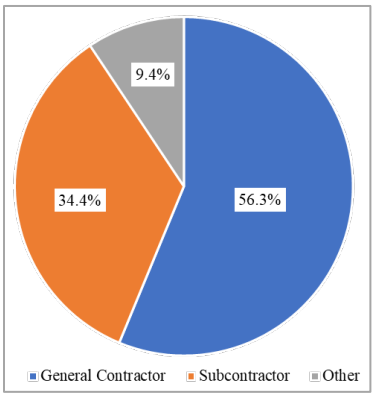
Sample Description

Overall, 18 responses were received. Most participants indicated that they were heavy/highway/bridge general contractors in companies with annual revenue greater than $75 million. They held positions of executives or operating officers and management roles within their companies. Also, 70 percent of the respondents have over ten years of experience performing nighttime roadway operations and participating in construction projects (e.g., paving, milling, earthworks). A few respondents indicated that they worked on bridge/structure and maintenance

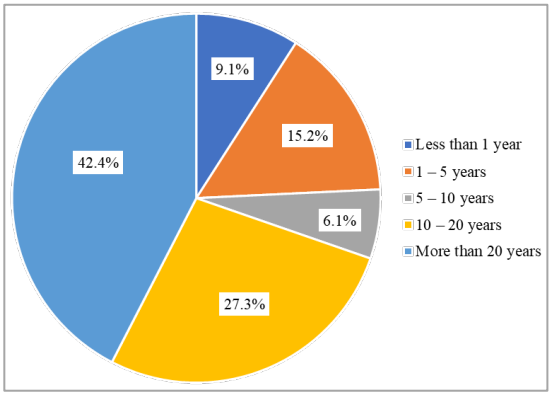
projects (e.g., patching, resurfacing, stripping) and to a lesser degree on repair/replacement projects (See Figure 3.2).



(a) Size of company (annual revenue in millions of dollars)



(b) Type of company



(c) Repondents' years of experience in nighttime roadway operations

Figure 3.2. Respondents' Demographics.

Descriptive analysis of the survey results of the lighting systems used on nighttime highway work zones in Indiana

As described in Section 3.1.1, the second part of the survey questionnaire addressed the roadway contractor's experience on work zone lighting and it also included participants' experiences preparing for nighttime operation and lighting plans and their experiences using lighting systems in work zones. Of the eighteen participants, only one indicated that preparation of a nighttime operation and lighting plan is mandatory for all nighttime roadway construction operations, 44.4% of the respondents stated that the state transportation agency (STA) does not

require them to submit a lighting plan prior to beginning their operations at night, and 50% of the respondents indicated that the STA sometimes requires them to submit such plan (See Figure 3.3). They also reported that a lighting plan is typically prepared by the lighting subcontractor to later be sent to the prime contractor and STA. The lighting plan submitted by respondents typically includes information about the work zone location(s), details of lighting systems and light sources used, and if the lighting systems are attached to or installed on construction equipment.

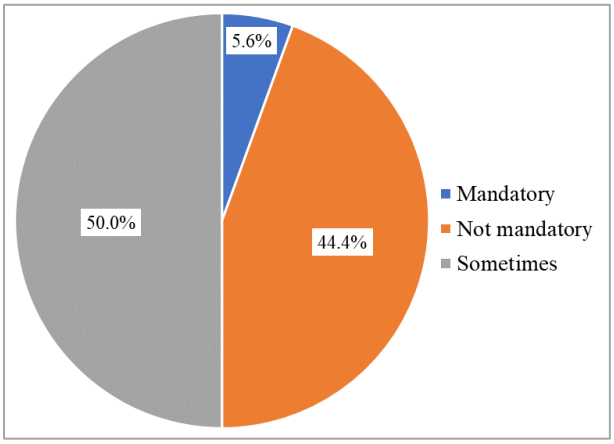
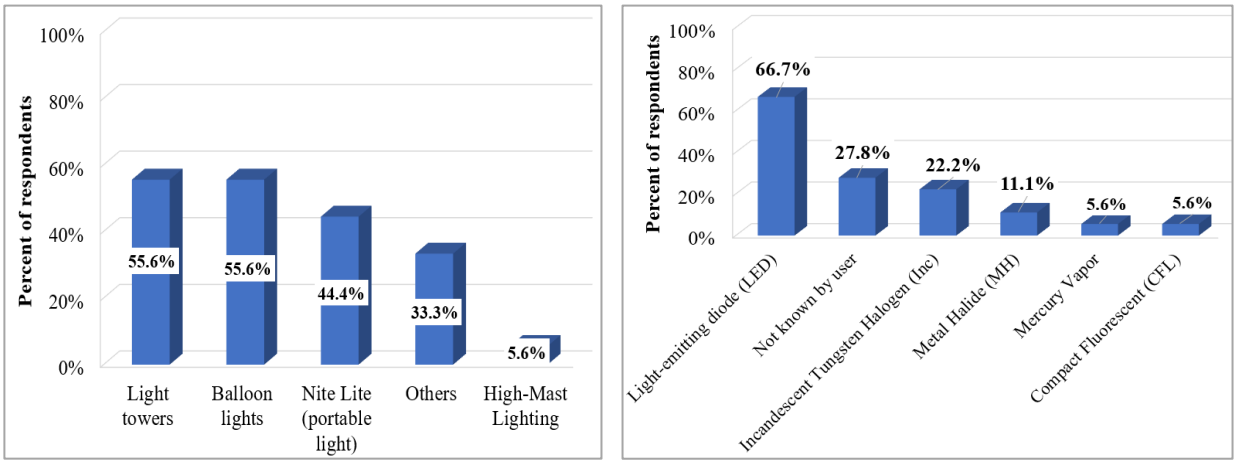


Figure 3.3. Lighting plan submission requested by the State Transportation Agency.

Additionally, participants were asked to indicate their preference for the lighting system type and light source, to indicate if these systems are mounted/installed on construction equipment or vehicle, and to rate a list of decision-related factors when selecting lighting systems for their projects. Figure 3.4(a) shows that light towers and balloon lights are among the most common lighting equipment used in nighttime roadway operations and portable lights (or nite-lite). Other lighting systems used by respondents on-site include work lights on trucks and illuminated hard hats for each worker on the ground (halo lights). Existing street lighting was also reported to sometimes contribute to a well-lit work zone. As shown in Figure 3.4(b), light-emitting diode (LED) is the most common source of light, followed by incandescent tungsten halogen and metal halide. Interestingly, some respondents did not identify the light source of their lighting equipment. Most respondents indicated that lighting systems are mounted on vehicles or construction equipment such as pavers. A few respondents indicated that lighting systems such as halo lights are attached to workers' hard hats (See Figure 3.5).



(a) Lighting systems (b) Light sources

Figure 3.4. Typical lighting systems and light sources used by respondents on their projects.

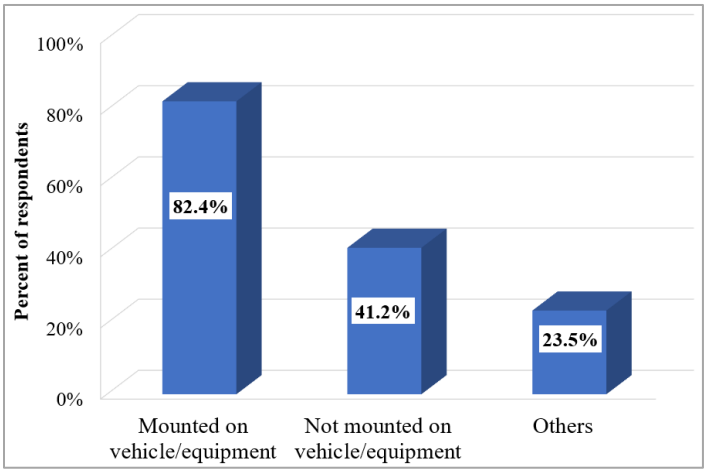


Figure 3.5. Typical location of lighting systems when installed/mounted.

Respondents rated factors affecting their decision to select lighting systems for nighttime operations using a rate range from one to three, with one indicating that the factor has no influence on the decision of selecting a lighting system, two indicating some influence, and three showing a strong influence. As described in Table 3.1, the amount of light output, ease of operation, and ability to move or relocate the light fixtures are among the top three factors in selecting lighting equipment, followed by the source of light emitted, maintenance, and cost of the lighting.

Table 3.1. Summary of rating values of factors when deciding a selection of a lighting system.

Type	Average rating value
Amount of light output	2.89
Ease of operation	2.83
Ability to move/relocate	2.78
Availability	2.40
Size of lighting system	2.35
Height to which it can be raised	2.35
Source of light emitted	2.31
Lighting system maintenance	2.31
Cost (purchase, rent, or lease)	2.11

Finally, the survey asked participants about the placement of lighting equipment in a work zone and their perceptions on the role of light positions in reducing motorists' speed as they pass through the work zone. Most of the respondents placed their lighting equipment in the activity and transition areas (See Figure 3.6). A few participants placed lighting systems in the advance warning and termination areas. About 17% of respondents indicated that lighting systems do not influence the speed reduction of motorists.

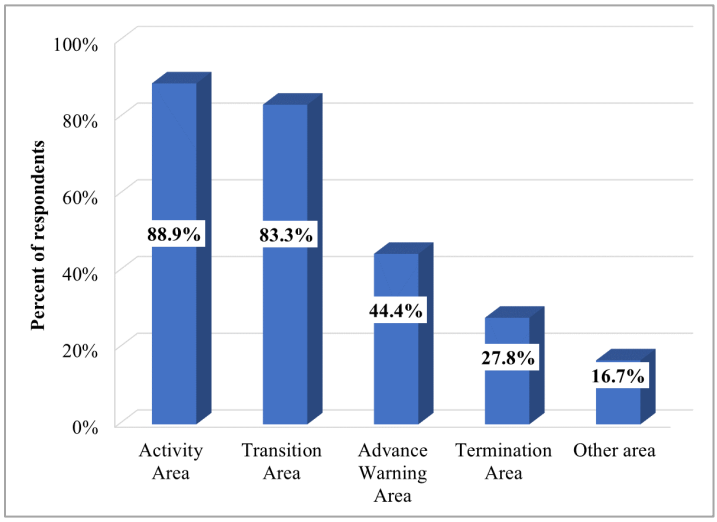


Figure 3.6. Typical placement of lighting systems on a work zone.

3.1.2 Discussion – Interviews with ICI Safety Officers

The survey questionnaire deployed to roadway contractors identified key aspects of work zone lighting, lighting systems and light sources used on nighttime operations, the factors that influence the selection of lighting systems in nighttime operations, and the placement of these systems on a typical nighttime work zone. Since roadway contractors' perceptions regarding lighting issues or challenges in nighttime work zones were not addressed in the survey, the SPR 4542 research team conducted an interview on September 8, 2021, with five safety officers of construction companies' members associated with the Indiana Constructors, Inc. (ICI). The discussion focused on good practices related to work zone lighting in nighttime operations. The insights provided by the safety officers are described in three parts: (1) challenges faced by practitioners when planning or designing nighttime operations; (2) work zone lighting; and (3) lighting systems used for flagging operations.

Safety challenges in nighttime operations

One of the most significant challenges practitioners faces during nighttime roadway operations is the motoring public. There was consensus among the safety officers that there are more traffic congestions that tend to slow down motorists when they pass through work zones during the day. During daytime hours, increased traffic may cause other problems, such as motorists trying to merge and get through the zone. Also, the possibility of motor vehicle crashes at the rear of the queue is high. On the other hand, traffic tends to be lower at night, so motorists tend to increase their speed when passing through work zones. In both situations, there are challenges and safety risks. Practitioners indicated that at night: (1) drivers tend not to follow or pay attention to the speed control signs, channelizing devices, and other types of traffic control devices placed through the illuminated construction area; (2) motorists tend to drive recklessly (e.g., speeding up); and (3) there is a greater likelihood of encountering impaired drivers (due to fatigue, intoxication), especially during the weekends and late-night hours. These unsafe conditions produced by the motoring public may result in work zone intrusions, and thus motor-vehicle crashes within the work zone. The safety officers also stated that INDOT frequently requests contractors to perform work at night since nighttime operations could reduce the number

of queue accidents to motorists; however, this approach creates safety risks when drivers increase their speed through work zones.

Another major challenge while performing nighttime operations is worker fatigue. Practitioners indicated that extended working hours, especially those extended to later hours, may physically affect workers and their alertness. Fatigue concerns are noted more towards the end of the work shift. For instance, at nighttime shifts, fatigue concerns are noted between 2 a.m. or 6 a.m. Similarly, workers driving back home was also considered a concern during nighttime operations. Apart from traffic and work zone safety, the most significant aspect of safety, in general, was the personal and physical impact on workers.

Work zone lighting

Providing adequate illumination levels to perform construction and maintenance operations at night without producing excessive glare that may blind motorists is crucial for safe nighttime operations and safe driving through nighttime work zones.

Safety officers stated that two lighting system types are currently used on their nighttime highway operations: portable light towers and balloon lights. Portable light towers, especially those with trailer-mounted features, are widely used on various tasks performed at night. The primary advantages of portable lights are (a) their ability to be positioned at different sections within and across the work zone, since they can be easily moved from one location to another, and (b) their ease of operation and maintenance (Ellis et al., 2003). Another advantage identified by practitioners is the mounting height of these systems at which luminaires can be raised; this setting allows them to cover the work area that needs to be illuminated fully. Typically, mounting heights of light towers range from 1.8 m (6 ft) to a fully extended 9.1 m (30 ft), and the light tower pole is usually rotatable 360 degrees. However, one disadvantage identified by practitioners is that the light intensity produced by luminaires of portable light towers is higher when luminaires are installed at low mounting heights than when they are fully extended. This condition may pose a significant glare hazard for motorists and workers in work zones. For instance, a light tower mounted at 12 ft generates more light intensity than when mounted at 30 ft, resulting in an increase in glare levels. Practitioners stated that extreme caution must be exercised to address the glare issue when positioning and aiming light towers. They also indicated that when setting the aiming

angles of luminaries, the following conditions are typically considered: road geometry (e.g., straight road sections, curved sections, and others), available area within work zone, surface conditions of the work zone, and available width of the road's shoulders to position the lighting equipment.

The other common lighting equipment used by practitioners is balloon lights. Unlike light towers, balloon lights do not require changes in angles of luminaries because these systems provide the same light intensity in all directions (i.e., 360 degrees of illumination). These systems employ a diffusion mechanism and are thus less prone to glare. The safety officers indicated that these lighting systems are typically mounted on construction equipment such as pavers or the backside of vehicles.

Lighting systems for flagging operations

The NCHRP Report 476, titled "*Guidelines for Design and Operation of Nighttime Traffic Control for Highway Maintenance and Construction* (Bryden & Mace, 2002b)" recommends that whenever possible, flagging operations on maintenance and construction projects should be avoided at night. However, if flagging operations are scheduled at night, appropriate lighting systems are mandatory to make the flagger as visible as possible. During the interview with the safety officers, they identified that nighttime driving impairs the motorist's ability to detect objects, flaggers, workers, and road details, resulting in longer response times. They recommended that this visibility issue could be solved by providing illumination directly overhead (perpendicular to the ground) rather than from the front or back. Particularly, this lighting arrangement helps to eliminate harmful glare levels in comparison to other lighting configurations. They explained that when the flagger faces traffic with the lighting system behind it, the lighting configuration generates glare toward the public motorist. Similarly, if the lighting system is located directly ahead of the flagger, it creates glare for motorists traveling in the opposite direction. Additionally, the safety officers indicated that a flagger should be stationed to isolate him/her from the remaining work zone, preferably in the shoulder or closed lane, while wearing safety vests with front and back reflective markings.

3.2 Determination of Glare – An Experimental Approach

Lighting was deemed the most effective method of providing for the safety of workers and drivers during total and partial road closures (Hinze & Carlisle, 1990). However, inadequate lighting conditions and arrangements could cause glare to motorists when passing the work zone and impair their visibility. The contractor's responses regarding work zone lighting obtained from the survey showed that sometimes STAs do not require the preparation and submission of lighting plans for nighttime construction projects. Still, this does not include glare control measures when the lighting plan is required. Moreover, discussions with safety officers pointed out that careful evaluations of work zone lighting and glare should be made before any nighttime operation begins, especially for nighttime flagging operations. These insights point to a need to assess the impact of glare on workers and motorists and develop practical recommendations for reducing and controlling glare in nighttime work zones. Hence, this section addresses how disability glare can be determined and what field measurements should be taken on a simulated work zone to calculate glare values.

The determination of disability glare on nighttime highway work zones requires the input of two variables: veiling luminance and pavement luminance. The ratio between these two variables is named veiling luminance ratio ($V_{L\ ratio}$), and it is the metric of disability glare. The calculation of veiling luminance values also required the input of vertical illuminance readings emitted by a light source and measured using a light meter held flat against the vertical plane. Similarly, pavement luminance measurements are taken directly at different point locations in the simulated work zone. The simulated work zone was designed to replicate a one-lane closure nighttime work zone with its typical areas (transition area, activity area, and termination area), which are typically delimited with traffic control devices such as cones and drums. A detailed procedure of determining disability glare on a simulated nighttime highway work zone is described in the following subsections.

3.2.1 Site Preparation

Field lighting experiments were conducted to measure vertical illuminances and pavement luminance on a simulated nighttime work zone. These measurements served as input values for determining disability glare in nighttime highway work zones. The INDOT Research and

Development facility located at Yeager Road and Kent Avenue in West Lafayette, Indiana, was used to conduct the experiments which simulated a typical nighttime one-lane closure work zone. The facility is a private two-lane asphalt paved segment with street lighting approximately 161 meters long and 13 meters wide, as illustrated in Figure 3.7.

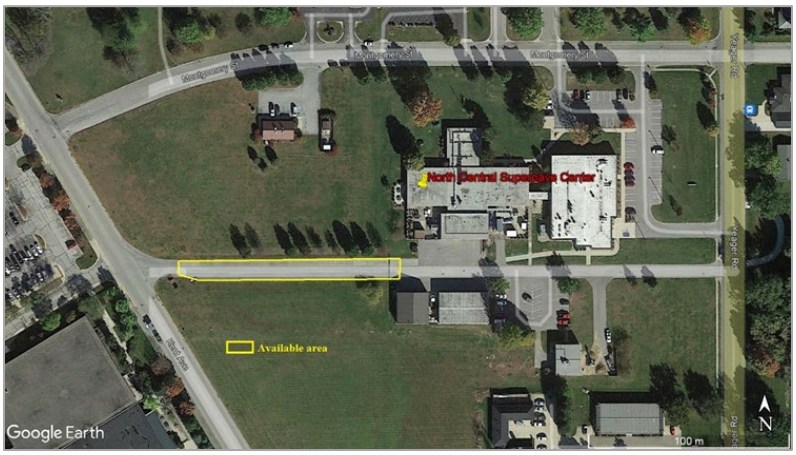


Figure 3.7. INDOT Research and Development facility (Google Earth, 2021).

The closed lane (right lane) was used to set up and test several lighting arrangements. The open lane (left lane) was used to measure vertical illuminance and pavement luminance which can be used later to calculate the veiling illuminance ratio, and hence the disability glare. A typical construction work zone is divided into four areas: advance warning area, transition area, activity area, and termination area. Such areas were replicated on a simulated work zone in this experiment. The total area of the simulated work zone is approximately 347.8 m^2 (3743.7 ft^2). The activity area (or work area) is 54 m. (177 ft) long and 3.7 m. (12 ft) wide, as shown in Figure 3.8. The work zone area was delimited by placing cones and drums every 4.5 m.

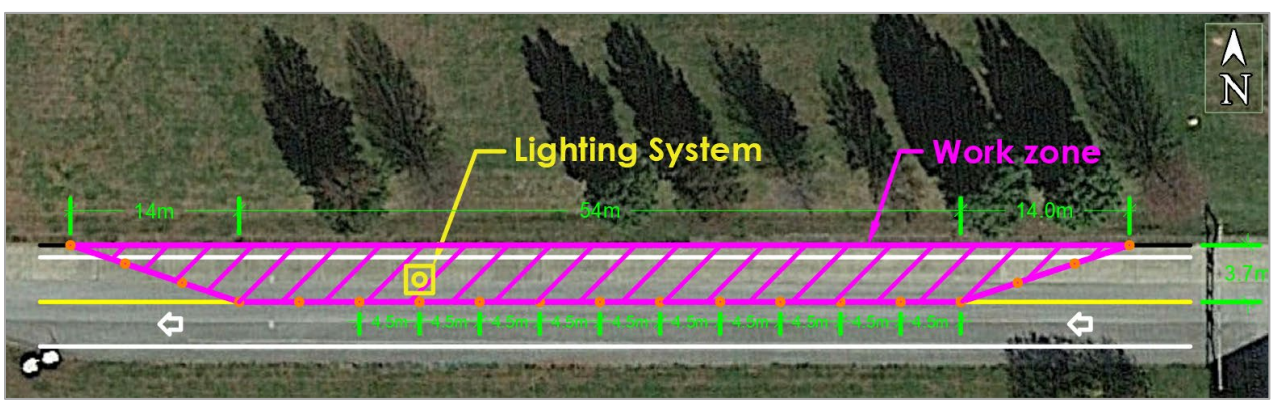


Figure 3.8. Simulated work zone layout at INDOT R&D facility, dimensions in m.

3.2.2 Equipment Used

The field experiments used four lighting systems: two balloon lights and two portable light towers. The lighting experiments employed a light meter, a luminance meter, distance measurement meters, and an angle gauge to perform measurements of illuminance, luminance, mounting heights, rotation and aiming angles of lighting fixtures, respectively. The following subsections will describe each of these lighting systems and measuring devices.

Balloon lights

As shown in Figure 3.9, balloon lights are luminaires inflated with air or helium and are typically designed to be mounted on equipment or in fixed locations such as flagger stations. This lighting system uses a large balloon-shaped luminaire that distributes light evenly and is relative glare-free. Balloon lights can illuminate an area between 108,000 and 432,000 square feet (Shane et al. 2012; Gambatese and Jafarnejad 2018). The main advantages of balloon lights are that they distribute light over 360 degrees, offer relative glare-free lighting, and some of them can be mounted as high as 164 ft (Gambatese, 2005).

Two balloon lighting were utilized in the lighting experiments. The balloon lights are manufactured by Multiquip Inc., the models used were the GloBug Series, as shown in Figure 3.9. The specifications of the balloon lighting systems are described in Table 3.2.

(a) GB3LED (b) GB8LED

Figure 3.9. Balloon lights – GloBug Series (Multiquip Inc., 2020)

Table 3.2. Balloon lights specifications.

Specification	LED Balloon Light	
Model	GloBug Series GB3LED	GloBug Series GB8LED
Lamps output	300-watt LED	800-watt LED
Light output	38,000 lumens	110,000 lumens
Minimum generator power	350 Watts	1200 Watts
Weight	27 lb.	48 lb.
Balloon dimensions	33.5" x 21"	47" x 28"
Maximum height	10'	13.2'

Light towers

Portable light towers, also known as light plants, are the most used lighting equipment in roadway construction projects. They are composed of various luminaries or fixtures (typically two to six light fixtures) mounted to a mast arm capable of supporting the luminaires at various mounting heights. Each of these components is mounted on a trailer towable by a construction vehicle. Typically, light tower luminaires are equipped with 1000- or 1500-watt metal-halide (MH), light-emitting diode (LED), high-pressure sodium (HPS), or tungsten-halogen bulbs. The retractable mast can be raised and rotated 360 degrees around its vertical axis between 1.8 m (6 ft) and 9.1 m (30 ft).

Two light towers were used in the field experiments - one light tower with light-emitting diode (LED) fixtures and one with metal-halide fixtures (MH), as shown in Figure 3.10(a) and (b). The specifications of the portable lighting systems are described in Table 3.3.

(a) Terex RL4000 – Metal halide lamps

(b) Trime X-Smart – LED lamps

Figure 3.10. Portable light towers (TEREX, 2009; TRIME, 2018)

Table 3.3. Portable light towers specifications.

Specification	Metal-halide light tower	LED light tower
Model	Terex RL4000	Trime X-Smart
Lamps output	4400 watts	4x320-watt
Light output	110,000 lumens	188,000 lumens
Fuel tank (diesel)	30 gal.	46 gal.
Weight	1725 lb. (783 kg)	2108 lb. (956 kg)
Maximum height	30 ft. (9.1 m)	25 ft. (7.6 m)

Illuminance Meter

An illuminance (or light) meter was used to measure the vertical illuminance that reaches the observer's eyes. The illuminance meter selected to perform the lighting measurements was the T-10A model manufactured by Konica Minolta which was capable to capture illuminance readings ranging from 0.01 to 299,900 lux (0.001 to 29,990 fc.). This instrument was installed inside of a car model CX-7 Mazda 2010, attached to the center of the car's windshield at 45 cm from the driver's line of sight and at height 1.45 m from the ground surface, as shown in Figure 3.11. The vertical illuminance readings taken served as input for calculating the veiling luminance.

Additionally, the illuminance meter was used to measure the horizontal illuminances of the activity area which were later served as inputs for the calculation of the horizontal uniformity ratio at the work area.

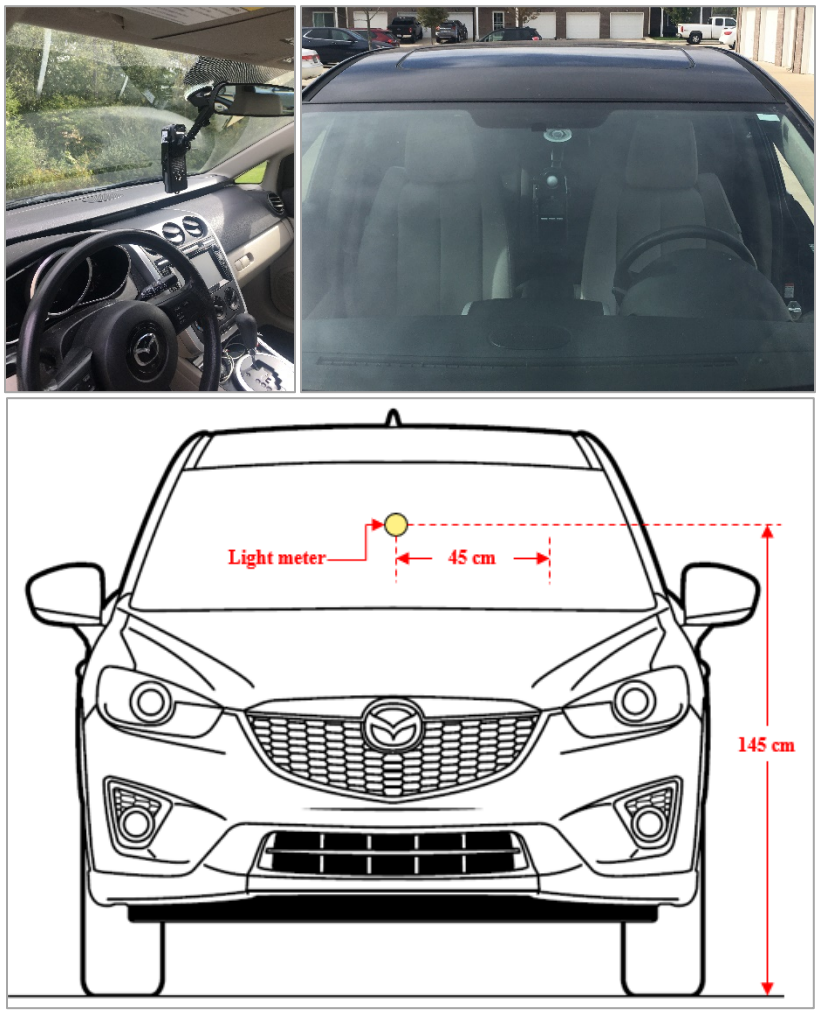


Figure 3.11. Illuminance meter T-10A model installation

Luminance Meter

A luminance meter was used to measure the pavement luminance values that reaches the observer's eyes. These luminance readings served as input for calculating the veiling luminance ratio (disability glare). The luminance meter used in this experiment was the LS-160, manufactured by Konica Minolta, which measures luminance from 0.01 to 9,999 candelas per square meters and has one-third degree acceptance angle as shown in Figure 3.12.

Figure 3.12. Digital luminance meter LS-160 model

Distance Measurement Meters

Two measuring devices, namely a laser distance meter, and one measuring wheel were used to setup up the lighting arrangements as shown in Figure 3.13. The laser distance meter model is Leica DISTO D1, manufactured by Leica, has an accuracy of 2mm per reading and a measurement range up to 40 m (120 ft). The metric measuring wheel, manufactured by Zozen, can measure distances up to 9,999 meters. Both devices were used to locate and position: (1) the grid points in the work zone (equally spaced every 5m); (2) the lighting systems along the four sub-areas within the work zone (warning, transition, activity, and termination area); and (3) the mounting heights of the lighting equipment.

(a) Laser distance meter D1 (Leica, 2010)

(b) Measuring wheel (Zozen, 2021)

Figure 3.13. Distance measuring devices.

Digital Electronic Level and Angle Gauge

A digital angle gauge was used in the lighting experiments to determine and identify the aiming angle for the luminaires (fixtures) of the light towers. The digital angle locator model is 935DAG, manufactured by Klein Tools, which measures or sets angles between 0 to 180 degrees of any surface from the horizontal plane. The angle gauge can also be used as a digital level. This device is equipped with a strong magnetic base that can easily be attached to any ferromagnetic surface, as shown in Figure 3.14. The orientation of the portable light towers (or rotation angles) was obtained by rotating the height mast on its vertical axis, as shown in Figure 3.15.

Figure 3.14. Digital Electronic Level and Angle Gauge 935DAG model (Klein Tools, 2019).

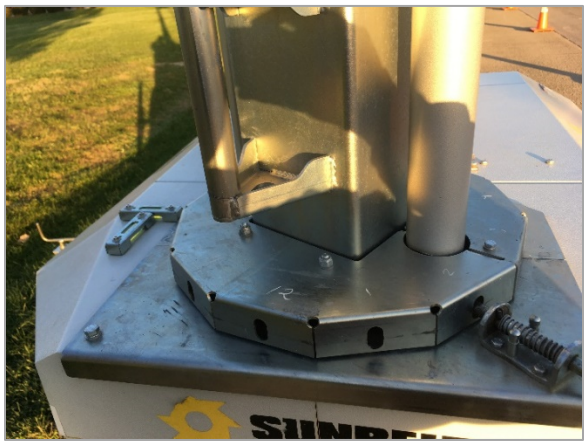


Figure 3.15. Rotatable 360 degrees light tower.

3.2.3 Determination of Veiling Luminance Ratio (Disability Glare)

Disability glare is evaluated using the veiling luminance ratio, which is the maximum veiling luminance divided by the average luminance of the road surface (IES, 2018). The Illumination Engineering Society of North America (IES) recommends that the veiling luminance ratio can be determined by selecting a grid for straight roadway sections between traffic conflict areas (or intersections), curves, or traffic conflict areas. The grid of calculation points is chosen so the area of each grid cell is identical for straight roadway sections between traffic conflict areas.

A grid cell is defined as the area enclosed by an imaginary line that connects all adjacent grid intersections and touches the traveled lane's edge. IES recommends that there should be two grid lines per lane, one-quarter of the distance from the edge of each lane. Longitudinally, the grid lines should extend as a minimum of 10 calculation points along the road equally spaced, not more than 5 m on center ($x \leq 5$ m). Although the starting point of the gridline cannot be located directly under the lighting equipment, it can start at a point half of the grid cell size (½ x) from the luminaire, as shown in Figure 3.16.

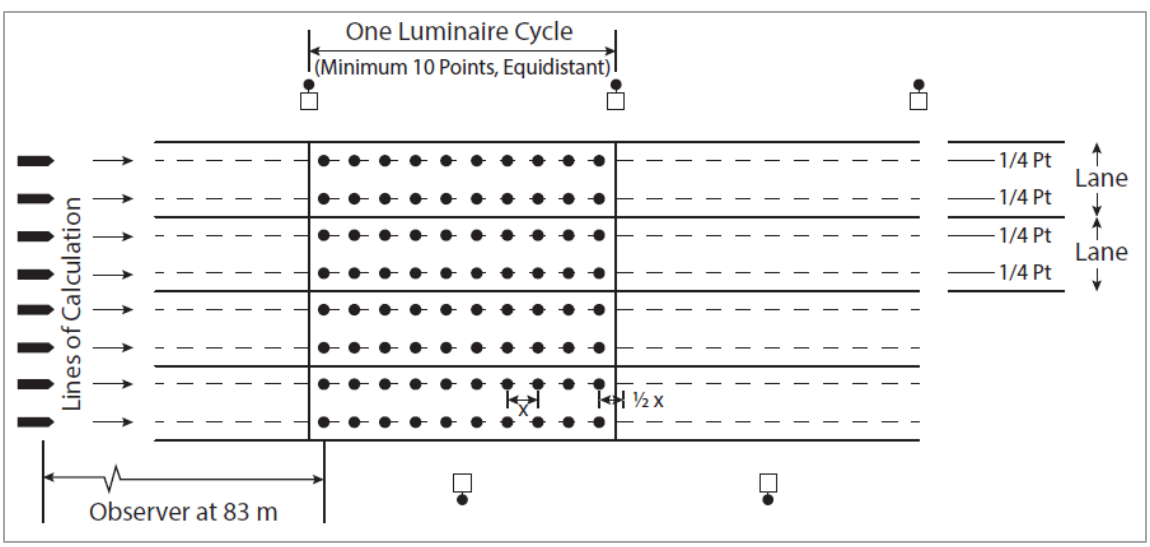


Figure 3.16. Location of calculation points, luminaires, and observer for illuminance, luminance, and veiling luminance calculations on roadways (IES, 2018).

Based on the IES recommended practice, a grid cell was sketched on the layout of the simulated work zone. The grid cell is located on the left lane (open lane), and it is composed of one line of calculation (or one line of sight), as shown in Figure 3.17. Each line of sight has eleven points; the starting points are located at 1.4 m of the distance from the edge of the closed lane (3.1 m). The grid points along the left lane were spaced every 4.5 m. and referenced by cones and drums to delimitate the work zone.

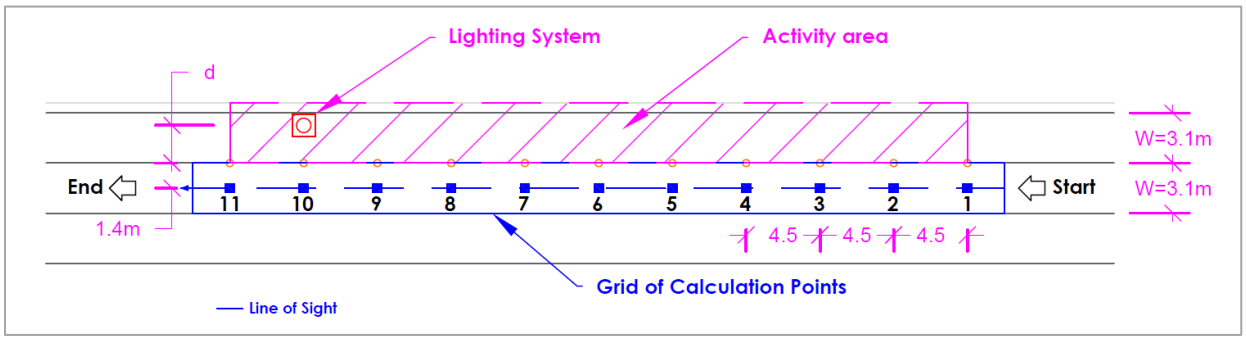


Figure 3.17. Grid of points for measuring vertical illuminance and pavement luminance, dimensions in m.

Measurements of illuminance and luminance, and calculations of veiling luminance must be done to determine the veiling luminance ratio (or disability glare). The measurements correspond to readings of vertical illuminance and pavement luminance for each of the grid points captured by an illuminance meter and a luminance meter, respectively. The calculations are used to determine the veiling luminance values on each of the grid points. Finally, when the veiling luminance values of each of the grid points and average pavement luminance values per line of sight are determined, veiling luminance ratio can be calculated. These measurements and calculations tasks are described in detail in the following subsections.

Measurement of vertical illuminance (VI)

The vertical illuminance (*VI*) was measured at 1.45 meters above ground or roadway surface using an illuminance meter at each location on the grid for both lines of sight (or lines of calculation). These measurements were taken from inside of a car to simulate the vertical illuminance experienced by nighttime drivers passing by the construction zone. The vertical illuminance nomenclature for each measurement is defined as $VI_{a,\,b}$. where a represents the number

of lines of sight and *b* the number of points. For instance, the first vertical illuminance measurement for the first line of sight was taken at point $VI_{1,1}$ located at 1.4 meters from the edge of the closed lane as, shown in Figure 3.18. Then the car moved 4.5 m along the first line of sight and the next reading was taken ($VI_{1,2}$). This measuring process may continue if more lines of sight are added and the measuring of vertical illuminance with the illuminance meter should be repeated for the rest of the additional grid points.

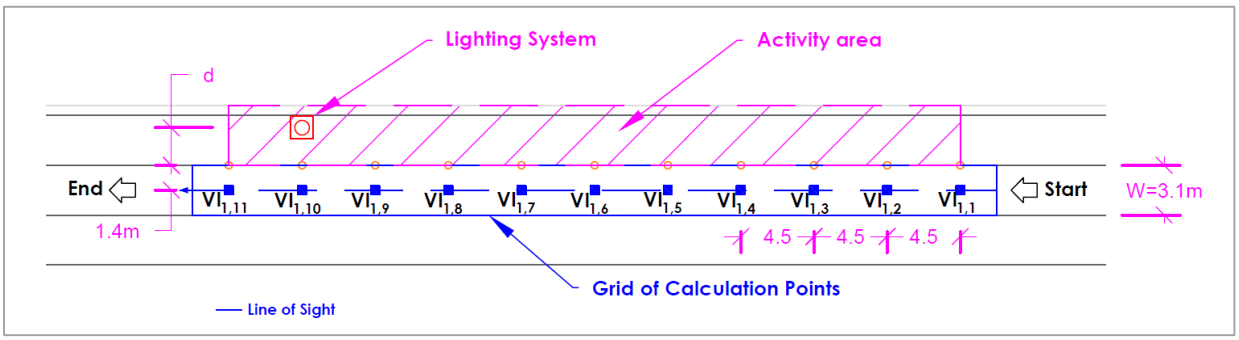


Figure 3.18. Vertical illuminance measurements per one line of sight, dimension in m.

Measurement of pavement luminance (PL)

The pavement luminance (*PL*) was measured using a luminance meter for each grid point along the line of sight, as shown in Figure 3.19. Based on IESNA recommendations, the observer was located at a distance of 83.07 m from each grid point on a line parallel to the centerline of the roadway (IES, 2018). The eye height of the observer was 1.45 m in compliance with the IES recommended practice, which results in a downward direction of view of one degree.

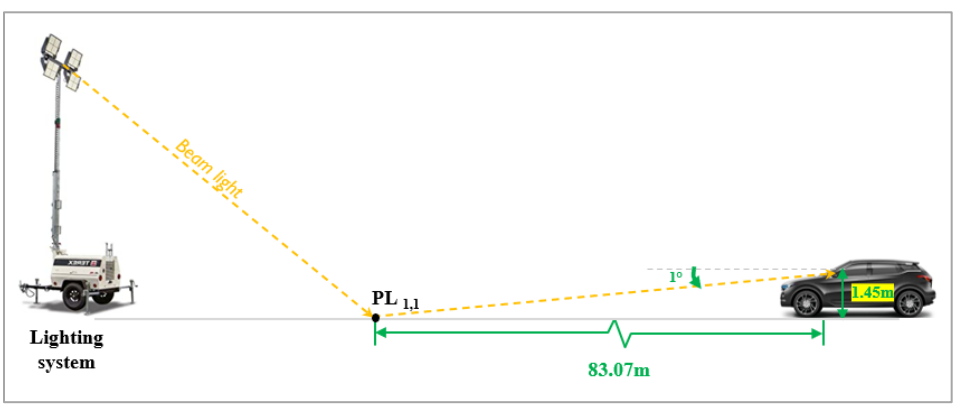


Figure 3.19. Pavement luminance field measurements.

The pavement luminance was measured inside a vehicle to simulate the conditions experienced by motorists driving by the construction zone. The first pavement luminance measurement at point $PL_{1,1}$ on the first line of sight was taken by positioning the car and observer at point "A" at a distance of 83.07 m from point $PL_{1,1}$, as shown in Figure 3.20. The car then moved 4.5 m along the first line of sight at point "B" and the next reading was taken ($PL_{1,2}$). This process was repeated until the last pavement luminance reading ($PL_{1,11}$) was reached. The measuring process may continue if more lines of sight are added and the measuring of pavement luminance with the luminance meter should be repeated for the rest of the grid points added. Finally, the average pavement luminance was then calculated by averaging the pavement luminance measurements for all the points per line of sight.

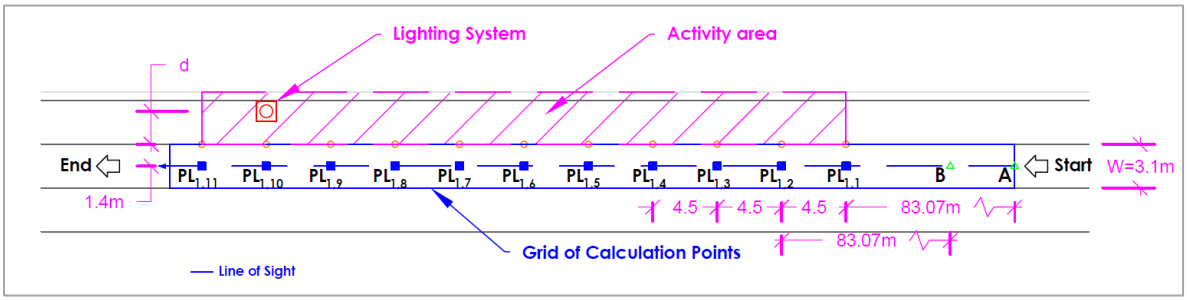


Figure 3.20. Pavement illuminance measurements per one line of sight, dimension in m.

Determination of veiling luminance (V_L)

The veiling luminance (V_L) calculation due to all light sources is the sum of the individual sources' veiling luminance. Veiling luminance (V_L) is determined by three factors: (i) vertical illuminance (VI) from each individual luminaire; (ii) glare angle (θ) formed between the directions of the glare source and the direction of viewing; (iii) the age factor (k) of the observer (this factor increases with age of the observer). At this point, the vertical illumination measurements should be recorded and stored by each of the grid points, as shown in Figure 3.21. Then, the veiling luminance values for the same grid points can be determined by using the Equation (3.1).

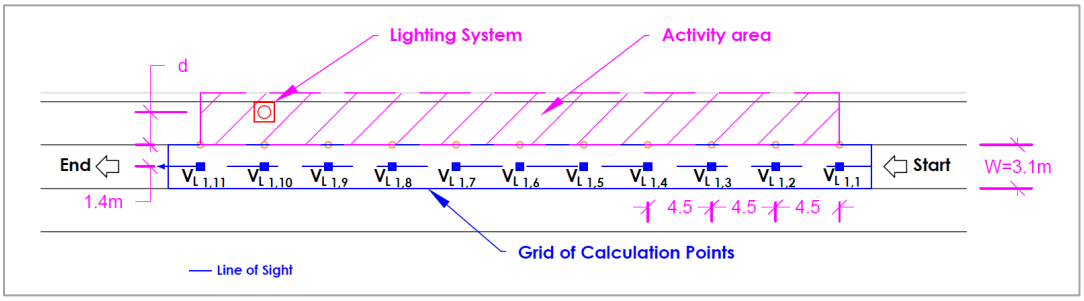


Figure 3.21. Veiling luminance calculations per line of sight, dimension in m.

$$V_L = k * \frac{VI}{\theta^n} \tag{3.1}$$

Where veiling luminance from one individual luminaire is V_L, θ is the glare angle, between the directions of the glare source and the direction of viewing (See Figure 3.22). Both, V_L and VI are expressed in compatible units (candela/m2 and lux, respectively) and θ in degrees, and the variable n depends on the glare angle θ and is calculated using Equation (3.2).

$$n = 2.3 - 0.7 \log_{10} \theta \quad for\ \theta < 2°;\ n = 2 \quad for\ \theta \geq 2° \tag{3.2}$$

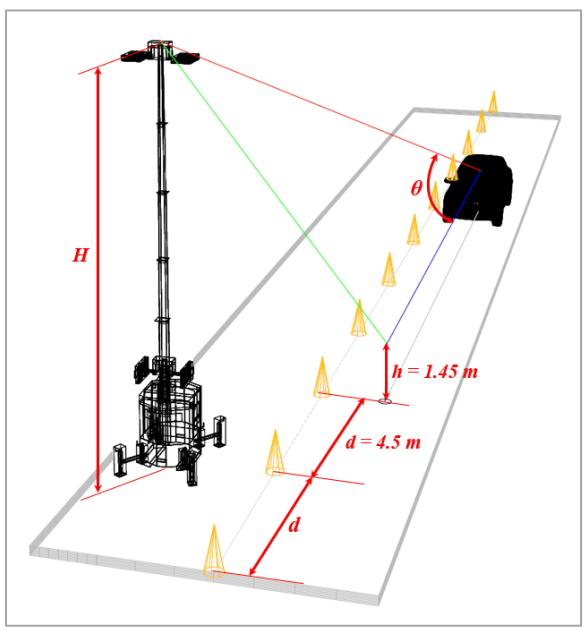


Figure 3.22. Geometric relationships for calculating veiling luminance.

The constant "k" has an initial value of 10 for a 25-year-old-observer. However, the k value increases with age, as shown in Equation (3.3).

$$k = 10 \times AF \tag{3.3}$$

The calculated veiling luminance can be multiplied by a factor to account for the natural physiological changes that occur in the observers' eyes as they age. This factor is referred to as the aging factor (AF), and it is calculated as follows in Equation (3.4).

$$AF = \left[1 + \left(\frac{Age}{70}\right)^4\right] \tag{3.4}$$

Incorporating the aging factor (AF) results in an increase in the calculated veiling luminance value which indicates a sharp increase beyond 70 years of age.

Determination of veiling luminance ratio ($V_{L\ ratio}$)

The veiling luminance ratio (disability glare), by each of the grid points, is the ratio between the veiling luminance (V_L), which was calculated previously for each point in the grid, as shown in Figure 3.21, and the average pavement luminance (PL_{avg}) calculated per each line of sight. For instance, the veiling luminance ratio for the point first point on the first line of sight represented as $V_{L\ ratio\ (1,1)}$, is determined by dividing the veiling luminance (V_L) on that point, $V_{L\ (1,1)}$, by the average of pavement luminance values of the first line of sight (PL_{avg}). The representation of these calculations is shown in Figure 3.23.

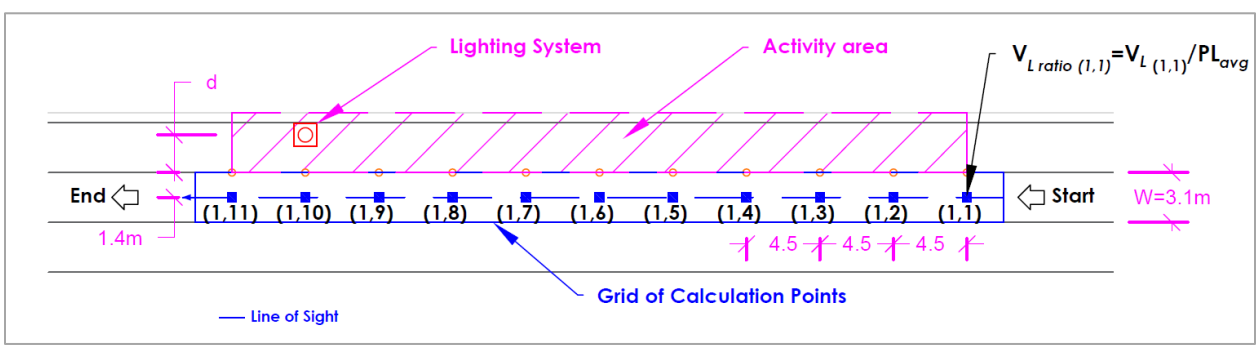


Figure 3.23. Veiling luminance ratio calculation per line of sight.

3.3 Data Analysis

This section describes the data analysis procedure that was used to examine the values of veiling luminance ratio (or disability glare) calculated by using the vertical illuminance and pavement luminance measurements obtained from the different lighting arrangements on the controlled work zone environment. A Factorial Analysis of Variance (or ANOVA) was used to evaluate the effects of the dependent variables (type of lighting system, type of light source, mounting height, orientation, or rotation angles, aiming angles, and wattage) on the single independent variable (veiling luminance ratio or disability glare). Additionally, post-hoc Tukey's tests HSD ("honestly significant difference") were used to investigate pairwise mean differences between all dependent variables.

3.3.1 Analysis of Variance (ANOVA): Fixed and Random Effects

Fixed factors are those whose values correspond to the populations of interest. Conclusions about the effects of a fixed factor are limited to the specific category levels investigated, and subsequent experiments involving the factor must use the same specific category levels. On the other hand, random factors are those whose category levels are chosen at random from all possible population levels and used as random representatives of the population.

One-way ANOVA

A one-way ANOVA compares the means of two or more groups for a single dependent variable. In such cases, the t-test is not applicable. As is the case with t-tests, there is only one independent and one dependent variable in the one-way ANOVA test. For nominal groups, interval dependent variables are required. The assumption of normal distribution is not required. ANOVA compares the variation within a group (on average) to the variation associated with the group means. A minimum sample size of 30 is desirable when performing a one-way ANOVA, and equal numbers per group are not required (Ross & Willson, 2017). One-way ANOVA uses one factor (i.e., a categorical variable used for analysis with two or more categories) to measure change in a dependent (continuous) variable. This produces a single F value (or F-statistic) when differences are present, and post hoc tests are used to find where the differences lie (Mertler et al., 2021).

Factorial ANOVA

A Factorial Analysis of Variance (ANOVA) is a statistical technique that enables the investigation of the relationship between two or more independent variables (factors) and a single dependent variable. A factorial ANOVA is used to predict change in a single dependent variable using two or more independent variables with two or more categories. This statistical analysis has two advantages it allows the examination of the effect of multiple independent variables on the dependent variable's change, this effect is quantified using the main effects of each factor in isolation, as well as the interaction effect of all factors; and it reduces the variance associated with possible errors.

Factorial ANOVAs are defined by the number of factors and categories on each used factor (Mertler et al., 2021). For instance, a Factorial ANOVA with two factors with three categories each would be a 3 x 3, or if there are three factors, all with three categories would be a 3 x 3 x 3. Because Factorial ANOVAs contain two or more independent variables, multiple F tests and post hoc analyses are used to determine distinctions between categories (Mertler et al., 2021). Factorial ANOVAs are used to determine the main and interaction effects of the factor means. The term "*main effects*" refers to the comparisons of the means for each factor. These effects indicate distinctions between categories for each factor included in the design. The effect of one independent variable on the dependent variable that is not consistent across levels of another independent variable is called an interaction. The "*interaction effects*" examine the differences between the combined categories created by the factors' main effects and demonstrate how category combinations can affect the dependent variable. For instance, the linear models for two- and three-factor designs are defined by Equations (3.4) and (3.5).

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \tag{3.5}$$

$$y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijkl} \tag{3.6}$$

where μ is the overall mean, α is the effect of Factor A, β is the effect of Factor B, γ is the effect of Factor C and ε is the random unexplained or residual component. Moreover, in a two-factor design ANOVA, the null hypothesis for factor A is defined as $H_0(A)$ in Equation (3.6). The

mean of population 1 is equal to that of population 2 and so on, and thus all population means are equal to an overall mean.

$$H_0(A): \mu_1 = \mu_2 = \cdots = \mu_i = \mu \tag{3.7}$$

If the effect of the ith group is the difference between the ith group mean and the overall mean $(\alpha_i = \mu_i - \mu)$, then the $H_0(A)$ can alternatively be written as Equation (3.7). A statistically significant result ($p < 0.05$) would suggest that the null hypothesis $H_o(A)$ can be rejected in favor of an alternative statistical hypothesis that somewhere, among the population means, there is a difference.

$$H_0(A): \alpha_1 = \alpha_2 = \cdots = \alpha_i = 0 \tag{3.8}$$

If one or more of the α_i is different from zero (the response mean for this factor is different than the response means for all factors), the null hypothesis is false, indicating that the explanatory variable influences the response variable (Logan 2009). Similarly, the null hypothesis for a factor B is defined in Equation (3.8).

$$H_0(A): \beta_1 = \beta_2 = \cdots = \beta_i = 0 \tag{3.9}$$

The null hypothesis for factor A and factor B (AB) interaction is defined in Equation (3.9). The population group means will be equal to the difference between the overall population mean and the simple additive effects of the individual factor group mean for any given combination of factor levels. The effects of the primary treatment factors are additive and self-sustaining. This null hypothesis is equivalent to $H_o(AB)$: $\alpha\beta_{ij} = 0$, no interaction between Factor A and Factor B (Logan 2009).

$$H_0(AB): \mu_{ij} = \mu_i + \mu_j - \mu \tag{3.10}$$

3.3.2 Factorial ANOVA design for Disability Glare Factors.

Designing a factorial ANOVA for this study consisted of two steps. The first step identified the dependent and independent variables. The dependent variable is the veiling luminance ratio (or disability glare) and the independent variables are the type of lighting system, light source, mounting height, rotation angle, and aiming angle. Table 3.4 summarizes the dependent and independent variables for the tested lighting arrangements.

Table 3.4. Summary of the dependent and independent variables.

Dependent variable	
Veiling luminance ratio (or disability glare)	
Independent variables	
Lighting System-Specific Variables	***Luminaire-Specific Variables***
Lighting type (1) Balloon light (2) Portable light tower	Mounting Height (H) (1) 8 and 10 ft (2) 12, 18, 25, and 30 ft
Light source (1) Metal-halide (MH) (2) light-emitting diode (LED)	Rotation Angle (RA) (1) 45-, 90-, 135-degree angle
Wattage (W) (1) 300-W (2) 400-, 600-, and 800-W	Aiming Angles (AA) (1) 30-, 45-, 60-degree angle

The second step defines the Null Hypothesis, as described in Section 3.3.1. A total of three Factorial ANOVA designs were proposed to examine the effects of the independent variables in the single dependent variable (veiling luminance ratio or disability glare). Each factorial design is described as follows:

1. Factorial ANOVA design for balloon light (2x4)

   For the case of balloon lights, two factors have an influence on the veiling luminance ratio (or disability glare): mounting height and wattage. The statistical test used two categories for mounting heights (8ft and 10ft) and four categories for wattage factor (300-, 400-, 600-, and 800-W). Table 3.5 summarizes the null and alternative hypothesis for a balloon light (2x4) design.

   - H_0: There will be no difference in the veiling luminance ratio means between the mounting height factor (*H*) categories: 8 ft (2.4 m.) and 10 ft (3.1 m.)
   - H_0: There will be no difference in the veiling luminance ratio means between the electrical power factor (W) categories: 300-, 400-, 600-, and 800-W
   - H_0: There will be no interaction between the mounting height factor and the wattage in the veiling luminance ratio means.

Table 3.5. Null and alternative hypothesis for a balloon light (2x4).

Factorial Design	Main Effects		Interaction Effects	
	Null Hypothesis (H_0)	Alternative Hypothesis (H_1)	Null Hypothesis (H_0)	Alternative Hypothesis (H_1)
Balloon lighting (2x4)	$\alpha_i = 0$ *i =1 and 2*	$\alpha_i \neq 0$ *i=1 and 2*	$(\alpha\beta)_{ij} = 0$ *i =1 and 2* *j =1, 2, 3, and 4*	$(\alpha\beta)_{ij} \neq 0$ *i=1 and 2* *j =1, 2, 3, and 4*
	$\beta_j = 0$ *j =1, 2, 3, and 4*	$\beta_j \neq 0$ *j=1, 2, 3, and 4*		

Mounting Height factor (α_i) and Wattage factor (β_j)

2. Factorial ANOVA design for metal-halide light tower (3x3x2)

   For the case of metal-halide lights, three factors, namely, mounting height, rotation angles, and aiming angles are used in the Factorial ANOVA design. Three categories are used for mounting height (12ft, 18ft, and 30ft), three categories for orientation (45 degrees, 90 degrees, and 135 degrees), and two categories for aiming angle of luminaires (30 degrees and 45 degrees). Table 3.6 summarizes the null and alternative hypothesis for a metal-halide light tower (3x3x2) design.

   - H_0: There will be no difference in the veiling luminance ratios means between the mounting height factor (H) categories: 12 ft, 18 ft, and 30 ft.
   - H_0: There will be no difference in the veiling luminance ratios means between the rotation angle factor (RA) categories: 45°, 90°, and 135°.
   - H_0: There will be no difference in the veiling luminance ratios means between the aiming angle factor (AA) categories: 30°, and 45°.
   - H_0: There will be no interaction between the mounting height and the rotation angle factors in the veiling luminance ratios.
   - H_0: There will be no interaction between the mounting height and the aiming angle factors in the veiling luminance ratios.
   - H_0: There will be no interaction between the rotation angle factor and the aiming angle factors in the veiling luminance ratios.
   - H_0: There will be no interaction between all factors (H, RA, AA) in the veiling luminance ratios.

Table 3.6. Null and alternative hypothesis for a metal-halide light tower (3x3x2)

Factorial Design	Main Effects		Interaction Effects	
	Null Hypothesis (H_0)	Alternative Hypothesis (H_1)	Null Hypothesis (H_0)	Alternative Hypothesis (H_1)
Metal-halide light tower(3x3x2)	$\alpha_i = 0$ *i =1,2, and 3*	$\alpha_i \neq 0$ *i =1,2, and 3*	$(\alpha\beta)_{ij} = 0$ *i =1,2, and 3* *j =1,2, and 3*	$(\alpha\beta)_{ij} \neq 0$ *i =1,2, and 3* *j =1,2, and 3*
	$\beta_j = 0$ *j =1,2, and 3*	$\beta_j \neq 0$ *j =1,2, and 3*	$(\alpha\gamma)_{ik} = 0$ *i =1,2, and 3* *k =1 and 2*	$(\alpha\gamma)_{ik} \neq 0$ *i =1,2, and 3* *k =1 and 2*
	$\gamma_k = 0$ *k =1 and 2*	$\gamma_k \neq 0$ *k =1 and 2*	$(\beta\gamma)_{jk} = 0$ *j =1,2, and 3* *k =1 and 2*	$(\beta\gamma)_{jk} \neq 0$ *j =1,2, and 3* *k =1 and 2*
			$(\alpha\beta\gamma)_{ijk} = 0$ *i =1,2, and 3* *j =1,2, and 3* *k =1 and 2*	$(\alpha\beta\gamma)_{ijk} \neq 0$ *i =1,2, and 3* *j =1,2, and 3* *k =1 and 2*

Mounting Height factor (αi), Rotation angle factor (βj), and Aiming angle factor (γ_k)

3. Factorial ANOVA design for LED light tower (3x3x2)

For the case of LED lights, three factors have an influence on the veiling luminance ratio (or disability glare): mounting height, rotation angles, and aiming angles. Three categories are used for mounting height factor (12ft, 18ft, and 25ft), three categories for orientation factor (45 degrees, 90 degrees, and 135 degrees), and two categories for aiming angle factor (45 degrees and 60 degrees) are used in the test Table 3.7 summarizes the null and alternative hypothesis for a LED light tower (3x3x2) design.

- H_0: There will be no difference in the veiling luminance ratios means between the mounting height factor (H) categories: 12 ft, 18 ft, and 25 ft
- H_0: There will be no difference in the veiling luminance ratios means between the rotation angle factor (RA) categories: 45°, 90°, and 135°.
- H_0: There will be no difference in the veiling luminance ratios means between the aiming angle factor AA: 45°, and 60°.
- H_0: There will be no interaction between the mounting height and the rotation angle factors in the veiling luminance ratios.
- H_0: There will be no interaction between the mounting height and the aiming angle factors in the veiling luminance ratios

- H_0: There will be no interaction between the rotation angle factor and the aiming angle factors in the veiling luminance ratios
- H_0: There will be no interaction between all factors (H, RA, AA) in the veiling luminance ratios.

Table 3.7. Null and alternative hypothesis for a LED light tower (3x3x2)

Factorial Design	Main Effects		Interaction Effects	
	Null Hypothesis (H_0)	Alternative Hypothesis (H_1)	Null Hypothesis (H_0)	Alternative Hypothesis (H_1)
LED-light tower (3x3x2)	$\alpha_i = 0$ $i = 1,2,$ and 3	$\alpha_i \neq 0$ $i = 1,2,$ and 3	$(\alpha\beta)_{ij} = 0$ $i = 1,2,$ and 3 $j = 1,2,$ and 3	$(\alpha\beta)_{ij} \neq 0$ $i = 1,2,$ and 3 $j = 1,2,$ and 3
	$\beta_j = 0$ $j = 1,2,$ and 3	$\beta_j \neq 0$ $j = 1,2,$ and 3	$(\alpha\gamma)_{ik} = 0$ $i = 1,2,$ and 3 $k = 1$ and 2	$(\alpha\gamma)_{ik} \neq 0$ $i = 1,2,$ and 3 $k = 1$ and 2
	$\gamma_k = 0$ $k = 1$ and 2	$\gamma_k \neq 0$ $k = 1$ and 2	$(\beta\gamma)_{jk} = 0$ $j = 1,2,$ and 3 $k = 1$ and 2	$(\beta\gamma)_{jk} \neq 0$ $j = 1,2,$ and 3 $k = 1$ and 2
			$(\alpha\beta\gamma)_{ijk} = 0$ $i = 1,2,$ and 3 $j = 1,2,$ and 3 $k = 1$ and 2	$(\alpha\beta\gamma)_{ijk} \neq 0$ $i = 1,2,$ and 3 $j = 1,2,$ and 3 $k = 1$ and 2

Mounting Height factor (αi), Rotation angle factor (βj), and Aiming angle factor (γ_k)

3.4 Chapter Summary

A survey was deployed to contractors involved in roadway construction and maintenance projects to identify their perceptions of lighting systems used in Indiana nighttime highway operations. Also, a formal interview with safety officers linked with roadway construction projects was conducted to determine the current practices regarding controlling or minimizing glare on work zones. The data gathered from the roadway contractor's responses to the survey helped select the lighting equipment for the field lighting experiments. The key insights obtained from the formal interview with ICI's safety officers helped design the lighting arrangements to be tested during the field lighting experiments.

Finally, a detailed procedure for determining disability glare on work zones was developed. This procedure consisted of two major stages. The first stage describes the steps to measure the vertical illuminance and pavement luminance on site and the second stage describes the steps needed to calculate the veiling luminance and the veiling luminance ratio (or disability glare). Chapter 4 will describe the results of the measurements taken from the field experiments and the calculations performed to obtain the disability glare values. The chapter will also describe the results from the three Factorial ANOVA designs of light towers and balloon lights, explaining the independent variables' effects (lighting system, light source, mounting height, orientation, aiming angle, and wattage) on the independent variable (veiling luminance ratio or disability glare).

4. DETERMINATION OF VEILING LUMIANCE RATIOS AND IMPLICATIONS FOR SELECTION OF LIGHTING COMBINATIONS

This chapter summarizes the results from the set of lighting experiments conducted on a simulated nighttime construction site to assess the disability glare generated by commonly used lighting configurations used in nighttime roadway construction work zones. The experiments began on November 1, 2021, and were completed on November 7, 2021, and were conducted between 7:00 p.m. – 11:30 p.m. The setup began approximately one hour before sunset to complete the following tasks during daylight hours: (1) setting up of the simulated work zone; (2) positioning the construction cones to represent the measurement points in the grid (as discussed in Section 3.2.3); and (3) positioning and setting up the lighting equipment. A total of 49 lighting arrangements were tested during the field experiments as shown in Table 4.1.

Table 4.1. Lighting arrangements.

Lighting Arrangement	Type of Lighting System	Mounting Height (H)	Rotation Angle (RA)	Aiming Angle (AA)
1	One LED balloon light	2.4 m (8 ft)	N/A	
2				
3				
4				
5		3.1 m (10 ft)	N/A	
6				
7				
8				
9	Two LED balloon lights	2.4 m (8 ft)	N/A	
10		3.1 m (10 ft)	N/A	
11				
12				
13				
14	One metal-halide light tower	3.7 m (12 ft)	45°	30°, 30°, 30°, 30°
15				45°, 45°, 45°, 45°
16			90°	30°, 30°, 30°, 30°
17				45°, 45°, 45°, 45°
18			135°	30°, 30°, 30°, 30°
19				45°, 45°, 45°, 45°

Table 4.1 Continued.

Lighting Arrangement	Type of Lighting System	Height (H)	Rotation Angle (RA)	Aiming Angle (AA)
20	One metal-halide light tower	5.5 m (18 ft)	45°	30°, 30°, 30°, 30°
21				45°, 45°, 45°, 45°
22			90°	30°, 30°, 30°, 30°
23				45°, 45°, 45°, 45°
24			135°	30°, 30°, 30°, 30°
25				45°, 45°, 45°, 45°
26		9.1 m (30 ft)	45°	30°, 30°, 30°, 30°
27				45°, 45°, 45°, 45°
28			90°	30°, 30°, 30°, 30°
29				45°, 45°, 45°, 45°
30			135°	30°, 30°, 30°, 30°
31				45°, 45°, 45°, 45°
32	One LED light tower	3.7 m (12 ft)	45°	45°, 45°, 45°, 45°
33				60°, 60°, 60°, 60°
34			90°	45°, 45°, 45°, 45°
35				60°, 60°, 60°, 60°
36			135°	45°, 45°, 45°, 45°
37				60°, 60°, 60°, 60°
38		5.5 m (18 ft)	45°	45°, 45°, 45°, 45°
39				60°, 60°, 60°, 60°
40			90°	45°, 45°, 45°, 45°
41				60°, 60°, 60°, 60°
42			135°	45°, 45°, 45°, 45°
43				60°, 60°, 60°, 60°
44		7.6 m (25 ft)	45°	45°, 45°, 45°, 45°
45				60°, 60°, 60°, 60°
46			90°	45°, 45°, 45°, 45°
47				60°, 60°, 60°, 60°
48			135°	45°, 45°, 45°, 45°
49				60°, 60°, 60°, 60°

The lighting experiments were conducted to measure the vertical illuminance and pavement luminance for 49 lighting arrangements. These measurements served as input values to determine the veiling luminance ratio which is a measure of the disability glare produced by a lighting system. The combinations were selected to represent typical configurations used on typical roadway nighttime operations such as Hot Mix Asphalt (HMA) placement, rolling HMA surfaces, asphalt milling, pavement cleaning and sweeping, pavement patching, and work zone flagger stations.

The following sections describe the measurements of vertical illuminance and pavement luminance taken during the field experiments as well as the calculations performed to obtain the veiling luminance and veiling luminance ratio tested for each lighting combination. The tested

lighting systems were: (1) a single metal-halide light tower; (2) a single LED light tower; (3) two LED balloon lights (LED).

4.1 LED Balloon Light Testing

As described in Chapter 3, two LED balloon lights were tested on a simulated work zone as shown in Figure 4.1. Thirteen balloon lighting configurations were evaluated, as shown in Table 4.2. Eight lighting configurations correspond to individual balloon lights, while the remaining configurations correspond to two balloon lights tested simultaneously. As mentioned in Section 3.2.2, the field experiments utilized GloBug balloon systems. One balloon light was the model GB3LED, which has an adjustable power output of up to 300 watts. The other balloon light was the GB8LED, which features wattage adjustment values of 300-, 400-, 600-, and 800-watts. Both balloon lights were evaluated at two different mounting heights 2.4 m (8 ft) and 3.1m (10 ft). These mounting heights are consistent with nighttime highway construction and maintenance activities such as Hot Mix Asphalt (HMA) placement, rolling HMA surfaces, asphalt milling, pavement cleaning and sweeping and work zone flagger stations.

For each of the balloon lights configurations tested, vertical illuminance (*VI*) and pavement luminance (*PL*) were measured. Also, for each combination, the values of veiling luminance (V_L) and veiling luminance ratio ($V_{L\ ratio}$) were calculated for one line of sight, according to the glare determination procedure explained in Section 3.2.3.

Figure 4.1. Two balloon lights positioned parallel to the lane.

Table 4.2. Tested lighting arrangements for balloon lights.

Lighting Arrangement	Lighting System	Mounting Height (H)	Wattage (Watts)	Distance Between Lighting Systems
1	One Balloon Light	2.4 m (8 ft)	300 W	N/A
2			400 W	N/A
3			600 W	N/A
4			800 W	N/A
5		3.1 m (10 ft)	300 W	N/A
6			400 W	N/A
7			600 W	N/A
8			800 W	N/A
9	Two Balloon Lights	2.4 m (8 ft)	300- and 400-W	N/A
10		3.1 m (10 ft)	300- and 400-W	N/A
11			300- and 800-W	9.0 m
12				13.5 m
13				18.0 m

4.1.1 One LED Balloon Light

Eight lighting arrangements used one balloon light. The balloon light was positioned at 40.5 meters from the origin (or D= 0.0m) of the activity area and a lateral distance of 1.4 m from the centerline of the closed lane, as shown in Figure 4.2. Two different mounting heights and four different power outputs were configured for the field experiments. As shown in Table 4.2, the lighting arrangement 1 to 4 correspond to 8-ft height and four power outputs. Similarly, the lighting arrangements 5 to 8 correspond to 10-ft height and four power outputs. The balloon lights were adjusted to power outputs of 300-watt, 400-watt, 600-watt, and 800-watt to simulate one balloon light mounted/or attached on construction equipment such as road pavers and rollers.

For each lighting arrangements the vertical illuminance (*VI*) and pavement luminance (*PL*) were measured according to the glare determination procedure explained in Section 3.2.3. The calculations performed to determine the veiling luminance ratios ($V_{L\ ratio}$) are summarized in Table 4.3.

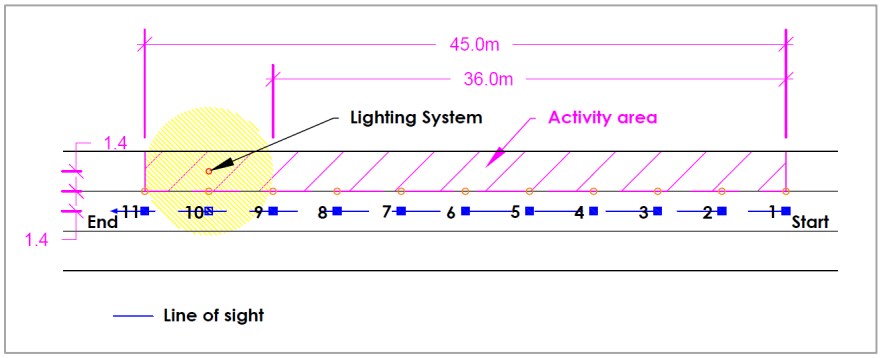


Figure 4.2. Work zone layout for one balloon light.

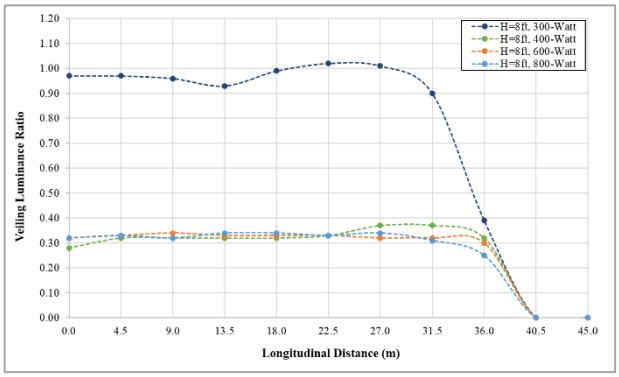
The Illuminating Engineering Society (IES) recommend maximum values of veiling luminance ratio based on practical experience and consensus among lighting experts. Since, these recommended values are applied for roadway lighting design criteria, it can be also applicable to nighttime work zones. As described in Chapter 2 in Table 2.12, roadways with visual complexity, with partial and full control of access, and high traffic volumes (freeways, expressways, and major roadways) shall not exceed a 0.3 veiling luminance ratio value. Also, roadways servicing traffic between major and local streets (collectors), and those used for direct access to residential, commercial, industrial, or other abutting property (locals) shall not exceed a 0.4 veiling luminance ratio value. These recommended values served to examine the veiling luminance ratios obtained from eight lighting arrangements of a single balloon light.

The key findings of the eight lighting arrangements based on mounting height and power output, are described as follows:

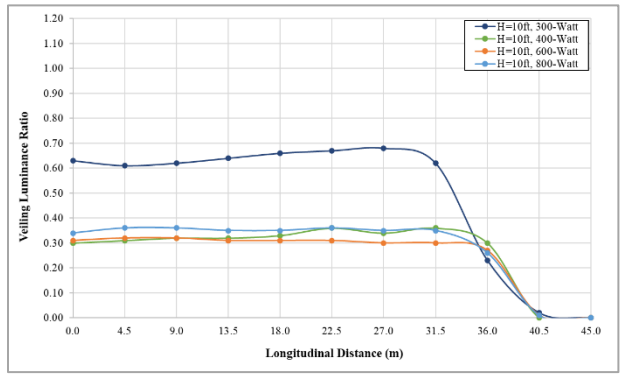
1. In all eight-lighting arrangements, the veiling luminance ratio increases for motorists as they approach the light source, and veiling illuminance ratio reaches its peak at 13.5 m (45 ft) away from the balloon light for the 2.4 m (8 ft) and 3.1 m (10 ft) mounting heights (See Figure 4.3).
2. For most of the lighting arrangements up to 36 m (118 ft) of longitudinal distance, the veiling luminance ratio (on average) is consistently higher at lower heights (2.4 m or 8 ft) than those at higher heights (3.1 m or 10 ft), as shown in Table 4.3. This is pattern is clearly visible at the 300-watt lighting configuration showed in Figure 4.4(a). However, an exception is seen in Figure 4.5(b) where the veiling luminance ratio of the 800-watt lighting arrangement at 2.4 m (8 ft) height is higher compared to that of the 800-watt lighting

arrangement at 3.1 m (10 ft) height, due to the lower pavement luminance measured (2.12 cd/m^2 vs. 1.78 cd/cm^2).

3. As shown in Table 4.3, for all lighting testing combinations that used a single balloon light, the veiling luminance ratios (on average) were higher than 0.3 which is the maximum ratio allowed by IES (IES, 2018). In, the lighting arrangements for the 300-watt balloon light at 8-ft and 10-ft heights (GB3LED model), the highest values of veiling luminance ratios calculated were 1.016 and 0.683, respectively. Of notable interest, during the course of these experiments this lighting setup also appeared to cause the most 'glare impact' on the SUV driver. As shown in Figures 4.4(b) and 4.5, the GB8LED model, which corresponds to 400-, 600-, and 800-w at two heights (8 ft and 10ft) showed slightly higher veiling luminance values (on average) with respect to the IES recommended veiling luminance ratio value.
4. As shown in Table 4.3, the average vertical illuminance (*VI*) value calculated between D= 0 m. and D= 36 m. of both models GB3LED and GB8LED balloon light raised at 2.4m (8 ft) height ranges from 7.84 to 13.81 lux, and the average pavement luminance (PL_{avg}) value ranges from 0.54 to 2.12 candelas/m^2. Similarly, the average vertical illuminance (*VI*) value calculated between D= 0 m. and D= 36 m. of both models GB3LED and GB8LED balloon light raised at 3.1 m (10 ft) height ranges from 7.52 to 14.01 lux, and the average pavement luminance (PL_{avg}) value ranges from 0.71 to 1.78 candelas/m$^{2.}$ It can be noted that an increase in equipment electrical power from 300- to 800-watt leads to an increase in vertical illuminance and pavement luminance, respectively.
5. As shown in Figure 4.4(a), a lower power output (GB3LED 300-watt) produced higher values of veiling luminance ratio compared to those with high power outputs (GB8LED 400-, 600-, and 800-watt). This set of veiling illuminance ratios was unexpected since the intensity of the light depends on the power output of the lighting equipment. The higher the power output the higher is the intensity of the light produced, and hence higher veiling illuminance ratios were expected at higher wattages.

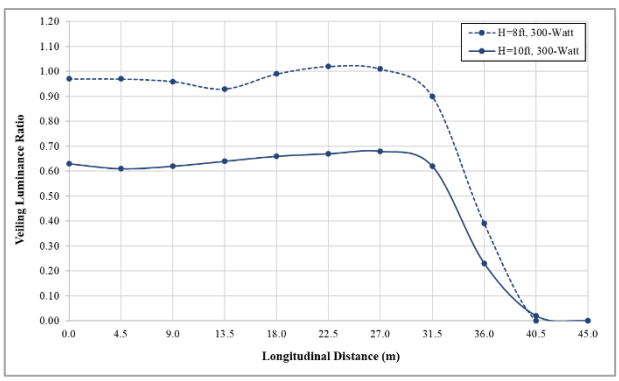


(a) 2.4 m (8 ft) height

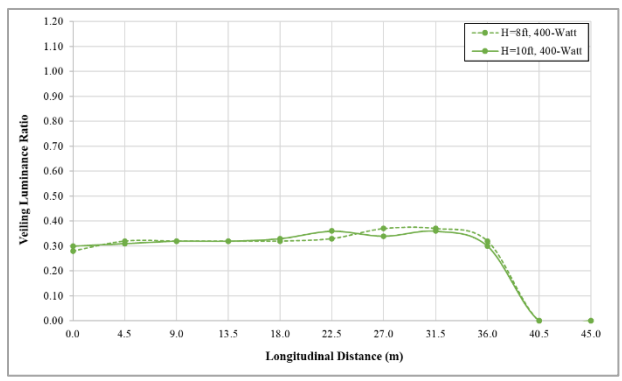


(b) 3.1 m (10 ft) height

Figure 4.3. $V_{L\ ratio}$ values by height for a single balloon light.

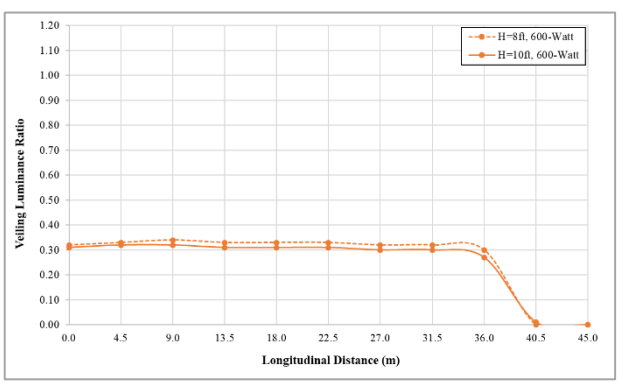


(a) 300-watt

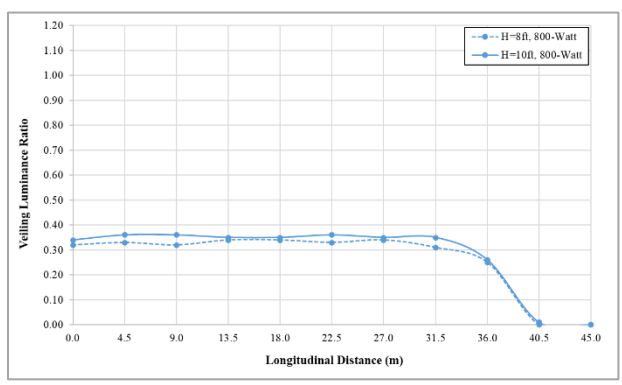


(b) 400-watt

Figure 4.4. $V_{L\ ratio}$ values by power output for a single balloon light.



(a) 600-watt



(b) 800-watt

Figure 4.5. $V_{L\ ratio}$ values by power output for a single balloon light.

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Table 4.3. Vertical illuminance (*VI*) and veiling luminance ratio ($V_{L\ ratio}$) values for a single LED balloon light.

Distance (m)	Height	2.4 m (8 ft)								3.1 m (10 ft)							
	Power	300-W		400-W		600-W		800-W		300-W		400-W		600-W		800-W	
		GB3LED		GB8LED						GB3LED		GB8LED					
		VI (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$
D= 0.0m		1.07	**0.97**	0.8	**0.29**	1.1	**0.32**	1.4	**0.32**	1.05	**0.63**	0.84	**0.3**	1.11	**0.31**	1.44	**0.34**
D= 4.5m		1.35	**0.97**	1.15	**0.32**	1.46	**0.33**	1.79	**0.33**	1.28	**0.61**	1.11	**0.31**	1.44	**0.32**	1.89	**0.36**
D= 9.0m		1.75	**0.96**	1.48	**0.32**	1.91	**0.34**	2.3	**0.32**	1.69	**0.62**	1.47	**0.32**	1.84	**0.32**	2.46	**0.36**
D= 13.5m		2.31	**0.94**	1.99	**0.32**	2.56	**0.33**	3.29	**0.34**	2.37	**0.64**	2.03	**0.32**	2.42	**0.31**	3.32	**0.35**
D= 18.0m		3.51	**0.99**	2.91	**0.32**	3.66	**0.33**	4.71	**0.34**	3.53	**0.66**	2.98	**0.33**	3.46	**0.31**	4.69	**0.35**
D= 22.5m		5.58	**1.02**	4.58	**0.33**	5.72	**0.33**	7.1	**0.33**	5.53	**0.67**	4.99	**0.36**	5.45	**0.31**	7.44	**0.36**
D= 27.0m		9.73	**1.01**	8.98	**0.37**	9.64	**0.32**	12.66	**0.34**	9.86	**0.68**	8.31	**0.34**	9.31	**0.30**	12.76	**0.35**
D= 31.5m		18.74	**0.91**	19.66	**0.37**	21	**0.32**	25.47	**0.31**	19.16	**0.62**	19.02	**0.37**	19.96	**0.30**	27.51	**0.35**
D= 36.0m☼		26.56	**0.39**	55.4	**0.32**	63.8	**0.3**	65.7	**0.25**	23.17	**0.23**	49.7	**0.3**	57.5	**0.27**	64.6	**0.26**
D= 40.5m		0.33	**0**	0.3	**0**	0.97	**0**	7.07	**0**	13.21	**0.02**	0.48	**0**	6.27	**0.01**	10.09	**0.01**
D= 45.0m		0.11	**0**	0.1	**0**	0.2	**0**	2.49	**0**	0.11	**0**	0.12	**0**	0.21	**0**	0.28	**0**
Maximum		26.56	1.02	55.4	0.37	63.8	0.34	65.7	0.34	23.17	0.68	49.7	0.37	57.5	0.32	64.6	0.36
Minimum		1.07	0.39	0.8	0.29	1.1	0.3	1.4	0.25	1.05	0.23	0.84	0.3	1.11	0.27	1.44	0.26
Average		7.84	0.91	10.77	0.33	12.32	0.33	13.82	0.32	7.52	0.6	10.05	0.33	11.39	0.31	14.01	0.34
Avg. PL (cd/m^2)		0.54		1.38		1.70		2.12		0.71		1.19		1.50		1.78	

Note: minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D=0m to D=36m.
Avg. PL: Average Pavement luminance
☼*: Lighting system position*

- $V_{L\ ratio} > 0.4$ *(Unacceptable glare levels)*
- $0.3 < V_{L\ ratio} \leq 0.4$ *(Acceptable glare levels but limited to work zones located at major and local streets)*
- $0 \leq V_{L\ ratio} \leq 0.3$ *(Acceptable glare levels applicable to work zones located at freeways, expressways, and major roadways)*

4.1.2 Two LED Balloon Lights

As shown in Table 4.2, five lighting arrangements were used to test different combinations of two balloon lights simultaneously. Two lighting arrangements corresponding to balloon lights (one GB3LED and one GB8LED) that were positioned perpendicular to the lane, at 36 m from Point 1, and separated 1.2 m and tested at two different mounting heights (8 ft and 10 ft), as shown in Figure 4.6. The balloon lights were adjusted at 300-w and 400-watt to simulate the use of two balloon lights attached/mounted on construction equipment or vehicles during nighttime highway construction operations.

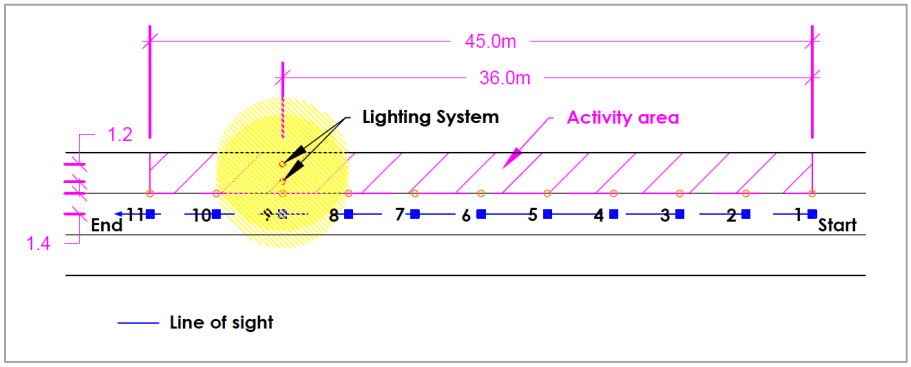


Figure 4.6. Work zone layout for two balloon lights (perpendicular).

The other three lighting arrangements correspond to two balloon lights placed parallel to the lane and separated 9 m., 13.5 m., and 18 m. from each other, as shown in Figure 4.7. The balloon lights were adjusted at 800-w and 300-watt and at 10-ft height to simulate presence lighting on work zone. The GB8LED balloon light were fixed at a longitudinal distance of 31.5 m, and the GB3LED balloon light were moved to three different points located at 22.5 m, 18 m, and 13.5 m, from the starting point no. 1.

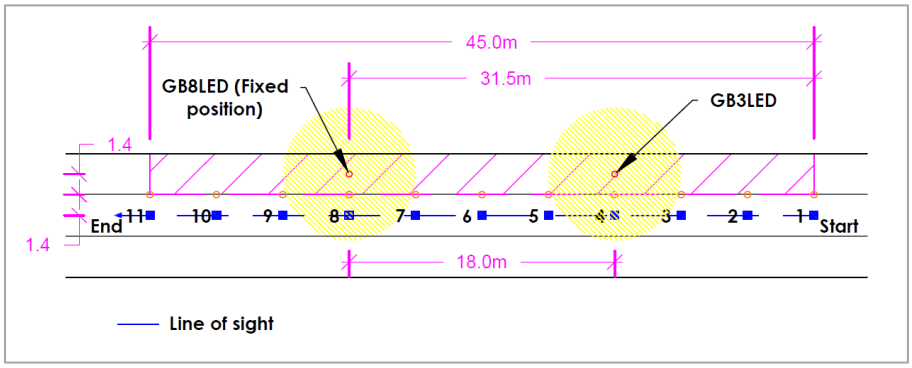


Figure 4.7. Work zone layout for two balloon lights separated 18 m. (parallel).

For each lighting arrangements the vertical illuminance (*VI*) and pavement luminance (*PL*) were measured according to the glare determination procedure described in Section 3.2.3. The calculations performed to determine the veiling luminance ratios ($V_{L\ ratio}$) are summarized in Table 4.4.

As described in Chapter 2, Table 2.12, the maximum recommended values for veiling luminance ratios in freeways, expressways, and major roadways is 0.3. For collector and local roads, the veiling luminance shall not exceed 0.4. These recommended values served to examine the veiling luminance ratios obtained from the lighting combinations performed using two balloon lights.

The key findings of the five lighting arrangements based using two balloon lights are described as follows:

1. When balloon lights (300-watt and 400-watt) are placed perpendicular to the lane, the veiling luminance ratio increases as vehicle drivers approach the light source and it reaches a peak at 9 m before the position of the balloon lights located at 36 meters away from the starting activity area. (see Figure 4.8a).
2. When the two balloon lights (300-watt and 400-watt) are placed perpendicular to the lane, the veiling luminance ratio (on average) is consistently higher on lower heights (2.4 m or 8 ft) than those on higher heights (3.1 m or 10 ft). At both heights tested, the veiling luminance ratios (on average) were higher than 0.3 which is the maximum ratio allowed by IES (IES 2018).
3. When the two balloon lights (300-watt and 800-watt) are installed parallel to the lane and separated by 9, 13.5, and 18 m, the veiling luminance ratio increases as vehicle drivers

approach the first light source (GB3LED), peaks at 4.5 m before reaching the first light source, and then decreases until reaching the second light source (GB8LED), as illustrated in Figure 4.8. If the horizontal separation between balloon lights is greater than 9.0 m, there appears to be a decrease in veiling luminance values in the zone between lights.

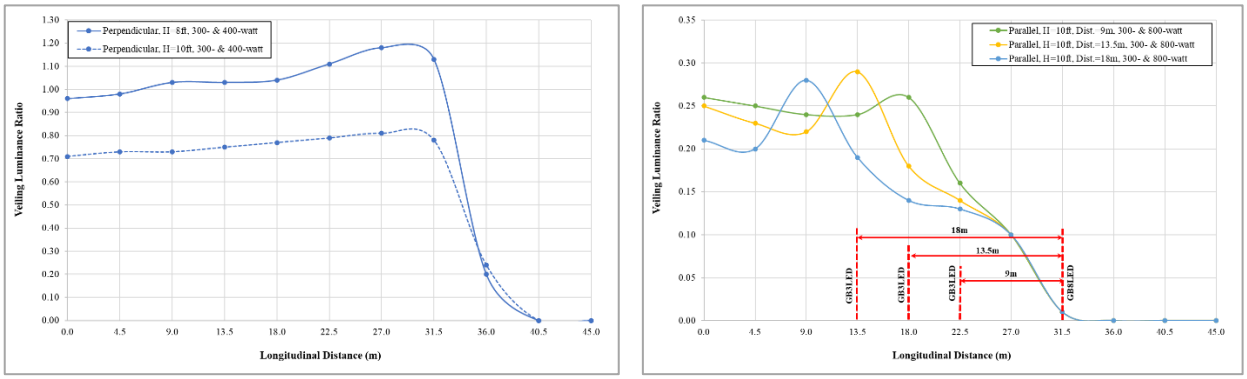
4. As shown in Table 4.4, the average vertical illuminance (*VI*) value calculated between D=0m and D=36 m of two balloon lights installed perpendicular (one next to another) both raised at 2.4 m (8 ft) and 3.1m (10 ft) height ranges from 13.72 to 15.05 lux and the average pavement luminance (PL_{avg}) value ranges from 1.03 to 1.23 candelas/m^2. Similarly, the average vertical illuminance (*VI*) value calculated between D=0m and D=36 m of two balloon lights (both separated 9, 13.5, and 18 m) raised at 3.1 m (10 ft) height ranges from 21.86 to 22.50 lux, and the average pavement luminance (PL_{avg}) value ranges from 3.6 to 4.1 candelas/m^2.
5. When balloon lights (300-watt and 800-watt) are installed parallel to the lane, in all the lighting configurations, the veiling luminance ratio is lower than 0.3, which is the IES recommended value of veiling luminance ratio, as shown in Table 4.4.

Table 4.4. Vertical illuminance (*VI*) and veiling luminance ratio ($V_{L\ ratio}$) values for two LED balloon lights.

Distance	Position	Perpendicular		Perpendicular		Parallel		Parallel		Parallel	
	Height	2.4 m (8 ft)		3.1 m (10 ft)		3.1 m (10 ft)		3.1 m (10 ft)		3.1 m (10 ft)	
	Separation	1.2 m (4 ft)		1.2 m (4 ft)		9.0 m (30 ft)		13.5 m (45 ft)		18 m (60 ft)	
	Wattage	300- & 400-watt		300- & 400-watt		300- & 800-watt		300- & 800-watt		300- & 800-watt	
		VI (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$
D= 0.0m		2.01	**0.96**	2.07	**0.72**	5.11	**0.26**	6.79	**0.25**	9.86	**0.22**
D= 4.5m		2.61	**0.98**	2.68	**0.73**	7.22	**0.25**	10.20	**0.23**	17.75	**0.20**
D= 9.0m		3.55	**1.03**	3.49	**0.73**	11.35	**0.24**	18.64	**0.22**	40.80	**0.28**
D= 13.5m		4.86	**1.03**	4.83	**0.75**	21.59	**0.24**	40.60	**0.29**	24.50	**0.19**
D= 18.0m		7.00	**1.04**	7.18	**0.77**	42.00	**0.26**	27.70	**0.18**	11.94	**0.14**
D= 22.5m		11.55	**1.11**	11.40	**0.79**	37.40	**0.16**	23.35	**0.14**	23.57	**0.13**
D= 27.0m		21.68	**1.19**	20.44	**0.81**	52.50	**0.10**	53.80	**0.10**	56.10	**0.10**
D= 31.5m		44.42	**1.13**	42.10	**0.78**	19.26	**0.01**	15.82	**0.01**	17.57	**0.01**
D= 36.0m 💡		25.80	**0.20**	41.30	**0.24**	0.31	**0**	0.36	**0**	0.38	**0**
D= 40.5m		0.35	**0**	0.53	**0**	0.12	**0**	0.12	**0**	0.12	**0**
D= 45.0m		0.13	**0**	0.16	**0**	0.09	**0**	0.08	**0**	0.08	**0**
Maximum		44.42	1.19	42.10	0.81	52.50	0.26	53.80	0.29	56.10	0.28
Average		13.72	0.96	15.05	0.70	21.86	0.17	21.92	0.16	22.50	0.14
Avg. PL (cd/m^2)			1.03		1.23		3.60		3.71		4.14

Note: minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D=0m to D=36m.
Avg. PL: Average Pavement luminance
💡*: Lighting system position*

- $V_{L\ ratio} > 0.4$ *(Unacceptable glare levels)*
- $0.3 < V_{L\ ratio} \leq 0.4$ *(Acceptable glare levels but limited to work zones located at major and local streets)*
- $0 \leq V_{L\ ratio} \leq 0.3$ *(Acceptable glare levels applicable to work zones located at freeways, expressways, and major roadways)*



(a) Perpendicular (b) Parallel

Figure 4.8. $V_{L\ ratio}$ values of two balloon lights positioned perpendicular and parallel to the open lane.

4.2 Portable Light Towers Testing

As mentioned in Section 3.2.2, the field experiments utilized two trailer-mounted light towers, namely a metal halide light tower model Terex RL4000 with a power output of 4000-watt, and a LED light tower model Trime X-Smart with 1280-watt. Both light towers were equipped with four luminaires and the maximum heights of operation were 9.1 m (30 ft) and 7.6 m (25 ft), respectively.

The lighting experiments were designed to test the light towers inside of the work area and positioned at 2.1 m from the edge of the open lane, as shown in Figure 4.9. A total of 36 lighting arrangements were tested on the simulated work zone, as described in Table 4.5 (lighting arrangements 14 to 49). The lighting configurations tested simulate nighttime construction and maintenance activities such as pavement cleaning and sweeping, pavement patching, and work zone flagger stations.

The impact of three different lighting parameters on the veiling illuminance ratio were assessed using these lighting systems. These parameters are: (1) the mounting height; (2) the rotation angle; and (3) the aiming angle (See Figure 4.10). The mounting height (H) represents the vertical distance between the ground surface and the center of the fixtures. The rotation angle (RA) represents the horizontal rotation of the light tower pole around its vertical axis. The aiming angle (AA) of each of the four fixtures represents the vertical angle between the center of the beam spread of the lamps and the nadir.

Figure 4.9. LED light tower positioned at the center of the closed lane.

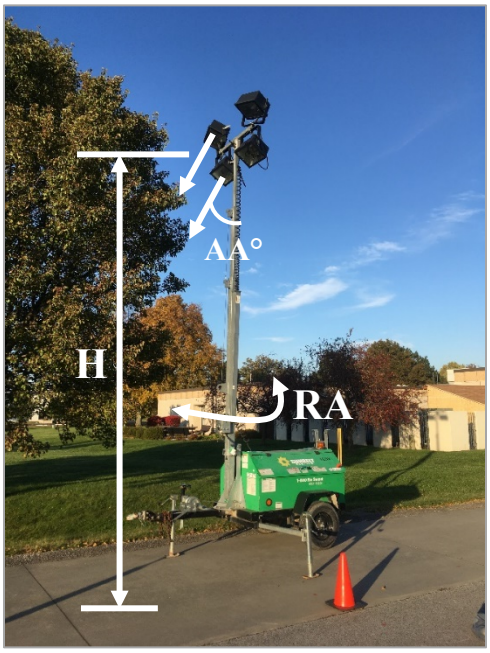


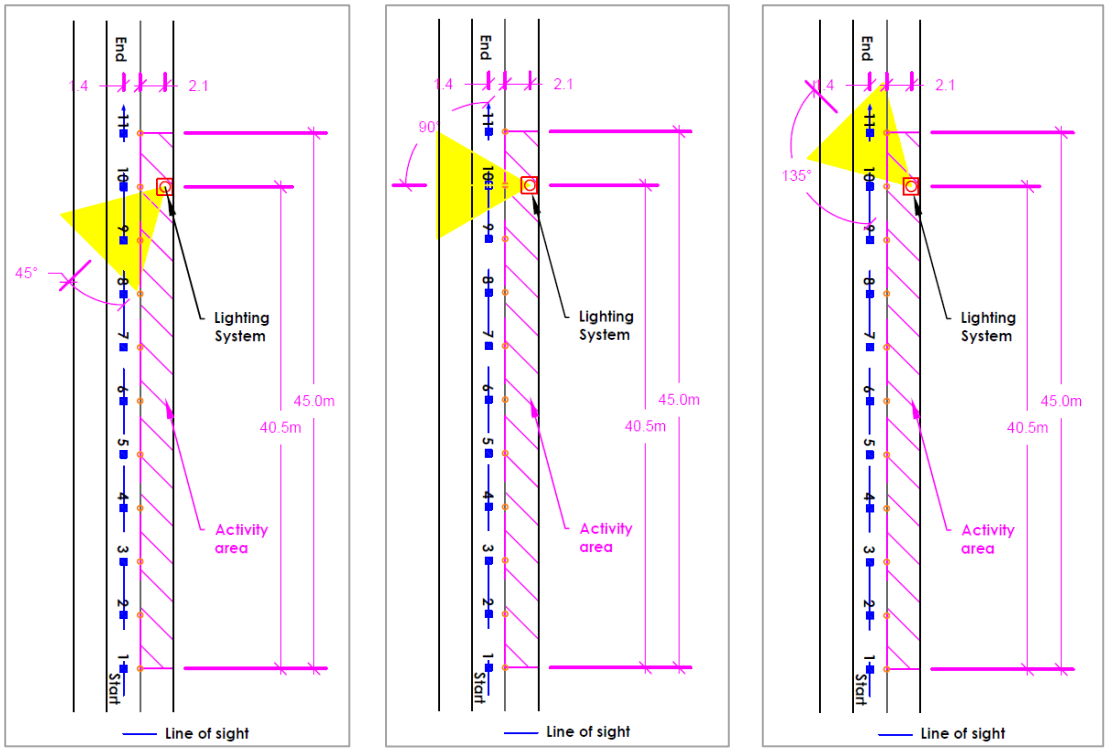
Figure 4.10. Lighting variables tested on the trailer-mounted light towers.

Table 4.5. Tested lighting arrangements for portable light towers.

Lighting Arrangement	Light Source	Mounting Height (H)	Rotation Angle (RA)	Aiming Angle (AA)
14	Metal-halide	3.7 m (12 ft)	45°	4x30°
15	Metal-halide		45°	4x45°
16	Metal-halide		90°	4x30°
17	Metal-halide		90°	4x45°
18	Metal-halide		135°	4x30°
19	Metal-halide		135°	4x45°
20	Metal-halide	5.5 m (18 ft)	45°	4x30°
21	Metal-halide		45°	4x45°
22	Metal-halide		90°	4x30°
23	Metal-halide		90°	4x45°
24	Metal-halide		135°	4x30°
25	Metal-halide		135°	4x45°
26	Metal-halide	9.1 m (30 ft)	45°	4x30°
27	Metal-halide		45°	4x45°
28	Metal-halide		90°	4x30°
29	Metal-halide		90°	4x45°
30	Metal-halide		135°	4x30°
31	Metal-halide		135°	4x45°
32	LED	3.7 m (12 ft)	45°	4x45°
33	LED		45°	4x60°
34	LED		90°	4x45°
35	LED		90°	4x60°
36	LED		135°	4x45°
37	LED		135°	4x60°
38	LED	5.5 m (18 ft)	45°	4x45°
39	LED		45°	4x60°
40	LED		90°	4x45°
41	LED		90°	4x60°
42	LED		135°	4x45°
43	LED		135°	4x60°
44	LED	7.6 m (25 ft)	45°	4x45°
45	LED		45°	4x60°
46	LED		90°	4x45°
47	LED		90°	4x60°
48	LED		135°	4x45°
49	LED		135°	4x60°

Three variables were analyzed on light towers: mounting height, orientation, and aiming angles of luminaires. Three different mounting heights (H) were tested for each of the two light towers. Three metal-halide light tower 12 ft, 18 ft, and 30 ft mounting heights were tested and a 12-ft, 18-ft, and 25-ft mounting heights for LED light tower were also tested. Three rotation angles (RA) were also tested for each of the two light towers (See Figure 4.11). According to Ellis et al., (2003) luminaires should be aimed so that a line drawn from the luminaire beam axis intersects normal lines of sight at an angle of 45° to 135° in the horizontal. Finally, two aiming angles (AA) were tested per light tower: 30° and 45° for metal-halide fixtures; and 45° and 60° for LED fixtures. These AA values were tested following the recommendations of the *NCHRP Report 498* (Ellis et al., 2003) which suggest to aim the lamp less than 60° between main beam axis and nadir.

For each of the balloon light configurations tested, vertical illuminance (*VI*) and pavement luminance (*PL*) were measured. Also, for each combination the values of veiling luminance (V_L) and veiling luminance ratio ($V_{L\ ratio}$) were calculated for one line of sight, based on the glare determination procedure described in Section 3.2.3.



(a) Towards (45°) (b) Perpendicular (90°) (c) Away (135°)

Figure 4.11. Rotation angles (RA) of a light tower.

4.2.1 One Metal-halide Light Tower

Eighteen lighting arrangements used one metal-halide light tower. The metal-halide light tower was positioned at 40.5 meters from the origin (or D= 0.0m) and a lateral distance of 2.1 m from the edge of the work zone, as shown in Figure 4.12. Different lighting arrangements resulted from the combinations of three different mounting heights (3.7 m, 5.5 m, and 9.1m), three orientations (towards, perpendicular, and away), and two aiming angles (30° and 45°). As shown in Table 4.5, the lighting arrangements 14 to 31 correspond for a metal-halide light tower. The vertical illuminance and veiling luminance ratio ($V_{L\ ratio}$) for each lighting arrangements using a single metal-halide light tower are summarized in Tables 4.6, 4.7, and 4.8.

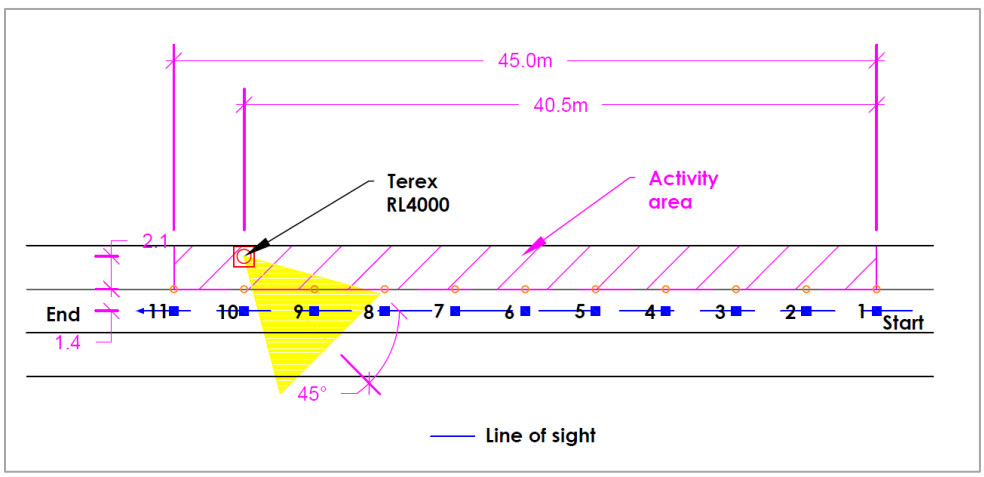


Figure 4.12. Work zone layout for one metal-halide light tower.

The Illuminating Engineering Society (IES) recommends maximum values of veiling luminance ratio of 0.3 in freeways, expressways, and major roadways. For collector and local roads, the veiling luminance shall not exceed 0.4. These recommended values served to examine the veiling luminance ratios obtained from the lighting combinations performed using one metal-halide light tower.

The key findings of the eighteen lighting arrangements for a single metal-halide light tower, are described as follows:

1. In all eight-lighting arrangements, the veiling luminance ratio increases for a vehicle driver as they approach to the light source, and it reaches its peak between 13.5 m and 18 m before

to reach the metal-halide light tower for the 3.7 m (12 ft), 5.5 m (18 ft), and 9.1 m (30 ft) mounting heights, as shown in Figures 4.13, 4.14, and 4.15, and in Tables 4.6, 4.7, and 4.8.

2. The metal-halide light orientation affects the veiling luminance ratios experienced at all three mounting heights. The value of the veiling luminance ratio decreases as the rotation angle increases. Moreover, the veiling luminance ratio decreases as the equipment is raised in all light orientations of the metal-halide light tower, as shown in Tables 4.6, 4.7, and 4.8.
3. In all light orientations of the metal-halide light tower, it can be noted that the veiling luminance ratio decreases as the equipment is raised. This can be seen in Tables 4.6, 4.7, and 4.8.
4. The veiling luminance ratio values for a 45-degree orientation (See Figure 4.13) exceed the IES recommended veiling luminance ratio value (0.3) at two mounting heights: 3.7 m (12 ft) and 5.5 m (18 ft). At 9.1 m (30 ft) height, only four $V_{L\ ratio}$ values exceeded the maximum IES value.
5. The veiling luminance ratio values for the 90- and 135-degree orientations and under all three mounting height combinations showed $V_{L\ ratio}$ values lower than the IES recommended veiling luminance ratio value (0.3). $V_{L\ ratio}$ values greater than 0 and lower or equal to 0.3 (highlighted as green) indicate acceptable levels of disability glare. $V_{L\ ratio}$ values greater than 0.3 but lower or equal to 0.4 (highlighted as yellow) indicate are also acceptable levels of disability glare, but it is limited to nighttime work performed at collectors and local roads. $V_{L\ ratio}$ values greater than 0.4 (highlighted as red) indicate unacceptable levels, according to IES.
6. In all cases, when the metal-halide light tower is oriented 135°, the $V_{L\ ratio}$ value is below 0.1, as shown in Figure 4.15.
7. As shown in Tables 4.6 through 4.8, the average vertical illuminance (*VI*) value calculated between D=0m. and D=36 m of a single metal-halide light tower mounted at three different heights (3.7 m, 5.5 m, and 9.1 m) and aimed 45° towards the traffic ranges from 128.27 to 198.95 lux and the average pavement luminance (PL_{avg}) value ranges from 6.33 to 9.82 candelas/m^2. Similarly, when the single metal-halide light tower is aimed perpendicular to the traffic, the average vertical illuminance (*VI*) ranges from 45.92 to 79.44 lux and the average pavement luminance (PL_{avg}) value ranges from 3.36 to 8.63 candelas/m^2. It can be noted that both *VI* and PL_{avg} values decreases when the mounting height of the metal-

halide light tower increases, and the light is oriented from 45° to 135°. Moreover, these *VI* values indicate acceptable values in accordance with the IES recommended practice for design and maintenance of roadway and facility lighting (ANSI/IES RP-8-18). This recommend practice suggests that average vertical illuminance level of 20 to 40 lux measured at 1.5 m above the roadway is an adequate lighting level to assist the driver in identifying pedestrians.

Table 4.6. Vertical illuminance (*VI*) and veiling luminance ratio ($V_{L\ ratio}$) for a single metal-halide light tower mounted at 3.7 m (12 ft)

Distance	H =	3.7 m (12 ft)											
	RA =	45°				90°				135°			
	AA =	30°, 30°, 30°, 30°		45°, 45°, 45°, 45°		30°, 30°, 30°, 30°		45°, 45°, 45°, 45°		30°, 30°, 30°, 30°		45°, 45°, 45°, 45°	
		VI (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$
D= 0.0m		15.30	**0.415**	12.61	**0.475**	0.33	**0.011**	0.48	**0.015**	0.20	**0.012**	0.29	**0.008**
D= 4.5m		19.35	**0.415**	16.86	**0.503**	0.47	**0.013**	0.67	**0.016**	0.24	**0.011**	0.37	**0.008**
D= 9.0m		24.58	**0.405**	24.06	**0.551**	0.75	**0.015**	0.97	**0.018**	0.30	**0.011**	0.46	**0.008**
D= 13.5m		34.40	**0.419**	35.60	**0.602**	1.27	**0.019**	1.53	**0.021**	0.39	**0.010**	0.62	**0.008**
D= 18.0m		50.10	**0.426**	55.70	**0.659**	2.15	**0.023**	2.67	**0.026**	0.57	**0.010**	0.90	**0.008**
D= 22.5m		75.40	**0.416**	93.70	**0.719**	4.26	**0.029**	5.15	**0.032**	0.86	**0.010**	1.38	**0.008**
D= 27.0m		138.50	**0.443**	158.30	**0.703**	12.52	**0.050**	13.92	**0.051**	1.34	**0.009**	2.29	**0.008**
D= 31.5m		328.00	**0.503**	265.70	**0.566**	65.50	**0.126**	60.30	**0.105**	2.69	**0.009**	4.51	**0.007**
D= 36.0m		631.00	**0.332**	609.00	**0.445**	326.00	**0.215**	396.00	**0.237**	13.25	**0.015**	22.78	**0.013**
D= 40.5m 💡		377.00	**0.047**	392.00	**0.068**	578.00	**0.091**	296.00	**0.042**	132.70	**0.036**	125.70	**0.017**
D= 45.0m		0.19	**0**	0.57	**0**	3.23	**0**	3.19	**0**	4.97	**0.001**	5.33	**0**
Maximum		631.00	0.503	609.00	0.719	578.00	0.215	396.00	0.237	132.70	0.015	125.70	0.013
Minimum		15.30	0.332	12.61	0.445	0.33	0.011	0.48	0.015	0.20	0.009	0.29	0.007
Average		146.29	0.419	141.28	0.580	45.92	0.056	53.52	0.058	2.20	0.011	3.73	0.008
Avg. PL (cd/m^2)		9.82		7.07		7.84		8.63		4.58		9.27	

Note: minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D=0m to D=36m
Avg. PL: Average Pavement luminance
💡*: Lighting system position*

- $V_{L\ ratio} > 0.4$ *(Unacceptable glare levels)*
- $0.3 < V_{L\ ratio} \leq 0.4$ *(Acceptable glare levels but limited to work zones located at major and local streets)*
- $0 \leq V_{L\ ratio} \leq 0.3$ *(Acceptable glare levels applicable to work zones located at freeways, expressways, and major roadways)*

Table 4.7. Vertical illuminance (*VI*) and veiling luminance ratio ($V_{L\ ratio}$) for a single metal-halide light tower mounted at 5.5 m (18 ft)

Distance	H =	5.5 m (18 ft)											
	RA =	45°				90°				135°			
	AA =	30°, 30°, 30°, 30°		45°, 45°, 45°, 45°		30°, 30°, 30°, 30°		45°, 45°, 45°, 45°		30°, 30°, 30°, 30°		45°, 45°, 45°, 45°	
		VI (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$
D= 0.0m		18.36	**0.356**	16.23	**0.397**	0.84	**0.026**	0.63	**0.015**	0.18	**0.008**	0.27	**0.009**
D= 4.5m		24.30	**0.373**	21.97	**0.425**	1.07	**0.026**	0.95	**0.018**	0.22	**0.008**	0.33	**0.009**
D= 9.0m		33.60	**0.397**	31.00	**0.461**	1.65	**0.031**	1.43	**0.021**	0.26	**0.007**	0.42	**0.008**
D= 13.5m		46.60	**0.407**	44.30	**0.488**	2.62	**0.036**	2.14	**0.023**	0.34	**0.007**	0.55	**0.008**
D= 18.0m		72.80	**0.446**	67.60	**0.522**	4.80	**0.046**	3.76	**0.029**	0.46	**0.007**	0.77	**0.008**
D= 22.5m		133.60	**0.534**	100.20	**0.505**	11.48	**0.072**	9.39	**0.047**	0.67	**0.006**	1.14	**0.008**
D= 27.0m		252.30	**0.591**	147.70	**0.436**	44.80	**0.165**	28.03	**0.082**	1.06	**0.006**	1.75	**0.007**
D= 31.5m		464.00	**0.536**	260.80	**0.38**	132.70	**0.241**	104.70	**0.151**	2.13	**0.006**	3.82	**0.008**
D= 36.0m		745.00	**0.324**	527.00	**0.289**	515.00	**0.353**	365.00	**0.199**	20.99	**0.022**	21.41	**0.016**
D= 40.5m		241.60	**0.032**	257.00	**0.043**	279.00	**0.058**	201.50	**0.033**	115.00	**0.036**	158.20	**0.036**
D= 45.0m		0.50	**0**	0.89	**0**	5.87	**0.001**	3.90	**0**	6.22	**0.001**	6.69	**0.001**
Maximum		745.00	0.503	527.00	0.719	515.00	0.215	365.00	0.237	115.00	0.015	158.20	0.013
Minimum		18.36	0.332	16.23	0.445	0.84	0.011	0.63	0.015	0.18	0.009	0.27	0.007
Average		198.95	0.440	135.20	0.434	79.44	0.111	57.34	0.065	2.92	0.009	3.38	0.009
Avg. PL (cd/m^2)		9.35		7.41		5.94		7.48		3.92		5.46	

Note: minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D=0m to D=36m
Avg. PL: Average Pavement luminance
: Lighting system position

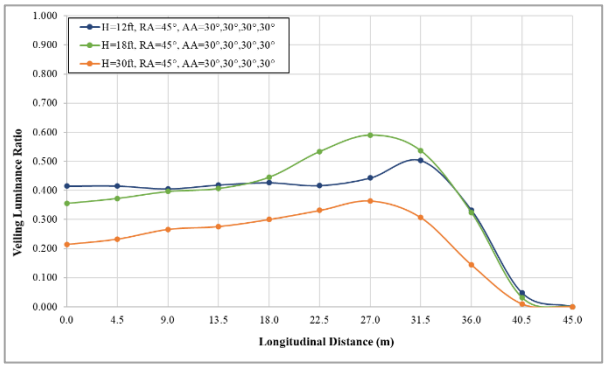
- $V_{L\ ratio} > 0.4$ *(Unacceptable glare levels)*
- $0.3 < V_{L\ ratio} \leq 0.4$ *(Acceptable glare levels but limited to work zones located at major and local streets)*
- $0 \leq V_{L\ ratio} \leq 0.3$ *(Acceptable glare levels applicable to work zones located at freeways, expressways, and major roadways)*

Table 4.8. Vertical illuminance (*VI*) and veiling luminance ratio ($V_{L\ ratio}$) for a single metal-halide light tower mounted at 9.1 (30 ft)

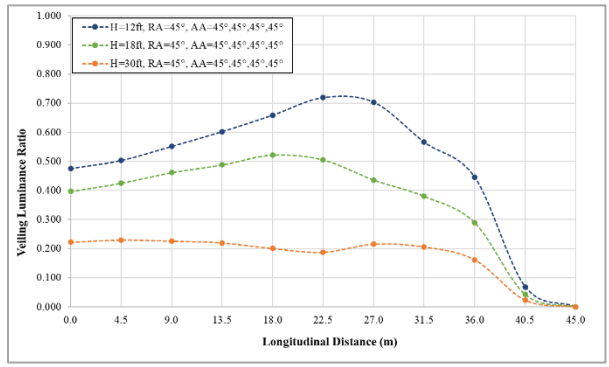
Distance	H =	9.1 m (30 ft)											
	RA =	45°				90°				135°			
	AA =	30°, 30°, 30°, 30°		45°, 45°, 45°, 45°		30°, 30°, 30°, 30°		45°, 45°, 45°, 45°		30°, 30°, 30°, 30°		45°, 45°, 45°, 45°	
		VI (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$
D= 0.0m		19.19	**0.215**	22.10	**0.222**	0.67	**0.014**	0.93	**0.016**	0.21	**0.005**	0.25	**0.004**
D= 4.5m		26.13	**0.233**	28.72	**0.230**	0.97	**0.016**	1.33	**0.018**	0.25	**0.005**	0.31	**0.004**
D= 9.0m		38.60	**0.266**	36.50	**0.226**	1.51	**0.020**	2.17	**0.023**	0.30	**0.005**	0.38	**0.004**
D= 13.5m		53.60	**0.276**	47.60	**0.220**	2.70	**0.026**	3.43	**0.027**	0.37	**0.004**	0.47	**0.004**
D= 18.0m		81.80	**0.301**	60.90	**0.201**	5.22	**0.036**	7.19	**0.040**	0.47	**0.004**	0.65	**0.003**
D= 22.5m		134.60	**0.332**	85.00	**0.188**	15.72	**0.073**	26.50	**0.099**	0.62	**0.003**	0.83	**0.003**
D= 27.0m		239.90	**0.364**	158.30	**0.215**	48.40	**0.139**	41.50	**0.096**	0.87	**0.003**	1.64	**0.004**
D= 31.5m		366.00	**0.307**	274.30	**0.206**	119.20	**0.188**	120.80	**0.154**	3.10	**0.006**	4.50	**0.006**
D= 36.0m		353.00	**0.144**	441.00	**0.162**	237.50	**0.183**	316.00	**0.197**	23.12	**0.021**	60.20	**0.036**
D= 40.5m 💡		51.60	**0.01**	130.90	**0.023**	89.50	**0.033**	134.20	**0.040**	31.40	**0.013**	92.60	**0.026**
D= 45.0m		1.06	**0**	1.81	**0**	3.37	**0.001**	6.81	**0.001**	6.74	**0.002**	7.83	**0.001**
Maximum		366.00	0.364	441.00	0.23	237.50	0.188	316.00	0.197	31.40	0.021	92.60	0.036
Minimum		19.19	0.144	22.10	0.162	0.67	0.014	0.93	0.016	0.21	0.003	0.25	0.003
Average		145.87	0.271	128.27	0.208	47.99	0.077	57.76	0.074	3.26	0.006	7.69	0.008
Avg. PL (cd/m^2)		6.33		7.06		3.36		4.16		2.90		4.33	

Note: minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D=0m to D=36m
Avg. PL: Average Pavement luminance
💡*: Lighting system position*

- $V_{L\ ratio} > 0.4$ *(Unacceptable glare levels)*
- $0.3 < V_{L\ ratio} \leq 0.4$ *(Acceptable glare levels but limited to work zones located at major and local streets)*
- $0 \leq V_{L\ ratio} \leq 0.3$ *(Acceptable glare levels applicable to work zones located at freeways, expressways, and major roadways)*

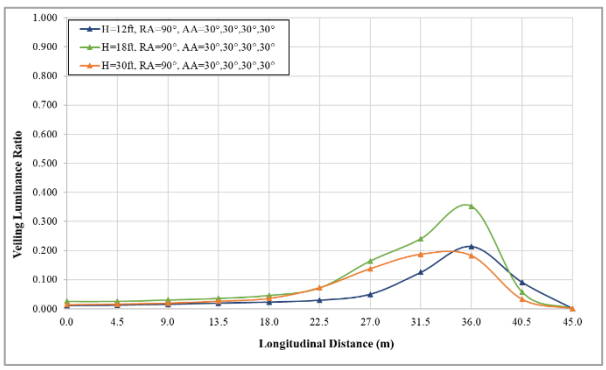


(a) Aiming angle = 30°

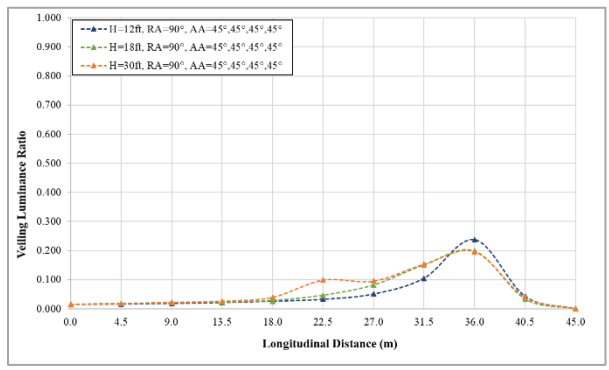


(b) Aiming angle = 45°

Figure 4.13. $V_{L\ ratio}$ values for a single metal-halide light tower at 12-, 18-, and 30-ft height and 45-degree orientation

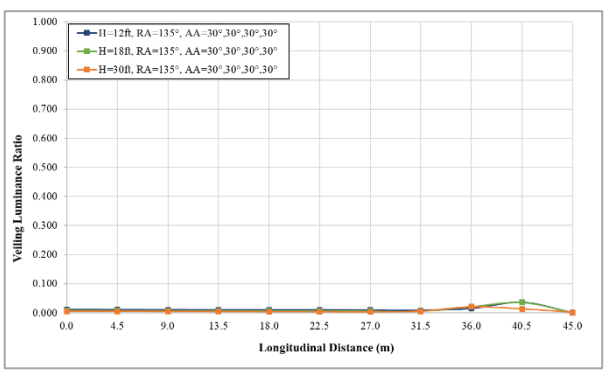


(a) Aiming angle = 30°

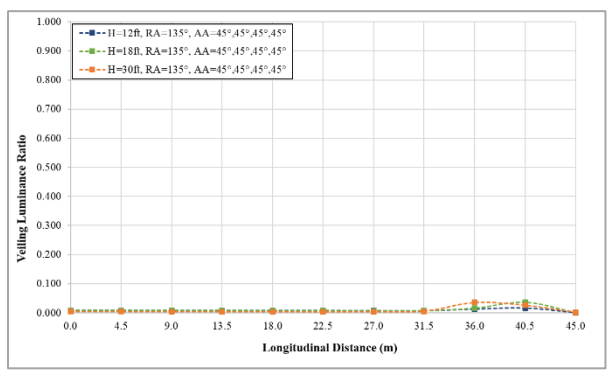


(b) Aiming angle = 45°

Figure 4.14. $V_{L\ ratio}$ values for a single metal-halide light tower at 12-, 18-, and 30-ft height and 90-degree orientation.



(a) Aiming angle = 30°



(b) Aiming angle = 45°

Figure 4.15. $V_{L\ ratio}$ values for a single metal-halide light tower at 12-, 18-, and 30-ft height and 135-degree orientation.

4.2.2 One LED Light Tower

Eighteen lighting arrangements used one LED light tower. The LED light tower was positioned at 40.5 meters from the origin (or D= 0.0m) and a lateral distance of 2.1 m from the edge of the work zone, as shown in Figure 4.16. Different lighting arrangements resulted from the combinations of three different mounting heights (12 ft, 18 ft, and 25 ft), three orientations (towards, perpendicular, and away), and two aiming angles (45° and 60°). As shown in Table 4.6, lighting arrangements 32 to 49 correspond for a metal-halide light tower. The calculations performed to obtain the veiling luminance ratios ($V_{L\ ratio}$) are summarized in Tables 4.9, 4.10, and 4.11.

Figure 4.16. A LED light tower oriented 90 degrees, raised 25-ft height, and aimed 30 degrees from the vertical.

As described in section 4.2.1, the Illuminating Engineering Society (IES) recommends maximum values of veiling luminance ratio of 0.3 in freeways, expressways, and major roadways, and 0.4 for collector and local roads. These recommended values served to examine the veiling luminance ratios obtained from the lighting combinations performed using one metal-halide light tower.

The key findings of the eighteen lighting arrangements for a single LED light tower, are described as follows:

1. In all lighting arrangements when the LED light tower is mounted at 3.7 m (12 ft), 5.5 m (18 ft), and 7.6 m (25 ft), the veiling luminance ratio increases for a vehicle driver as they approach to the light source, and it reaches its peak between 4.5 m and 9 m before reaching the LED light tower, as shown in Figures 4.17, 4.18, and 4.19.
2. The rotation angle and the aiming angles of a single LED light tower affects the veiling luminance ratio experienced at 3.7 m (12 ft), 5.5 m (18 ft), and 7.6 m (25 ft). The $V_{L\ ratio}$ decreases as the rotation angle increases, as shown in Tables 4.9, 4.10, and 4.11. Similarly, as the aiming angle of luminaires increases (from 45° to 60°), the veiling luminance ratio value increases as well.
3. When the LED light tower is oriented 45° and 90° and when the luminaries are tilted 60° from the vertical, the veiling luminance ratio (on average) is consistently higher at lower heights (3.7 m or 12 ft) than those on higher heights (7.6 m or 25 ft), as shown in Figures 4.17b, and 4.18b.
8. In all three mounting heights, when the LED light tower is oriented 45° and 90°, and when the LED light fixtures are tilted 60° from the vertical, the veiling luminance values exceed the IES maximum recommended $V_{L\ ratio}$ (0.3). In all the remaining lighting arrangements where the LED light tower was oriented 135°, the $V_{L\ ratio}$ value were lower than 0.3. As described in Tables 4.9, 4.10, and 4.11, $V_{L\ ratio}$ values greater than 0 and lower or equal to 0.3 (highlighted as green) indicate acceptable levels of disability glare. $V_{L\ ratio}$ values greater than 0.3 but lower or equal to 0.4 (highlighted as yellow) indicate are also acceptable levels of disability glare, but it is limited to nighttime work performed at collectors and local roads. $V_{L\ ratio}$ values greater than 0.4 (highlighted as red) indicate unacceptable levels, according to IES.
9. In all cases, when the LED light tower is oriented 135°, the $V_{L\ ratio}$ value is below 0.1, as shown in Figure 4.19.
10. As shown in Tables 4.9 through 4.11, the average vertical illuminance (*VI*) value calculated between D= 0 m. and D= 36 m. of a single LED light tower mounted at three different heights (3.7 m, 5.5 m, and 7.6 m) and aimed 45° towards the traffic ranges from 49.54 to 147.19 lux and the average pavement luminance (PL_{avg}) value ranges from 3.05 to 9.33

candelas/m^2. Similarly, when the single LED light tower is aimed perpendicular to the traffic, the average vertical illuminance (*VI*) ranges from 14 to 34.02 lux and the average pavement luminance (PL_{avg}) value ranges from 1.92 to 6.55 candelas/m^2. It can be noted that both *VI* and PL_{avg} values decrease when the mounting height of the LED light tower increases, and the light tower is oriented from 45° to 135°. Moreover, these *VI* values indicate acceptable values in accordance with the IES recommended practice for design and maintenance of roadway and facility lighting (ANSI/IES RP-8-18). This recommend practice suggests that average vertical illuminance level of 20 to 40 lux measured at 1.5 meters above the roadway is an adequate lighting level to assist the driver in identifying pedestrians.

Table 4.9. Vertical illuminance (*VI*) and veiling luminance ratio ($V_{L\ ratio}$) for a single LED light tower mounted at 3.7 m (12 ft)

Distance	H =	3.7 m (12 ft)											
	RA =	45°				90°				135°			
	AA =	45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°	
		VI (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$
D= 0.0m		1.39	**0.040**	3.12	**0.133**	0.24	**0.010**	0.24	**0.017**	0.17	**0.012**	0.17	**0.009**
D= 4.5m		1.88	**0.042**	4.48	**0.151**	0.31	**0.010**	0.37	**0.021**	0.20	**0.011**	0.21	**0.009**
D= 9.0m		2.71	**0.047**	7.09	**0.184**	0.42	**0.010**	0.53	**0.023**	0.26	**0.011**	0.25	**0.008**
D= 13.5m		3.67	**0.047**	12.91	**0.247**	0.59	**0.011**	0.83	**0.027**	0.34	**0.010**	0.34	**0.008**
D= 18.0m		6.00	**0.054**	19.61	**0.262**	1.03	**0.013**	1.42	**0.032**	0.49	**0.011**	0.48	**0.008**
D= 22.5m		12.08	**0.070**	40.80	**0.354**	1.82	**0.015**	2.98	**0.043**	0.76	**0.011**	0.73	**0.008**
D= 27.0m		31.30	**0.105**	90.60	**0.455**	4.55	**0.022**	9.53	**0.080**	1.34	**0.011**	1.32	**0.009**
D= 31.5m		95.20	**0.154**	194.10	**0.467**	15.33	**0.035**	25.59	**0.104**	3.84	**0.015**	3.02	**0.009**
D= 36.0m		291.60	**0.161**	952.00	**0.787**	101.70	**0.080**	264.70	**0.367**	12.80	**0.017**	15.12	**0.016**
D= 40.5m 💡		417.00	**0.055**	371.00	**0.073**	262.00	**0.049**	418.00	**0.139**	105.80	**0.034**	161.20	**0.041**
D= 45.0m		1.39	**0**	0.30	**0**	2.73	**0**	2.27	**0**	3.91	**0.001**	8.18	**0.001**
Maximum		417.00	0.161	952.00	0.787	262.00	0.08	418.00	0.367	105.80	0.017	161.20	0.016
Minimum		1.39	0.040	3.12	0.133	0.24	0.01	0.24	0.017	0.17	0.01	0.17	0.008
Average		49.54	0.080	147.19	0.338	14.00	0.023	34.02	0.079	2.24	0.012	2.40	0.009
Avg. PL (cd.m2)		9.33		6.25		6.55		3.72		2.90		4.33	

Note: minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D=0m to D=36m
Avg. PL: Average Pavement luminance
💡*: Lighting system position*

- $V_{L\ ratio} > 0.4$ *(Unacceptable glare levels)*
- $0.3 < V_{L\ ratio} \leq 0.4$ *(Acceptable glare levels but limited to work zones located at major and local streets)*
- $0 \leq V_{L\ ratio} \leq 0.3$ *(Acceptable glare levels applicable to work zones located at freeways, expressways, and major roadways)*

Table 4.10. Vertical illuminance (*VI*) and veiling luminance ratio ($V_{L\ ratio}$) for a single LED light tower mounted at 5.5 m (18 ft)

Distance	H =	5.5 m (18 ft)											
	RA =	45°				90°				135°			
	AA =	45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°	
		VI (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$
D= 0.0m		1.60	**0.050**	3.39	**0.149**	0.25	**0.009**	0.30	**0.023**	0.16	**0.009**	0.15	**0.012**
D= 4.5m		2.11	**0.052**	5.24	**0.183**	0.31	**0.009**	0.44	**0.027**	0.19	**0.009**	0.18	**0.011**
D= 9.0m		3.25	**0.062**	8.21	**0.22**	0.42	**0.010**	0.66	**0.031**	0.23	**0.008**	0.23	**0.011**
D= 13.5m		4.98	**0.070**	13.73	**0.273**	0.71	**0.012**	1.00	**0.035**	0.31	**0.008**	0.29	**0.010**
D= 18.0m		9.63	**0.096**	25.29	**0.352**	1.04	**0.012**	1.67	**0.041**	0.45	**0.008**	0.43	**0.010**
D= 22.5m		23.13	**0.150**	49.10	**0.446**	2.04	**0.016**	3.28	**0.053**	0.65	**0.008**	0.64	**0.010**
D= 27.0m		61.90	**0.235**	95.50	**0.508**	4.48	**0.020**	9.88	**0.093**	1.19	**0.009**	1.08	**0.010**
D= 31.5m		134.20	**0.251**	196.50	**0.517**	16.13	**0.036**	29.69	**0.137**	2.97	**0.010**	2.77	**0.013**
D= 36.0m		254.20	**0.179**	734.00	**0.726**	148.20	**0.124**	257.00	**0.448**	8.45	**0.011**	15.88	**0.027**
D= 40.5m 💡		558.00	**0.119**	116.60	**0.035**	339.00	**0.086**	327.00	**0.173**	176.60	**0.071**	103.60	**0.054**
D= 45.0m		3.17	**0**	0.65	**0**	8.13	**0**	2.61	**0.001**	20.53	**0.004**	10.66	**0.003**
Maximum		558.00	0.251	734.00	0.726	339.00	0.124	327.00	0.448	176.60	0.011	103.60	0.027
Minimum		1.60	0.050	3.39	0.149	0.25	0.009	0.30	0.023	0.16	0.008	0.15	0.01
Average		55.00	0.127	125.66	0.375	19.29	0.028	33.77	0.099	1.62	0.009	2.41	0.013
Avg. PL (cd.m2)		5.77		4.11		4.85		2.33		3.06		2.35	

Note: minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D=0m to D=36m
Avg. PL: Average Pavement luminance
💡*: Lighting system position*

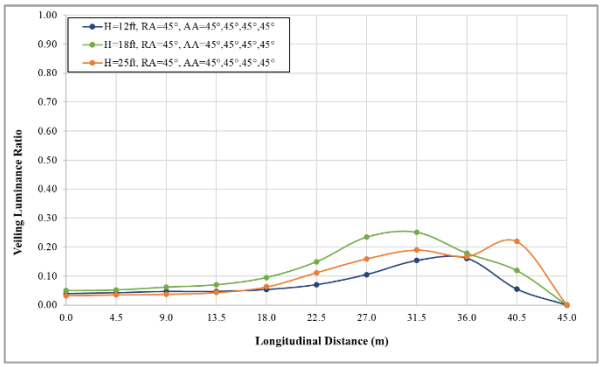
- $V_{L\ ratio} > 0.4$ *(Unacceptable glare levels)*
- $0.3 < V_{L\ ratio} \leq 0.4$ *(Acceptable glare levels but limited to work zones located at major and local streets)*
- $0 \leq V_{L\ ratio} \leq 0.3$ *(Acceptable glare levels applicable to work zones located at freeways, expressways, and major roadways)*

Table 4.11. Vertical illuminance (*VI*) and veiling luminance ratio ($V_{L\ ratio}$) for a single LED light tower mounted at 7.6 m (25 ft)

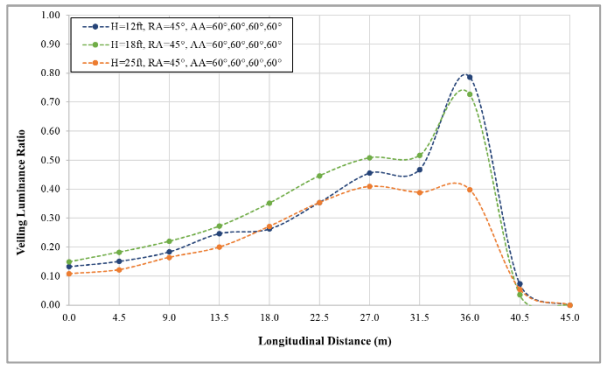
Distance	H =	7.6 m (25 ft)											
	RA =	45°				90°				135°			
	AA =	45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°	
		VI (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$	*VI* (lux)	$V_{L\ ratio}$
D= 0.0m		1.54	**0.033**	3.35	**0.108**	0.26	**0.008**	0.28	**0.014**	0.15	**0.004**	0.15	**0.009**
D= 4.5m		2.07	**0.035**	4.76	**0.122**	0.31	**0.008**	0.39	**0.016**	0.18	**0.004**	0.18	**0.009**
D= 9.0m		2.87	**0.038**	8.33	**0.165**	0.42	**0.008**	0.50	**0.016**	0.22	**0.004**	0.21	**0.008**
D= 13.5m		4.43	**0.043**	13.61	**0.2**	0.65	**0.009**	0.72	**0.017**	0.28	**0.004**	0.26	**0.007**
D= 18.0m		9.06	**0.063**	26.12	**0.272**	1.11	**0.011**	1.62	**0.027**	0.39	**0.004**	0.34	**0.007**
D= 22.5m		24.42	**0.112**	51.30	**0.353**	2.26	**0.015**	3.23	**0.035**	0.58	**0.004**	0.49	**0.007**
D= 27.0m		57.70	**0.160**	98.40	**0.409**	5.86	**0.023**	9.52	**0.063**	1.20	**0.005**	0.86	**0.007**
D= 31.5m		130.20	**0.190**	177.30	**0.388**	22.08	**0.046**	23.47	**0.082**	2.91	**0.006**	2.21	**0.009**
D= 36.0m		259.00	**0.168**	409.00	**0.398**	157.20	**0.145**	173.90	**0.270**	8.18	**0.007**	6.49	**0.012**
D= 40.5m		815.00	**0.220**	134.60	**0.054**	276.20	**0.106**	133.20	**0.086**	125.00	**0.047**	77.60	**0.061**
D= 45.0m		5.66	**0.001**	1.01	**0**	10.75	**0**	3.78	**0.001**	20.99	**0.004**	9.29	**0.004**
Maximum		815.00	0.190	409.00	0.409	276.20	0.145	173.90	0.27	125.00	0.007	77.60	0.012
Minimum		1.54	0.033	3.35	0.108	0.26	0.008	0.28	0.014	0.15	0.004	0.15	0.007
Average		54.59	0.094	88.02	0.268	21.13	0.030	23.74	0.060	1.57	0.005	1.24	0.008
Avg. PL (cd.m2)		4.58		3.05		3.21		1.92		3.30		1.57	

Note: minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D=0m to D=36m
Avg. PL: Average Pavement luminance
: Lighting system position

- $V_{L\ ratio} > 0.4$ *(Unacceptable glare levels)*
- $0.3 < V_{L\ ratio} \leq 0.4$ *(Acceptable glare levels but limited to work zones located at major and local streets)*
- $0 \leq V_{L\ ratio} \leq 0.3$ *(Acceptable glare levels applicable to work zones located at freeways, expressways, and major roadways)*

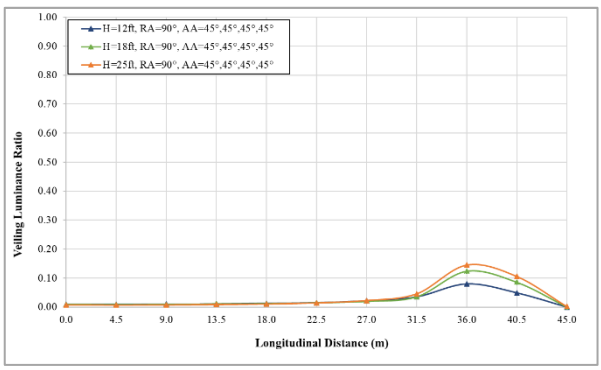


(a) Aiming angle = 45°

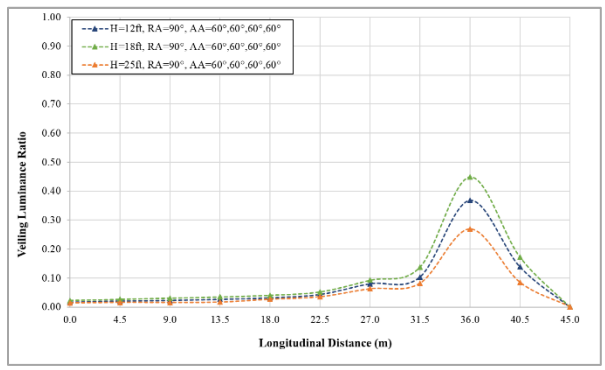


(b) Aiming angle = 60°

Figure 4.17. $V_{L\ ratio}$ values for a single LED light tower at 12-, 18-, and 25-ft height and 45-degree orientation.

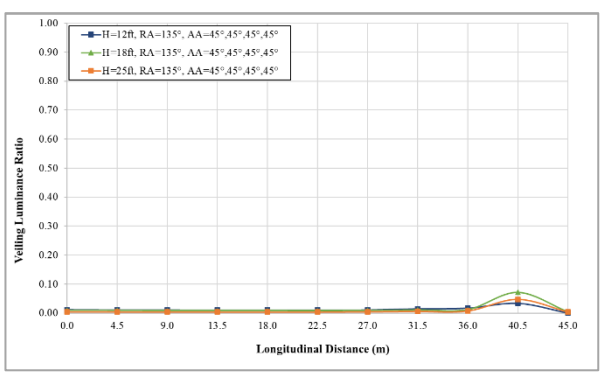


(a) Aiming angle = 45°

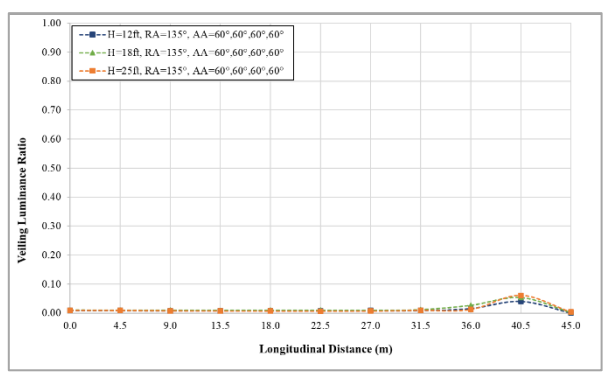


(b) Aiming angle = 60°

Figure 4.18. $V_{L\ ratio}$ values for a single LED light tower at 12-, 18-, and 25-ft height and 90-degree orientation.



(a) Aiming angle = 45°



(b) Aiming angle = 60°

Figure 4.19. $V_{L\ ratio}$ values for a single LED light tower at 12-, 18-, and 25-ft height and 135-degree orientation.

4.3 Impact of Drivers Age and Lighting Equipment Features on Disability Glare

To determine the effect of lighting equipment characteristics on the disability glare produced by balloon lights and light towers, three factorial ANOVA analyses were conducted. The factorial analyses examined the effect of lighting system type, light source, mounting height, electrical power (wattage), orientation, and aiming angles on the values of the veiling luminance ratio. Additionally, an evaluation of effects of observers' ages on disability glare levels was conducted. The following sections discuss the results of the factorial designs and effects of observer's age.

4.3.1 Balloon light (2x4): Main Effects and Interactions

The SPSS Statistics software was used to conduct the factorial ANOVA design for balloon lights (2x4), The two-way interaction analysis (2x4) examines the main and interaction effects of two factors: (1) mounting height and (2) power output (watt). The two by four nomenclature designates two mounting height factor categories (8 ft and 10 ft) and four wattage factor categories (300-, 400-, 600-, and 800-watt). The description of the data used in SPSS is summarized in Table 4.12.

Table 4.12. Descriptive statistics for a single balloon light (2x4).

Dependent Variable: Veiling Luminance Ratio				
Power	Height	Mean	Std. Deviation	Number of observations
300W	H=8 ft	0.741	0.406	11
	H=10 ft	0.489	0.266	11
	Total	0.615	0.359	22
400W	H=8 ft	0.269	0.135	11
	H=10 ft	0.268	0.134	11
	Total	0.268	0.131	22
600W	H=8 ft	0.266	0.132	11
	H=10 ft	0.251	0.124	11
	Total	0.259	0.125	22
800W	H=8 ft	0.262	0.131	11
	H=10 ft	0.280	0.140	11
	Total	0.271	0.133	22
Total	H=8 ft	0.385	0.307	44
	H=10 ft	0.322	0.196	44
	Total	0.353	0.258	88

As described in Table 4.13, the results of factorial ANOVA analysis showed that main effect of power output [F (3,80) = 15.719, $p < 0.001$] was statistically significant. Looking at the means, the significant effect of equipment power output supported the alternative hypothesis (See Table 3.5) that changing the power output on a LED balloon light (from 800-, 600-, 400-watt to 300-watt) would be associated to an increase in veiling luminance ratio. The mounting height [F (1,80) = 2.013, $p > 0.05$] and a two-way interaction [F (3,80) = 2.084, $p > 0.05$] involving power output and mounting height were not statistically significant. As shown in Figure 4.20, The change in heights and power outputs was not substantial for the model GB8LED (800-,600-, and 400-w).

Table 4.13. Tests of between subjects' effects of a factorial ANOVA for a single balloon light (2x4)

Dependent Variable: Veiling Luminance Ratio						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	2.363[a]	7	.338	7.917	.000	.409
Intercept	10.984	1	10.984	257.592	.000	.763
Power	**2.011**	**3**	**.670**	**15.719**	**.000**	**.371**
Height	.086	1	.086	2.013	.160	.025
Power * Height	.267	3	.089	2.084	.109	.072
Error	3.411	80	.043			
Total	16.758	88				
Corrected Total	5.774	87				

a. R Squared = .409 (Adjusted R Squared = .358)

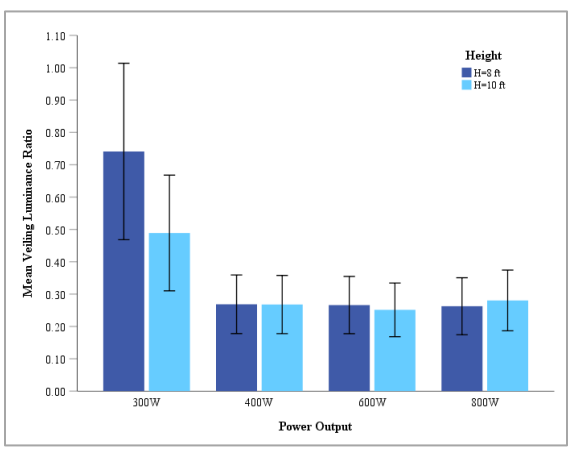


Figure 4.20. $V_{L\ ratio}$ values of a single LED balloon light by electrical power. Values are means of $V_{L\ ratio}$, and error bars represent standard errors.

Effect of Observer's Age

To evaluate the increase in disability glare levels of a single balloon light by incorporating the aging factor on the calculated veiling luminance, four different ranges of observer's age were selected, as shown in Table 4.14. For observers with ages between 25 to 40 years old, the $V_{L\ ratio}$ values were greater than 0.3 but less than 0.4 in six out of eight lighting combinations, suggesting acceptable disability glare levels according to the IES (2018). For observers with ages greater than 50 years old, the disability glare levels calculated suggest harmful levels of disability glare in all balloon lighting arrangements.

Table 4.14. Veiling luminance ratio mean values for a single balloon light by observers' age.

Lighting Arrangement	Lighting System	Mounting Height (H)	Power Output	$V_{L\ ratio}$ *				
				Age				
				25	40	50	60	75
1	One LED Balloon Light	8 ft (2.4m)	300 W	**0.906**	**1.002**	**1.141**	**1.394**	**2.099**
2			400 W	**0.328**	**0.363**	**0.414**	**0.505**	**0.761**
3			600 W	**0.325**	**0.360**	**0.410**	**0.501**	**0.754**
4			800 W	**0.320**	**0.354**	**0.404**	**0.493**	**0.742**
5		10 ft (3.0m)	300 W	**0.595**	**0.659**	**0.750**	**0.916**	**1.379**
6			400 W	**0.327**	**0.362**	**0.412**	**0.504**	**0.758**
7			600 W	**0.306**	**0.339**	**0.386**	**0.472**	**0.710**
8			800 W	**0.342**	**0.378**	**0.431**	**0.526**	**0.792**

* *$V_{L\ ratio}$ mean values were calculated between D=0m to D=36m.*

- *$V_{L\ ratio} > 0.4$ (Unacceptable glare levels)*
- $0.3 < V_{L\ ratio} \leq 0.4$ *(Acceptable glare levels but limited to work zones located at major and local streets)*
- $0 \leq V_{L\ ratio} \leq 0.3$ *(Acceptable glare levels applicable to work zones located at freeways, expressways, and major roadways)*

4.3.2 Metal-halide light tower (3x3x2): Main Effects and Interactions

The three-way interaction analysis (3x3x2) conducted on the veiling illuminance ratios for a metal-halide light tower examines the main and interaction effects of three factors: mounting height, rotation angles, and aiming angles. Three categories for mounting height factor (12 ft, 18 ft, and 30 ft), three categories for orientation factor (45°, 90°, and 135°), and two categories for aiming angle factor (30° and 45°) were included in this analysis. The description of the data enter to SPSS is summarized in Table 4.15.

The results of the veiling luminance ratio (disability glare) values showed that two-way interaction of the mounting height [F (2,180) = 7.915, p < 0.001], and the rotation angle (or

orientation) [F (2,180) = 160.592, $p < 0.000$], was statistically significant. The main effect of the aiming angle, the interaction between mounting height and aiming angle, the interaction between rotation angle and aiming angle, and the three-way interaction between all factors were not statistically significant, as shown in Table 4.16.

The combined effect of mounting height and rotation angle (or light orientation) on veiling luminance ratios are shown in Figure 4.21. Veiling luminance ratio values are dependent on both mounting height and rotation angle. Higher $V_{L\ ratio}$ values were observed at the "toward" orientation compared to the perpendicular and away orientations for all three mounting heights. Also, in the "toward" orientation, lower heights show higher veiling luminance values. To further analyze the interaction of mounting height and rotation angle, differences between the rotation angle within the mounting heights were considered.

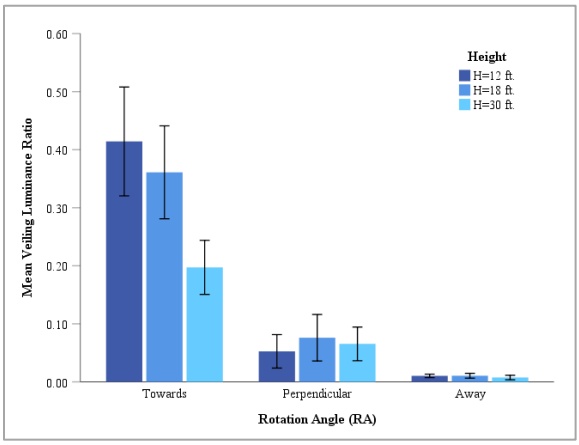


Figure 4.21. $V_{L\ ratio}$ values of a single metal-halide light tower by orientation. Values are means of $V_{L\ ratio}$, and error bars represent standard errors.

Table 4.15. Descriptive statistics for a single metal-halide light tower (3x3x2).

Dependent Variable: Veiling Luminance Ratio					
Height	Rotation angle	Aiming angle	Mean	Std. Deviation	Number of observations
H=12 ft.	Towards	30 degrees	0.347	0.165	11
		45 degrees	0.481	0.238	11
		Total	0.414	0.211	22
	Perpendicular	30 degrees	0.054	0.066	11
		45 degrees	0.051	0.068	11
		Total	0.053	0.065	22
	Away	30 degrees	0.012	0.009	11
		45 degrees	0.009	0.004	11
		Total	0.010	0.007	22
	Total	30 degrees	0.138	0.181	33
		45 degrees	0.180	0.257	33
		Total	0.159	0.222	66
H=18 ft.	Towards	30 degrees	0.363	0.191	11
		45 degrees	0.359	0.179	11
		Total	0.361	0.181	22
	Perpendicular	30 degrees	0.096	0.111	11
		45 degrees	0.056	0.063	11
		Total	0.076	0.090	22
	Away	30 degrees	0.010	0.010	11
		45 degrees	0.011	0.009	11
		Total	0.011	0.009	22
	Total	30 degrees	0.156	0.196	33
		45 degrees	0.142	0.189	33
		Total	0.149	0.192	66
H=30 ft.	Towards	30 degrees	0.223	0.123	11
		45 degrees	0.172	0.082	11
		Total	0.197	0.105	22
	Perpendicular	30 degrees	0.066	0.070	11
		45 degrees	0.065	0.064	11
		Total	0.065	0.065	22
	Away	30 degrees	0.006	0.006	11
		45 degrees	0.009	0.011	11
		Total	0.007	0.009	22
	Total	30 degrees	0.098	0.122	33
		45 degrees	0.082	0.090	33
		Total	0.090	0.107	66
Total	Towards	30 degrees	0.311	0.169	33
		45 degrees	0.337	0.216	33
		Total	0.324	0.193	66
	Perpendicular	30 degrees	0.072	0.084	33
		45 degrees	0.057	0.063	33
		Total	0.065	0.074	66
	Away	30 degrees	0.010	0.008	33
		45 degrees	0.009	0.008	33
		Total	0.009	0.008	66
	Total	30 degrees	0.131	0.170	99
		45 degrees	0.135	0.194	99
		Total	0.133	0.182	198

Table 4.16 Tests of between subjects' effects of a factorial ANOVA for a single metal-halide light tower (3x3x2).

Dependent Variable: Veiling Luminance Ratio					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4.416[a]	17	0.260	22.388	0.000
Intercept	3.490	1	3.490	300.788	0.000
Height	**0.184**	**2**	**0.092**	**7.915**	**0.001**
Orientation	**3.727**	**2**	**1.863**	**160.592**	**0.000**
Aiming angle	0.001	1	0.001	0.059	0.808
Height*Orientation	**0.385**	**4**	**0.096**	**8.289**	**0.000**
Height*Aiming angle	0.037	2	0.019	1.600	0.205
Orientation*Aiming angle	0.014	2	0.007	0.609	0.545
Height *Orientation* Aiming angle	0.069	4	0.017	1.487	0.208
Error	2.089	180	0.012		
Total	9.995	198			
Corrected Total	6.505	197			

a. R Squared = .679 (Adjusted R Squared = .649)

Effect of rotation angle in each mounting height

The pairwise comparisons between the rotation angle (or light orientation) within the three mounting height categories is summarized in Table 4.17. In the toward orientation, the veiling luminance ratio mean values between all three mounting heights were significantly different from one another, with the 12-ft height having the highest $V_{L\ ratio}$, and the 30-ft height having the lowest $V_{L\ ratio}$, as illustrated in Figure 4.22. In the perpendicular orientation, the interaction between rotation angle and all three mounting heights were not statistically significant, as shown in Figure 4.23. Similar results were observed on the away orientation in which the interaction between rotation angle and mounting height was not statistically significant, as shown in Figure 4.24.

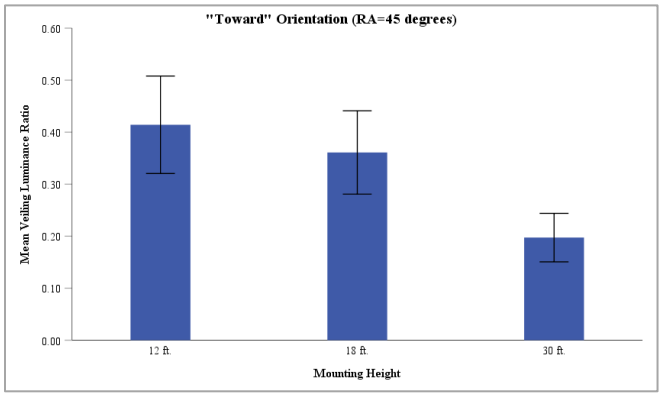


Figure 4.22. $V_{L\ ratio}$ values for three different mounting heights of a single metal halide light tower oriented "towards" the traffic. Values are means of $V_{L\ ratio}$, and error bars represent standard errors.

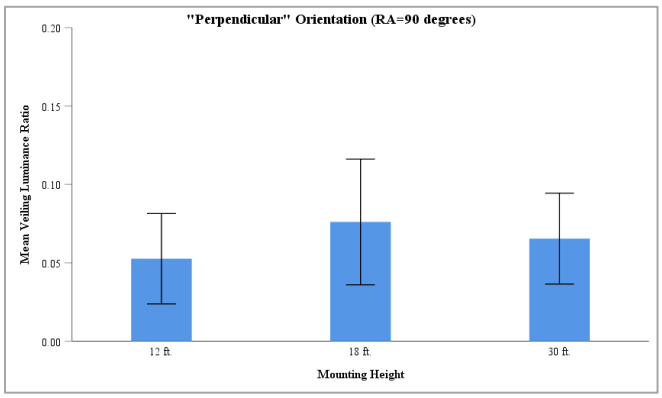


Figure 4.23. $V_{L\ ratio}$ values for three different mounting heights of a single metal halide light tower oriented "perpendicular" to the traffic. Values are means of $V_{L\ ratio}$, and error bars represent standard errors.

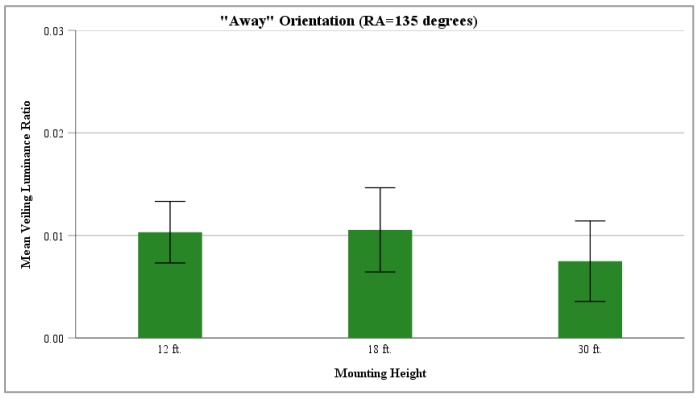


Figure 4.24. $V_{L\ ratio}$ values for three different mounting heights of a single metal halide light tower oriented "away" from the traffic. Values are means of $V_{L\ ratio}$, and error bars represent standard errors.

Table 4.17. Pairwise Comparisons between the orientations within the mounting heights for a metal-halide light tower.

Height	H (I)	H (J)	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
45°	12 ft.	18 ft.	0.053	0.032	0.103	-0.011	0.117
		30 ft.	.217*	0.032	0.000	0.153	0.281
	18 ft.	12 ft.	-0.053	0.032	0.103	-0.117	0.011
		30 ft.	.164*	0.032	0.000	0.100	0.228
	30 ft.	12 ft.	-.217*	0.032	0.000	-0.281	-0.153
		18 ft.	-.164*	0.032	0.000	-0.228	-0.100
90°	12 ft.	18 ft.	-0.023	0.032	0.471	-0.088	0.041
		30 ft.	-0.013	0.032	0.694	-0.077	0.051
	18 ft.	12 ft.	0.023	0.032	0.471	-0.041	0.088
		30 ft.	0.011	0.032	0.744	-0.053	0.075
	30 ft.	12 ft.	0.013	0.032	0.694	-0.051	0.077
		18 ft.	-0.011	0.032	0.744	-0.075	0.053
135°	12 ft.	18 ft.	0.000	0.032	0.994	-0.064	0.064
		30 ft.	0.003	0.032	0.931	-0.061	0.067
	18 ft.	12 ft.	0.000	0.032	0.994	-0.064	0.064
		30 ft.	0.003	0.032	0.925	-0.061	0.067
	30 ft.	12 ft.	-0.003	0.032	0.931	-0.067	0.061
		18 ft.	-0.003	0.032	0.925	-0.067	0.061

Based on estimated marginal means:
**. The mean difference is significant at the .05 level.*
b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Effect of Observer's Age

To evaluate the increase in disability glare levels of a single metal-halide light tower due to different values of aging factors on $V_{L\ ratio}$ values, four different ranges of observer's age were selected, as shown in Table 4.18. For observers' age between 25 to 50 years old, the $V_{L\ ratio}$ values were less than 0.4 in 14 of 18 lighting arrangements, suggesting acceptable disability glare levels. This trend is consistent up to 75-year-old-observer. However, in the rest of lighting arrangements, especially for observers' age greater than 50 years old, the $V_{L\ ratio}$ values exceed 0.4 which is also a maximum $V_{L\ ratio}$ value recommended by the IES (2018), when a single metal-halide light tower was oriented 45 degrees, the luminaries raised up to 12 ft and 18 ft, and the lighting fixtures were aimed at 30- and 45-degree angle. Similarly, for observers' age greater than 60 years old, harmful levels of disability glare were found ($V_{L\ ratio}$ values exceed 0.4), when a single metal-halide light tower was oriented 45 degrees, the luminaries raised at 30 ft, and the lighting fixtures were aimed at 30- and 45-degree angle.

Table 4.18. Veiling luminance ratio mean values for a single metal-halide light tower by observers' age

Lighting Arrangement	Lighting System	Mounting Height (H)	Rotation Angle (RA)	Aiming Angle (AA)	$V_{L\ Ratio}$ *				
					Age				
					25	40	50	60	75
14	One Metal-halide light tower	12 ft (3.7 m)	45°	30° (x4)	**0.419**	**0.464**	**0.529**	**0.646**	**0.972**
15				45° (x4)	**0.580**	**0.642**	**0.731**	**0.893**	**1.345**
16			90°	30° (x4)	**0.056**	**0.062**	**0.070**	**0.086**	**0.129**
17				45° (x4)	**0.058**	**0.064**	**0.073**	**0.089**	**0.134**
18			135°	30° (x4)	**0.011**	**0.012**	**0.014**	**0.017**	**0.025**
19				45° (x4)	**0.009**	**0.009**	**0.011**	**0.013**	**0.020**
20		18 ft (5.5 m)	45°	30° (x4)	**0.440**	**0.487**	**0.555**	**0.678**	**1.021**
21				45° (x4)	**0.434**	**0.480**	**0.547**	**0.668**	**1.005**
22			90°	30° (x4)	**0.111**	**0.122**	**0.139**	**0.170**	**0.256**
23				45° (x4)	**0.065**	**0.072**	**0.082**	**0.100**	**0.151**
24			135°	30° (x4)	**0.009**	**0.010**	**0.011**	**0.013**	**0.020**
25				45° (x4)	**0.009**	**0.010**	**0.011**	**0.014**	**0.021**
26		30 ft (9.1 m)	45°	30° (x4)	**0.271**	**0.300**	**0.341**	**0.417**	**0.628**
27				45° (x4)	**0.208**	**0.230**	**0.262**	**0.320**	**0.481**
28			90°	30° (x4)	**0.077**	**0.086**	**0.097**	**0.119**	**0.179**
29				45° (x4)	**0.074**	**0.082**	**0.094**	**0.115**	**0.172**
30			135°	30° (x4)	**0.006**	**0.007**	**0.008**	**0.009**	**0.014**
31				45° (x4)	**0.007**	**0.008**	**0.009**	**0.011**	**0.017**

* *$V_{L\ ratio}$ mean values were calculated between D=0m to D=36m.*

▪ *$V_{L\ ratio} > 0.4$ (Unacceptable glare levels)*

▪ $0.3 < V_{L\ ratio} \leq 0.4$ *(Acceptable glare levels but limited to work zones located at major and local streets)*

▪ $0 \leq V_{L\ ratio} \leq 0.3$ *(Acceptable glare levels applicable to work zones located at freeways, expressways, and major roadways)*

4.3.3 LED light tower (3x3x2): Main Effects and Interactions

The three-way interaction analysis (3x3x2) conducted on the veiling illuminance ratios for a LED light tower examines the main and interaction effects of three factors: mounting height, rotation angles, and aiming angles. Three categories for mounting height factor (12 ft, 18 ft, and 25 ft), three categories for orientation factor (45°, 90°, and 135°), and two categories for aiming angle factor (45° and 60°) were included in this analysis. The description of the data enter to SPSS is summarized in Table 4.19.

The results of the veiling luminance ratio (disability glare) values showed that main effect of mounting height [F (2,180) = 1.085, $p > 0.05$] was not statistically significant. Additionally, the two-way interaction between mounting height and rotation angle, the two-way interaction between height and aiming angle, and the three-way interaction between all factors were also not

statistically significant. However, the main effect of the rotation angle (or orientation) [F (2,180) = 54.056, $p < 0.000$], the aiming angle [F (1,180) = 29.303, $p < 0.000$], and the two-way interaction involving them was statistically significant, as shown in Table 4.20.

The combined effects of rotation angle and aiming angle on veiling luminance ratios are shown in Figure 4.25. Veiling luminance ratio values are dependent on both the rotation angle and the aiming angle. Higher $V_{L\ ratio}$ values were observed at the "toward" orientation compared to the perpendicular and away orientations in all three rotation angles. Also, in the "toward" and the "perpendicular" orientation, tilt angles of luminaries at 60° show higher veiling luminance values compared to tilt angles of 45°. To further analyze the interaction of rotation angles and aiming angles, differences between the rotation angle within the aiming angles were considered.

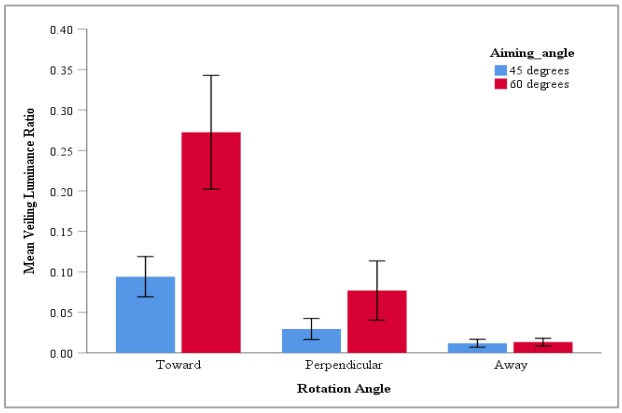


Figure 4.25. $V_{L\ ratio}$ values by LED light tower orientation. Values are means of $V_{L\ ratio}$, and error bars represent standard errors.

Table 4.19. Descriptive statistics for a single LED light tower (3x3x2).

Dependent Variable: Veiling Luminance Ratio					
Height	Rotation angle	Aiming angle	Mean	Std. Deviation	N
H=12 ft.	Towards	45 degrees	0.071	0.050	11
		60 degrees	0.283	0.223	11
		Total	0.177	0.192	22
	Perpendicular	45 degrees	0.023	0.023	11
		60 degrees	0.078	0.105	11
		Total	0.050	0.079	22
	Away	45 degrees	0.013	0.008	11
		60 degrees	0.012	0.010	11
		Total	0.012	0.009	22
	Total	45 degrees	0.036	0.040	33
		60 degrees	0.124	0.181	33
		Total	0.080	0.138	66
H=18 ft.	Towards	45 degrees	0.115	0.080	11
		60 degrees	0.310	0.223	11
		Total	0.213	0.192	22
	Perpendicular	45 degrees	0.030	0.039	11
		60 degrees	0.097	0.128	11
		Total	0.064	0.098	22
	Away	45 degrees	0.014	0.019	11
		60 degrees	0.016	0.014	11
		Total	0.015	0.016	22
	Total	45 degrees	0.053	0.068	33
		60 degrees	0.141	0.191	33
		Total	0.097	0.149	66
H=25 ft.	Towards	45 degrees	0.097	0.076	11
		60 degrees	0.224	0.147	11
		Total	0.161	0.132	22
	Perpendicular	45 degrees	0.035	0.047	11
		60 degrees	0.057	0.076	11
		Total	0.046	0.063	22
	Away	45 degrees	0.008	0.013	11
		60 degrees	0.013	0.016	11
		Total	0.011	0.014	22
	Total	45 degrees	0.047	0.063	33
		60 degrees	0.098	0.131	33
		Total	0.072	0.105	66
Total	Towards	45 degrees	0.094	0.070	33
		60 degrees	0.273	0.198	33
		Total	0.183	0.173	66
	Perpendicular	45 degrees	0.029	0.037	33
		60 degrees	0.077	0.103	33
		Total	0.053	0.081	66
	Away	45 degrees	0.012	0.014	33
		60 degrees	0.013	0.013	33
		Total	0.013	0.013	66
	Total	45 degrees	0.045	0.058	99
		60 degrees	0.121	0.169	99
		Total	0.083	0.132	198

Table 4.20. Tests of between subjects' effects of a factorial ANOVA for a single LED light tower (3x3x2).

Dependent Variable: Veiling Luminance Ratio					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.675[a]	17	0.099	10.148	0.000
Intercept	1.365	1	1.365	140.636	0.000
Height	0.021	2	0.011	1.085	0.340
Orientation	**1.050**	**2**	**0.525**	**54.056**	**0.000**
Aiming angle	**0.285**	**1**	**0.285**	**29.303**	**0.000**
Height*Orientation	0.014	4	0.003	0.359	0.838
Height*Aiming angle	0.015	2	0.007	0.754	0.472
Orientation*Aiming angle	**0.278**	**2**	**0.139**	**14.319**	**0.000**
Height *Orientation* Aiming angle	0.013	4	0.003	0.337	0.853
Error	1.748	180	0.010		
Total	4.788	198			
Corrected Total	3.423	197			

a. R Squared = .489 (Adjusted R Squared = .441)

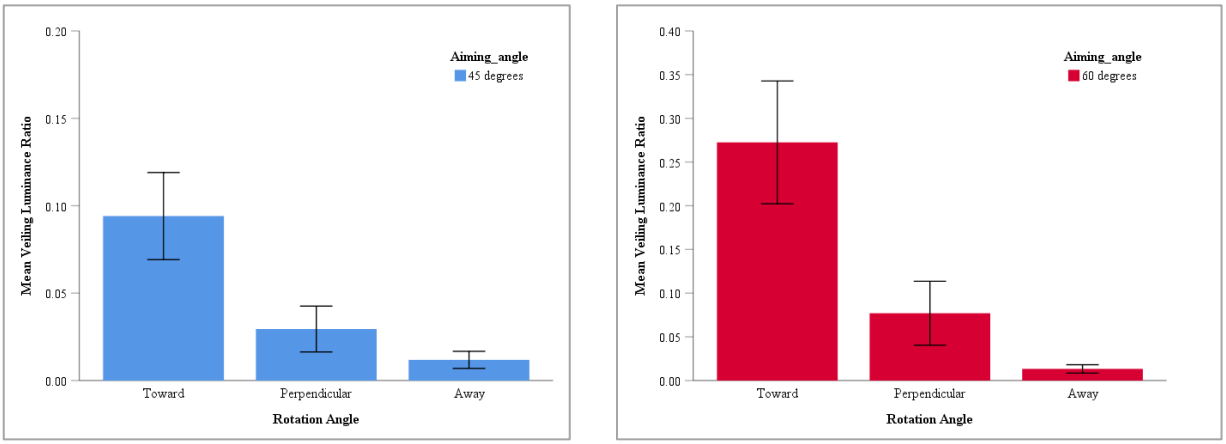
Effect of rotation angle in each aiming angle

The pairwise comparisons between the rotation angle (or light orientation) within the two aiming angles categories (45° and 60°) is summarized in Table 4.21. At the "toward" orientation, the interactions between within aiming angles were significantly different from each other, with the 60-degree luminaire's aiming angle having the highest $V_{L\ ratio}$, and the 45-degree luminaire's aiming angle having the lowest $V_{L\ ratio}$. At the "perpendicular" and "away" orientations of the LED light tower, the interaction between rotation angle and all two aiming angles were not statistically significant, as illustrated in Figure 4.26.

Table 4.21. Pairwise Comparisons between orientations within tilt angles for a LED light tower.

Rotation Angle (RA)	AA (I)	AA (J)	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
45°	45°	60°	-.178*	0.024	0.000	-0.226	-0.131
	60°	45°	.178*	0.024	0.000	0.131	0.226
90°	45°	60°	-0.048	0.024	0.051	-0.095	0.000
	60°	45°	0.048	0.024	0.051	0.000	0.095
135°	45°	60°	-0.001	0.024	0.952	-0.049	0.046
	60°	45°	0.001	0.024	0.952	-0.046	0.049

Based on estimated marginal means:
** The mean difference is significant at the .05 level.*
b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).



(a) Aiming angle = 45° (b) Aiming angle = 60°

Figure 4.26. $V_{L\ ratio}$ values for three different orientations of a single LED light tower. Values are means of $V_{L\ ratio}$, and error bars represent standard errors.

Effect of Observer's Age

To evaluate the increase in disability glare levels of a single metal-halide light tower due to different values of aging factors on $V_{L\ ratio}$ values, four different ranges of observer's age were selected, as shown in Table 4.22. For almost all the lighting arrangements for observers' age between 25 and 40 years old showed acceptable disability glare levels ($V_{L\ ratio} \leq 0.4$), except from one lighting combinations in which a single LED light tower was mounted at 18 ft, oriented 45°, and light fixtures aimed at 60°. In this lighting combination $V_{L\ ratio}$ exceed 0.4, suggesting unacceptable glare levels. For observer's age greater than 50 years old, the $V_{L\ ratio}$ exceed 0.4 in three of eighteen lighting combinations. This occurred when a single LED light tower was mounted at 12 ft, 18 ft, and 25 ft, oriented 45°, and all light fixtures aimed at 60°. In the fifteen remaining combinations (heights, orientations, and aiming angles), the $V_{L\ ratio}$ values were less than 0.4, suggesting acceptable levels of glare.

Table 4.22. Veiling luminance ratio mean values for a single LED light tower by observers' age

Lighting Arrangement	Lighting System	Mounting Height (H)	Rotation Angle (RA)	Aiming Angle (AA)	$V_{L\ Ratio}$*				
					Age				
					25	40	50	60	75
32	One LED light tower	12 ft (3.7 m)	45°	45°(x4)	**0.080**	**0.089**	**0.101**	**0.123**	**0.186**
33				60°(x4)	**0.338**	**0.374**	**0.426**	**0.520**	**0.783**
34			90°	45°(x4)	**0.023**	**0.025**	**0.029**	**0.035**	**0.053**
35				60°(x4)	**0.079**	**0.088**	**0.100**	**0.122**	**0.184**
36			135°	45°(x4)	**0.012**	**0.013**	**0.015**	**0.018**	**0.028**
37				60°(x4)	**0.009**	**0.010**	**0.012**	**0.015**	**0.022**
38		18 ft (5.5 m)	45°	45°(x4)	**0.127**	**0.141**	**0.160**	**0.196**	**0.295**
39				60°(x4)	**0.375**	**0.415**	**0.473**	**0.577**	**0.869**
40			90°	45°(x4)	**0.028**	**0.031**	**0.035**	**0.042**	**0.064**
41				60°(x4)	**0.099**	**0.109**	**0.124**	**0.152**	**0.229**
42			135°	45°(x4)	**0.009**	**0.010**	**0.011**	**0.014**	**0.021**
43				60°(x4)	**0.013**	**0.014**	**0.016**	**0.020**	**0.029**
44		25 ft (7.6 m)	45°	45°(x4)	**0.094**	**0.104**	**0.118**	**0.144**	**0.217**
45				60°(x4)	**0.268**	**0.297**	**0.338**	**0.413**	**0.622**
46			90°	45°(x4)	**0.030**	**0.034**	**0.038**	**0.047**	**0.070**
47				60°(x4)	**0.060**	**0.066**	**0.076**	**0.092**	**0.139**
48			135°	45°(x4)	**0.005**	**0.005**	**0.006**	**0.007**	**0.011**
49				60°(x4)	**0.008**	**0.009**	**0.011**	**0.013**	**0.020**

4.4 Discussion of Results

The objectives of this thesis were to examine the effects of lighting system type, mounting height, light orientation, aiming angles of luminaires, and the observers' age on disability glare for both light towers and balloon lights. Four major findings were evident based on the analysis conducted in this study. First, an increase in mounting heights of both LED balloon lights and light towers (LED and metal-halide) resulted in lower veiling luminance ratio values (or disability glare). Second, compared to the "perpendicular" and "away" orientations, orienting the light towers (LED and metal-halide) in a "toward" direction (45 degrees) produces greater veiling luminance ratio values (or disability glare). Third, increasing the tilt angles of luminaires of the LED light tower resulted in increase in veiling luminance ratios (or disability glare). Fourth, by directly incorporating the observer's age via the aging factor (AF), the calculated veiling luminance was increased, resulting also in an increase in veiling luminance ratio values (or disability glare).

Regarding the effects of mounting height of light towers on disability glare levels, the analyses indicated that veiling luminance ratio is consistently higher at lower heights (12 ft) than those on higher heights (25 ft to 30 ft). Particularly, at a height of 12-ft, the metal-halide light

tower had higher veiling luminance ratios compared to the LED light tower at the "toward" orientation. Similar results were also obtained across the 18-ft height, 25-, and 30-ft on the "toward" orientation. This finding was supported by the fact that the mounting height is statistically significant on a metal-halide light tower and that any changes in heights may impact the disability glare levels at the work zone. On the contrary, the mounting height was not statistically significant on the LED light towers. Although, the mounting height on a LED light tower was not statistically significant, the change in height may not affect the veiling luminance ratio. Hence, increasing the mounting height for both lighting systems is recommended to alleviate higher disability glare levels produced by metal-halide and LED light towers. For both light towers, mounting heights greater than 18 feet and up to full extension of the light mast (30-ft or 9.1 m) is recommended to secure veiling luminance ratios values lower than 0.3 which is the maximum recommended value by IES, to ensure reduction of disability glare levels on work zones.

In the case of LED balloon lights, the effect of increasing the mounting height to minimize the disability glare level was only evident in two situations: (1) when a single 300-watt balloon lighting was used; and (2) when two balloon lights were placed perpendicular to the lane used. For the other cases in which the lighting equipment were adjusted to 400-w, 600-w, and 800-watt, the differences in $V_{L\ ratio}$ values were minimal. Conversely, this result indicated that a lower power output produced higher values of veiling luminance ratio compared to those with high power outputs. In fact, the effect power output was determined to be a statistically significant on the veiling luminance ratio. Balloon lights with power outputs higher than 400-watt and mounted at heights greater than 8 ft. are recommended for nighttime highway operations because those features secure acceptable levels of disability glare in work zones in accordance with the IES's $V_{L\ ratio}$ maximum value.

Regarding the effects of light orientations of light towers, the results show that the "toward" orientation of light towers results in increasing disability glare levels. In the "toward" orientation, the $V_{L\ ratio}$ values were higher on metal-halide light towers compared to LED light towers. Moreover, the veiling luminance ratio was marginally greater in the perpendicular orientation than in the away orientation. These findings were supported by the fact that in both light towers, the orientation is statistically significant, indicating that changes in light orientation may significantly impact the veiling luminance ratio. Moreover, these findings demonstrate the importance of being cautious when not aiming light towers in the direction of traffic movement. To prevent or minimize

disability glare in work zones, light towers should be aimed away from or perpendicular to oncoming traffic. In the aforementioned orientations, LED light towers would be preferable over metal-halide light towers due to the lower values of veiling luminance ratios (or disability glare) they generate in each orientation, under similar values of vertical illuminance.

The effect of aiming angles of luminaries of a single LED light tower on disability glare levels was statistically significant, which means that any changes in the angle between the main axis and the vertical may significantly impact the veiling luminance ratio (or disability glare). Although, the aiming angle of luminaries of a metal-halide light tower was not statistically significant, aiming angles less than or equal to 45° are recommended to minimize disability glare levels on work zones. In the case of a LED light tower, luminaries aimed at 60° or less are recommended to reduce veiling luminance ratio values (or disability glare).

Finally, the scattering of light in the eye increases with age. The calculated veiling luminance ratio ($V_{L\ ratio}$) values in 44 lighting arrangements were determined by using a constant k equal to 10 which represents a 25-year-old-observer. However, these calculated $V_{L\ ratio}$ values can be multiplied by the aging factor (AF) to account for the eye's normal physiological changes as it ages. Incorporating this factor results in an increase in the calculated veiling luminance (V_L) value. For instance, for a 50-year-old driver, the calculated V_L is 30% more than the calculated V_L of a 25-year-old driver.

(i) For a single LED balloon light with power output of 300 watts, and mounted at 8 ft and 10 ft, harmful levels of glare ($V_{L\ ratio} \geq 0.4$) were found at observers' age greater than 25 years old. For a single LED balloon light with adjustable power output up to 800 watts, and mounted at 8 ft and 10 ft, acceptable levels of glare ($V_{L\ ratio} \leq 0.4$) were found to observers' age between 25 to 40 years old, but for observers' age greater than 50 years, the calculated $V_{L\ ratio}$ values (or disability glare) were found to be dangerous (0.413 to 0.622).

(ii) For a single metal-halide light tower, when aging factor was evaluated on observers' age greater than 25 years old, unacceptable glare levels ($V_{L\ ratio} \geq 0.4$) were noticed on four of eighteen lighting arrangements. These lighting combinations were when: (i) the light tower was mounted at 12 ft, oriented towards the traffic, and all light fixtures were aimed at 30 and 45 degrees; and (ii) the light tower was mounted at 18 ft, oriented towards the traffic, and all light fixtures were aimed 30 and 45 degrees.

Moreover, for observers' age greater than 60 years old, harmful levels of glare ($V_{L\ ratio} \geq 0.4$) were found on a single light tower mounted at 30 ft, oriented towards the traffic, and all light fixtures aimed 30 and 45 degrees. Finally, the assessment of changes in aging factor k for the perpendicular and away orientations in all three mounting heights resulted in acceptable levels of glare ($V_{L\ ratio} \leq 0.4$).

(iii) For a single LED light tower, three of eighteen lighting combinations were determined to generate unacceptable glare levels ($V_{L\ ratio} \geq 0.4$) when the aging factor k was evaluated on observer's age between 25 to 75 years. First, when a single LED light tower was mounted at 12 ft, oriented towards the traffic, and all light fixtures aimed 60 degrees, harmful levels of glare were found on observers' age greater than 50 years old. Second, when a single LED light tower was mounted at 18 ft, oriented towards the traffic, and all light fixtures aimed 60 degrees, harmful levels of glare were found on observers' age greater than 40 years old. Third, when a single LED light tower was mounted at 30 ft, oriented towards the traffic, and all light fixtures aimed 60 degrees, harmful levels of glare were found on observers' age greater than 60 years old. Finally, the assessment of changes in aging factor k for perpendicular and away orientations in all three mounting heights resulted in acceptable levels of glare ($V_{L\ ratio} \leq 0.4$).

4.5 Chapter Summary

A set of field experiments were conducted on a simulated work zone to measure vertical illuminance and pavement luminance. These readings served as input to determine the veiling luminance ratio, which is an objective measure of disability glare. A total of 49 lighting arrangements were tested during one-week of experiments. Two types of lighting systems were tested: two LED balloon lights, a LED light tower, and a metal-halide light tower.

The veiling luminance (or disability glare) experienced by a drive-by motorist progressively grows as they approach the light source, reaches a peak, and then drops to the point where it is minimal. This pattern was explained by several factors such as the lighting type, light source, mounting height, power output, rotation angle, and aiming angles of luminaires. A series of factorial ANOVA (Analysis of Variance) designs were prepared to explain the effect of such independent variables on a single dependent variable: the veiling luminance ratio or disability glare.

The results of the 49 lighting arrangements tested indicated that the mounting height, power output, light orientation, and aiming angles of luminaries, play a critical role affecting disability glare levels. Increased mounting heights for LED balloon lights and light towers (LED and metal-halide) resulted in decreased veiling luminance ratio values (or disability glare). Additionally, when comparing the "perpendicular" and "away" orientations of a single light tower (LED or metal-halide) to the "toward" direction (45 degrees), the 45-degree orientation yielded higher veiling luminance ratio values than the other two orientations. Raising the angle of the LED light tower's luminaires resulted in an increase in veiling luminance ratios (or disability glare). Finally, this study calculated the impact of the age of the motorist on the disability glare produced by different lighting arrangements and found that single-LED light tower arrangements in perpendicular and away orientations at mounting heights of 12 ft, 18 ft, and 25 ft resulted in acceptable levels of glare ($V_{L\ ratio} \leq 0.4$).

5. CONCLUSIONS

This thesis focuses on determining and evaluating disability glare on nighttime work zones as a step towards developing appropriate lighting strategies for improving the safety of workers and motorists during nighttime highway construction and maintenance projects. The data collection process intended to gather data related to roadway contractor's perspectives regarding their experiences on nighttime operations. Roadway contractor's perspectives regarding work zone lighting, preparations of lighting plans, and lighting systems used in work zones were assessed by the deployment of a survey questionnaire and by conducting formal interviews with contractors' safety officers. The main insights obtained from participants on the survey and formal interviews, indicated a lack of work zone lighting strategies regarding glare control at nighttime work zones. For this reason, an experimental approach to determine disability glare was designed and a series of field experiments were performed to measure illuminance and luminance levels of portable lighting systems (balloon lights and light towers). The measurements of vertical illuminance and pavement luminance were used as inputs for calculating the veiling luminance ratio (which is a metric for disability glare). The study allowed for the determination and recommendation of work zone lighting strategies to minimize or avoid disability glare levels produced commonly used lighting systems such as balloon lights and portable light towers on nighttime roadway construction and maintenance projects.

5.1 Summary of the Research Process

The first objective of this research was to develop an objective procedure to determine disability glare and provide acceptable levels of disability glare on work zones by using the veiling luminance ratio. To achieve this objective, a comprehensive state-of-the-art literature review and state-of-practice review was conducted to examine past and ongoing research studies, as well as current work zone lighting practices regarding glare in nighttime work zones. In addition to gain deeper understanding about the lighting systems that cause disability glare on work zones, two tasks were performed: (1) a survey was distributed to roadway contractors to gather their perspectives using lighting systems on their projects, and (2) an interview with safety officers was

conducted to discuss common practices related to the adequate use of lighting systems on nighttime highway operations.

The second objective of this research was to evaluate and compare the effects of the lighting type, orientation, aiming angles, mounting height, electrical power, and observer's age on the values of veiling luminance ratio (metric for disability glare) of different lighting arrangements. For this purpose, a set of field experiments were conducted to measure the vertical illuminance (*VI*) and the pavement luminance (*PL*) on a controlled environment which simulates a nighttime work zone lane closure. The experimental approach required the analysis of two types of lighting equipment: (i) balloon lights and (ii) portable light towers. Also, a set of lighting-related variables such as the type of the light source, power output, mounting height of the lighting system, rotation angle of the lighting system (or orientation), and the aiming angle of the luminaires (or tilt angle) were measured during the field experiments. The veiling luminance ratio (VL_{ratio}) was determined by using the vertical illuminance and pavement luminance readings for each of the 44 lighting combinations tested on-site. A descriptive and statistical analysis of the calculated VL_{ratio} values obtain from the 44 lighting arrangements were performed. The descriptive analysis compares if the veiling luminance ratio (VL_{ratio}) values for each lighting combination exceeds the maximum veiling luminance ratio values recommended by the Illuminating Engineering Society (IES), and the statistical analysis evaluates the effects of lighting system type, light source, mounting height, power output (wattage), orientation, aiming angles, and drivers ages on the calculated VL_{ratio} values by using the Factorial ANOVA technique.

The third objective of this research was to provide practical recommendations regarding optimal lighting arrangements that alleviate and/or control disability glare levels experienced by passing motorists and by workers on nighttime highway work zone. The evaluation of different mounting heights, rotation angles of luminaries, aiming angle of luminaires, and observer's age led to the determination of lighting combinations that could reduce or minimize the impact of disability glare on nighttime work zones. These lighting combinations can be used on-site during nighttime construction and maintenance projects such as Hot Mix Asphalt (HMA) placement, rolling HMA surfaces, asphalt milling, pavement cleaning and sweeping, pavement patching, and work zone flagger stations.

5.2 Research Conclusions

This thesis addresses three main research questions that were posed in Chapter 1 as follows: (1) What are the effects of lighting systems' mounting height, electrical power (wattage), and observer's age on veiling luminance ratios for light-emitting diode (LED) balloon lights? (2) What are the effects of lighting systems' mounting height, orientation, aiming angles of luminaries, and observer's age on veiling luminance ratios (or disability glare) for metal-halide (MH) and light-emitting diode (LED) light towers? and (3) Under what ranges of motorists' age and lighting configurations (lighting type, orientation, aiming angles, mounting height, and electrical power) can disability glare be minimized or avoided on nighttime work zones? Based on the data collected from the field experiments and the calculation of veiling luminance ratio values (or disability glare levels) of 49 lighting arrangements of balloon lights and light towers, the following conclusions can be drawn from this study.

The analysis of glare levels for LED balloon lights showed that an increase in the mounting height of luminaires resulted in lower values of veiling luminance ($V_{L\ ratio}$) or disability glare. This pattern was evident in two situations: (1) when a single 300-watt balloon lighting was used; and (2) when two balloon lights were placed perpendicular to the lane used. When balloon lights were adjusted to 400-w, 600-w, and 800-watt, the differences in $V_{L\ ratio}$ values at 8-ft and 10-ft height were minimal. Interestingly and counter-intuitively, the results indicated that balloon lights with lower power output produced higher values of $V_{L\ ratio}$ compared to those with high power outputs. The two-way interaction analysis of mounting height and power output showed that the effect of changing the power output on a LED balloon light from 800-, 600- or 400-watt to 300-watt could be associated to an increase in veiling luminance ratio.

The analysis of glare levels for a metal-halide light tower showed two major findings. First, an increase in mounting height resulted in lower veiling luminance ratio values or disability glare levels. Second, when the light tower is oriented in the "toward" direction, the veiling luminance ratio ($V_{L\ ratio}$) or disability glare levels increases, compared to those $V_{L\ ratio}$ values of light tower oriented in the "perpendicular" and "away" orientations. These findings were supported by the three-way interaction analysis of mounting height, rotation angle, and aiming angle of luminaires which showed that the mounting height and rotation angle variables were statistically significant on a metal-halide light tower, and that any changes in heights and orientations may impact the disability glare levels at the work zone.

The analysis of glare levels for a LED light tower showed also similar findings. First, an increase in mounting height resulted in lower disability glare levels. Second, when the light tower is oriented in the "toward" direction increases the veiling luminance ratio or disability glare levels compare to those values if the light tower is oriented perpendicular or away from the oncoming traffic. Third, increasing the aiming angles of luminaires resulted on an increment of veiling luminance values or disability glare levels. Unlike the case of $V_{L\ ratio}$ values for the metal-halide light tower, the factorial ANOVA design for the LED light tower indicated that any changes in orientation and aiming angle of luminaires have significant impact on the disability glare levels.

For both types of light towers (metal-halide and LED), increasing the mounting height is recommended to reduce higher disability glare levels generated by them. Mounting heights greater than 18 feet (5.5m) and up to full extension of the light mast (30-ft or 9.1 m) are recommended to achieve veiling luminance ratios values lower than 0.3. This value is the maximum recommended value by Illumination Engineering Society (IES) that prevents occurrence of disability glare levels on work zones. Additionally, light towers should be aimed away from or perpendicular to oncoming traffic. In these orientations, LED light towers would be preferable over metal-halide light towers due to the lower values of veiling luminance ratios (or disability glare) they generate in each orientation, under similar values of vertical illuminance. Aiming angles of luminaires less than or equal to 45° are recommended as well to minimize disability glare levels on work zones, but in the case of a LED light tower, luminaries aimed at 60° or less are recommended to reduce veiling luminance ratio values (or disability glare).

The typical calculation of veiling illuminance is based on a 25-year-old driver. Calculations of veiling luminance (V_L) of the lighting systems should consider different driver's age, because some older adult drivers may experience higher glare levels than young drivers. The observer's age factor "k" plays an important role in determining the veiling luminance. As the factor k increases, the veiling luminance also increases. For balloon lights, at observer's age greater than 50 years, $V_{L\ ratio}$ values were found to be greater than the maximum recommended. For LED light towers, at observer's age greater than 50 years, the $V_{L\ ratio}$ values in three of eighteen lighting combinations tested in this study, were greater than 0.3 (the recommended value). This occurred when the LED light tower was mounted at 12 ft, 18 ft, and 25, oriented 45°, and their light fixtures aimed at 60°. For metal-halide light towers, at observers' age between 25 to 50 years, the $V_{L\ ratio}$ values were greater than 0.3 but less than 0.4 in 14 of 18 lighting combinations, suggesting

acceptable disability glare levels. But, for observers' age greater than 50 years, the $V_{L\ ratio}$ values exceed 0.4 which is the maximum $V_{L\ ratio}$ value recommended by the IES. This occurred when a single metal-halide light tower was oriented 45°, the luminaries raised up to 12 ft and 18 ft, and the lighting fixtures were aimed at 30- and 45-degree angle.

5.3 Limitations of the Research

This study has a few limitations. First, due to the characteristics of a controlled work zone, no other vehicle besides the sport utility vehicle (SUV) used for testing the lighting systems was present in the experiments. Thus, the impact of light produced by headlights of construction equipment and moving vehicles in and around the simulated work zone was not considered when assessing disability glare levels. Moreover, the disability glare levels calculated are limited to a single vertical distance between the road surface and the level of driver's eyes (1.45 m.) when sitting in the SUV.

Second, the results reported in this study represent values for $V_{L\ ratio}$ (or disability glare) under ideal work zone lighting settings. For instance, illumination reductions should be expected under real-world road conditions due to existing road geometry (e.g., straight road sections, curved sections, and others), surface conditions (asphalt pavement vs. concrete pavement), lighting system conditions (e.g., new, well-, or poor-maintained lighting equipment), and weather conditions (e.g., wet surface and foggy weather conditions) that might be present during nighttime operations. The pavement luminance readings obtained during the experiments corresponded to a slightly deteriorated dark asphalt pavement, and the readings were taken on clear nights.

Third, only one line of sight was considered when measuring vertical illuminance and pavement luminance, only two mounting heights were tested on balloon lights and three on portable light towers, and only two aiming angles were tested on portable light towers, as well. Moreover, only four lighting systems were analyzed of which two were LED balloon lights, and two were light towers with metal-halide and LED fixtures. The lighting systems were used one at a time during the field experiments.

Finally, the findings of this study are applicable exclusively to work zones on limited-access roadways (freeways, expressways, major roadways, and collectors) with no presence of street lighting or other type of presence lighting different from portable lighting systems. Presence

lighting may help to minimize glare levels experienced by drive-by motorists (due to the increase in luminance adaptation levels of the motorists).

5.4 Contribution to the Body of Knowledge

This thesis identified ways to improve safety of workers and motorists during nighttime highway construction and maintenance projects by determining and evaluating disability glare levels generated by lighting systems (balloon lights and light towers) on a controlled environment that simulates a nighttime work zone. Very few prior publications related to glare on nighttime work zones addressed the assessment of glare on recent and more efficient lighting systems that use light-emitting diode (LED) as a light source. This study evaluated and compared several lighting-related variables of metal-halide and LED lighting systems that impact disability glare levels such as the mounting height, power output, orientation, and aiming angle of luminaires by assessing multiple lighting combinations. Also, this study includes an assessment of the effects of driver's age on disability glare levels produced by balloon lights and portable light towers, and how the driver's age ranges limit the use of the following lighting systems: (1) a single LED balloon light; (2) a metal-halide light tower; and (3) a LED light tower. In addition, a set of factorial ANOVA analyses were designed to test the main effects, interactions, and to determine the significance of the independent variables (e.g., heights, power output, orientations, and tilt angles) on the disability glare levels produced by these lighting systems on work zones.

5.5 Contribution to the Body of Practice

The determination and evaluation of disability glare generated by balloon lights and light towers on a simulated work zone environment has guided the development of the following recommendations to reduce or minimize disability glare levels during nighttime construction and maintenance projects:

(i) Selecting a proper mounting height for lighting systems that use metal-halide or LED light sources is vital to control or reduce glare in work zones. Owners and general contractors should raise the light towers to mounting heights of 18 ft (5.5m) or greater to full extension of the light mast (typically 30 ft or 9.1 m) in order to minimize disability glare levels.

(ii) Selecting a proper mounting height for balloon lights can help to prevent higher disability glare levels, but most important, it is critical to wisely choose the equipment's power output. LED balloon lights were demonstrated to have a consistent range of $V_{L\ ratio}$ values between 0.3 and 0.4 at mounting heights greater than 8 ft (2.4 m) under several power outputs tested (from 400- to 800-watt), indicating that these lighting systems are less prone to produce glare. These $V_{L\ ratio}$ values indicate acceptable levels of glare for motorists and workers ages under 50.

(iii) Portable light towers with traditional light sources and energy-efficient light sources using LED technology, should be oriented either perpendicular or away from the oncoming traffic. For the largest groups of motorists (ages 25-70), light towers oriented perpendicular to or away from the traffic demonstrated the capability to significantly counteract higher disability glare levels (particularly for drivers over 50 years of age). Metal-halide and LED light towers aimed in the direction of the traffic movement and mounted at heights lower than 18 ft should be avoided whenever possible, particularly for older adult drivers (over 50 years). However, if this arrangement is not possible, the light tower must be fully extended with the luminaires aimed at least 45 degrees from the horizontal. Moreover, an evaluation of calculated disability glare levels for multiple ranges of driver's age should be performed to determine acceptable or harmful glare levels for the aforementioned lighting arrangement.

(iv) LED light towers would be preferred over metal-halide light towers in all of the three orientations evaluated due to the lower values of veiling luminance ratios (or disability glare) they generate in each orientation, under similar values of vertical illuminance.

(v) Luminaires of light towers for metal-halide light towers should be aimed so that the angle formed by the nadir and the center of the luminaire's beam spread should not exceed 45 degrees to reduce higher disability glare levels. For LED light towers, all luminaires should be aimed at angles of 60 degrees or less below the horizontal as well to minimize glare.

5.6 Recommendations for Future Research

The purpose of this study was to determine the level of disability glare generated by various lighting systems in a simulated work zone and to develop strategies for reducing harmful glare levels experienced by motorists and workers during nighttime highway operations. While the conclusions suggest avenues for developing more effective glare control strategies for nighttime work, additional research is necessary. The following recommendations extend beyond the limitations of this research and address the issues which require further investigation.

The vertical illuminance and pavement luminance measurements obtained in the field studies corresponded to a somewhat deteriorated dark asphalt pavement surface with a rough texture that is usually utilized on roadways. Thus, the values for the average brightness of the pavement would be appropriate to roads with an asphalt surface. However, Portland cement concrete (PCC) pavement technologies are used on a large number of roadways. Future research should attempt to measure pavement luminance on PPC pavement systems in a simulated work zone environment or in real work zone conditions (with experimental setups to ensure no/low risk to the personnel involved in the experiments), testing all lighting system dependent variables (i.e., setup parameters) including the mounting height, power output, rotation angle, and aiming angle of luminaires constant. Moreover, future studies should consider the measurements of illuminance and luminance of lighting systems operating under different weather conditions including wet and foggy roads and should evaluate glare levels produced under such conditions.

The developed procedure for determining the veiling luminance ratio (glare) on work zone uses separate measurements of vertical illuminance and pavement luminance. Future research should attempt to improve the collection of lighting data by creating a system capable of integrating the readings of vertical illuminance, pavement luminance, and position (latitude and longitude) of each of the grid points of the line of sight (possibly using in-vehicle instrumentation). If such a system is developed and validated, it could be employed on real work zones saving time and without posing safety risks to workers and motorists when lighting data is collected.

The use of energy-efficient lighting technologies employed in nighttime highway construction and maintenance projects should be further evaluated. For instance, there are many commercially available lighting systems with LED light sources that are currently being used on different nighttime highway operations. Future study efforts should consider the assessment of disability glare and illumination levels produced by these energy-efficient lighting systems, for

instance, the evaluation of the effects of lighting-related factors (setup parameters, electrical power output, type of LED source, light intensity) on the illuminance levels and disability glare levels produced by these lighting systems.

Understanding drivers' perceptions of glare caused by temporary lighting systems in nighttime highway work zones may complement the objective determination of veiling luminance ratio values (or disability glare) for the lighting arrangements tested. Subjective evaluation of glare could be accomplished by recruiting participants from different age and gender groups and asking them to rate their perception of glare by means of a questionnaire, while driving on a simulated work zone and encountering different lighting arrangements.

Finally, glare levels experienced by drivers operating different types of vehicles should be further evaluated. There is a significant difference in how truck drivers and car drivers experience glare because of the difference in vertical distance between the road surface and their lines of sight.

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APPENDIX A. SURVEY INSTRUMENT FOR ROADWAY CONTRACTORS

PURDUE UNIVERSITY

Block 1

ROADWAY WORKZONE SAFETY AND PRODUCTIVITY – DAYTIME VS. NIGHTTIME OPERATIONS - CONTRACTORS' PERSPECTIVE

Joint Transportation Research Program
Project Number: SPR 4542

Dear Respondent,

Greeting from Purdue University. We invite you to participate in the research study titled "Roadway Workzone Safety and Productivity - Daytime vs. Nighttime Operations - Contractors' Perspective", with the IRB number: IRB-2021-924. The Principal Investigator (PI) is Dr. Dulcy Abraham and the Primary contact (PC) is Franklin Vargas.

The following information Sheet/Consent Form provides details about the survey:

RESEARCH PARTICIPANT CONSENT FORM

ROADWAY WORKZONE SAFETY AND PRODUCTIVITY – DAYTIME VS. NIGHTTIME OPERATIONS - CONTRACTORS' PERSPECTIVE

Dulcy M. Abraham

Lyles School of Civil Engineering

Purdue University

Key Information

Please take time to review this information carefully. This is a research study. Your participation in this study is voluntary which means that you may choose not to participate at any time without penalty or loss of benefits to which you are otherwise entitled. You may ask questions to the researchers about the study whenever you would like. If you decide to take part in the study, you will be asked to sign this form, be sure you understand what you will do and any possible risks or benefits.

Summary of Research

Roadway projects, including asphalt paving and milling, are often staged at nighttime to reduce inconvenience to motorists, give work crew less traffic to protect against, and to meet tighter project deadlines. State Transportation Agencies (STAs) are keen to shorten the closure of roadways for

construction or maintenance/renewal operations, while ensuring the safety of motorists and work crews, and the quality of the constructed/repaired roadway. This survey is intended to gather data related to contractors' perspectives related practices regarding nighttime construction and maintenance operations on roadways. This survey is a key component of the project "Alternative Strategies for Roadway Workzone Safety and Productivity". The project is funded by the Joint Transportation Research Program (JTRP)/INDOT. The data collection for this research project is expected to be completed by June 30, 2021. The research study will conclude in late December 2021

What is the purpose of this study?

This research aims to (1) identify the safety challenges with nighttime operations on roadways, (2) to determine the factors that contribute to worker injuries and crashes during daytime and nighttime work zone operations, and (3) to formulate recommendations of which work zone alternative ensures safety to work crews and roadway users, and under what circumstances.

How will subjects be recruited for the study?

Subjects will be recruited for the study using lists of Contractor/Subcontractors working groups (in different areas of roadway construction and maintenance operations). These lists will be used to to send the invitation to Contractor/Subcontractor personnel and they will be provided by the Indiana Constructors Inc. (ICI). This list is also available on the ICI website.

What will I do if I choose to be in this study?

As a participant, you will have to complete an online survey on our Qualtrics platform. This Information Sheet contains a link to the survey instrument. You will take 15-20 minutes to complete this survey, and it will be available until June 30, 2021.

How long will I be in the study?

The data collection via this survey is expected to be completed no later than June 30, 2021. The results of the project are expected by late December 2021.

What are the possible risks or discomforts?

There is no risk in answering these questions. The data will be stored in an encrypted database. The research team will use Purdue Box, which is a Box cloud storage that provides secure storage for controlled data). Breach of confidentiality is always a risk with data, but we will take precautions to minimize the risk as described in the confidentiality section.

Are there any potential benefits?

There are no direct benefits for the participants. The respondents can obtain the results of the survey and the final report once the study is concluded, and the final report is released by the Joint Transportation Research Program (JTRP) at Purdue University. There is a benefit to the society. The study is expected to provide a better understanding of factors that affect nighttime operation on

roadways and how these challenges can be addressed and mitigated in the work zone through the formulation of safer work zone alternatives for the benefit of workers and motorists.

Are there costs to me for participation?

There are no anticipated costs to participate in this research.

Will information about me and my participation be kept confidential?

This study is funded by the Joint Transportation Research Program (JTRP)/the Indiana Department of Transportation (INDOT). The project's research records may be reviewed by the study sponsor/funding agency (Joint Transportation Research Program (JTRP)/INDOT, US DHHS Office for Human Research Protections, and by departments at Purdue University responsible for regulatory and research oversight.

Confidentiality will be maintained throughout the research study, to the best of the ability of the research team (Franklin Vargas - PC and Professor Dulcy M. Abraham - PI). Both Franklin Vargas and Professor Abraham will have access to the data collected through the survey, and access to the data analysis and results. The data will be reported in aggregate form. The data records in aggregated form will be kept in Purdue Box which is secured electronic storage at Purdue University until December 15, 2022. No identifiable data will be stored.

What are my rights if I take part in this study?

You do not have to participate in this research project. If you agree to participate, you may withdraw your participation at any time without penalty. The participant can stop the survey and leave at any time.

Who can I contact if I have questions about the study?

If you have questions, comments, or concerns about this research project, you can talk to one of the researchers. Please contact Professor Dulcy M. Abraham (dulcy@purdue.edu) or Franklin Vargas (fvargasd@purdue.edu).

To report anonymously via Purdue's Hotline see www.purdue.edu/hotline

If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, please call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu) or write to:
Human Research Protection Program - Purdue University
Ernest C. Young Hall, Room 1032
155 S. Grant St.
West Lafayette, IN 47907-2114

Documentation of Informed Consent

I have had the opportunity to read this information sheet and have the research study explained. I have had the opportunity to ask questions about the research study, and have my questions answered. I am prepared to participate in the research study described above. I will keep a copy of this form.

I Agree ○ I Disagree ○

Demographics

Section A. Construction Work Experience

Please fill in the following information about your work experience in roadway construction/maintenance:

What type of company/organization do you work for?

- ○ General Contractor
- ○ Subcontractor
- ○ Consultant/Designer
- ○ Other (Please specify) _____

What is your job title/position?

- ○ Project Manager
- ○ Project Engineer
- ○ Traffic Control Designer
- ○ Safety Manager
- ○ Safety Engineer
- ○ Superintendent
- ○ Traffic Control Crew
- ○ Road Maintenance/Construction Crew
- ○ Other (Please specify) _____

How many years of experience do you have in roadway nighttime construction/maintenance operations?

- ○ Less than 1 year
- ○ 1 – 5 years
- ○ 5 – 10 years

- ◯ 10 – 20 years
- ◯ 10 – 20 years
- ◯ More than 20 years

What types of projects do you typically work on? (Select all that apply)

- ☐ Construction projects (e.g., paving, milling, earthworks)
- ☐ Bridge/structures
- ☐ Maintenance (e.g., sweeping, striping, patching, surfacing)
- ☐ Repair/Replacement (e.g. guardrail repairs)
- ☐ Other (Please specify) _____

Company Information

Section B. Company Information

Please fill in the following information about your company:

Indicate the size of your company (annual revenue in dollar amount, M=Million)

- ◯ <10 M
- ◯ 10-25 M
- ◯ 25-50 M
- ◯ 50-75 M
- ◯ >75 M

Project Characteristics

Section C. Project Characteristics

Please fill in the following information regarding the roadway project(s)/operation(s) in which you are currently involved:

Where is this project/operation located?

State	
County	
Town	
Roadway number	

What is the name of this project/operation?

At what time of the day, is this project typically performed?

- ◯ Daytime
- ◯ Nighttime
- ◯ Both

how many shifts are there on this project?

	1	2	3
Nighttime	◯	◯	◯

how many shifts are there on this project?

	1	2	3
Both	◯	◯	◯

Please fill in the time frame of the shift (for instance, 8 a.m.- 4 p.m., 9 p.m. – 6 a.m.).

Shift #1

Please fill in the time frame of the shift (for instance, 8 a.m.- 4 p.m., 9 p.m. – 6 a.m.).

Shift #1

Please fill in the time frame of each shift (for instance, 8 a.m.- 4 p.m., 9 p.m. – 6 a.m.).

Shift #1

Shift #2

Please fill in the time frame of each shift (for instance, 8 a.m.- 4 p.m., 9 p.m. – 6 a.m.).

Shift #1

Shift #2

Please fill in the time frame of each shift (for instance, 8 a.m.- 4 p.m., 9 p.m. – 6 a.m.).

Shift #1

Shift #2

Shift #3

Please fill in the time frame of each shift (for instance, 8 a.m.- 4 p.m., 9 p.m. – 6 a.m.).

Shift #1

Shift #2

Shift #3

What type of roadway construction tasks are typically performed on this roadway project at night? (Select all that apply)

- [ ] Earthmoving
- [ ] Milling and removal
- [ ] Paving / Resurfacing
- [ ] Base courses
- [ ] Traffic signal / Highway signing and lighting
- [ ] Painting stripes and markers
- [ ] Bridge deck construction
- [ ] Drainage structures
- [ ] Other (Please specify)

What type of roadway maintenance tasks are typically performed on this roadway project at night? (Select all that apply)

- [ ] Sweeping and cleanup
- [ ] Milling and removal
- [ ] Paving / Surface treatment
- [ ] Traffic signal / Highway signing and lighting
- [ ] Painting stripes and markers
- [ ] Crack filling / Pot filling
- [ ] Bridge deck rehabilitation and maintenance
- [ ] Other (Please specify)

What is the typical duration of the roadway nighttime operations in your project?

- ( ) Single day
- ( ) Week
- ( ) Greater than one month, but less than 3 months
- ( ) 3 months to 6 months
- ( ) Greater than 6 months
- ( ) Depends on the operation (Please specify)

In your opinion, what are the challenges faced on nighttime construction and maintenance operations on roadways, that are not faced during daytime construction and maintenance operations?

Lighting Systems Used in Practice

Section D. Lighting Systems Used in Practice

Does this project require the submission of a nighttime operation and lighting plan before nighttime construction/maintenance activities begin?

- ◯ Yes, it is mandatory
- ◯ No
- ◯ Sometimes (Please explain):

If "Yes", What are the key points that you usually include in your nighttime operation and lighting plan to ensure its conformity to the DoT/Transportation Agency requirements?

- ☐ Work zone layouts of the lighting equipment
- ☐ Type and features of lighting equipment to be used
- ☐ Glare control measures
- ☐ Lighting calculations by task (e.g., illuminance levels)
- ☐ Details of lights to be attached to equipment
- ☐ Other (Please describe):

What type of lighting equipment is typically used in your project(s) during roadway nighttime operations? (Select more than one if necessary)

- [ ] Light towers
- [ ] Balloon lights
- [ ] Nite Lite (portable light)
- [ ] High-Mast Lighting
- [ ] Other (Please specify) _____

What type of light source is used for the lighting equipment selected on the previous question? (Select more than one if necessary)

- [ ] Incandescent Tungsten Halogen (Inc)
- [ ] Mercury Vapor
- [ ] Metal Halide (MH)
- [ ] Low Pressure Sodium (LPS)
- [ ] High Pressure Sodium (HPS)
- [ ] Compact Fluorescent (CFL)
- [ ] Light-emitting diode (LED)
- [ ] Not known
- [ ] Other (Please specify) _____

During nighttime operations, where is the lighting equipment (selected in Section D - Question 3) typically mounted/installed? (Select more than one if necessary)

- [ ] Mounted on vehicle/equipment
- [ ] Not mounted on vehicle/equipment
- [ ] Other (please specify) _____

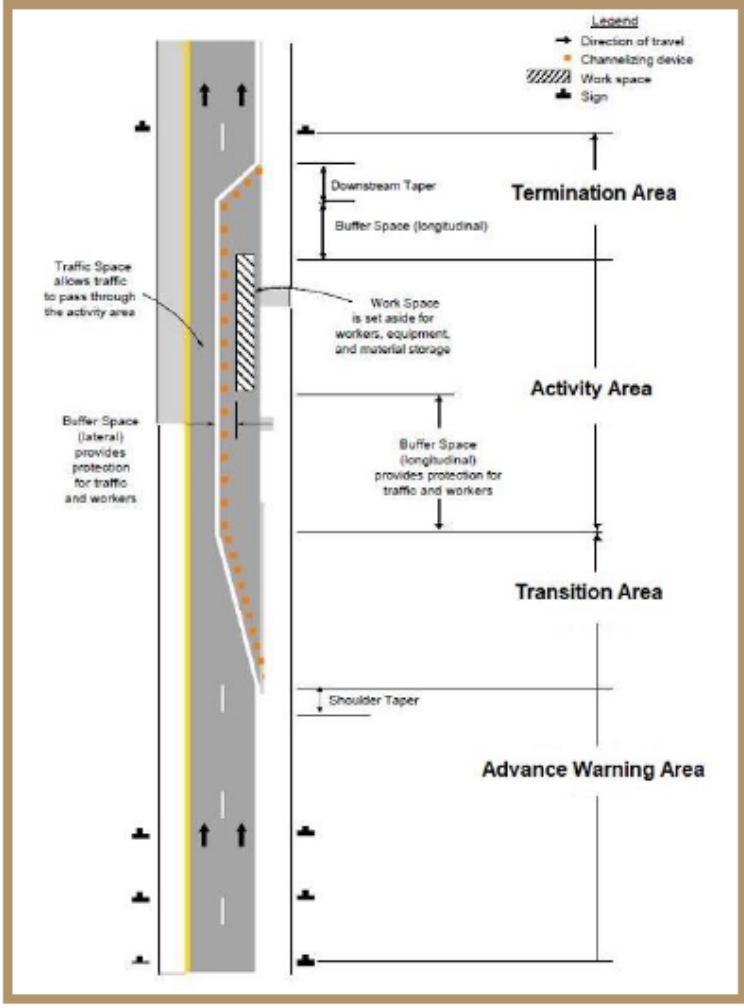
When deciding to select a lighting system on nighttime operations, please rate how each factor is considered in the selection. The scale is 1 to 3.

- **1** - factor has **no influence** on the decision
- **2** - factor has **some influence** on the decision
- **3** - factor has a **strong influence** on the decision

	1	2	3	Not Applicable
Size of lighting system	○	○	○	○
Height to which it can be raised	○	○	○	○
Ability to move/relocate	○	○	○	○
Ease of operation	○	○	○	○
Amount of light output	○	○	○	○
Source of light emitted	○	○	○	○
Lighting system maintenance	○	○	○	○

	1	2	3	Not Applicable
Cost (purchase, rent, or lease)	○	○	○	○
Availability	○	○	○	○
Other (Please Specify)	○	○	○	○
Other (Please Specify)	○	○	○	○
Other (Please Specify)	○	○	○	○

In your experience, where do you think the lighting system (e.g., light towers, balloon lights) should be placed in the work zone to reduce the speed of passing vehicles most effectively in the work zone? (Select more than one if necessary)



- [ ] Termination Area
- [ ] Activity Area
- [ ] Transition Area
- [ ] Advance Warning Area
- [ ] Other (Please specify)

Traffic Control

Section F. Traffic Control

Does this project require the submission of a traffic control plan before nighttime construction/maintenance activities commence?

- ○ Yes, it is mandatory
- ○ No
- ○ Sometimes (Please explain):

If "Yes", What are the key points that you frequently include in the Traffic Control Plan (TTC) to ensure the compliance of to the DoT/Transportation Agency requirements?

- [ ] Number and qualifications of traffic control personnel (including flaggers)
- [ ] Allowable hours/days for lane closures and road closures
- [ ] Work zone and lane closure layouts (Incl. length/area of closure, lateral clearance, and shoulder use)
- [ ] Details and explanations of setups and takedowns of traffic control devices
- [ ] Speed control strategies (law enforcement, CMSs, rumble strips, flashing beacons, lane width reduction, or flagging.)
- [ ] Other (Please describe)

If "Yes", who within your project is responsible for developing the traffic control strategy?

- ◯ Project Manager
- ◯ Project Engineer
- ◯ Superintendent
- ◯ Safety Manager
- ◯ Safety Officer
- ◯ Traffic Control Contractor/Subcontractor
- ◯ Other (Please specify) _____

Cost, Quality, and Productivity

Section F. Cost, Quality, and Productivity

Who decides whether the construction/maintenance operation will be conducted during the day or at night?

- ◯ Decision is made solely by the project owner
- ◯ Decision is made solely by the contractor
- ◯ Decision is made jointly by the project owner and the contractor

If the decision regarding scheduling of roadway project is made solely by the contractor or jointly by project owner and the contractor, please rate how each factor is considered in the selection. The scale is 1 to 3.

- **1** – factor has **no influence** on the decision
- **2** – factor has **some influence** on the decision
- **3** – factor has a **strong influence** on the decision

	1	2	3
Disruption to traffic	◯	◯	◯
Safety of workers	◯	◯	◯
Safety of motorists	◯	◯	◯
Material logistics	◯	◯	◯
Lighting	◯	◯	◯
Ambient temperature	◯	◯	◯
Type of activity	◯	◯	◯
Availability of agency supervision to inspect sites	◯	◯	◯
Cost of the activity	◯	◯	◯

	1	2	3
Other (Please Specify)	○	○	○
Other (Please Specify)	○	○	○
Other (Please Specify)	○	○	○

On average and depending on the type of the road category (low-volume roads, arterial collector road, and interstate and/or high-volume roads), where are your construction and/or maintenance project(s) conducted? (Select more than one if necessary)

	Daytime	Nighttime	Both	No Preference
Low volume roads	☐	☐	☐	☐
Arterial collector roads	☐	☐	☐	☐
Interstate and/or high-volume roads	☐	☐	☐	☐

Which of the following closure methods does your project frequently use for nighttime roadway operations? (Select as many as appropriate)

- ☐ Single lane closure
- ☐ Multiple lane closure
- ☐ Total closure
- ☐ Shoulder closure
- ☐ Lane constriction (Reducing lane width of one or more lanes)
- ☐ Other (Please specify)

Please rate the preference of use of the following closure methods in nighttime roadway operations. The scale is 1 to 3:

- **1 – Least preference** for this closure method
- **2 – Some preference** for this closure method
- **3 – Strong preference** for this closure method

	1	2	3
Single lane closure	○	○	○
Multiple lane closure	○	○	○
Total closure	○	○	○
Shoulder closure	○	○	○
Lane constriction (Reducing lane width of one or more lanes)	○	○	○
Other (Please specify)	○	○	○

Which of the following closure methods are generally used on your nighttime construction/maintenance operations?

	Single lane closure	Multiple lane closure	Total closure	Shoulder closure	Lane constriction	(${q://QID30/Cho
Construction						
Earthmoving	☐	☐	☐	☐	☐	
Milling and removal	☐	☐	☐	☐	☐	
Paving / Resurfacing	☐	☐	☐	☐	☐	
Base courses	☐	☐	☐	☐	☐	
Traffic signal / Highway signing and lighting	☐	☐	☐	☐	☐	
Painting stripes and markers	☐	☐	☐	☐	☐	
Bridge deck construction	☐	☐	☐	☐	☐	
Drainage structures	☐	☐	☐	☐	☐	
Other activity (Please specify)	☐	☐	☐	☐	☐	
Maintenance						
Sweeping and cleanup	☐	☐	☐	☐	☐	
Milling and removal	☐	☐	☐	☐	☐	
Paving / Surface treatment	☐	☐	☐	☐	☐	
Traffic signal / Highway signing and lighting	☐	☐	☐	☐	☐	
Painting stripes and markers	☐	☐	☐	☐	☐	
Crack filling / Pot filling	☐	☐	☐	☐	☐	
Bridge deck rehabilitation and maintenance	☐	☐	☐	☐	☐	
Other activity (Please specify)	☐	☐	☐	☐	☐	

How has the safety of your construction/maintenance operations been affected positively or adversely by the closure method most frequently used compared to traditional daytime operations?

	Higher	Lower	No noted Difference
Worker incident rate	○	○	○
Motorist incident rate	○	○	○

How has the quality of your construction/maintenance operations been affected positively or adversely by the closure method most frequently used compared to traditional daytime operations?

	Better	Lower	No noted Difference
Overall quality of work	○	○	○

APPENDIX B. IRB APPROVAL FOR DEPLOYING ONLINE SURVEY INSTRUMENT FOR ROADWAY CONTRACTORS

IRB-2021-924 - Initial: 1. COVID-19 EXEMPTION MEMO

do-not-reply@cayuse.com <do-not-reply@cayuse.com>
Fri 6/11/2021 4:43 PM
To: Abraham, Dulcy M <dulcy@purdue.edu>; Fricker, Jon D <fricker@purdue.edu>; Vargas Davila, Franklin <fvargasd@purdue.edu>

PURDUE
UNIVERSITY

This Memo is Generated From the Purdue University Human Research Protection Program System, Cayuse IRB.

Date: June 11, 2021
PI: DULCY ABRAHAM
Re: Initial - IRB-2021-924
ROADWAY WORKZONE SAFETY AND PRODUCTIVITY – DAYTIME VS. NIGHTTIME OPERATIONS - CONTRACTORS' PERSPECTIVE

The Purdue University Human Research Protection Program (HRPP) has determined that the research project identified above qualifies as exempt from IRB review, under federal human subjects research regulations 45 CFR 46.104. The Category for this Exemption is listed below . Protocols exempted by the Purdue HRPP do not require regular renewal. However, the administrative check-in date is June 10, 2024. The IRB must be notified when this study is closed. If a study closure request has not been initiated by this date, the HRPP will request study status update for the record.

Specific notes related to your study are found below.
Decision: Exempt
Category:
Category 2.(i). Research that only includes interactions involving educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior (including visual or auditory recording).
The information obtained is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects.

Research Notes:

Any modifications to the approved study must be submitted for review through Cayuse IRB. All approval letters and study documents are located within the Study Details in Cayuse IRB.

What are your responsibilities now, as you move forward with your research?

Document Retention: The PI is responsible for keeping all regulated documents, including IRB correspondence such as this letter, approved study documents, and signed consent forms for at least three (3) years following protocol closure for audit purposes. Documents regulated by HIPAA, such as Release Authorizations, must be maintained for six (6) years.

Site Permission: If your research is conducted at locations outside of Purdue University (such as schools, hospitals, or businesses), you must obtain written permission from all sites to recruit, consent, study, or observe participants. Generally, such permission comes in the form of a letter from the school superintendent, director, or manager. You must maintain a copy of this permission with study records.

Training: All researchers collecting or analyzing data from this study must renew training in human subjects research via the CITI Program (www.citiprogram.org) every 4 years. New personnel must complete training and be added to the protocol before beginning research with human participants or their data.

Modifications: Change to any aspect of this protocol or research personnel must be approved by the IRB before implementation, except when necessary to eliminate apparent immediate hazards to subjects or others. In such situations, the IRB should still be notified immediately.

Unanticipated Problems/Adverse Events: Unanticipated problems involving risks to subjects or others, serious adverse events,

and
noncompliance with the approved protocol must be reported to the IRB immediately through an incident report. When in doubt, consult with the HRPP/IRB.

Monitoring: The HRPP reminds researchers that this study is subject to monitoring at any time by Purdue's HRPP staff, Institutional Review Board, Post Approval Monitoring team, or authorized external entities. Timely cooperation with monitoring procedures is an expectation of IRB approval.

Change of Institutions: If the PI leaves Purdue, the study must be closed or the PI must be replaced on the study or transferred to a new IRB. Studies without a Purdue University PI will be closed.

Other Approvals: This Purdue IRB approval covers only regulations related to human subjects research protections (e.g. 45 CFR 46). This determination does not constitute approval from any other Purdue campus departments, research sites, or outside agencies. The Principal Investigator and all researchers are required to affirm that the research meets all applicable local/state/ federal laws and university policies that may apply.

THIS DOCUMENT SERVES AS PROTOCOL APPROVAL FROM THE HRPP/IRB, BUT DOES NOT PERMIT FACE TO FACE RESEARCH UNTIL AN APPROVED UNIVERSITY COVID-19 RESEARCH SPACE SOP PERMITS RESEARCH OPERATIONS.

If you have questions about this determination or your responsibilities when conducting human subjects research on this project or any other, please do not hesitate to contact Purdue's HRPP at irb@purdue.edu or 765-494-5942. We are here to help!

Sincerely,

Purdue University Human Research Protection Program/ Institutional Review Board
Login to Cayuse IRB

See Purdue HRPP/IRB Measures in Response to COVID-19 https://www.irb.purdue.edu/docs/IRB%20Covid-19%20Recommendations.pdf