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Workzone Lighting and Glare on Nighttime Construction and Maintenance Activities

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16. 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 alleviate traffic congestion delays. Working at night entails several advantages, including lower traffic volumes, less impact on local businesses, cooler temperatures for equipment and material, and fewer overall crashes. Although nighttime roadway operations may minimize traffic disruptions, there are several safety concerns about passing motorists and workers in the nighttime work zone. For instance, improper lighting arrangements or excessive lighting levels at the job site could cause harmful levels of glare for the traveling public and workers, which can lead to an increased level of hazards and crashes in the vicinity of the work zone.

To address the issue of glare, this report focuses on determining and evaluating disability glare on nighttime work zones in order to develop appropriate strategies for improving the safety of workers and motorists. 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 (VL ratio). In this study, disability glare values were determined by using lighting data (vertical illuminance and pavement luminance measurements) from the testing of 49 lighting arrangements. The glare assessment analyzed the effects of the lighting system setup's parameters, such as the 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 study revealed the following key findings: (1) an increase in mounting heights of both balloon lights and light towers resulted in lower disability glare levels; (2) compared to the "perpendicular" and "away" orientations, orienting the light towers "towards" the traffic (45 degrees) significantly increases the disability glare levels of the lighting arrangement; and (3) increasing the tilt angles of portable light tower luminaries resulted in an increase in disability glare levels.

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EXECUTIVE SUMMARY

Introduction

Roadway projects, including asphalt paving and milling, are often staged at night to reduce inconvenience to road users, give work crews less traffic to protect against, and help crews meet tighter project deadlines. However, there are safety challenges with nighttime operations. Examples of such challenges include adequate lighting to ensure the safety of workers and motorists and appropriate lighting for work activities. In addition, it is harder to see and be seen at night.

This study describes the results from the qualitative analysis of work zone incidents in maintenance projects recorded by INDOT between 2016 and 2020. The incidents include safety events that involved INDOT's employees, vehicles, and pieces of equipment that resulted in motor vehicle crashes, road-worker injuries, incidents, and near misses. Through on-site experiments, the report also discusses the determination and evaluation of disability glare on nighttime work zones and provides lighting-related guidelines to reduce disability glare and therefore improve the safety of workers and motorists during nighttime highway construction and maintenance projects.

Findings

This study analyzed work zone incidents during daytime and nighttime roadway operations on INDOT maintenance projects during a 2016–2020 time frame. Analysis of data from these projects indicated that most INDOT worker injuries and motor vehicle crashes occurred during daytime hours. A lower percentage of crashes occurred during nighttime shifts that could have been in darkness depending on the time of year. During night time shifts there were typically fewer vehicles on the roadways compared to daytime traffic volumes and therefore lower exposures of workers to motorists. Most worker injuries resulted from worker strains and sprains, which was followed by workers getting struck by vehicles or equipment or falling, slipping, or tripping at the work zone. Most of the motor vehicle crashes were linked to privately owned vehicles (POV) striking INDOT vehicles or equipment. The next most common vehicle crashes were single INDOT vehicles or equipment involved in a damage incident without other vehicles or equipment being involved, and INDOT vehicles or equipment striking other INDOT vehicles or equipment, building, fence, or other INDOT-owned structures. Most of these POV-struck INDOT crash types involved intrusion of POV drivers into the work zone, resulting in a rear-ended collision with a trailer-mounted attenuator (TMA).

The study provides practical recommendations to INDOT and roadway contractors in Indiana about optimal lighting arrangements. Findings from the on-site experiments indicated that an increase in the mounting heights of both balloon lights and light towers (LED and metal-halide) resulted in significant reduction of veiling illuminance ratio values, which represent disability glare levels. Compared to "perpendicular" and "away" orientations, orienting the light towers in a "towards" direction (45 degrees) significantly increases the disability glare levels of the lighting arrangement. Increasing the tilt angles of luminaires of the LED light tower also resulted in an increase in veiling luminance ratio values. The observer's age factor "k" plays an important role in determining the veiling luminance. As the factor k increases, the veiling luminance (and hence, disability glare value) also increases.

Implementation

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 greater than 18 ft. (5.5 m) and up to the full extension of the light mast (typically 30 ft. or 9.1 m) to minimize disability glare levels. Selecting proper mounting height for balloon lights can also help prevent higher disability glare levels, but most importantly, choosing the equipment's power output is critical.

Aiming light towers in the direction of the traffic movement should be avoided whenever possible. However, if this condition is not met, the light tower must be fully extended with the luminaires aimed at least 45 degrees from the horizontal.

LED light towers would be preferred over metal-halide light towers in the "towards" and "perpendicular" orientations due to the lower values of veiling luminance ratio values they generate in each orientation.

Luminaires of 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 60 degrees. For metal-halide light towers, an angle of luminaires less or equal to 45 degrees is recommended 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 to minimize glare.

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1. INTRODUCTION

Between 2018 and 2019, fatalities in work zones increased by 11% and the number of work zone fatalities occurring at night increased by nearly 9% (FHWA, 2022). These statistics indicate that work zone safety at night is a growing concern for motorists and workers in nighttime work zones, leading State Transportation Agencies (STAs) to seek ways to improve work zone lighting, work zone traffic control strategies, and work zone safety for motorists and workers alike.

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 (1) the identification of the safety issues of nighttime operations on roadways and determination of the factors that contribute to worker injuries and crashes during daytime and nighttime work zone operations; and (2) the formulation of recommendations to ensure the safety of work crews and roadway users, with a focus on lighting arrangements that eliminate or reduce glare.

This report describes the results of qualitative analysis of workzone incidents on maintenance work zones recorded by INDOT between 2016 and 2020. The data includes safety events that involved INDOT's employees, vehicles, and pieces of equipment and that resulted in motor vehicle crashes, road-worker injuries, incidents, and near misses. The analysis of this data provides insights about safety concerns in maintenance work zones through the identification of the most common safety events, the major cause(s) of these events, the time of day when these events occurred (daytime or nighttime hours), and the type of activity at which these safety events occurred. However, analysis of work zone *safety data from roadway contractors* and *productivity rates of major roadway construction/maintenance activities* is needed to establish safety and productivity differences between of nighttime vs. daytime construction on roadways.

The report also discusses the determination and evaluation of disability glare on nighttime work zones in order to improve 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 (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. The study provides a detailed disability glare determination procedure, a set of recommended veiling luminance ratio (or disability glare) values that ensure acceptable glare levels on nighttime work zones, a set of recommendations of regarding the type of lighting systems should be used, heights at which they should be mounted, the orientation and aiming angles to minimize disability glare experienced by drive-by motorists when passing through work zones. These recommendations could be adopted by INDOT in potential future work zone lighting policies.

2. STUDY OBJECTIVES

The first objective of this study is the analysis of work zone incidents in maintenance projects recorded by INDOT between 2016 and 2020, to determine possible causes of safety incidents involving INDOT's employees, vehicles, and pieces of equipment and resulting in motor vehicle crashes road-worker injuries, incidents, and near misses. The second objective aims to provide practical recommendations to INDOT and roadway contractors in Indiana regarding optimal lighting arrangements that alleviate, and control disability glare levels experienced by passing motorists by and workers on nighttime roadway work zones.

3. RESEARCH METHODOLOGY

The research methodology consisted of five steps. The first step was the literature review, which identified the advantages and challenges of nighttime highway operations, factors that affect nighttime operations, work zone lighting, and strategies for minimizing glare in work zones. 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 contractors' safety officers, and conducting field lighting experiments. The last step in the methodology was the analysis of the data collected to (1) determine the safety concerns and factors that affect nighttime operations on INDOT's roadway maintenance projects and (2) propose practical recommendations about optimal lighting arrangements to control harmful glare levels in work zones. Figure 3.1 shows the sequence of the research process and the research tools used in each step of the process.

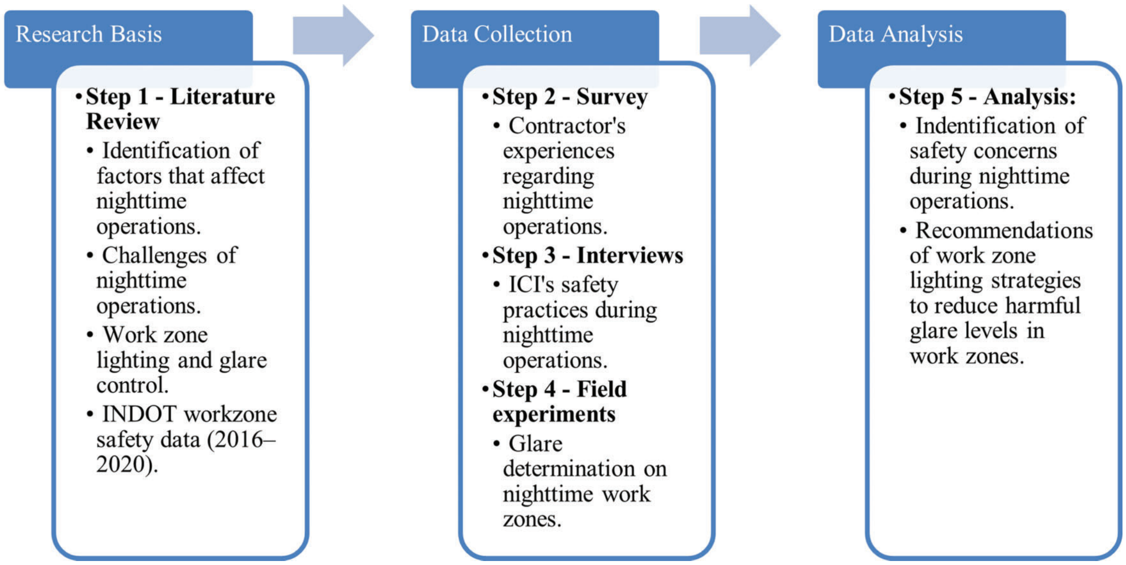


Figure 3.1 Research methodology.

4. LITERATURE REVIEW

The research team built on the findings of a preliminary state-of-the-art review conducted for this proposal to document prior research studies regarding common factors influencing nighttime operations and to describe current standard practices and developments employed by roadway contractors related to safety and productivity in nighttime construction work zones, particularly those related to work zone lighting and glare control in nighttime highway construction and maintenance projects.

4.1 Nighttime Highway Work Zones

The frequency of nighttime construction and maintenance operations in the United States has increased 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 have inherent advantages such as minimizing traffic disruptions, 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, there are several safety, operational, and socio-economic concerns in nighttime roadway operations, as shown in Table 4.1. For instance, limited visibility, higher worker/traffic accident rates, construction nuisances, possibly quality issues, and light pollution, are associated with nighttime operations (Al-Kaisy & Nassar, 2005; Cottrell, 1999; Ellis & Kumar, 1993; Elrahman, 2008; Elrahman & Perry, 1998).

The inherent safety, operational, and socio-economic factors present at nighttime operations may improve or reduce motorists and workers safety, productivity of the tasks being performed, and the quality of roadway products delivered. Table 4.2 shows the potential impacts (positive or negative) that these factors may have on the project's metrics. For instance, work zone lighting that was deemed as one of the major critical factors that affects nighttime construction and maintenance projects affects nearly every aspect of nighttime work (Hinze & Carlisle, 1990). The absence of natural lighting on the work zone reduces the visibility and awareness of work crews and it can have a direct impact on the safety of work crews and motorists (Mostafavi et al., 2012) and it also affects the quality of constructed product, productivity of work crews, and worker morale (Bryden & Mace, 2002a). Lighting as a controllable factor, if provided sufficiently and adequately at the jobsite, it may help to reduce unsafe working conditions to workers and construction quality issues (Abraham et al., 2007). This enhancement of work zone safety, quality, and productivity may be achieved throughout careful design of work zone lighting which implies selecting appropriate lighting systems for activities occurring on or near the roadway, providing enough illuminance levels to perform the operations, and minimizing glare for both workers and motorists (Hancher & Taylor, 2001).

4.2 Identifying Safety Issues Linked to Nighttime Operations on Roadways

To identify the safety issues linked to nighttime operations on roadways, the research team conducted the following three tasks: (1) analyzed work zone safety data (2016 to 2020) that was provided by INDOT; (2) collected data regarding nighttime operations throughout the development and deployment of survey to roadway contractors in Indiana; and (3) conducted formal interviews with Safety Officers from companies

TABLE 4.1
Advantages and Disadvantages of Nighttime Highway Work Zones

	Advantages	Disadvantages
	Traffic-Related Factors	
Congestion	There is significant decrease in traffic congestion and work-related delays and stops (Hancher & Taylor, 2001). Roadway operations scheduled at night reduces or avoids the negative effects of work zones traffic congestion and traveling public delays (Al-Kaisy & Nassar, 2005; Elrahman, 2008).	
Safety	Lower levels of traffic demand tend to keep work zone crash rates low (Elrahman, 2008; Park et al., 2002). Workers are more aware of hazards at night, they are more conscious of safety procedures and practices (Elrahman, 2008).	Poor visibility, inadequate lighting, worker fatigue, and impaired drivers increased accident risks at nighttime work zones (Rebholz et al., 2004). Inherent work zone restrictions such as the delimited area, distraction or lack of visibility of drivers due to ongoing operations, and lack of familiarity with traffic control along the work zone, increase the rates of traffic accidents (Rebholz et al., 2004). Less traffic at night encourages motorists to speed that results 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, 2008; Elrahman & Perry, 1998).
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, 2008; Elrahman & Perry, 1998; Rebholz et al., 2004).	The need for improved traffic control strategies at work zones may add additional project' cost and time (Elrahman, 2008; Rebholz et al., 2004) Placing and removing traffic control devices and lighting systems are difficult, and if they cannot be removed by the end of the night shifts, opening lanes for traffic may be become dangerous to motorists (Elrahman, 2008).
	Construction-Related Factors	
Quality	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 as a result of the cooler nighttime temperatures (Shepard & Cottrell, 1986).	
Productivity	Reduced traffic interference and longer work shifts affect nighttime construction productivity and efficiency (Elrahman, 2008; Hancher & Taylor, 2001). 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 will be difficult during nighttime operations (Elrahman, 2008; Hancher & Taylor, 2001).
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	Possibility of having both daytime and nighttime shifts may reduce project duration (Elrahman, 2008).	Scheduling field and office personnel may be more challenging at night. State and local policies may restrict nighttime operations as well as by unions and material suppliers (Elrahman, 2008; Hancher & Taylor, 2001).

(Continued)

TABLE 4.1
(Continued)

Traffic-Related Factors		
	Advantages	**Disadvantages**
	Economic Factors	
Business Cost	Businesses located 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 disruption of traffic (Holguín-Veras et al., 2003).	
Construction Cost	The selection of the most appropriate work zone type results in reduced traffic interference and increased 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	
Driver Condition		Concerns over driver fatigue, impaired drivers, and drivers unfamiliar with the work zone layout increase at night (Higa & Kim, 2013).
Worker Health	Health of workers can 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 as a result of 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). Worker's quality of life may be affected of 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 the identification and resolution of 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 works can cause noise, vibration, light and other disturbances to neighboring communities (Schexnayder, 2011).

TABLE 4.2
Potential Impacts of Factors Affecting Nighttime Operations

	Impact on Safety		**Impact on Productivity**		**Impact on Quality**	
Factors	↑	↓	↑	↓	↑	↓
Limited Visibility		×		×		×
Lower Traffic Congestion	×		×		×	
Presence of Impaired Drivers		×				
Construction Nuisances		×				
Lower Temperatures			×			×
Reflective Garments	×					
Presence of Traffic Control Devices	×		×			
Full Availability of Equipment During Nighttime Shifts			×		×	
Presence of Law Enforcement (if available)	×					
Worker Visual, Physical, and Mental Fatigue		×		×		×
Easier Material Delivery and Reduction of Travel Times			×		×	

↑ = improves safety, productivity, or quality.
↓ = reduces safety, productivity, or quality.

linked with the Indiana Constructors Inc. (ICI), to extract information regarding challenges faced in nighttime operations.

4.2.1 *Analysis of INDOT Workzone Safety Data*

The work zone safety data analyzed in this project is linked to incidents that involved employees, vehicles, or equipment on INDOT maintenance projects during a 5-year period (2016–2020). The research team did not have access to work zone safety data from roadway contractors during the same period. Thus, the scope of work zone incident analysis was limited to incidents on INDOT maintenance projects. The analysis of the data indicated, as shown in Figure 4.1, that 810 safety events occurred during a 5-year period (2016 to 2020). Most of these events (78%) occurred during daytime hours and 22% of them at night which, depending on the time of year, may have been in darkness. (Note: daytime hours were defined to begin at 6 am to 9 pm and night shifts from 9 pm to 6 am). In 2016, 132 safety events were reported. During the following years (2017 to 2019), the number of safety incidents remained constant (around 159 per year), but in 2020 this number increased by 26%.

Of the 810 work zone safety events during the 2016–2020 timeframe, 503 events corresponded to crashes, including those that did not result in an injury or in one or more injuries, 45 incidents where the employees did not seek professional medical attention, as shown in Figure 4.2. There were 240 safety events that involved injury without being involving a crash, and a total of 22 near misses which involved occurrences that "almost" resulted in an injury, crash, or both.

4.2.1.1 Worker injuries in work zones. The 5-year period of work zone safety data provided by INDOT recorded safety events that involved injury or illness of INDOT employees in workzone incidents. A total of 240 worker injuries occurred in work zones between 2016 and 2020. Of those occurrences, most INDOT employee's injuries (80%) occurred between 6 am to 9 pm and another 20% occurred between 9 pm to 6 am, hours that could have been in darkness depending on the time of year.

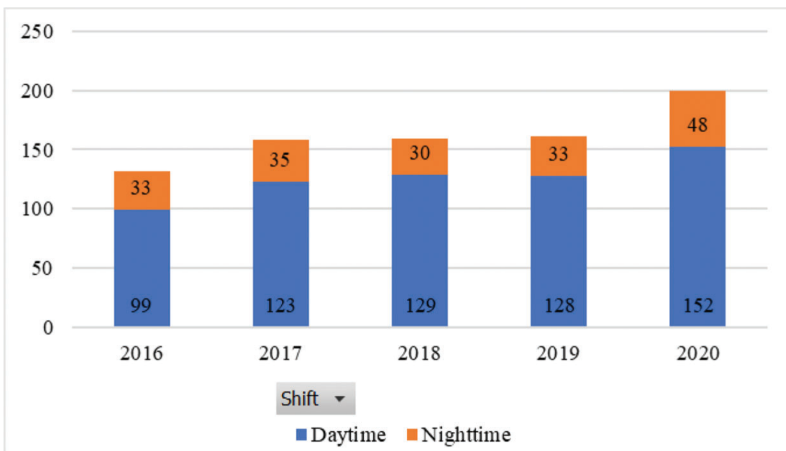


Figure 4.1 INDOT's work zone safety events per shift from 2016 to 2020.

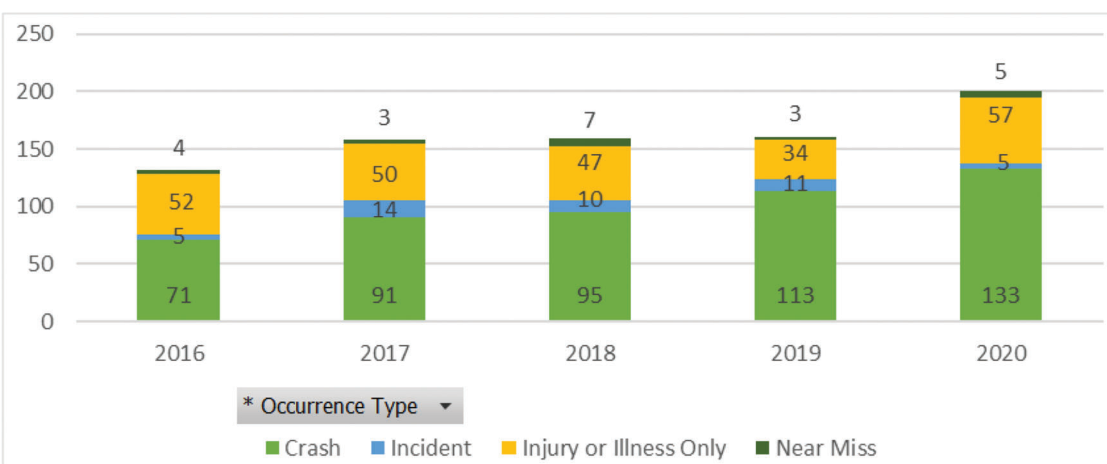


Figure 4.2 INDOT's work zone safety events per type of safety event from 2016 to 2020.

As shown in Figure 4.3, the most common type of injury found in work zones (29%) were found to be strains and sprains. These resulted from lifting, shoveling, pulling brush or small trees, and the use of heavy manual tools. A similar proportion of injuries were found when workers were hit by a vehicle or equipment (21%); 19% resulted from falling, slipping, or tripping. Typically, these injuries occurred when workers performed inspections of drainage structures, entering or exiting crew vehicles or equipment, buildings, or even while walking on the jobsite.

Worker injuries resulting from getting caught between material or machine (or pinch point hazards) is another common type of injury (8%). These events resulted from workers performing activities such as asphalt paving, operating tools (e.g., dynamic cone penetrometer), extracting cores from the pavement, opening lids of equipment, and during the traffic control set up. A similar percentage of injuries (8%) occurred due to exposure of workers to poisonous vegetation while performing maintenance activities such as manual and mechanical brush cutting, tree trimming and removal, spot mowing, and while placing a fence on the right-of-way.

About 15% of the injuries were related to burns, debris in eyes, insect bites, lacerations, and punctures.

Most of the worker injuries occurred during daytime hours resulted from strain/sprain (54), slip/fall/trip (40), and struck by vehicle or piece of equipment (36). 35 out of 193 injuries were classified as pinch point and vegetation exposure. At night, the number of injuries resulted from strain/sprain, struck by a vehicle or piece of equipment, and slip/trip/fall were significant lower (34) compared to those registered during the day.

4.2.1.2 Motor vehicle crashes in work zones. The 4-year period of work zone safety data provided by INDOT recorded 503 motor vehicle crashes that occurred in work zones between 2016 and 2020. Of those crashes, 379 occurred between 6 am to 9 pm and another 124 occurred between 9 pm to 6 am, hours that could have been in darkness depending on the time of year. These crashes were classified as follows: (1) animal strike (or wildlife-vehicle collisions); (2) INDOT vehicles or equipment striking other INDOT vehicles or equipment, building, fence, or other INDOT owned structure; (3) INDOT vehicles or equipment that struck a privately owned vehicle (or property); (4) miscellaneous equipment damage that was listed as being from an unknown source, or not related to a vehicle crash such as falling tree limbs or road debris; (5) privately owned vehicle striking an INDOT vehicle or equipment; and (6) INDOT single vehicle or equipment involved in a damage incident without other vehicles or equipment involved (due to weather-related road conditions, poor embankment support for equipment, or simple driver distraction).

In 2016, a total of 71 crashes that involved INDOT vehicles and equipment were reported. This number is lower compared to the 130 crashes reported in 2020 as shown in Figure 4.4. Of the 71 crashes reported in 2016, 24 crashes (34%) occurred at night. Similarly, in 2020, 30 crashes (23%) occurred during nighttime hours.

Most of the crashes resulted from a privately owned vehicle (POV) striking an INDOT vehicle or equipment, in the years 2016 and 2020. Of the 44 POV struck INDOT crashes reported in 2016, 80% (35 crashes) resulted from an intrusion of drive-by motorists into the work zone area. A similar number of crashes (40 crashes or 67%) were reported in 2020. Also, 25 of the 35 crashes resulted from an intrusion of drive-by motorists into the work zone area in 2016, directly involved a rear-ended collision of the POV with a trailer-mounted attenuator (TMA). The same number of crashes (25 crashes) that involved a INDOT's TMA were found in 2020.

During daytime hours, most of the crashes were caused by POV drivers distracted or not paying attention to their surroundings (84 of 249 crashes), especially to traffic control signs placed at the work zones.

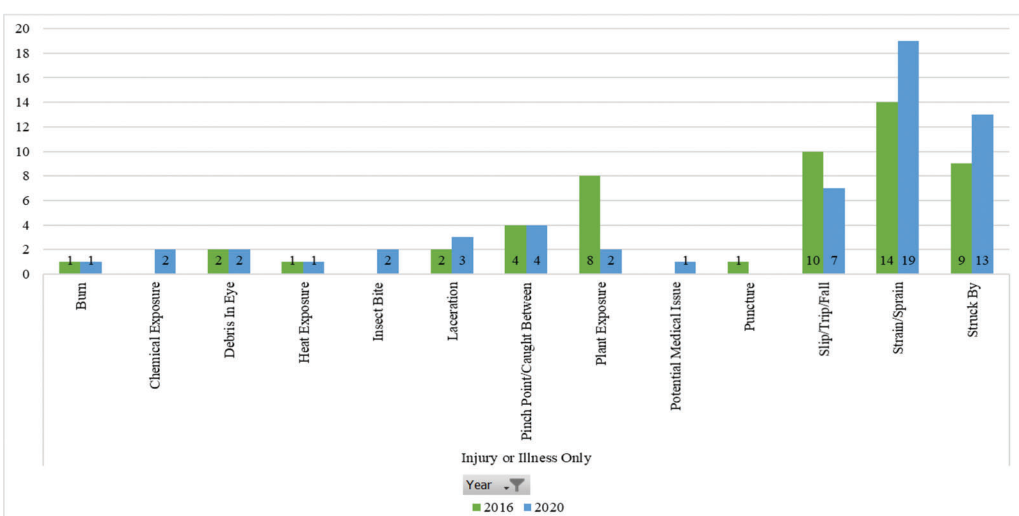


Figure 4.3 INDOT's work zone safety events per type of injury for 2016 and 2020.

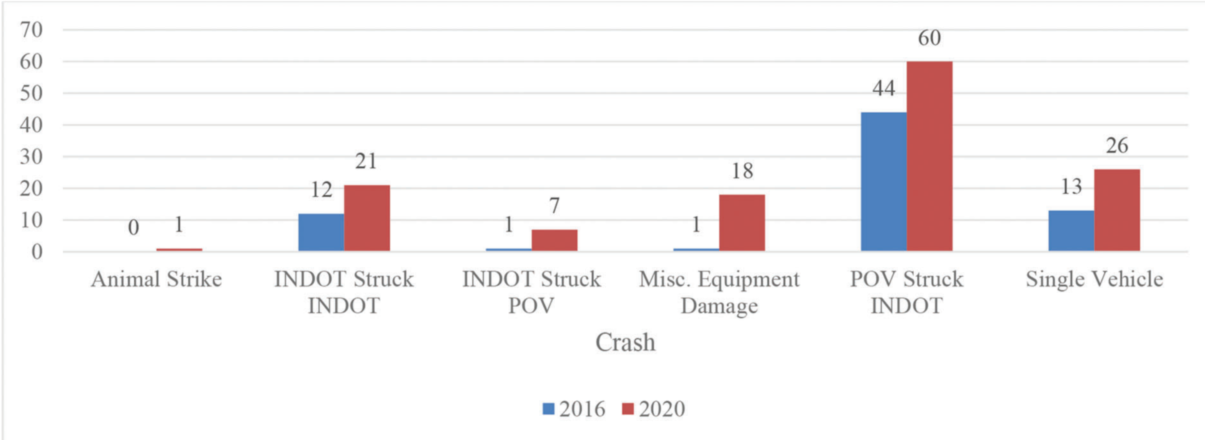


Figure 4.4 INDOT's work zone safety events per type of crash for 2016 and 2020.

The second major cause were found to be motorists driving recklessly, speeding up, and performing abrupt maneuvers (75 out of 249 crashes). Other motor vehicle crashes were due when POV drivers failed to maintain proper clearance (i.e., following/passing too closely) to vehicles or equipment in the proximity of the work zone (13) and presence of POV impaired drivers (6). Similarly, crashes occurred at night were caused by POV drivers distracted or not paying attention to their surroundings (25 of 249 crashes). A total of 14 out of 249 crashes were caused by impaired drivers and twelve resulted from reckless driving.

The analysis of work zone safety incidents (2016–2020) provided the following key insights regarding inherent hazards at work zones and how these hazards led to worker injuries and motor vehicle crashes.

1. Most of the worker injuries and motor vehicle crashes occurred during daytime hours. A lower percentage of worker injuries and motor vehicle crashes (involving INDOT's human and physical assets) occurred during nighttime shifts that could have been in darkness depending on the time of year, and when there are fewer vehicles on the roadways, compared to daytime traffic volumes and hence, lower exposures of workers to motorists.
2. The majority of worker injuries resulted from strains and sprains resulting from lifting, shoveling, pulling brush or small trees, and the use of heavy manual tools, followed by workers getting struck by vehicles or equipment and workers falling, slipping, or tripping at the work zone. The main causes that produce these workers injuries were determined to be (1) failing to maintain awareness of their surroundings; (2) failing to follow the proper procedures for the tasks being performed; (3) failing to identify properly the workplace hazards and hazard warnings; (4) failing to use adequate equipment or tools for the task being done; and (5) failing to wear proper personal protective equipment for the task being performed.
3. Most of the motor vehicle crashes corresponded to POV striking INDOT's vehicles or piece of equipment, followed by INDOT single vehicle or equipment involved in a damage incident without the involvement of other vehicles or equipment and INDOT vehicles or equipment striking other INDOT vehicles or equipment, building, fence, or other INDOT owned structure. The main causes of POV-struck INDOT crash type were due to POV drivers being distracted or not paying attention to their surroundings, driving recklessly, speeding up, or performing abrupt maneuvers, failing to maintain proper clearance (i.e., following/passing too closely) to vehicles or equipment in the proximity of the work zone, and driving a vehicle while impaired.
4. Most of these POV-struck INDOT crash-type involved intrusion of POV drivers into the work zone, resulting to a greater extent in a rear-ended collision with a trailer-mounted attenuator (TMA).

Despite of the number of safety events that resulted in greater number during daytime hours compared to nighttime hours, in both worker injuries and motor vehicle crashes, performing work at night may aggravate those numbers due to the reduced illumination. Enhancing visibility in work zones has the capacity to lower work-related injuries and vehicle accidents at night. Improved visibility could aid motorists in spotting workers in and around work zones, while also assisting workers in spotting other workers and identifying work zone hazards.

4.2.2 Work Zone Data Limitations

Additional information and data are needed to establish safety, productivity and quality differences between daytime and nighttime operations on roadways. Hence, the following types of data would be needed to explore these differences.

1. Work zone safety incidents/accidents that involve *roadway contractor's personnel/workers* on roadway construction/maintenance projects. The safety data should include the description of the event, time and day when the event occurred, potential or primary cause, type of

activity performed, type of work zone, recommended actions to improve safety in the work zone.

2. Work zone vehicle intrusions and crashes occurred within or near the work zone limits. The crash data come primarily from police crash report forms, and it includes items such as the time of crash occurrence (day or night), work zone type at the time of the crash (lane closure, shoulder closure, median crossover, full road or bridge closure, and others), crash severity, type of crash (rear-end, vehicle intrusion, sideswipe, etc.), contributing factors to the crash (driver inattention, impaired drivers, poor driver judgement, and others). This data may help to correlate where crashes are occurring if compared with the state police crash reports.
3. Work zone crash data collected by the State Transportation Agency (STA) or entered on STA records. If crash data is collected during the construction, this data should contain when the work zone was set up (activities' start and finish dates and durations), location of the work zone, periods when the work zone was active or inactive (worker presence), type of activity is being performed, and the type of work zone (lane closure, shoulder closure, median crossover, full road or bridge closure, and others).
4. Data regarding productivity of major roadway construction activities performed during daytime and nighttime hours (for instance, hot mix asphalt placement, resurfacing, milling, and full-depth reclamation) The data should include the project name, duration, type of activity, time and day at which the activity was performed, daily/hourly production rates, major constraints during the activities.
5. Data regarding quality of road-related products. The data should contain the nonconformance events (defects) during the construction and maintenance activities, specifications of materials used, time and day at which the activity was performed, location, and weather conditions.

4.2.3 Contractors' Perspectives Regarding Nighttime Roadways Operations

A questionnaire was designed to gather data related to roadway contractors' perspectives regarding their experiences on nighttime operations. This 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 to gain information about the contractor's experiences performing nighttime operations. The second section addressed lighting systems, while the third section addressed traffic control strategies or devices used in roadway construction operations. The contractor's perceptions on costs of nighttime work, productivity of work crews, and quality of the constructed/repaired roadway were included in the final section of part of the questionnaire.

Before the deployment of 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 minimal risk, the subjects' participation on 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) and it was available online until July 31, 2021. (Note: ICI is an organization that groups companies dedicated to highway, heavy and utility construction industry in Indiana.)

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% of the respondents have over 10 years of experience in performing nighttime roadway nighttime operations and participating on 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 less degree on repair/replacement projects.

4.2.3.1 Lighting systems used on nighttime operations. Only one respondent indicated that preparation of a nighttime operation and lighting plan is mandatory for all nighttime roadway construction operations; 44.4% of respondents stated that the INDOT does not require them to submit a lighting plan prior to begin their operations at night, and 50% of respondents indicated that the INDOT sometimes requires them to submit such plan. The requirement for a traffic control plan typically depends on the project contract and the special provisions stated in the contract. The respondents also reported that the lighting subcontractor typically prepares a lighting plan to be sent later to the prime contractor and INDOT. 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.

Survey respondents also indicated that light towers and balloon lights are among the most common lighting equipment used in their projects (56%). Other lighting systems used by respondents on-site include work lights on trucks and illuminated hard hats for each worker on the ground (e.g., halo lights). A significant majority (82%) of these lighting systems are mounted on vehicles or construction equipment such as pavers.

Light-emitting diode (LED) is the most common source of light (67%), followed by incandescent tungsten halogen (28%), and metal halide (22%). Interestingly, some respondents did not identify the light source of their lighting equipment. Respondents considered the amount of light output of the lighting systems, ease of operation, and ability to move or relocate among the top three factors when selecting lighting equipment. These features are also followed by the source of light emitted, maintenance, and cost of the lighting.

The survey asked participants about the placement of lighting equipment in work zone placed on a roadway and their perceptions on the role of light positions in reducing motorists' speed as they pass through work zones. As shown in Figure 4.5, most of the respondents placed their lighting equipment in the activity area and transition area (89%). A few placed lighting systems in the advance warning area in the termination areas as well. About 17% of respondents indicated that lighting systems do not influence the speed reduction of the motorists.

4.2.3.2 Traffic control plans for nighttime operations. Five of the eighteen respondents indicated that the submission of a traffic control plan is mandatory before any roadway nighttime operation begins. Interestingly, a third of the participants stated that submission of a traffic control plan is not required before starting a roadway nighttime operation. Seven respondents indicated that a traffic control plan is sometimes required before any nighttime operation begins and its submission depends on (1) the type of project; (2) when a lane is required to be taken to perform works; and (3) when daytime operations are moved into nighttime. Some respondents indicated that the requirement and submission for a traffic control plan is mandatory while others indicated that it was not mandatory. The difference in responses may be attributed to the fact that the requirement for a

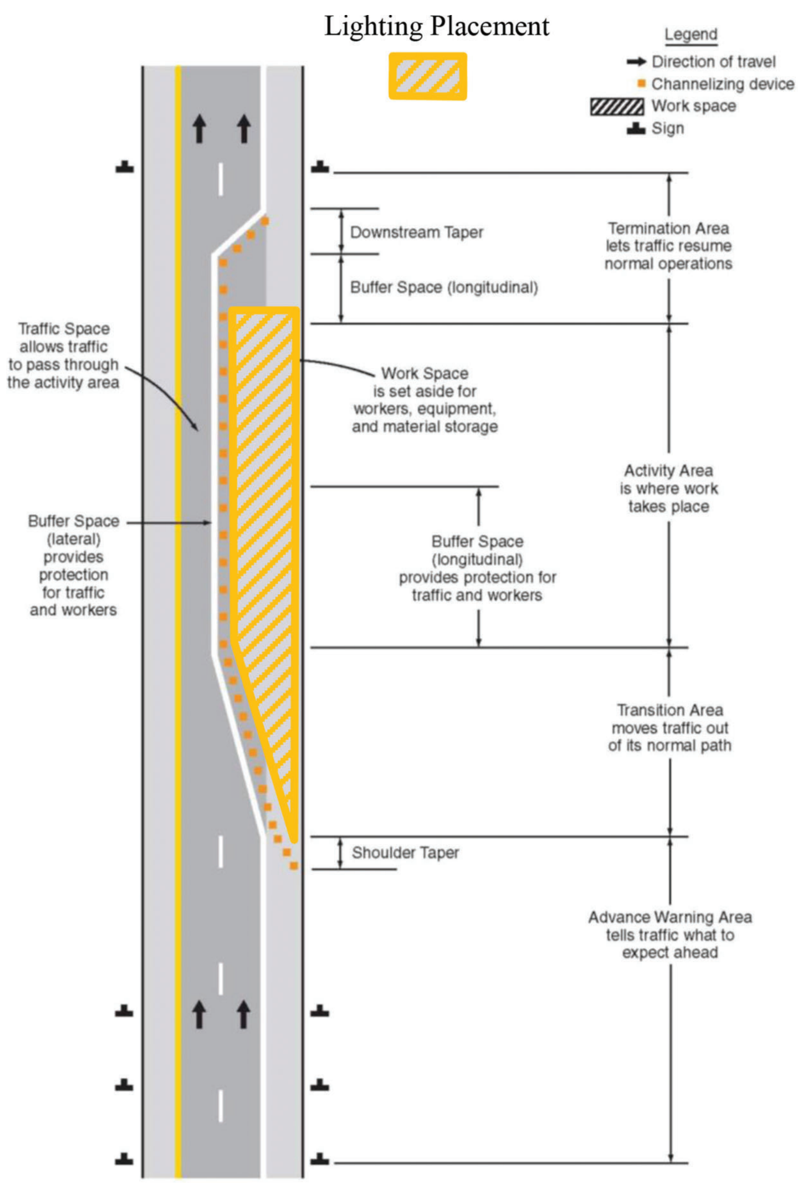


Figure 4.5 Work zone lighting placement (FHWA, 2009).

traffic control plan typically depends on the project contract and the special provisions stated in the contract.

The respondents who indicated that submission of a traffic control plan is mandatory before the commencement of nighttime operations, also stated that the traffic control plan would include (1) the allowable time window (in hours or days) for a lane closure or road closure; (2) number and qualification of personnel who would perform the traffic control tasks; (3) work zone and lane closure layouts; and (4) speed control strategies. To a lesser degree, respondents included details or explanations such as the setups and takedowns of the traffic control devices.

Only five responses indicated the person who is responsible to prepare the project's traffic control plan. For instance, two respondents indicated that this task is delegated to a traffic control subcontractor/contractor, others indicated that the traffic plan is developed by someone within their company (e.g., superintendent, project manager).

4.2.3.3 Cost, productivity, and quality of nighttime operations. The questionnaire asked participants whether the decision to perform roadway operations at night or during the day is made by the owner (agency), the contractor, or jointly by the project owner and the contractor. More than half of the of respondents (10 out of 18) reported that the owner solely makes the decision. A much lower percentage (6 out of 18) indicated that the agency and the contractor jointly make the decision. The remaining participants indicated the decision is made solely by the contractor.

Respondents rated decision-making factor that drive their decision to conduct a construction/maintenance operation during the day or at night using a value ranging from one to three, with one indicating that the factor has no influence on the decision of conducting roadway operations during the day or at night, two indicating some influence on the decision, and three shows a strong influence on the decision. As listed in Table 4.3, the safety of motorists, lighting, and safety of workers are among the top three factors in deciding to conduct roadway operations during the day or at night if the decision is made solely by the contractor and jointly between the agency and the contractor.

A majority of the respondents (14 out of 18) indicated that roadway construction and maintenance activities are performed during daytime hours on low-traffic volume roads. Eleven respondents also indicated execution of roadway operations on arterial collector roads during daytime and nighttime shifts (dual shifts) and eight responses indicated that they worked on construction operations only during daytime hours or only nighttime hours on high-volume roads. The typical work zone closure method used during nighttime operations was the single-lane closure (17 responses out of 18). The least common work zone closure methods are the shoulder closure and the full closure (total closure). Although single-lane closure is commonly used in practice on roadway operations, respondents prefer multiple-lane closures and total lane closures for greater ease of operation.

Half of the respondents did not note any difference in worker incident rate occurring at night compared to roadway operations during the day. Only, five out of 18 respondents stated that they noticed higher worker incidents rate at night, while three respondents noted lower worker incident rate at night compared to daytime operations. In contrast, incident rates involving motorists was reported to be higher at night (12 out of 18 respondents) compared to those during daytime operations.

Regarding quality of nighttime operations, survey results indicated that more than half of the respondents (11 out 18) reported that there is a reduction in the quality of roadway products produced at night compared to same roadway products constructed during the day. Interestingly, seven out 18 respondents indicated that they did not perceive any differences in the quality of roadway products produced at night from those produced during daytime operations.

Fourteen respondents (80%) reported that productivity in terms of average hourly production rate is lower on nighttime operations compared to traditional daytime operations. Also, the variability in hourly production rate is neither higher nor lower at night compared to activities performed during the day according to contractor's respondents.

The analysis of y provided the following key insights obtained from experienced roadway contractors regard-

TABLE 4.3
Summary of Rating Values of Factors When Deciding to Conduct a Roadway Operation at Night or During the Day

Factor	Average Rating Value
Safety of Motorists	2.75
Lighting	2.75
Safety of Workers	2.50
Type of Activity	2.38
Disruption to Traffic	2.25
Cost of the Activity	2.14
Material Logistics	2.00
Availability of Agency Supervision to Inspect Sites	2.00
Ambient Temperature	1.86

ing their perspectives executing nighttime construction and maintenance projects.

1. A total of 67% of survey respondents indicated that they submit a nighttime operation and lighting plan prior to beginning their operations at night. These plans typically include items such as work zone layout(s), details of lighting systems used, and if the lighting systems are attached to or installed on construction equipment. Also, the lighting plans indicated the use of balloon lights and light towers, particularly those with LED light fixtures.
2. Most respondents agreed that the submission of a traffic control plan is crucial before the commencement of nighttime operations. Several respondents indicated that such submissions would be contingent upon the following: (1) the type of project to be undertaken; (2) whether one or more lanes will need to be closed to perform work; and (3) when daytime operations are shifted to nighttime. Also, they typically include plan items such as the allowable time window (in hours or days) for a lane closure or road closure, work zone and lane closure layouts, and speed control strategies.
3. The majority of respondents reported that the decision to perform roadway operations at night or during the day is strictly made by the owner (agency).
4. More than 50% of the survey respondents perceived an increase of the motorist incident rates, a reduction of productivity in terms of average hourly production rate, and a reduction in the quality of roadway deliverables produced at work zones during nighttime hours compared to daytime hours.

4.2.4 Interviews with ICI's Safety Officers

The SPR-4542 research team conducted a formal interview on September 8, 2021, with five safety officers of construction companies' members associated with the Indiana Constructor, Inc. (ICI) to identify the opportunities and challenges related to nighttime construction operations and to gain insight about the use of lighting systems on nighttime operations.

This section describes the key insights provided by the safety officers grouped in three major discussions regarding (1) challenges faced by practitioners when planning or designing nighttime operations; (2) work zone lighting; and (3) lighting systems used for flagging operations.

4.2.4.1 Safety challenges when planning or designing nighttime operations. One of the biggest challenges that practitioners face during nighttime roadway operations is the motoring public. There was consensus among the safety officers that during the day there are more traffic congestions which tend to slow down motorists when they pass through work zones. During daytime hours, increased traffic may cause other problems such as motorists trying to merge and to get through the zone. Also, the possibility of motor vehicle crashes at the rear of the queue is high. On the other hand, at night, traffic tends to be lower, 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 type of traffic control devices placed thorough 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 have a physical effect on workers and their alertness. Fatigue concerns are noted more towards the end of the work shift. For instance, at nighttime shifts the fatigue concerns are noted at 2 am or 6 am. Similarly, workers driving back home was considered also 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.

4.2.4.2 Work zone lighting. Providing adequate illumination levels to perform construction and maintenance operation 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 types of lighting systems are currently used on their nighttime highway operations. Portable light towers, especially those with trailer-mounted features, are widely used on a variety of tasks performed at night. The primary advantages of portable lights are (1) 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 (2) their ease of operation and maintenance (Ellis et al., 2003). Another advantage identified by practitioners is that the mounting height of these systems allows them to fully cover the work area that needs to be illuminated. Mounting heights typically range from 1.8 m (6 ft.) to a fully extended 9.1 m (30 ft.) and the light pole is usually rotatable 360 degrees.

However, one disadvantage identified by practitioners is that that due to the high luminance sources and low mounting heights of light towers, these systems pose a significant glare hazard in work zones. To address this glare issue, practitioners stated that extreme caution must be exercised when positioning and aiming light towers. They also indicated that when setting the aiming angles of the light tower's luminaries on a work zone they consider the road geometry (e.g., straight road sections, curved sections, and others), available area within work zone, surface conditions of the work zone, and the available width of the road's shoulders to position the lighting equipment.

The other common lighting equipment used by practitioners are 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 on the back side of vehicles.

4.2.4.3 Lighting system for flagging operations. In general, work zone traffic control guidelines for nighttime highway maintenance and construction activities recommend that whenever possible flagging operations should be avoided at night and should only be used in emergency situations (Bryden & Mace, 2002b). For instance, the *INDOT Work Zone Traffic Control Guidelines* indicates that "flags should only be used in emergency situations or when a paddle would present a conflicting message to the motorist." Also, nighttime flagger stations *may* be allowed if the contractor *uses* Automated Flagging Assistance Device (AFAD) and additional lighting systems to make flaggers as visible as possible. During the interviews, the safety officers stated 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 can be addressed by providing illumination directly overhead (perpendicular to the ground), rather than from the front or back. This type of lighting configuration helps to eliminate glare in comparison to other lighting configurations. They explained that when the flagger faces traffic with the lighting system behind the flagger, 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 in a manner that isolates him/her from the remaining work zone, preferably in the shoulder or closed lane, while wearing safety vests with front and back reflective markings.

5. WORKZONE LIGHTING AND GLARE ON NIGHTTIME CONSTRUCTION AND MAINTENANCE WORKZONES

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

Similarly, inadequate lighting conditions and improper lighting arrangements may cause glare to motorists when passing the work zone and may impair their visibility. Glare is mainly produced by (1) fixed road lighting, (2) vehicles' headlights, and (3) construction and lighting equipment on the work zone (Ellis et al., 2003). Roadway lighting is a significant source of glare for drivers and motorists. 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). Glare levels produced by roadway lighting are affected by three factors: (1) the glare angle; (2) the distance between the driver and the light source; (3) the light source's mounting height in relation to the observer's height; and (4) the light's aiming (Bryden & Mace, 2002a). Additionally, glare is intensified in urban and semi-urban areas due to the presence of roadway lighting because it 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's 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. But, when the opposing vehicle approaches and the illumination increases significantly, the glare angle becomes large enough to mitigate the glare effect. 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 (Adrian & Jobanputra, 2005).

The presence of lighting and construction equipment on work zones can also cause glare. There are several factors that affect glare levels in and around of 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

(Ellis et al., 2003; El-Rayes & Hyari, 2005; El-Rayes et al., 2003).

5.1 Key Terms Related to Glare

This section briefly describes key terms related to glare on work zones.

5.1.1 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). Depending on the surface orientation either horizontal or vertical, illuminance can be classified as horizontal illuminance or vertical illuminance (IES, 2018). Illuminance is affected mainly by the number and the intensity of the light source and by the distance between light source and the surface area (Ellis et al., 2003; El-Rayes et al., 2003; Shane et al., 2012).

5.1.2 Light Uniformity

Uniformity evaluates the suitability of lighting arrangements in nighttime work zones and quantifies the degree to which light is distributed evenly across the target areas (Finley et al., 2013). Uniformity is calculated as the ratio between the average illuminance (E_{avg}), and the minimum illuminance over the relevant area (E_{min}).

5.1.3 Luminance

Luminance is the amount of luminous flux (light) reflected by a surface and is the light that is used to see an object. It is measured in candelas/m^2. 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 (Ellis et al., 2003; IES, 2018; Shane et al., 2012). For instance, the light reflected by the road surface is termed as pavement luminance or roadway 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 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 motorists with the information necessary to evaluate the visual scene. The roadway ahead of the motorist should have an average luminance sufficient to keep eyes adapted to the roadway, a minimum luminance level sufficient to ensure adequate visibility of any object on or near the roadway, and a uniformity sufficient to maintain continuity within the visual scene, to ensure comfort, and to eliminate the driver's need for frequent and rapid eye movements.

Pavement surfaces reflecting light towards the observer may be classified in three groups: (1) ideal specular surface; (2) perfectly diffuse surface; and (3) mixed reflection (see Figure 5.1). The ideal specular surface reflects all the light incident on a point at an angle of reflection equal to the angle of incidence. 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 and it would appear equally bright to an observer from any viewing angle. However, most surfaces exhibit characteristics of mixed reflection between specular and diffuse (King, 1973). For instance, road surfaces do not reflect light diffusely but in a semi-specular manner (i.e., a portion of the light is reflected secularly and a portion diffusely). The Illumination Engineering Society of North America (IES, 2018) classified pavement surfaces into four categories based on the pavement material's reflectance characteristics as shown in Table 5.1.

5.1.4 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 (Ellis et al., 2003; El-Rayes et al., 2003; Odeh, 2010). It can be classified into two types: disability glare and discomfort glare. Disability glare is the glare that impairs our vision of objects without necessarily causing discomfort (Vos, 2003). Disability glare occurs as a result of light scattering within the eye, effectively reducing contrast and, consequently, object visibility (Bryden & Mace, 2002a). 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). It can increase blink rate to tears and pain but does not reduce visibility (IES, 2018). While the disturbing effect on disability glare is a matter of masking by straight

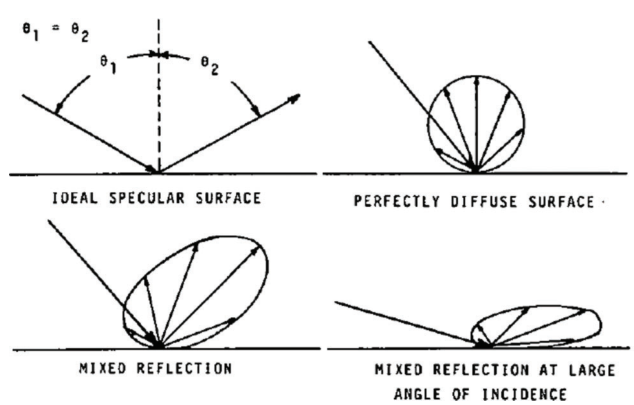


Figure 5.1 Surfaces reflecting light towards the observer (King, 1973).

TABLE 5.1
Road Surface Classifications (IES, 2018)

Class	Description	Mode of Reflectance
R1	Portland cement concrete road surface Asphalt road surface with a minimum of 12% of the aggregates composed of artificial brightener (e.g., Synopal) aggregates (examples: labradorite, quartzite)	Mostly diffuse
R2	Asphalt road surface with an aggregate composed of a minimum 60% gravel (size greater than 1 cm) Asphalt road surface with 10% to 15% artificial brightener in aggregate mix (not normally used in North America)	Mixed (diffuse and specular)
R3	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	Asphalt road surface with very smooth texture	Mostly specular

light, the disturbing effect on discomfort glare is distraction (Vos, 2003).

Disability 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 because 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). This type of glare depends on three factors: (1) illuminance on the eye from the glare source; (2) angle between the line of sight and the center of angle source; and (3) observer's age (Mace et al., 2001).

5.1.5 Light Trespass

Light trespass or obtrusive lighting is defined by three correlated elements: spill light, glare, and sky glow (IES, 2018; 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. Spill light can be controlled by taking measurement of vertical illuminance at the property boundary line or the edge of the road allowance. 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.

5.1.6 Visibility

Visibility was cited as the primary concern when working at night (Al-Kaisy & Nassar, 2005). The observer's visual perception and visibility 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). For instance, if the object's luminance is greater than the background, it is said to have positive contrast; if the object's luminance is less than the background, it is said to have negative contrast (see Figure 5.2). Increased luminance levels result in an increase in contrast. With increased contrast sensitivity, the eye becomes more capable of distinguishing objects or visual tasks that have a low contrast against their background. On the contrary, when contrast is extremely low, task visibility may fall below the threshold, making it unlikely that the task will be seen. 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 age of 40 years (Mace et al., 2001; Vos, 2003).

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, influences 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).

5.2 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-

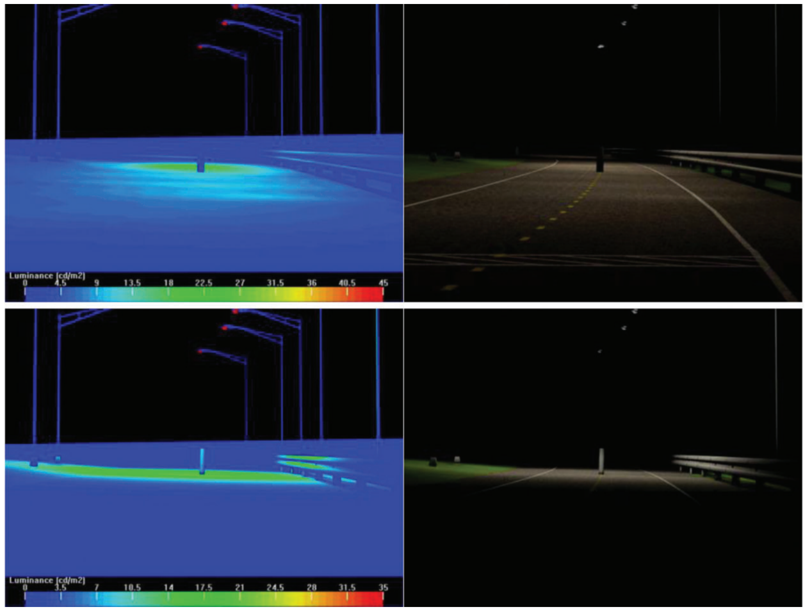


Figure 5.2 Contrast sensitivity (negative contrast in top two images and positive images in the bottom two images) (Lutkevich et al., 2012).

Rayes (2006) conducted a series of field experiments at the Advance Transportation Research and Engineering Laboratory (ATREL) in Illinois to identify practical and adequate lighting arrangements for nighttime work zones and to assess their compliance with existing lighting design criteria mandated by several State Transportation Agencies. For the field tests, two typical two-lane activity areas were chosen (7 m $\times$ 30 m, and 7 m $\times$ 75 m). These areas required the installation of two and three metal-halide light towers equipped with four 1,000-watt luminaires and maximum mounting height of 7.8 m, respectively. 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 (at 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. The findings indicated that when the distance between light towers was reduced from 30 to 20 m, the aiming angles of the four luminaires were reduced from 20° to 0°, and the mounting height was maintained at 7.8 m, 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 a series of field tests to determine and quantify the levels of disability glare and lighting performance induced by light towers at nighttime work zone. The experimental lighting design on 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 of 5 and 8 m, RA at 0°, 20°, and 45°, AA at 0°, 20°, and 45°, and the light tower was placed in the middle of the closed lane. Disability glare was determined by using the veiling luminance ratio metric on a grid of equally spaced points (at 5 m). In two cases the veiling luminance ratios exceeded the recommended 0.4 limit for the IES's roadway lighting design. Disability glare increased steadily as motorists approached the light tower reached a peak between 10 and 25 m from the light tower, and second, disability glare 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 5.3. The AA caused a steady increase in glare experienced by motorists and RA depended on the AA of the luminaires. The study was limited to the analysis of one conventional light tower with metal halide light fixtures.

In 2011, Hassan et al. (2011) complemented the study 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

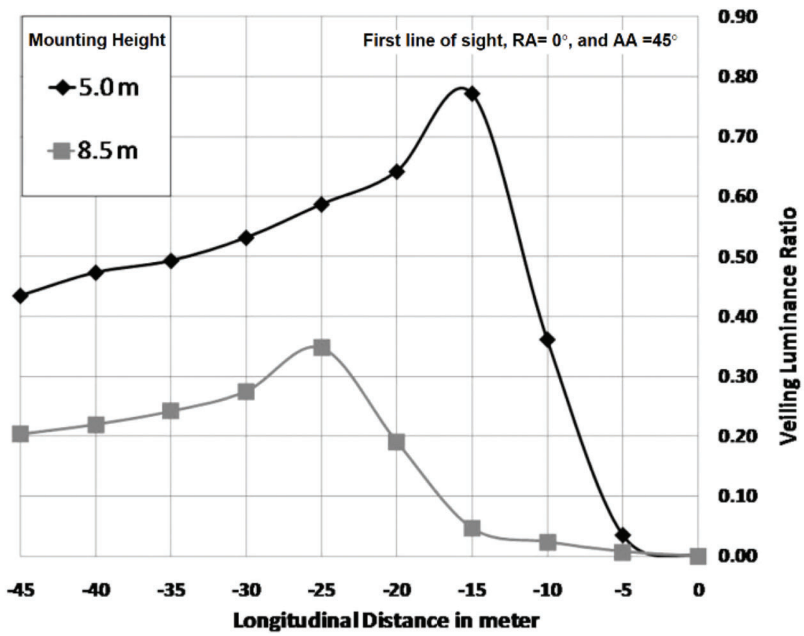


Figure 5.3 Impact of mounting height on veiling luminance ratio (Odeh et al., 2009).

the Louisiana State University (LSU) Petroleum Engineering Research Laboratory. The measurements of pavement luminance and illuminance (horizontal and vertical) 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 described in Table 5.1. Two types lighting systems were used for the field tests: two balloon lights with wattage of 1,000-W and light output of 115,000 lumens and 112,000, respectively, and one light tower with four 1,000-W floodlights and a luminous flux of 110,000 lumens. The mounting heights in the case of balloon lights were extended up to 5.4 m and for the light tower up to 9 m. Fourteen (14) lighting arrangements were evaluated by combining the type of lighting system, mounting height, aiming angle (25°, 35°, and 45°), distance of the lighting system from the lane edge, and the number of luminaires used (light tower). One additional arrangement was tested in the absence of any source of light on the site to account for inferences caused by both external and moonlight and the illuminances measured for this case were subtracted from those measured for each of the experimental cases. The major finding 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 5.4; and (3) increasing the mounting height and decreasing the aiming angle of the light system reduces glare but also reduces the coverage distance available for construction activities.

Very few research studies have been done to evaluate discomfort glare in realistic settings.

Bullough et al. (2014) conducted a study to evaluate relative visual performance of workers under different work zone illumination 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 100 ft. away). The range of light levels used in the analyses were 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, accuracy, and RVP $= 0$ represents the threshold for visual identification. An RPV ≥ 0.8 is desirable for consistent visibility that is 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 (RVP $\geq$ 0.8) for most visual tasks performed by most workers. 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

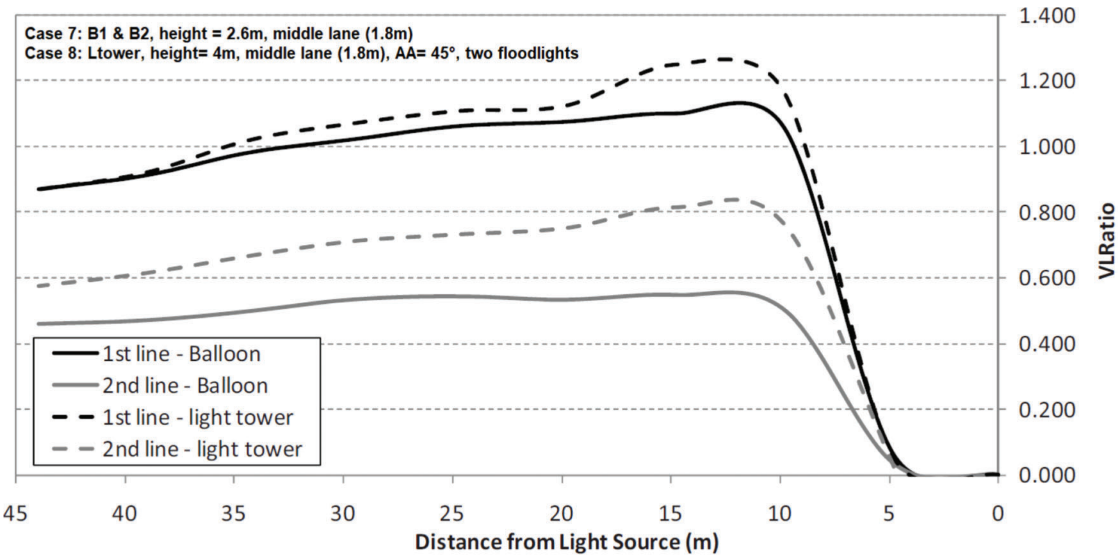


Figure 5.4 Veiling luminance ratio for two balloon lights and a light tower (Hassan et al., 2011).

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. 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 Figure 5.5 and Figure 5.6).

Bhagavathula and Gibbons (2017) conducted a study to evaluate the effect of light tower type and their orientation on driver visual performance and to understand the perceptions of drivers in terms of visibility and glare. The perceptions of driver's 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 (10 m × 3 m) at the Virginia Smart Road (speed limit 55 mph). Multiple lighting arrangements were tested with three lighting systems: (1) a metal halide with four 1,000-W luminaires (440,000 lumens), (2) a balloon light with four 1,000-W metal halide luminaries enclosed within a balloon, which diffuses the light, and (3) 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. Using a Likert scale (1-Strongly agree, 2-Disagree, 3-Neutral, 4-Agree, and 5-Strongly Agree), the participants provided their perceptions of glare based on 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.

Six distinct linear mix models (LMMs) were used to evaluate the lighting system's effect on visibility and glare for each of the three light tower orientations. The LMM statistical results for glare indicated that the primary effect 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 5.7. The mean glare rating for the LED light tower was less than "neutral," and for 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 toward orientation. Also, the effect of light type was significant for each of the three orientations. When the three lighting systems were viewed perpendicularly, the glare ratings were significantly different; 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, for light towers, only a 60° aiming angle of luminaires was used. 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.

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 work zone lane closure on the Virginia Smart Road (speed limit 55 mph). Participants rated the discomfort glare levels produced by portable light towers and under various lighting configurations

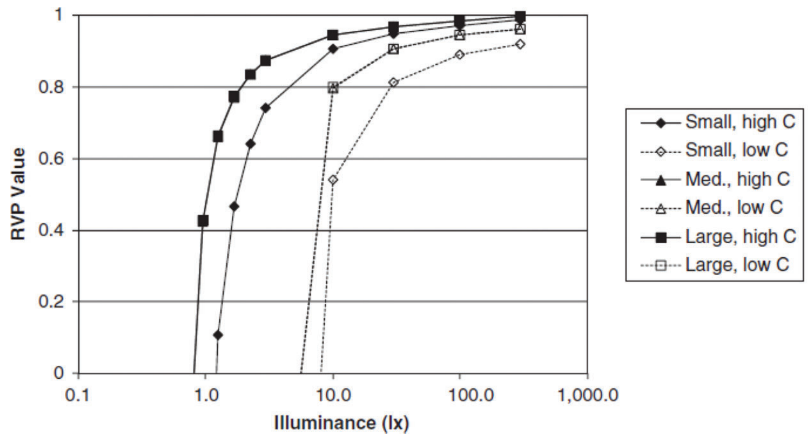


Figure 5.5 RPV values (task sizes and contrast), 20–60 year-old worker, glare of 20 lx (Bullough et al., 2014).

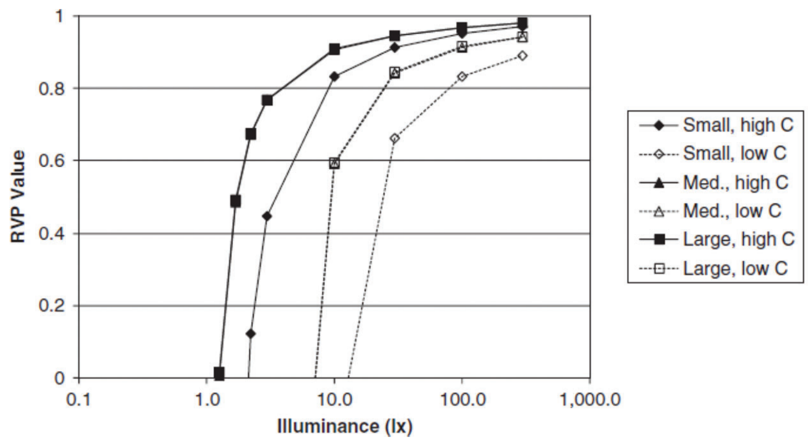


Figure 5.6 RPV values (task sizes and contrast), 60+ year-old worker, glare of 20 lx (Bullough et al., 2014).

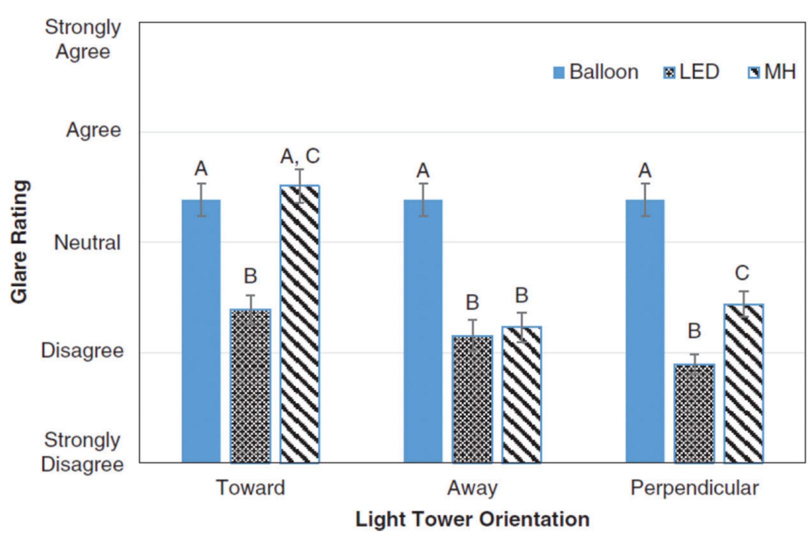


Figure 5.7 Ratings of glare in light tower systems; higher ratings are associated with higher glare. Uppercase letters denote groupings based on significant ($p < .05$) paired comparisons of light tower types with respect to each orientation (Bhagavathula et al., 2017).

(mounting height, offset distance, and number of light towers) by means of a 0 to 6 rating scale (0 indicated "no discomfort glare" to 6 indicated "glare intolerable"). Three lighting systems were used on the field tests: (1) a metal halide light tower with four 1,000-W (440,000 lumens) luminaires, (2) a balloon light with four 1,000-W metal halide luminaires (440,000 lumens) enclosed within a balloon, which diffuses the light, and (3) a smaller balloon light with an 800-W LED luminaire (84,000 lumens). Also, three different mounting height 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 when combining light tower type, mounting height, offset distances, and number of lighting equipment and they were merged into one single variable called "light tower orientation." Nine (9) of these arrangements were designed by combining the three mounting heights and three offset distances of the 4,000-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 a height of 15 ft. and placed in the center of the closed lane, and a single control condition without a light system (unlit zone).

To evaluate the effect of light tower orientation on discomfort glare rating, a linear mix model (LMM) was used. 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 5.8. The study demonstrated that an increase of the offset distances and mounting heights resulted in lower discomfort glare ratings. For instance, the 4,000-W metal halide light tower mounted at 20 ft. 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 a 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 with ages 60 or higher. The results reflect drivers' glare ratings in ideal conditions, and lighting performance decrements that may be 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.

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 on nighttime work zones, researchers provided practical recommendations to State Transportation Agencies (STAs) and roadway contractors about reducing and controlling harmful levels of glare on nighttime work zones. Most of these recommendations were adopted and implemented by some STAs 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.

5.3 Work Zone Lighting Standards

This section provides a summary of 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.

5.3.1 State Transportation Agencies (STAs)

To obtain a perspective of work zone lighting standards and specifications for nighttime operations

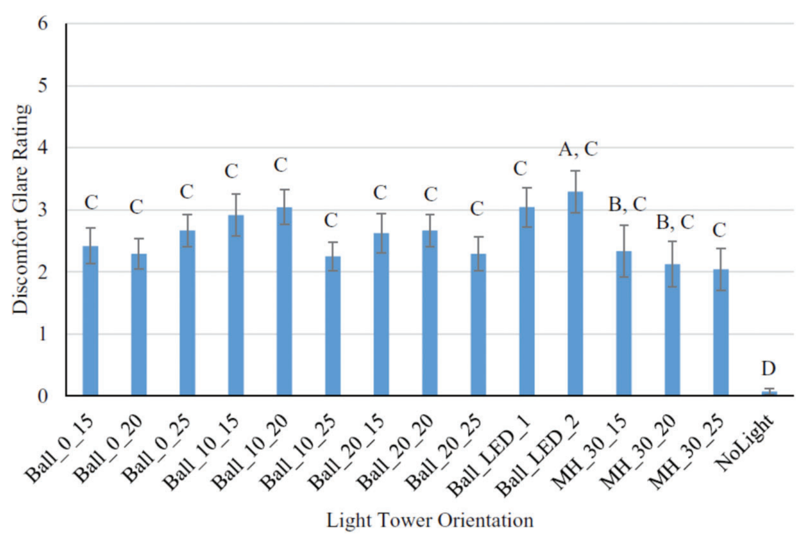


Figure 5.8 Effect of "light tower orientation" on discomfort glare rating. Uppercase letters indicate significant ($p < .05$) post hoc groupings of light tower types within each mounting height (Bhagavathula & Gibbons, 2018).

used by transportation agencies, the lighting standards of nine State Transportation Agencies (STAs) were explored (some of these states are Indiana's neighboring states; others have strong experience in transportation research.) All the STAs in this group focused on work zone lighting provisions that were typically found in the *State Manual on Uniform Traffic Control Devices* (MUTCD) and typically included a state supplement(s) when they developed the lighting standards and specifications for their transportation agency. 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; (2) maximum light uniformity ratio values; (3) if lighting plans are required before commencement of nighttime operations; and (4) 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 the submission of a nighttime lighting plan before any operation begins, and six STAs provide glare control recommendations.

Table 5.2 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 to control or reduce glare by Illinois Department of Transportation were based on studies performed by Odeh et al. (2009).

5.3.2 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.

5.3.2.1 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 common construction and maintenance activities performed at night. 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 5.3 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 requirements for glare control and avoidance as shown in Table 5.4.

5.3.2.2 Illuminating Engineering Society (IES). The Illuminating Engineering Society (IES) 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.

The IES (2018) recommends average values of luminance and light uniformity, as well as maximum values for veiling luminance ratio based on practical experience and consensus among lighting experts. These recommended values for temporary and work zone lighting are summarized in Table 5.5. In addition, IES recommends several strategies to mitigate glare experienced by motorists such as (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. Finally, the IES recommended practice contains recommendations lighting travel lanes in long-duration work zones as shown in Table 5.6. Long-duration work zones are construction or maintenance areas that are occupied for more than three nights.

The Illuminating Engineering Society's (IES) guidelines provide lighting design guidance for the majority of roadway and roadway-related applications. These standards go beyond straightforward criteria such as lighting levels and light uniformity design by including methods for quantifying glare and recommending values for reducing harmful glare levels to the traveling public. In contrast, the National Cooperative Highway Research Program (NCHRP) Report 498, *Illumination Guidelines for Nighttime Highway Work*, provides guidelines for determining the lighting requirements such as recommended illuminance values for conducting construction and maintenance activities within a work area at night. The *NCHRP Report 498* was adopted by most State Transportation Agencies on their work zone lighting provisions as minimum illuminance values by type of work. Glare control measurements provided on these provisions were based on the evaluation of glare levels on work zones. These levels of glare were assessed and determined through glare determination procedures developed by the IES, i.e., the determination of the veiling luminance ratio which is a criterion for limiting glare in roadway lighting.

TABLE 5.2
Summary of STA's Work Zone Lighting Recommendations

State	Minimum Illuminance Levels fc (lx)	Maximum Uniformity Ratio	Lighting Plan Required	Glare Addressed	Recommendations to Reduce or Avoid Glare
Illinois (IDOT, 2022)	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	Not specified	Yes	Yes	Lighting systems employing flood, spot, or stadium luminaires shall be aimed downward at the work and rotated outward by no more than 30 degrees 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)	Not specified	No	No	Not specified
Missouri (Engineering_Policy_Guide Contributors, 2022)	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)	Not specified	No	No	Not specified
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	Not specified	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 ft. above the roadway.
Ohio, Kentucky, and Wisconsin (FHWA, 2009; OhioDOT, 2005)	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	Not specified	No	No	Not specified

(Continued)

TABLE 5.2
(Continued)

State	Minimum Illuminance Levels fc (lx)	Maximum Uniformity Ratio	Lighting Plan Required	Glare Addressed	Recommendations to Reduce or Avoid Glare
Virginia (VDOT, 2015)	5 fc (50 lx)—general construction activities and flagger stations 20 fc (216 lx)—tasks requiring high levels of precision (e.g., signalization)	Not specified	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, 2022)	5 fc (50 lx)—through the workspace and flagging stations (light output of less than 2,500 watts)	Not specified	No	Yes	Temporary glare shields and glare screens shall be 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.
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)	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, 2021)	3 fc (32 lx)—general construction area 5 fc (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	Not specified	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).

TABLE 5.3
Summary of Illumination Categories (Ellis et al., 2003)

Category	Minimum 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 jobsite	Excavation Sweeping Movement in 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 5.4
Glare Control Recommendations (Ellis et al., 2003)

Glare Control Factor	Recommended Glare Control
Beam Spread	Select 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

TABLE 5.5
Lighting Design Criteria for Highways and Streets (IES, 2018)

Road Classification	Pedestrian Activity Classification	Average Luminance L_{avg} (cd/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

Note:
L_{avg}: maintained average pavement luminance.
L_{min}: minimum pavement luminance.
$L_{v,max}$: maximum veiling luminance.

TABLE 5.6
Guidelines 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

Note: Lighting should meet the values established in Table 5.5.

6. DETERMINATION OF GLARE–AN EXPERIMENTAL APPROACH

Very few studies have addressed glare evaluation on nighttime work zones. Also, very few work zone lighting provisions and standards developed by STAs address glare control. The second objective of this study addresses this need and intends to develop practical work zone lighting recommendations, especially those linked to the minimization of harmful levels of glare experienced by passing motorists and workers on nighttime highway work zones. Towards addressing this objective, the research team conducted a series of field experiments to determine disability glare levels produced by typical lighting systems used in roadway construction and maintenance projects.

The determination of disability glare on nighttime highway work zones requires the input of two variables: (1) veiling luminance and (2) pavement luminance. The ratio between these variables is termed veiling luminance ratio and it is the metric of disability glare. The calculation of the veiling luminance values requires vertical illuminance readings emitted by the light sources at different locations on the work zone. Similarly, the pavement luminance measurements are taken directly at different locations on the work zone.

The INDOT Research and Development facility located at Yeager Road and Kent Avenue in West Lafayette, Indiana was used to simulate a typical nighttime one-lane closure work zone and a set of field experiments were conducted on this simulated nighttime work zone to measure vertical illuminances and pavement luminance. As shown in Figure 6.1, the simulation site is a private two-lane street segment partially illuminated with street lighting with approximately 161-m long and 13 m. The total area used to simulate the work zone was approximately 370 m^2 (54 m × 6.8 m). The pavement surface was an asphalt road surface with dark aggregates (used on typical highways) and may be classified as R3 according to the IES recommended practice for design and maintenance of roadway and parking facility lighting (IES, 2018).

Based on input obtained from roadway contractors in Indiana regarding typical nighttime lighting systems, two different types of lighting systems were selected and evaluated in this study. These included two LED

Figure 6.1 INDOT research and development facility/simulation site.

balloon lights and two light towers, as shown in Figure 6.2. These lighting systems are commonly used for hot mix asphalt (HMA) placement, rolling HMA surfaces, asphalt milling, pavement cleaning and sweeping, pavement patching, and at work zone flagger stations.

The first lighting equipment was a LED balloon with power output of 300 W and a total light output of 38,000 lumens. The second, a LED balloon with a set of adjustable power output up to 800 W and a total light output of 110,000 lumens (Multiquip Inc., Models GB3LED and GB8LED). These balloon lights can be extended up to 10 ft. (3 m) or mounted on vehicles or construction equipment (e.g., pavers, road rollers). Also, these lighting systems employ a diffusion mechanism, which makes them less prone to produce glare. In the case of portable light towers, one was metal halide light tower manufactured by Terex, Model RL4000, with four 1,000-W (110,000-lumen) metal halide luminaires and the other was a light tower manufactures by Trime, Model X-Smart, with four 320-W (188,000-lumen) LED luminaires. These lighting systems are frequently used in active nighttime work zones, and they can be extended up to 30 ft. (9.1 m).

Based on the IES recommended practice for design and maintenance of roadway and parking facility lighting (IES, 2018), 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). The line of sight has eleven points, and they are located at 1.4 m 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 placed to delimitate the work zone. Further details about the experimental setup can be found in Davila (2022).

Readings of vertical illuminance (*VI*) and pavement luminance (*PL*) for each of the grid points were obtained using an illuminance meter and a luminance meter, respectively. The values of veiling luminance were calculated at each grid point. The veiling luminance on each grid point and average pavement luminance per line of sight were used to calculate the veiling luminance.

Detailed steps in this measurement and calculation processes are described as follows.

1. The vertical illuminance (*VI*) was measured at 1.45 m above ground or roadway surface using a T-10A Konica Minolta illuminance meter at each point location on the grid for the line of sight (or line of calculation). These measurements were taken from inside of a sport utility vehicle (SUV) 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 m from the edge of the closed lane as shown in Figure 6.3, 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. In such cases, the measurements of vertical illuminance with the illuminance meter should also be repeated for the rest of the grid points added.
2. The pavement luminance (*PL*) was measured inside a vehicle to simulate the conditions experienced by motorists driving by the construction zone using an LS-10 Konica Minolta luminance meter. 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 6.4. 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 measurement process should be continued if more lines of sight are added and the measurement of pavement luminance with the luminance meter should also be repeated for the rest of the grid points added.

(a) Terex RL4000–Metal halide light tower (b) Trime X-Smart–LED light tower (c) Balloon Lights–GloBug Series

Figure 6.2 Lighting systems used in study.

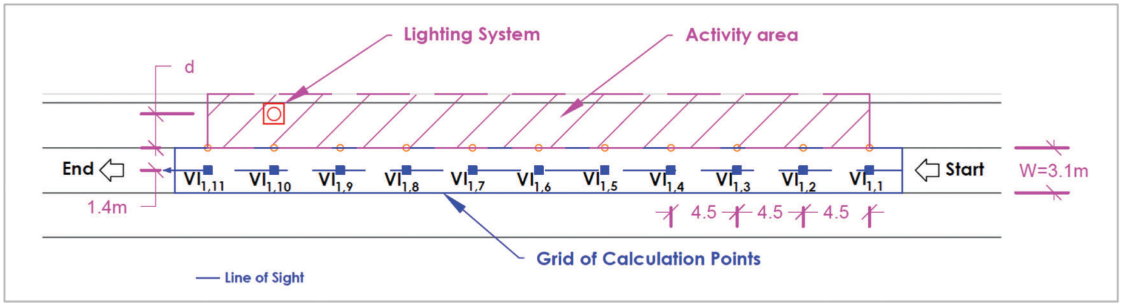


Figure 6.3 Vertical illuminance measurements per one line of sight, dimension in m.

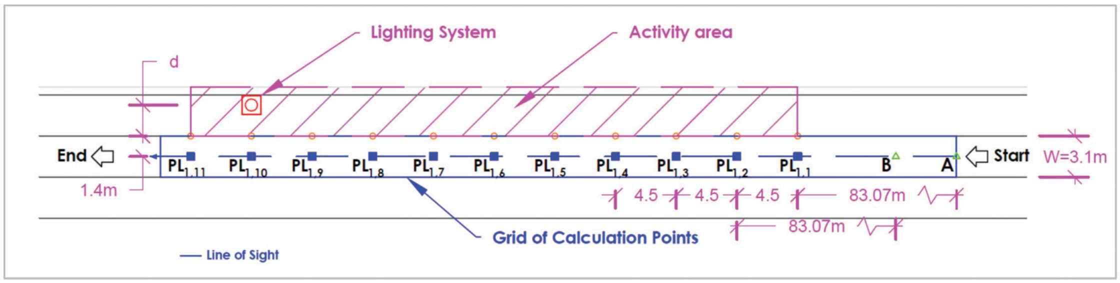


Figure 6.4 Pavement illuminance measurements per one line of sight, dimension in m.

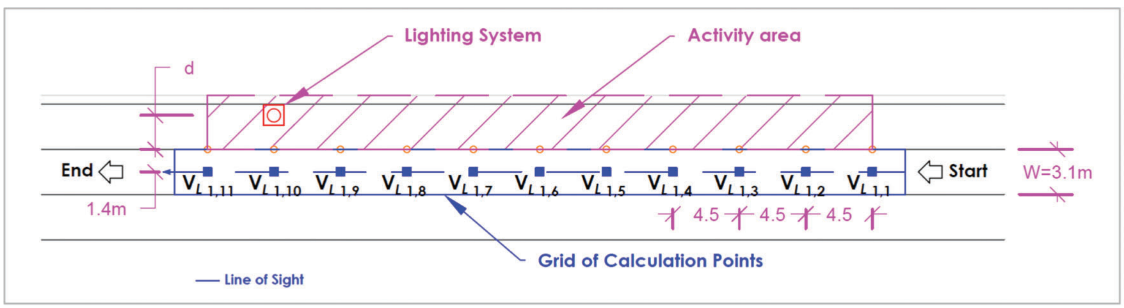


Figure 6.5 Veiling luminance calculations per line of sight, dimension in m.

The average pavement luminance is then determined for all the points per line of sight.

3. 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: (1) vertical illuminance (VI) from each individual luminaire; (2) glare angle (θ) formed between the directions of the glare source and the direction of viewing; (3) the age factor (k) of the observer (this factor increases with age of the observer). The veiling luminance values can be recorded for each grid point, as shown in Figure 6.5. The veiling luminance values for the same grid points can be determined by using Equation 6.1.

$$V_L = k * \frac{VI}{\theta^n} \qquad \text{(Equation 6.1)}$$

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 6.6).

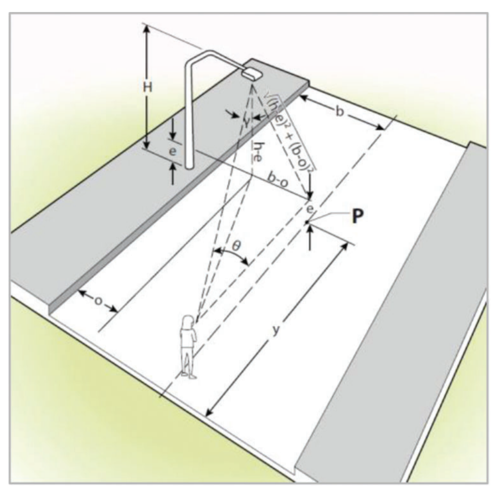


Figure 6.6 Geometric relationships for calculating veiling luminance (IES, 2018).

Both, V_L and VI should be listed in compatible units (candela/m^2 and lux, respectively) and θ in degrees, and the variable n depends on the glare angle θ and is calculated using Equation 6.2.

$$n = 2.3 - 0.7\ \log_{10}\theta\ for\ \theta < 2^\circ;$$
$$n = 2\ for\ \theta \geq 2^\circ \qquad \text{(Equation 6.2)}$$

The aging factor k has a value of 10 for a 25-year-old-observer. This value was used to perform all the calculations regarding the veiling luminance. It is important point out, that the k value increases with age, as shown in Equation 6.3, and shows a sharp increase beyond 70 years of age.

$$k = 10\left[1 + \left(\frac{Age}{70}\right)^4\right] \qquad \text{(Equation 6.3)}$$

4. The veiling luminance ratio ($V_{L\ ratio}$), at each of the grid points, is the ratio between the veiling luminance (V_L), calculated in Step 3, and the average pavement luminance (PL_{avg}). For instance, the veiling luminance ratio for the first point on the first line of sight represented as $V_{L\ ratio\ (1,1)}$, is determined by dividing the veiling luminance (V_L) at that point, $V_{L(1,1)}$, by the average of pavement luminance values of the first line of sight (PL_{avg}), as shown in Equation 6.4. The representation of these calculations is shown in Figure 6.7.

$$V_{Lratio} = \frac{V_{L(a,b)}}{PL_{avg}} \qquad \text{(Equation 6.4)}$$

6.1 Determining the Impact of Lighting Parameter on Glare

A series of 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.

A factorial analysis of variance (ANOVA) is a statistical technique used to predict change in a single dependent variable using two or more independent variables with two or more categories. This analysis has two advantages: (1) 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 (2), it is a more powerful test because it reduces the variance associated with possible errors (Mertler et al., 2021).

Balloon lights were tested to examine the impact of two parameters on the veiling luminance ratio (or disability glare). The tested parameters include (1) the mounting height and (2) the power output. Two categories for mounting heights (8 ft. and 10 ft.) and four categories for wattage factor (300-, 400-, 600-, and 800-Watt power output) were used in the factorial (2×4) ANOVA.

Similarly, light towers were also tested to examine the impact of three parameters on the veiling luminance ratio (or disability glare). The tested parameters include (1) the light tower's mounting height (H), which is the vertical distance between the luminaries' centers and the road surface; (2) The rotation angle or orientation (RA) of the light tower which is the angle at which the light tower pole rotates around a vertical axis; and (3) the aiming angle of luminaires (AA) which is the vertical angle formed by the luminaire's center of beam spread and its nadir. For the metal-halide light tower, three categories are for mounting height (12 ft., 18 ft., and 30 ft.), three categories for orientation (45°, 90°, and 135°), and two categories for aiming angle (30° and 45°). For the LED light tower, 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 used in the factorial ($3 \times 3 \times 2$) ANOVA.

6.2 Vertical Illuminance and Pavement Luminance Measurements

Field experiments were 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. A total of 49 lighting arrangements were tested using balloon lights and light towers during the field experiments as shown in Table 6.1. These lighting combinations represent typical configurations used on typical roadway nighttime operations such as hot mix asphalt

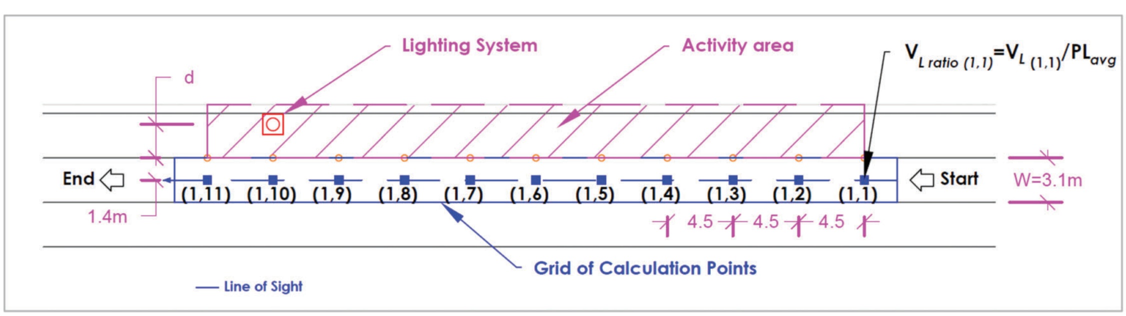


Figure 6.7 Veiling luminance ratio calculation per line of sight.

TABLE 6.1
Lighting Arrangements

Lighting Arrangement	Type of Lighting System	Mounting Height (H)	Wattage	Rotation Angle (RA)	Aiming Angle (AA)
1	One LED balloon light	8 ft. (2.4 m)	300 W	N/A	N/A
2			400 W		
3			600 W		
4			800 W		
5		10 ft. (3.0 m)	300 W	N/A	N/A
6			400 W		
7			600 W		
8			800 W		
9	One metal-halide light tower	12 ft. (3.7 m)	1,100 W (×4)	45°	30°, 30°, 30°, 30°
10					45°, 45°, 45°, 45°
11				90°	30°, 30°, 30°, 30°
12					45°, 45°, 45°, 45°
13				135°	30°, 30°, 30°, 30°
14					45°, 45°, 45°, 45°
15		18 ft. (5.5 m)	1,100 W (×4)	45°	30°, 30°, 30°, 30°
16					45°, 45°, 45°, 45°
17				90°	30°, 30°, 30°, 30°
18					45°, 45°, 45°, 45°
19				135°	30°, 30°, 30°, 30°
20					45°, 45°, 45°, 45°
21		30 ft. (9.1 m)	1,100 W (×4)	45°	30°, 30°, 30°, 30°
22					45°, 45°, 45°, 45°
23				90°	30°, 30°, 30°, 30°
24					45°, 45°, 45°, 45°
25				135°	30°, 30°, 30°, 30°
26					45°, 45°, 45°, 45°
27	One LED light tower	12 ft. (3.7 m)	320 W (×4)	45°	45°, 45°, 45°, 45°
28					60°, 60°, 60°, 60°
29				90°	45°, 45°, 45°, 45°
30					60°, 60°, 60°, 60°
31				135°	45°, 45°, 45°, 45°
32					60°, 60°, 60°, 60°
33		18 ft. (5.5 m)	320 W (×4)	45°	45°, 45°, 45°, 45°
34					60°, 60°, 60°, 60°
35				90°	45°, 45°, 45°, 45°
36					60°, 60°, 60°, 60°
37				135°	45°, 45°, 45°, 45°
38					60°, 60°, 60°, 60°
39		25 ft. (7.6 m)	320 W (×4)	45°	45°, 45°, 45°, 45°
40					60°, 60°, 60°, 60°
41				90°	45°, 45°, 45°, 45°
42					60°, 60°, 60°, 60°
43				135°	45°, 45°, 45°, 45°
44					60°, 60°, 60°, 60°

(HMA) placement, rolling HMA surfaces, asphalt milling, pavement cleaning and sweeping, pavement patching, and work zone flagger stations.

Eight lighting arrangements used one balloon light. The balloon light was positioned at 40.5 m from the origin (or D = 0.0 m) and a lateral distance of 1.4 m from the centerline of the closed lane, as shown in Figure 6.8. Two different mounting heights and four different power outputs were configured for the field experiments. As shown in Table 6.1, 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 at 300-, 400-watt, 600-w, and 800-watt to simulate one balloon light mounted/or attached on construction equipment such as road pavers and rollers.

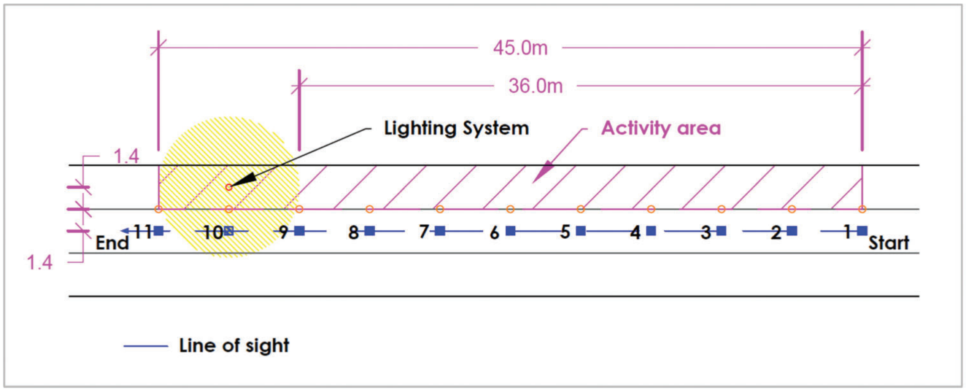


Figure 6.8 Work zone layout for one balloon light.

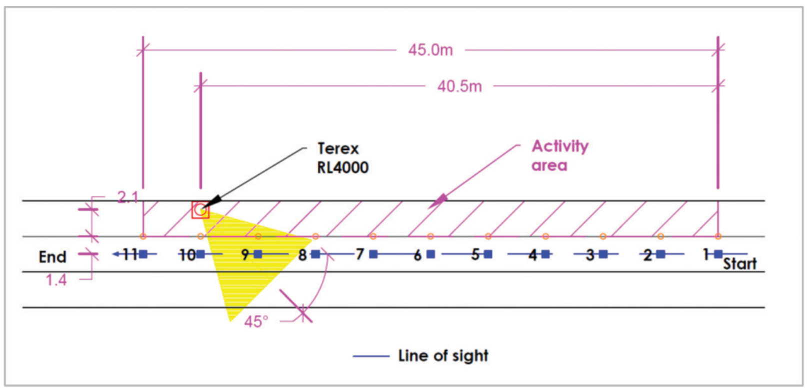


Figure 6.9 Light tower position on the simulated work zone.

Eighteen lighting arrangements used one metal-halide light tower (lighting arrangements #9 to #26). The metal-halide light tower was positioned at 40.5 m from the origin (or D = 0.0 m) and a lateral distance of 2.1 m from the edge of the work zone, as shown in Figure 6.9. The same position was considered for testing the LED light tower and similar lighting arrangements were designed (#27 to #44).

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 as a benchmark when examining the veiling luminance ratios obtained from the lighting combinations used in the field experiments. The $V_{L\ ratio}$ values showed in Tables 6.2, 6.3, 6.5, 6.6, 6.7, 6.8, 6.10, 6.11, 6.12, and 6.13 are based on IES recommended values. Three glare levels were defined and showed on those tables: (1) $V_{L\ ratio}$ values greater than 0 and lower or equal to 0.3 indicate acceptable levels of disability glare for freeways (cells highlighted in green); (2) $V_{L\ ratio}$ values greater than 0.3 but lower or equal to 0.4 are also acceptable levels but limited to nighttime work performed at collectors and local roads (cells highlighted in yellow); and (3) $V_{L\ ratio}$ values greater than 0.4 which indicates unacceptable levels of disability glare (cells highlighted in red).

6.3 Veiling Luminance Ratio of Balloon Lights

Table 6.2 shows that for all lighting arrangements, the values of veiling luminance ratio (on average) were higher than 0.3 which is the maximum ratio allowed by IES (IES, 2018). The 300-watt balloon light (GB3LED) showed the highest values of veiling luminance ratio ($V_{L\ ratio}$) at the 8 ft. and 10 ft., while the model GB8LED showed uniform $V_{L\ ratio}$ values as shown in Figure 6.10. In addition, for all the lighting arrangements, $V_{L\ ratio}$ increases for motorists as they approach the light source, and it reaches its peak at 13.5 m away from the balloon light for the 8-ft. and 10-ft. mounting heights. Moreover, for most of the lighting arrangements up to 36 m of longitudinal distance, the veiling luminance ratio (on average) is consistently higher at lower heights (8 ft.) than those at higher heights (10 ft.), as shown in Table 6.2. Interestingly, Figure 6.10 also shows that a lower power output (GB3LED 300-watt) produced higher values of $V_{L\ ratio}$ compared to those with high power outputs (GB8LED 400-, 600-, and 800-watt). This set of $V_{L\ ratio}$ was unexpected and counterintuitive since the intensity of the light depends

TABLE 6.2
Vertical Illuminance and Veiling Luminance Ratio Values for a Single Balloon Light

Distance (m)	8 ft. (2.4 m)								10 ft. (3.1 m)							
	300-W		400-W		600-W		800-W		300-W		400-W		600-W		800-W	
	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 = 0.0 m	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 = 4.5 m	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 = 9.0 m	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 = 13.5 m	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 = 18.0 m	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 = 22.5 m	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 = 27.0 m	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 = 31.5 m	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 = 36.0 m	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 = 40.5 m	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 = 45.0 m	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:
Green text = $0 \leq VL_{ratio} \leq 0.3$.
Red text = $VL_{ratio} > 0.4$.
Blue text = $0.3 < VL_{ratio} \leq 0.4$.
Minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D = 0 m to D = 36 m.
Avg. PL: average pavement luminance.

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 $V_{L\ ratio}$ are expected at higher wattages.

The $V_{L\ ratio}$ values shown in Table 6.2 were calculated using an aging factor k equal to 10 which represents a 25-year-old-observer. However, this factor increases with age, as shown in Equation 6.3. For all the lighting combinations, $V_{L\ ratio}$ values for the following set of ages were also calculated: 40-, 50-, 60-, and 75-year-olds. As shown in Table 6.3, for observers age 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. 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 6.4 shows the results of the factorial (2×4) ANOVA analysis. This analysis indicates that the 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 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 (counter-intuitive as discussed in the previous paragraph). The mounting height [F (1, 80) = 2.013, $p >$ 0.05] and the 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 6.11, no substantial impacts in the mean values of veiling luminance ratio of the model GB8LED (800-, 600-, and 400-w) were found resulted from changing the heights and power output.

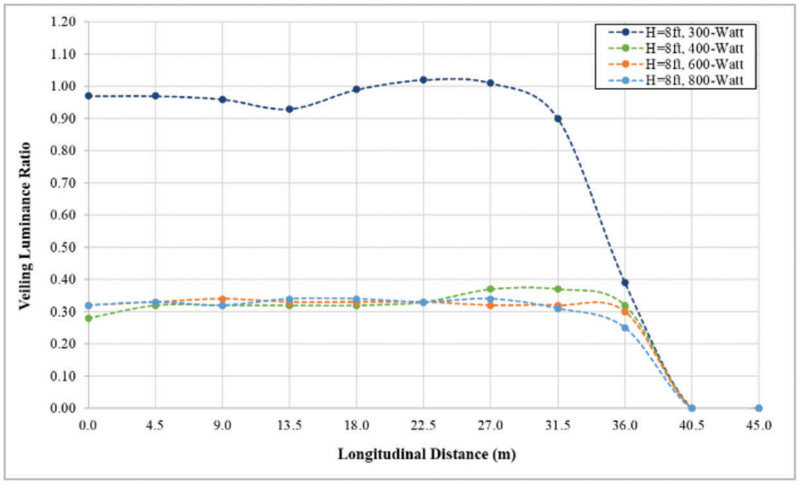
6.4 Veiling Luminance Ratio of Light Towers

The lighting configurations designed for trailer-mounted light towers, tested two commonly used light sources of roadway contractors in Indiana: metal halide and light-emitting diode. The lighting combinations intended to test simulated nighttime construction and maintenance activities such as pavement cleaning and sweeping, pavement patching, and work zone flagger stations.

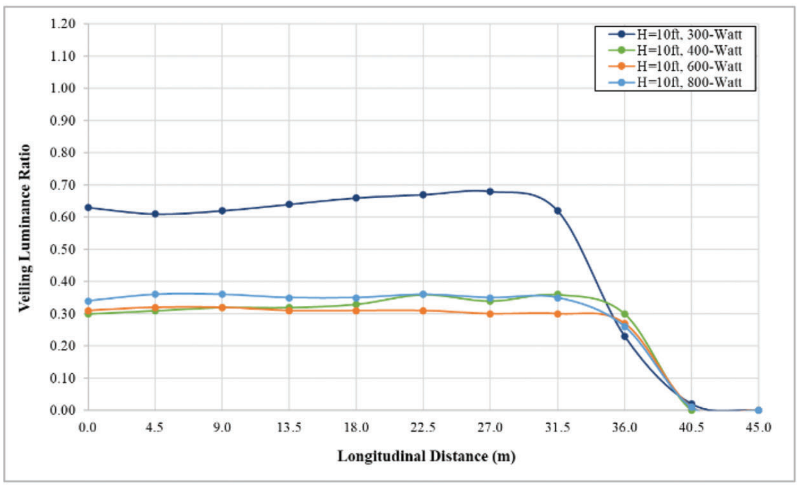
6.4.1 Metal Halide Light Tower

As shown in Figures 6.12, 6.13, and 6.14, trends in all the metal-halide lighting arrangements agree with the veiling luminance ratio ($V_{L\ ratio}$) values reported on previous studies (Hassan et al., 2011; Odeh et al., 2009). The $V_{L\ ratio}$ increases as a vehicle driver approaches the light source, and this ratio reaches its peak between 13.5 m and 18 m before reaching the metal-halide light tower. The light orientation affects the veiling luminance ratios experienced at all three mounting heights. The $V_{L\ ratio}$ value decreases as the rotation angle increases. Also, the $V_{L\ ratio}$ decreases as the equipment is raised in all light orientations of the metal-halide light tower, as shown in Tables 6.5, 6.6, and 6.7.

In 14 out of 18 lighting arrangements tested for 90- and 135-degree light tower orientations in all the three



(a) 8-ft. height



(b) 10-ft. height

Figure 6.10 $V_{L\ ratio}$ values for a single balloon light mounted at 8 ft. and 10 ft.

TABLE 6.3
Veiling Luminance Ratio Mean Values for a Single Balloon Light by Observer Age

Lighting Arrangement	Type of Lighting System	Mounting Height (H)	Wattage	Rotation Angle (RA)	Aiming Angle (AA)	$V_{L\ ratio}$[1] Age = 25	Age = 40	Age = 50	Age = 60	Age = 75
1	One LED balloon light	8 ft. (2.4 m)	300 W	N/A	N/A	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. (3.0 m)	300 W	N/A	N/A	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

Note:
Red text = $VL_{ratio} > 0.4$.
Blue text = $0.3 < VL_{ratio} \leq 0.4$.
[1] $V_{L\ ratio}$ mean values were calculated between D = 0 m to D = 36 m.

TABLE 6.4
Tests of Between-Subjects Effects on a Factorial ANOVA for Balloon Light (2 × 4)

Dependent Variable: Veiling Luminance Ratio						
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**
Corrected Model	2.363[1]	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	—	—	—	—

[1]R Squared = .409 (Adjusted R Squared = .358).

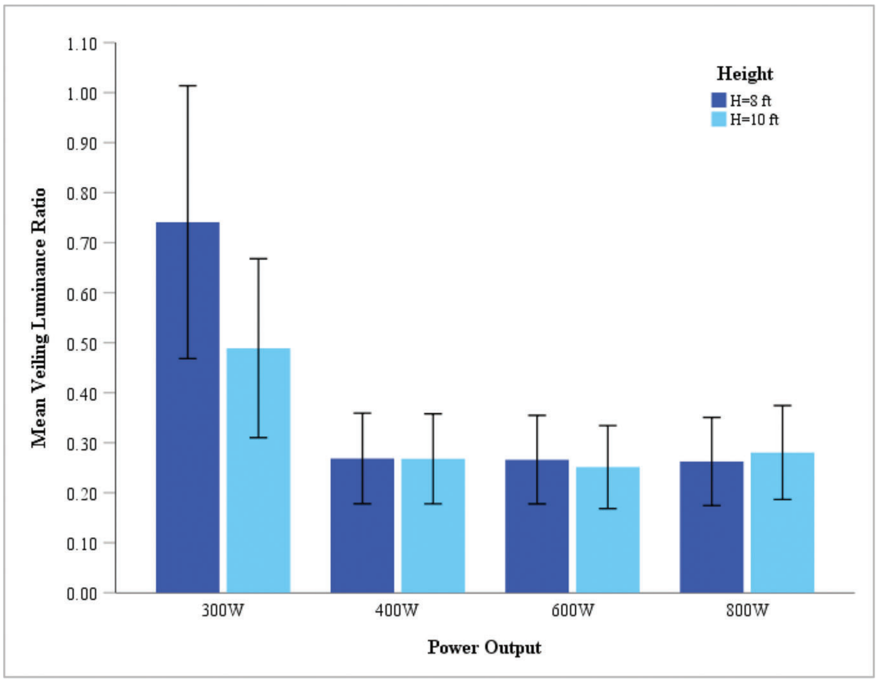
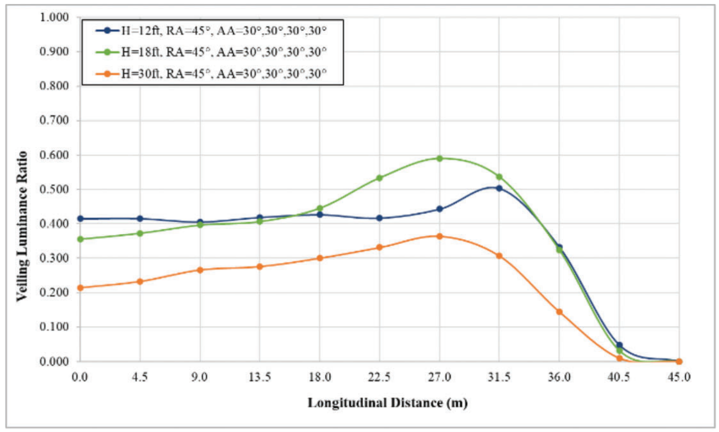


Figure 6.11 $V_{L\ ratio}$ values for a single LED balloon light by electrical power output. Mean values of veiling luminance ratios and error bars represent standard errors.

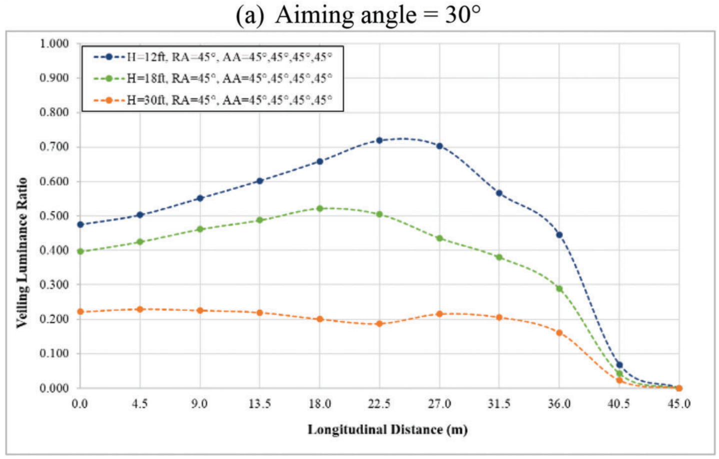
mounting heights $V_{L\ ratio}$ were found lower than 0.3 which is maximium recommended threshold for veiling illuminance. As shown in Figure 6.12, only in four lighting arrangements when the metal halide light tower was oriented 45°, the luminaries raised up to 12 ft. and 18 ft., and the lighting fixtures were aimed at 30- and 45-degree angle, did the $V_{L\ ratio}$ values exceed the maximum $V_{L\ ratio}$ recommended by the IES.

The $V_{L\ ratio}$ values shown in Tables 6.5, 6.6, and 6.7 were calculated using an aging factor k equal to 10 which represents a 25-year-old-observer. However, this factor increases with age, as shown in Equation 6.3. For all the lighting combinations, $V_{L\ ratio}$ values for the following set of ages were also calculated: 40-, 50-, 60-, and 75-year-olds. As shown in Table 6.8, for observers 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 (orientations, mounting heights, and aiming angles). This trend is consistent throughout observer's ages up to 75. However, in the rest of lighting arrangements, especially for observers older than 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, 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. Similarly, for observers older 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°, the luminaries raised at 30 ft., and the lighting fixtures were aimed at 30- and 45-degree angle.

The statistical analysis indicates that the two-way interaction of the mounting height [F (2,180) = 7.915,



(a) Aiming angle = 30°



(b) Aiming angle = 45°

Figure 6.12 $V_{L\ ratio}$ values for a single metal-halide light tower at 12-, 18-, and 30-ft. height and 45-degree orientation.

$p < 0.001$], and the rotation angle (or orientation) [$F\ (2,180) = 160.592$, $p < 0.000$], was statistically significant. However, the main effects 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 (see Table 6.9).

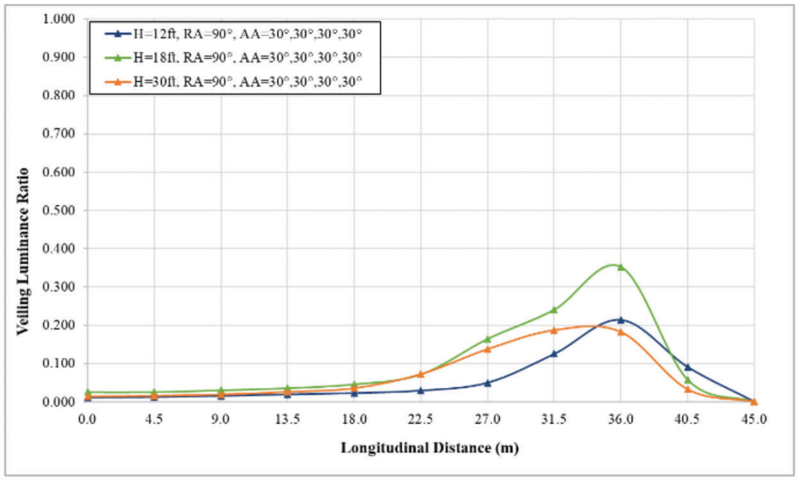
The interaction between light tower's height and orientation showed that in the "perpendicular" and "away" orientations, the $V_{L\ ratio}$ values in all mounting heights were not significant. In contrast, in the "toward" orientation, $V_{L\ ratio}$ values in all three mounting heights were significantly different from one another, with the 12-ft. height having the highest $V_{L\ ratio}$, and the 30-ft. height having the lowest value (see Figure 6.15).

6.4.2 LED Light Tower

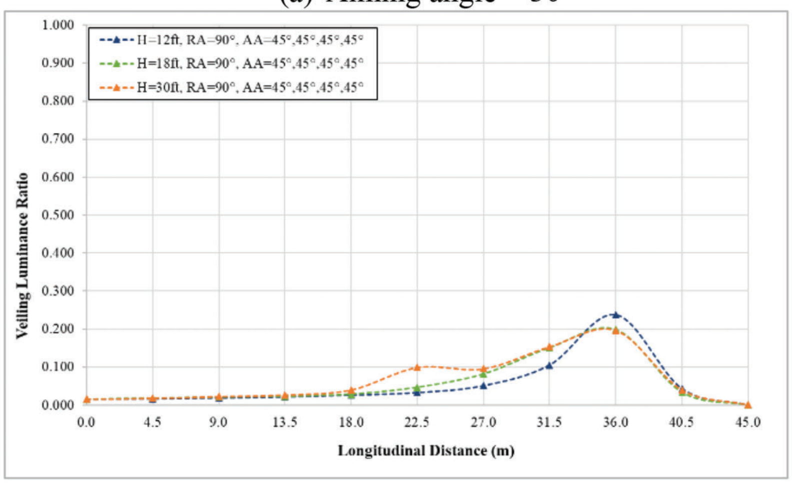
In all lighting arrangements when the LED light tower is mounted at 12-ft., 18-ft., and 30-ft., the veiling luminance ratio ($V_{L\ ratio}$) increases as a vehicle driver approaches the light source, and it reaches its peak between 4.5 m and 9 m before reaching the LED light tower, as shown in Figures 6.16, 6.17, and 6.18. The light orientation and the aiming angles of a single LED light tower affects the veiling luminance ratio experienced at all three mounting heights. For instance, $V_{L\ ratio}$ decreases as the rotation angle increases (from 45° to 135°) and $V_{L\ ratio}$ increases as the aiming angle of luminaires increases (from 45° to 60°), as shown in Tables 6.10, 6.11, and 6.12. When the LED light tower is oriented 45° and 90° and its luminaries are aimed 60° from the vertical, the $V_{L\ ratio}$ (on average) is consistently higher at lower heights (12 ft.) than those on higher heights (25 ft.).

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 $V_{L\ ratio}$ resulted lower than 0.3. Finally, the average pavement luminance decreases as the mounting height of the LED light tower increases and it also decreases as the light is oriented from 45° to 135°. Similarly, the vertical illuminance decreases as the light is oriented from a "toward" orientation to an "away" orientation of luminaires.

The $V_{L\ ratio}$ values shown in Tables 6.10, 6.11, and 6.12 were calculated using an aging factor k equal to 10 which represents a 25-year-old-observer. However, this



(a) Aiming angle = 30°



(b) Aiming angle = 45°

Figure 6.13 $V_{L\ ratio}$ values for a single metal-halide light tower at 12-, 18-, and 30-ft. height and 90-degree orientation.

factor increases with age, as shown in Equation 6.3. For all the lighting combinations, $V_{L\ ratio}$ values for the following set of ages were also calculated: 40-, 50-, 60-, and 75-year-olds. As shown in Table 6.13, almost all the lighting arrangements for observers 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 observers older 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.

In the case of LED powered light towers, the statistical analysis indicates that that the main effect of mounting height [F (2,180) = 1.085, $p > 0.05$] was not statistically significant. Similarly, 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, as shown in Table 6.14. However, the main effect of the light tower's rotation angle (or orientation) [F (2,180) = 54.056, $p < 0.000$], aiming angle [F (1,180) = 29.303, $p < 0.000$], and the two-way interaction involving them was statistically significant.

The mean values of veiling luminance ratio 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, $V_{L\ ratio}$ mean differences between the rotation angle within the aiming angles were considered. At "toward" orientation, the interactions within aiming angles were significantly different from each other, with the 60-degree luminaire's aiming angle

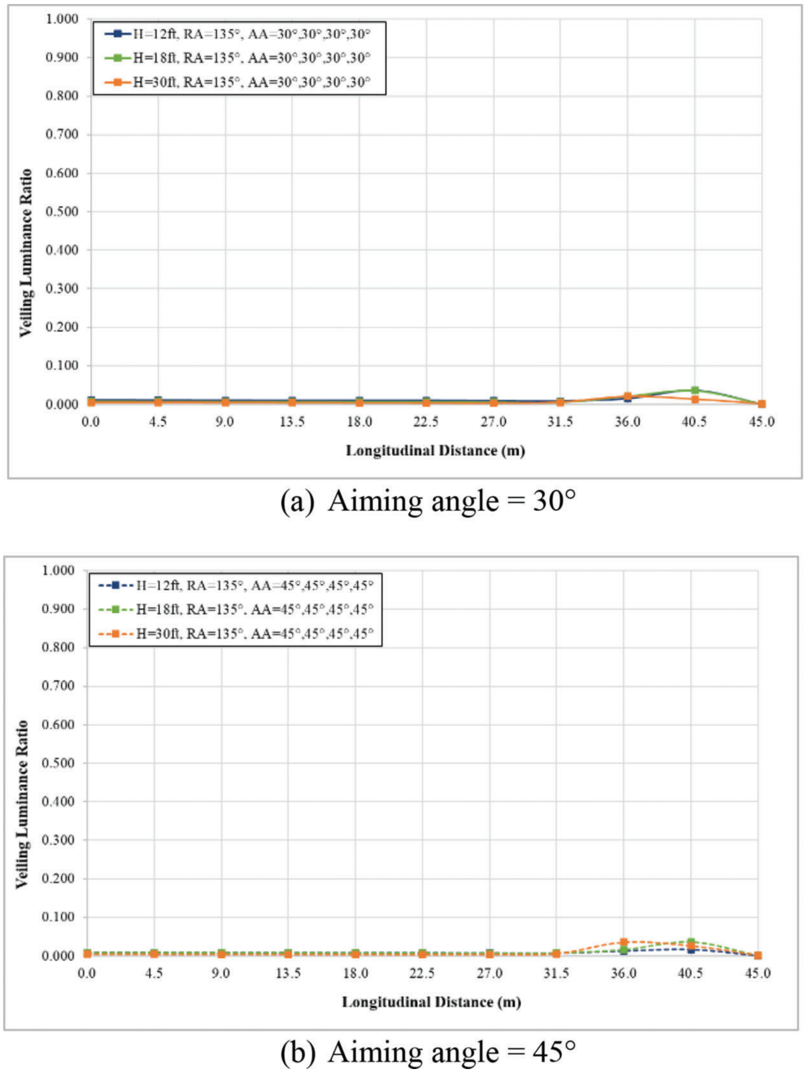


Figure 6.14 $V_{L\ ratio}$ values for a single metal-halide light tower at 12-, 18-, and 30-ft. height and 135-degree orientation.

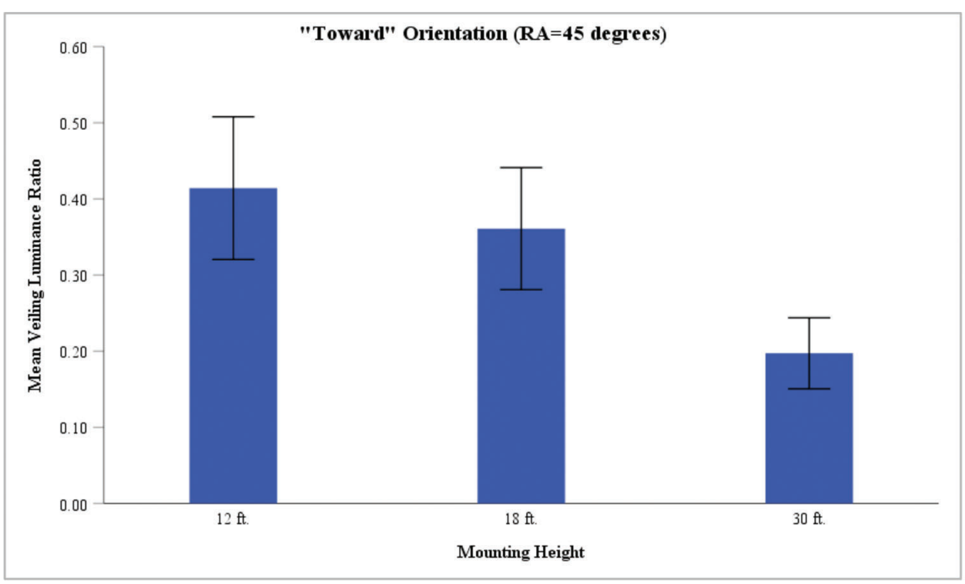


Figure 6.15 $V_{L\ ratio}$ values for a single metal-halide light tower when oriented "towards" the traffic and mounted at three heights. Mean values of veiling luminance ratios and error bars represent standard errors.

TABLE 6.5
Vertical Illuminance and Veiling Luminance Ratio for a Single Metal-Halide Light Tower Mounted at 12 ft.

	H =	**12 ft. (3.7 m)**											
	RA =	**45°**				**90°**				**135°**			
		30°, 30°, 30°, 30°		**45°, 45°, 45°, 45°**		**30°, 30°, 30°, 30°**		**45°, 45°, 45°, 45°**		**30°, 30°, 30°, 30°**		**45°, 45°, 45°, 45°**	
Distance	**AA =**	***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 = 0.0 m		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 = 4.5 m		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 = 9.0 m		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 = 13.5 m		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 = 18.0 m		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 = 22.5 m		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 = 27.0 m		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 = 31.5 m		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 = 36.0 m		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 = 40.5 m[1]		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 = 45.0 m		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:
Green text = $0 \leq VL_{ratio} \leq 0.3$.
Red text = $VL_{ratio} > 0.4$.
Blue text = $0.3 < VL_{ratio} \leq 0.4$.
Minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D = 0 m to D = 36 m.
Avg. PL: average pavement luminance.
[1]Lighting system position.

TABLE 6.6
Vertical Illuminance and Veiling Luminance Ratio for a Single Metal-Halide Light Tower Mounted at 18 ft.

	H =	**18 ft. (5.5 m)**											
	RA =	**45°**				**90°**				**135°**			
		30°, 30°, 30°, 30°		**45°, 45°, 45°, 45°**		**30°, 30°, 30°, 30°**		**45°, 45°, 45°, 45°**		**30°, 30°, 30°, 30°**		**45°, 45°, 45°, 45°**	
Distance	**AA =**	***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 = 0.0 m		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 = 4.5 m		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 = 9.0 m		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 = 13.5 m		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 = 18.0 m		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 = 22.5 m		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 = 27.0 m		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 = 31.5 m		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 = 36.0 m		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 = 40.5 m[1]		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 = 45.0 m		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:
Green text = $0 \leq VL_{ratio} \leq 0.3$.
Red text = $VL_{ratio} > 0.4$.
Blue text = $0.3 < VL_{ratio} \leq 0.4$.
Minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D = 0 m to D = 36 m.
Avg. PL: average pavement luminance.
[1]Lighting system position.

TABLE 6.7
Vertical Illuminance and Veiling Luminance Ratio for a Single Metal-Halide Light Tower Mounted at 30 ft.

	H =	30 ft. (9.1 m)											
	RA =	45°				90°				135°			
		30°, 30°, 30°, 30°		45°, 45°, 45°, 45°		30°, 30°, 30°, 30°		45°, 45°, 45°, 45°		30°, 30°, 30°, 30°		45°, 45°, 45°, 45°	
Distance	AA =	*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 = 0.0 m		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 = 4.5 m		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 = 9.0 m		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 = 13.5 m		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 = 18.0 m		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 = 22.5 m		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 = 27.0 m		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 = 31.5 m		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 = 36.0 m		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 = 40.5 m[1]		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 = 45.0 m		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:
Green text = $0 \leq VL_{ratio} \leq 0.3$.
Blue text = $0.3 < VL_{ratio} \leq 0.4$.
Minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D = 0 m to D = 36 m.
Avg. PL: average pavement luminance.
[1]Lighting system position.

TABLE 6.8
Veiling Luminance Ratio Mean Values for a Single Metal-Halide Light Tower by Observer Age

Lighting Arrangement	Type of Lighting System	Mounting Height (H)	Wattage	Rotation Angle (RA)	Aiming Angle (AA)	$V_{L\ ratio}$[1] Age = 25	Age = 40	Age = 50	Age = 60	Age = 75
9	One metal-halide light tower	12 ft. (3.7 m)	1,100 W (×4)	45°	30°, 30°, 30°, 30°	0.419	0.464	0.529	0.646	0.972
10					45°, 45°, 45°, 45°	0.580	0.642	0.731	0.893	1.345
11				90°	30°, 30°, 30°, 30°	0.056	0.062	0.070	0.086	0.129
12					45°, 45°, 45°, 45°	0.058	0.064	0.073	0.089	0.134
13				135°	30°, 30°, 30°, 30°	0.011	0.012	0.014	0.017	0.025
14					45°, 45°, 45°, 45°	0.009	0.009	0.011	0.013	0.020
15		18 ft. (5.5 m)	1,100 W (×4)	45°	30°, 30°, 30°, 30°	0.440	0.487	0.555	0.678	1.021
16					45°, 45°, 45°, 45°	0.434	0.480	0.547	0.668	1.005
17				90°	30°, 30°, 30°, 30°	0.111	0.122	0.139	0.170	0.256
18					45°, 45°, 45°, 45°	0.065	0.072	0.082	0.100	0.151
19				135°	30°, 30°, 30°, 30°	0.009	0.010	0.011	0.013	0.020
20					45°, 45°, 45°, 45°	0.009	0.010	0.011	0.014	0.021
21		30 ft. (9.1 m)	1,100 W (×4)	45°	30°, 30°, 30°, 30°	0.271	0.300	0.341	0.417	0.628
22					45°, 45°, 45°, 45°	0.208	0.230	0.262	0.320	0.481
23				90°	30°, 30°, 30°, 30°	0.077	0.086	0.097	0.119	0.179
24					45°, 45°, 45°, 45°	0.074	0.082	0.094	0.115	0.172
25				135°	30°, 30°, 30°, 30°	0.006	0.007	0.008	0.009	0.014
26					45°, 45°, 45°, 45°	0.007	0.008	0.009	0.011	0.017

Note:
Green text = $0 \leq VL_{ratio} \leq 0.3$.
Red text = $VL_{ratio} > 0.4$.
Blue text = $0.3 < VL_{ratio} \leq 0.4$.
[1]$V_{L\ ratio}$ mean values were calculated between D = 0 m to D = 36 m.

TABLE 6.9
Tests of Between-Subjects Effects on a Factorial ANOVA for a Single Metal-Halide Light Tower (3 × 3 × 2)

Dependent Variable: Veiling Luminance Ratio					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	4.416[1]	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	—	—	—

[1]R Squared = .679 (Adjusted R Squared = .649).

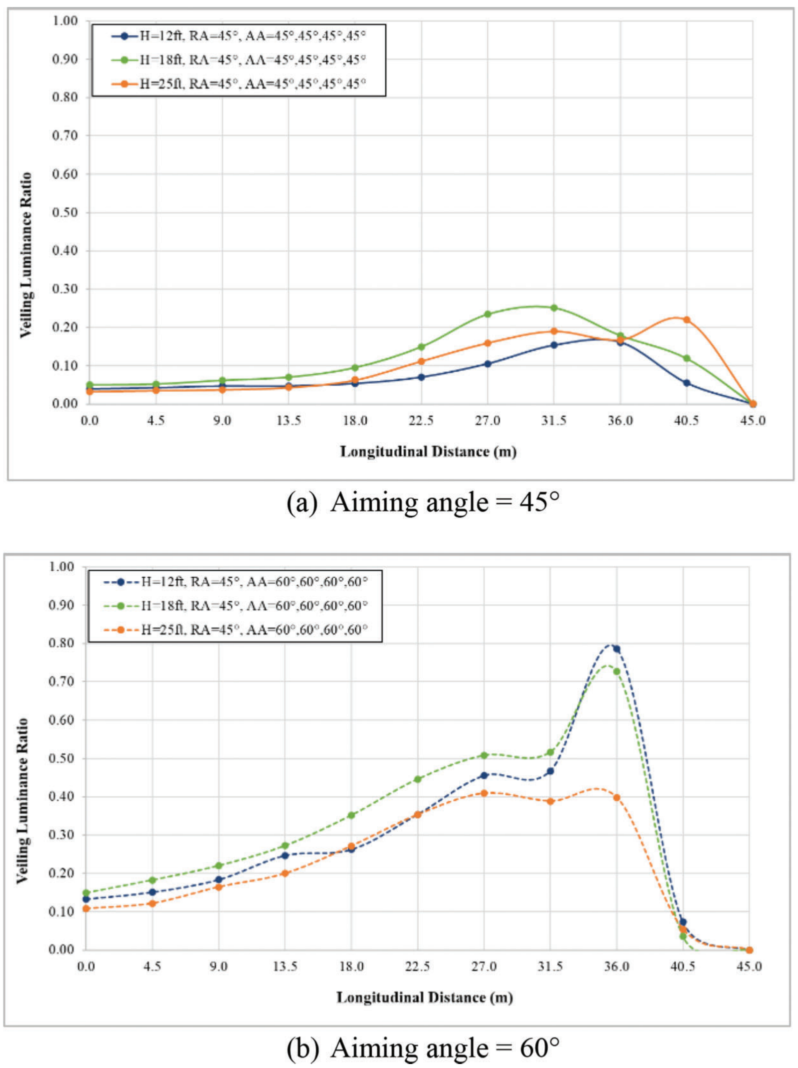
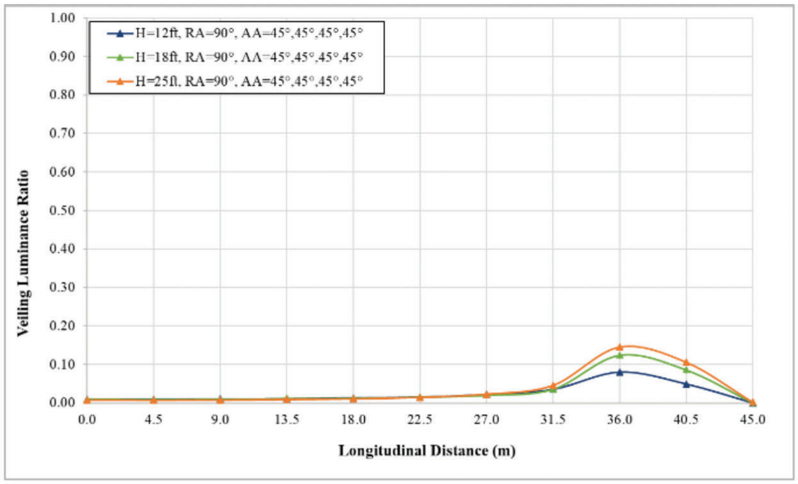
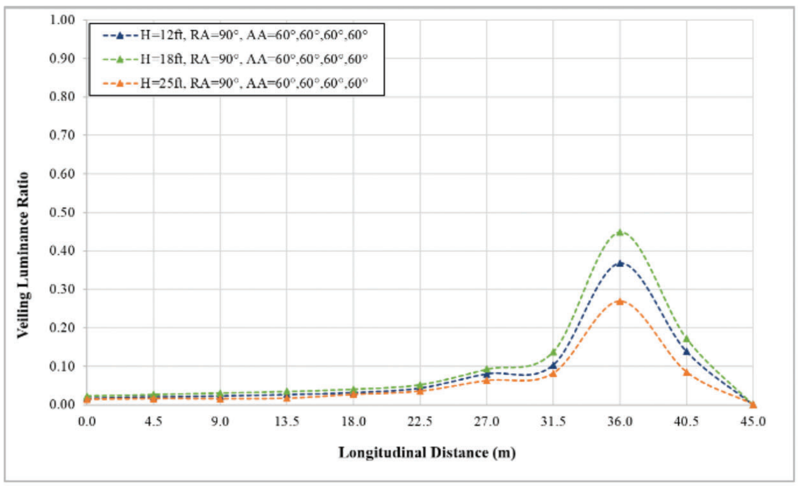


Figure 6.16 $V_{L\ ratio}$ values for a single LED light tower at 12-, 18-, and 30-ft. height and 45-degree orientation.



(a) Aiming angle = 45°



(b) Aiming angle = 60°

Figure 6.17 $V_{L\ ratio}$ values for a single LED light tower at 12-, 18-, and 30-ft. height and 90-degree orientation.

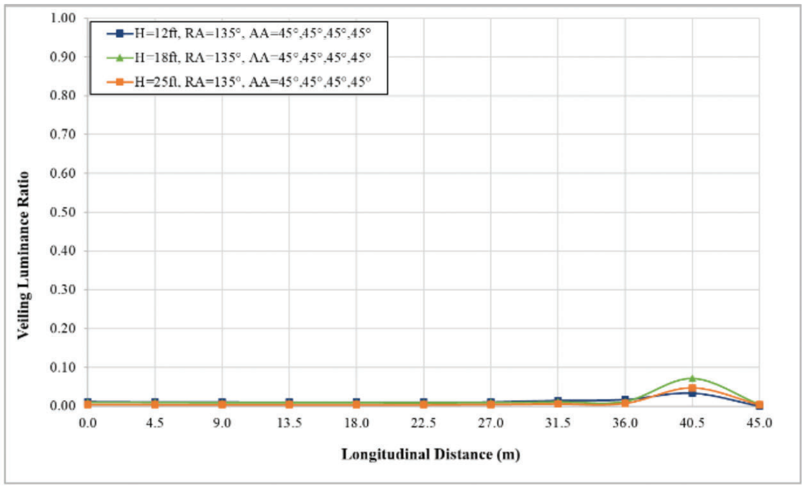
having the highest $V_{L\ ratio}$, and the 45-degree luminaire's aiming angle having the lowest $V_{L\ ratio}$. At the "perpendicular" and "away" orientation of the LED light tower, the interaction between rotation angle and all two aiming angles were not statistically significant (see Figure 6.19).

6.5 Discussion of Results

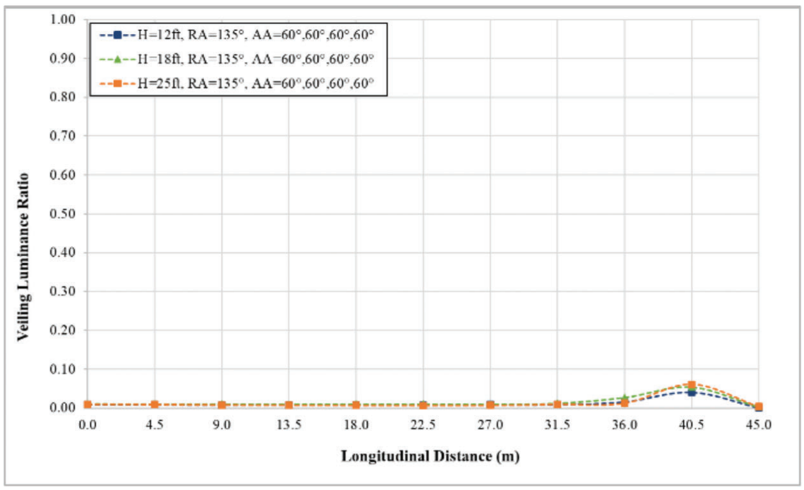
The primary objective for conducting field experiments were to determine disability glare levels produced by balloon lights and light towers used to illuminate nighttime work zones. Based on the analysis of the results regarding the veiling luminance ratio values obtained from the field experiments, the following observations are provided.

For balloon lights, the veiling luminance ratio (or disability glare) values were determined to be greater than 0.3 but less than 0.4 in six out of eight lighting combinations. This range of disability glare levels or $V_{L\ ratio}$ values are acceptable levels of glare at work zones but restricted to nighttime operations performed only at collectors and local roads. This set of lighting arrangements corresponded to a single balloon light with adjustable power output from 400 to 800 W. Only in two cases, did the veiling luminance ratio (or disability glare) values exceed the recommended 0.3 limit which is maximum recommended threshold for veiling illuminance. These lighting arrangements correspond to a single balloon light with power output of 300 W. This finding indicates that a balloon light with lower power output may generate higher values of veiling luminance ratio compared to those balloon lights with high power outputs.

For a single metal-halide light towers, disability glare levels are affected by mounting height and orientation of the luminaries. The analyses of disability glare levels in 4 out of 18 lighting arrangements showed that $V_{L\ ratio}$ values were greater than 0.4, thus unacceptable for nighttime operations. These lighting arrangements corresponded to a single metal-halide light tower oriented 45° "towards" the traffic, the luminaires aimed



(a) Aiming angle = 45°



(b) Aiming angle = 60°

Figure 6.18 $V_{L\ ratio}$ values for a single LED light tower at 12-, 18-, and 30-ft. height and 135-degree orientation.

30- and 45-degree vertical angle between the center of the beam spread of the lamps and the nadir, and the luminaries mounted up to 18 ft. (5.5 m). Acceptable disability glare levels ($V_{L\ ratio} < 0.3$) were found in 14 lighting arrangements. These combinations correspond to (1) a single metal-halide light tower oriented (rotated horizontally) 45° "towards" the traffic, the luminaires aimed 30- and 45-degree vertical angle, and the luminaries mounted at 30 ft. (9.1 m); (2) a single metal-halide light tower oriented "perpendicular" to the traffic, the luminaires aimed 30- and 45-degree vertical angle, and mounted at 12 ft., 18 ft., and 30 ft.; (3) a single metal-halide light tower "away" from the traffic, the luminaires aimed 30- and 45-degree vertical angle, and mounted at 12 ft., 18 ft., and 30 ft.

For a single LED light tower, disability glare levels are affected mainly by the orientation of the luminaries and the aiming angle of them. The analyses of disability glare levels in 2 out of 18 lighting arrangements showed that $V_{L\ ratio}$ values were greater than 0.3 but less than 0.4, thus acceptable glare levels for nighttime operations. These lighting arrangements corresponded to a single LED light tower oriented 45° "towards" the traffic, the luminaires aimed 60-degree vertical angle between the center of the beam spread of the lamps and the nadir, and the luminaries mounted up to 18 ft. (5.5 m). Moreover, $V_{L\ ratio}$ values less than 0.3 were found in 16 lighting arrangements. These combinations correspond to (1) a single LED light tower oriented (rotated horizontally) 45° "towards" the traffic, the luminaires aimed 45-degree vertical angle, and the luminaries mounted at 12 ft., 18 ft., and 25 ft.; (2) a single LED light tower oriented "perpendicular" to the traffic, the luminaires aimed 45- and 60-degree vertical angle, and mounted at 12 ft., 18 ft., and 30 ft.; (3) a LED light tower "away" from the traffic, the luminaires aimed 30- and 45-degree vertical angle, and mounted at 12 ft., 18 ft., and 30 ft.

The scattering of light in the eye increases with age. The calculated veiling luminance ratio ($V_{L\ ratio}$) values for the 44 lighting arrangements were determined by using an aging factor k equal to 10 which represents a

TABLE 6.10
Vertical Illuminance and Veiling Luminance Ratio for a Single LED Light Tower Mounted at 12 ft.

H =	12 ft. (3.7 m)											
RA =	45°				90°				135°			
	45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°	
Distance AA =	*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 = 0.0 m	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 = 4.5 m	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 = 9.0 m	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 = 13.5 m	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 = 18.0 m	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 = 22.5 m	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 = 27.0 m	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 = 31.5 m	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 = 36.0 m	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 = 40.5 m[1]	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 = 45.0 m	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.m^2)	9.33		6.25		6.55		3.72		2.90		4.33	

Note:
Green text = $0 \leq VL_{ratio} \leq 0.3$.
Red text = $VL_{ratio} > 0.4$.
Blue text = $0.3 < VL_{ratio} \leq 0.4$.
Minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D = 0 m to D = 36 m.
Avg. PL: average pavement luminance.
[1]Lighting system position.

TABLE 6.11
Vertical Illuminance and Veiling Luminance Ratio for a Single LED Light Tower Mounted at 18 ft.

H =	18 ft. (5.5 m)											
RA =	45°				90°				135°			
	45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°	
Distance AA =	*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 = 0.0 m	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 = 4.5 m	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 = 9.0 m	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 = 13.5 m	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 = 18.0 m	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 = 22.5 m	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 = 27.0 m	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 = 31.5 m	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 = 36.0 m	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 = 40.5 m[1]	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 = 45.0 m	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.m^2)	5.77		4.11		4.85		2.33		3.06		2.35	

Note:
Green text = $0 \leq VL_{ratio} \leq 0.3$.
Red text = $VL_{ratio} > 0.4$.
Blue text = $0.3 < VL_{ratio} \leq 0.4$.
Minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D = 0 m to D = 36 m.
Avg. PL: average pavement luminance.
[1]Lighting system position.

TABLE 6.12
Vertical Illuminance and Veiling Luminance Ratio for a Single LED Light Tower Mounted at 25 ft.

	H =	25 ft. (7.6 m)											
	RA =	45°				90°				135°			
		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°		45°, 45°, 45°, 45°		60°, 60°, 60°, 60°	
Distance	AA =	*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 = 0.0 m		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 = 4.5 m		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 = 9.0 m		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 = 13.5 m		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 = 18.0 m		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 = 22.5 m		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 = 27.0 m		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 = 31.5 m		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 = 36.0 m		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 = 40.5 m[1]		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 = 45.0 m		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 ($cd.m^2$)		4.58		3.05		3.21		1.92		3.30		1.57	

Note:
Green text = $0 \leq VL_{ratio} \leq 0.3$.
Red text = $VL_{ratio} > 0.4$.
Blue text = $0.3 < VL_{ratio} \leq 0.4$.
Minimum, maximum, and average $V_{L\ ratio}$ values were calculated between D = 0 m to D = 36 m.
Avg. PL: average pavement luminance.
[1]Lighting system position.

TABLE 6.13
Veiling Luminance Ratio Mean Values for a Single LED Light Tower by Observer Age

Lighting Arrangement	Type of Lighting System	Mounting Height (H)	Wattage	Rotation Angle (RA)	Aiming Angle (AA)	$V_{L\ ratio}$[1] Age = 25	Age = 40	Age = 50	Age = 60	Age = 75
27	One LED light tower	12 ft. (3.7 m)	320 W (×4)	45°	45°, 45°, 45°, 45°	0.080	0.089	0.101	0.123	0.186
28					60°, 60°, 60°, 60°	0.338	0.374	0.426	0.520	0.783
29				90°	45°, 45°, 45°, 45°	0.023	0.025	0.029	0.035	0.053
30					60°, 60°, 60°, 60°	0.079	0.088	0.100	0.122	0.184
31				135°	45°, 45°, 45°, 45°	0.012	0.013	0.015	0.018	0.028
32					60°, 60°, 60°, 60°	0.009	0.010	0.012	0.015	0.022
33		18 ft. (5.5 m)	320 W (×4)	45°	45°, 45°, 45°, 45°	0.127	0.141	0.160	0.196	0.295
34					60°, 60°, 60°, 60°	0.375	0.415	0.473	0.577	0.869
35				90°	45°, 45°, 45°, 45°	0.028	0.031	0.035	0.042	0.064
36					60°, 60°, 60°, 60°	0.099	0.109	0.124	0.152	0.229
37				135°	45°, 45°, 45°, 45°	0.009	0.010	0.011	0.014	0.021
38					60°, 60°, 60°, 60°	0.013	0.014	0.016	0.020	0.029
39		25 ft. (7.6 m)	320 W (×4)	45°	45°, 45°, 45°, 45°	0.094	0.104	0.118	0.144	0.217
40					60°, 60°, 60°, 60°	0.268	0.297	0.338	0.413	0.622
41				90°	45°, 45°, 45°, 45°	0.030	0.034	0.038	0.047	0.070
42					60°, 60°, 60°, 60°	0.060	0.066	0.076	0.092	0.139
43				135°	45°, 45°, 45°, 45°	0.005	0.005	0.006	0.007	0.011
44					60°, 60°, 60°, 60°	0.008	0.009	0.011	0.013	0.020

Note:
Green text = $0 \leq VL_{ratio} \leq 0.3$.
Red text = $VL_{ratio} > 0.4$.
Blue text = $0.3 < VL_{ratio} \leq 0.4$.
[1]$V_{L\ ratio}$ mean values were calculated between D = 0 m to D = 36 m.

TABLE 6.14
Tests of Between-Subjects Effects on a Factorial ANOVA for LED Light Tower (3 × 3 × 2)

Dependent Variable: Veiling Luminance Ratio					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	1.675[1]	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	—	—	—

[1]R Squared = .489 (Adjusted R Squared = .441).

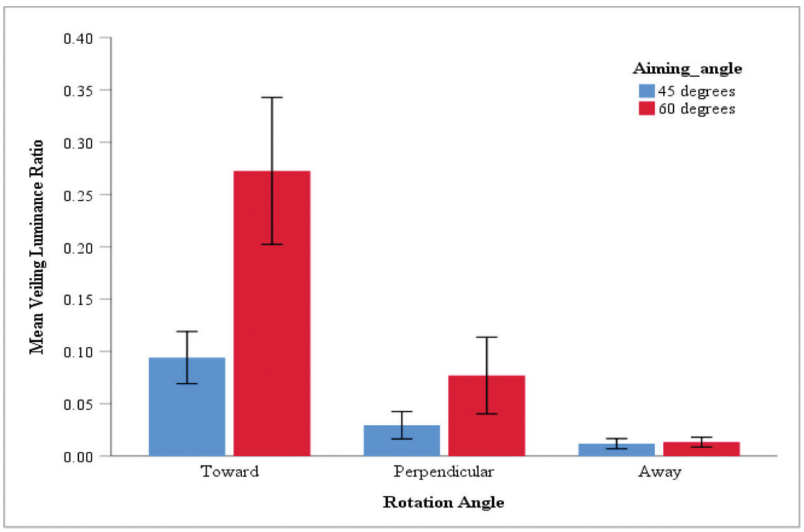


Figure 6.19 $V_{L\ ratio}$ values for a single LED light tower at two aiming angles by each orientation. Mean values of veiling luminance ratios and error bars represent standard errors.

25-year-old-observer. However, these calculated $V_{L\ ratio}$ values can be multiplied by a factor to account for the eye's normal physiological changes as it ages. Incorporating this factor results in an increase in the calculated veiling luminance value. 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 for observers older 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 for observers between 25 to 40 years old, but for observers older than 50 years old, the calculated $V_{L\ ratio}$ values (or disability glare) were found to be dangerous.

For a single metal-halide light tower, when aging factor was evaluated on observers older than 25 years old, unacceptable glare levels ($V_{L\ ratio} \geq 0.4$) were calculated on four of eighteen lighting arrangements. These lighting combinations were when (1) the light tower was mounted at 12 ft., oriented towards the traffic, and all light fixtures were aimed at 30° and 45°; and (2) the light tower was mounted at 18 ft., oriented towards the traffic, and all light fixtures were aimed 30° and 45°. Moreover, for observers older 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°. 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 ($V_{L\ ratio} \leq 0.4$).

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°, harmful levels of glare were found for observers older 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°, harmful levels of glare were found for observers older 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°, harmful levels of glare were found for observers older 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 ($V_{L\ ratio} \leq 0.4$).

7. SUMMARY AND CONCLUSION

The first objective of Theme 1 in this research project was the identification of safety issues of nighttime operations on roadways and the determination of factors that contribute to worker injuries and crashes during daytime and nighttime work zone operations.

Based on the analysis of INDOT work zone safety data between 2016 and 2020, the following insights may be drawn.

1. Most of the INDOT worker injuries and motor vehicle crashes occurred during daytime hours. A lower percentage occurred during nighttime shifts that could have been in darkness depending on the time of year, and when there are fewer vehicles on the roadways, compared to daytime traffic volumes and hence, lower exposures of workers to motorists.
2. The majority of worker injuries resulted from worker strains and sprains, followed by workers getting struck by vehicles or equipment and workers falling, slipping, or tripping at the work zone. The main causes of these workers injuries were found because workers failed to (1) maintain awareness of their surroundings, (2) follow proper procedures for the tasks being performed; (3) identify properly the workplace hazards and hazard warnings; (4) use adequate equipment or tools for the task being done; and (5) wear proper personal protective equipment for the task being performed.
3. Most of the motor vehicle crashes corresponded to privately owned vehicles (POV) striking INDOT's vehicles or piece of equipment, followed by INDOT single vehicle or equipment involved in a damage incident without other vehicles or equipment involved, and INDOT vehicles or equipment striking other INDOT vehicles or equipment, building, fence, or other INDOT owned structure. The main causes of POV striking INDOT crash type were due to POV drivers distracted or not paying attention to their surroundings, driving recklessly, speeding up, or performing abrupt maneuvers, failing to maintain proper clearance (i.e., following/passing too closely) to vehicles or equipment in the proximity of the work zone, and driving a vehicle while impaired.
4. Most of these POV-struck INDOT crash type involved intrusion of POV drivers into the work zone, resulting to a greater extent in a rear-ended collision with a trailer-mounted attenuator (TMA).

The second objective aimed to provide practical recommendations to INDOT and roadway contractors in Indiana regarding optimal lighting arrangements that alleviate, and control disability glare levels experienced by passing motorists and workers on nighttime highway work zones. Field experiments were conducted to determine and evaluate disability glare levels produced by typical lighting systems and under different lighting arrangements in nighttime work zones. A total of 44 lighting arrangements were tested to evaluate the main effects and interactions of the mounting height, power output, light orientation, and aiming angle of luminaires of light towers and balloon lights on veiling luminance ratio ($V_{L\ ratio}$ or disability glare). The findings of the field experiments confirm the following.

1. The veiling luminance ratio complied with the recommended 0.3 limit for roadway lighting design in 30 of the 44 tested lighting combinations. Also, the minimum horizontal illuminance levels suggested Table 5.3, were also obtained (200 lux in average) in all lighting arrangements. These illuminance measurements indicate that the lighting arrangements tested on the simulated work zone provides adequate illumination for the following nighttime operations: hot mix asphalt (HMA) placement, rolling HMA surfaces, asphalt milling, pavement cleaning and sweeping, pavement patching, and work zone flagger stations.
2. An increase in mounting heights of both balloon lights and light towers (LED and metal-halide) resulted in a significant reduction of disability glare levels. A light tower's mounted at 18 ft. and up to full extension of its light mast (typically 30 ft. or 9.1 m) significantly reduces harmful levels of glare created by the lighting configuration to potential drive-by motorists and workers. This lighting system configuration resulted in acceptable levels of glare in observers between 25 to 40 years old. Similarly, a balloon light mounted at 10 ft. (3.1 m) or greater than reduces harmful levels of glare produced by lighting arrangements. These lighting configurations were also notice in observer's age between 25 to 40 years old.
3. Compared to the "perpendicular" and "away" orientations, orienting the light towers (LED and metal-halide) in a "towards" direction (45 degrees) significantly increases the disability glare levels of the lighting arrangement. The veiling luminance ratio values in four lighting combinations of the metal-halide light tower exceed 0.3 which is maximum recommended threshold for veiling illuminance (or disability glare). These values were found on a single metal-halide light tower mounted at 12 ft. and 18 ft., and oriented 45°. These unacceptable levels of glare were found to be similar for observers older than 25 years. In contrast, the veiling luminance ratio values in two lighting combinations of the LED light tower were greater than 0.3 but less than 0.4 which is also a maximum recommended threshold for veiling illuminance (or disability glare) but appropriate for collector roads and for observers between 25 to 40 years old. Unacceptable glare levels were also found in these two lighting combinations for observers older than 40 years.

4. Increasing the tilt angles of luminaires of the LED light tower resulted in an increase in veiling luminance ratio values. Although the increase of aiming angles of luminaries from 45° to 60° tested in all lighting combinations generated by a single LED light tower resulted in significant increment of veiling luminance ratio values, these values did not create harmful levels of glare.
5. 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, for observers older than 50 years old, veiling luminance ratio values were found to be greater than the maximum recommended. For LED light towers, for observers older than 40 years old, the $V_{L\ ratio}$ values exceed 0.3 in three of eighteen lighting combinations tested in this study. 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, for observers between 25 to 50 years old, 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 older than 50 years old, 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.

Based on these findings, the following practical recommendations are provided to reduce and control glare in nighttime highway work zones.

1. Select 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. Hence, owners and general contractors should raise the light towers to mounting heights greater than 18 ft. (5.5 m) and up to full extension of the light mast (typically 30 ft. or 9.1 m) in order to minimize disability glare levels.
2. Select a proper mounting height for balloon lights can also help to prevent higher disability glare levels, but most important, it is critical to choose the equipment's power output. Balloon lights with adjustable power output from 400- to 800-watt were found to generate less glare than those with 300 watts at mounting heights greater than 10 ft. (3.0 m).
3. Aiming light towers in the direction of the traffic movement should be avoided whenever possible 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.
4. LED light towers would be preferred over metal-halide light towers in the "towards" and "perpendicular" orientations due to the lower values of veiling luminance ratio values they generate in each orientation, under similar values of vertical illuminance and mounting heights greater than 18 ft. Careful attention should be taken when evaluating glare on the "towards" orientation because metal-halide light towers produce more harmful levels of glare than LED light towers in motorists and workers older than 50 years.
5. Luminaires of 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 60 degrees. For metal-halide light towers, aiming angle of luminaires less or equal to 45 degrees are recommended 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.

7.1 Limitations and Future Research

This section includes the limitations of the study and recommendations for future investigation regarding (1) work zone safety, productivity, and quality of nighttime operations on roadways (2) determination of the disability glare in nighttime roadway work zones.

1. The work zone safety data analyzed in this study, was limited to only maintenance projects executed by INDOT. As discussed in Section 4.2.2 additional information and data regarding work zone safety, productivity, and quality of roadway construction and maintenance projects executed during daytime/nighttime shifts by *roadway contractors* would be required for deeper analysis. This information may allow researchers to identify the differences between daytime and nighttime operations on roadways. For instance, the analysis of daily/hourly production rates for asphalt pavement operations performed during daytime and nighttime hours might provide information if there are significant differences between operations conducted during the day and those conducted at night.
2. The field experiments conducted to determine disability glare in nighttime work zones had certain limitations listed as follows.

   a. No other vehicle besides the one used (sport utility vehicle (SUV)) to take the measurements (vertical illuminance and pavement luminance) was present during the experiments. Thus, glare produced by headlights of construction equipment and other moving vehicles in and around the controlled work zone was not considered in assessing disability glare. Further research should incorporate the presence of vehicles traveling on adjacent lanes or construction equipment in and around the controlled work zone. Moreover, glare levels experienced by drivers operating different types of vehicles such as trucks should be evaluated.
   b. No other light source (e.g., street lighting and presence lighting) besides the balloon lights and light towers were used during the field experiments. Presence lighting may help to minimize glare levels experienced by drive-by motorists (due to the increase in luminance adaptation levels of the motorists).
   c. Only two types of lighting systems with LED light sources were tested (1) two LED balloon lights and (2) a single LED light tower. However, there are several other lighting equipment with different LED, power output, and setup characteristics that are currently being used on different nighttime highway operations without being evaluated in terms of glare levels they produced. Future study efforts should consider the assessment of disability glare and illumination levels produced by these energy-efficient lighting systems in direct coordination with lighting equipment providers.
   d. The measurements of pavement luminance were taken on a dark asphalt pavement with a rough texture,

typically observed on roadways, and during clear nights. However, other types of road surfaces which are also used on a large number of roadways (e.g., concrete pavement technologies) and the presence of different weather conditions might affect the pavement luminance measurements. Future research should attempt to measure pavement luminance on other road surfaces and under different weather conditions including for instance wet and foggy roads.

e. The disability glare determination steps listed in this study followed the recommended procedure developed by the Illumination Engineering Society (IES). This procedure for determining the veiling luminance ratio (glare) on work zone uses separate measurements of vertical illuminance and pavement luminance. Future investigation 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 in real work zones saving time and without posing safety risks to workers and motorists when lighting data is collected.

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APPENDICES

Appendix A. Survey Instrument for Roadway Contractors

Appendix B. IRB Approval for Deploying Online Survey Instrument for Roadway Contractors

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) ______

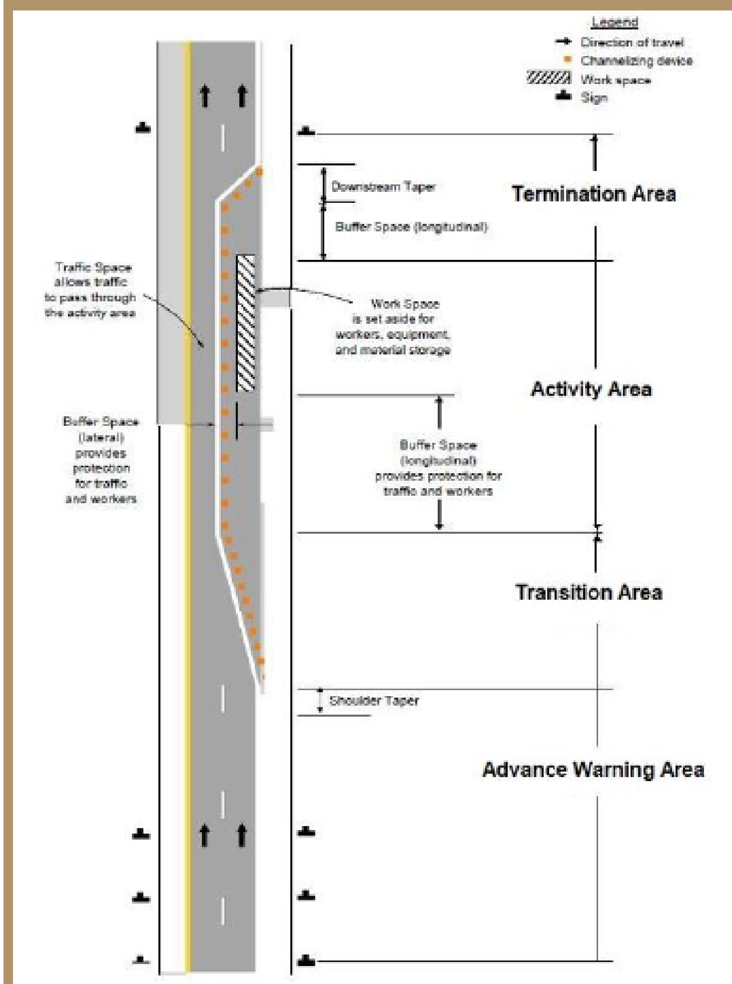
When deciding to select a lighting system on nighttime operations, please rate how each factor is considered in the selection. The scale is 1 to 3.

- 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

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

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