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16. Abstract
This report describes the methodology and results of analyses performed to assess the impact of work zone lighting on motorists. Field studies were conducted to provide insight into how drivers' eyes react to typical temporary work zone lighting configurations in Texas compared to standard lighting situations (i.e., no lighting and standard fixed lighting). Researchers also conducted closed-course studies to evaluate the impact of various work zone lighting scenarios upon the ability of drivers to detect low-contrast objects (e.g., debris) and workers. The findings from these studies, as well as information from a literature review and review of other state agency specifications, were used to develop work zone lighting guidelines for nighttime operations that considered both worker and motorist needs.

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STUDIES TO ASSESS THE IMPACT OF NIGHTTIME WORK ZONE LIGHTING ON MOTORISTS

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Melisa D. Finley, P.E. (TX-90937).

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CHAPTER 1: INTRODUCTION

STATEMENT OF THE PROBLEM

Over the past 10 years, the Texas Department of Transportation (TxDOT) has shifted their priority from building new facilities to maintaining and improving those already in existence. Daytime lane closures for reconstruction, restoration, and rehabilitation work result in heavy congestion on roadways that already operate at capacity. As a result, more construction and maintenance work is being performed at night when traffic volumes are lower. In addition to several obvious advantages of nighttime work, such as cooler temperatures for equipment and material and fewer traffic delays, there are also certain disadvantages. Night work comprises many complex issues and a variety of challenges, which include: lighting conditions, safety, effect on quality, manpower availability, and administrative considerations.

Lighting is one of the most important factors for nighttime construction as it affects motorist and worker safety, quality of work, productivity, and worker morale. In a recent publication by the National Institute for Occupational Safety and Health (NIOSH) concerning work zone safety (*1*), illumination of the work zone was listed as an injury prevention measure. NIOSH also recommended that federal, state, and local policy makers develop a comprehensive consensus standard for the illumination of work zones.

Currently, TxDOT only requires contractors to provide adequate lighting during nighttime work activities to ensure the quality of work and that inspection can occur (*2*). Thus, decisions pertaining to temporary work zone lighting are usually left to the discretion of the site engineer and the contractor, who may feel that existing fixed lighting and/or conventional vehicle headlights are adequate to illuminate nighttime work. However, standard roadway lighting (which is designed to produce minimum average illuminance levels between 3 and 17 lux) is generally inadequate to properly light the area where nighttime highway construction and maintenance work is performed. In addition, conventional vehicle headlights do not produce adequate task lighting and can produce glare for drivers when the vehicle headlights are facing oncoming traffic. Thus, standard roadway lighting or vehicle headlights should not be permitted as the sole means of nighttime highway work illumination.

Work zone illumination guidelines for nighttime highway work do exist, but they are solely based on the visual needs of workers. Research has not been conducted to assess the impact of work zone lighting on motorists approaching and driving through the work zone. So before work zone lighting guidelines for nighttime operations, considering both worker and motorist needs, could be developed, research was needed to investigate the impact of work zone lighting on motorists.

CONTENTS OF THIS REPORT

This report describes the methodology and results of analyses conducted to: 1) assess the impact of work zone lighting on motorists, and 2) develop work zone lighting guidelines for nighttime operations, considering both worker and motorist needs. Chapter 2 documents the state-of-the-practice regarding work zone lighting in the United States. Chapter 3 and Chapter 4 detail the experimental design and findings from the field studies and closed-course studies, respectively. Chapter 5 contains a summary of all of findings and guidelines for work zone lighting for nighttime operations, considering both workers and motorists.

CHAPTER 2:
STATE-OF-THE-PRACTICE

INTRODUCTION

In order to determine the state-of-the-practice of work zone lighting across the U.S., researchers reviewed previous literature regarding the design, selection, application, and measurement of work zone lighting. In addition, researchers contacted state departments of transportation (DOTs) to:

- Obtain work zone lighting standards, specifications, and policies.
- Determine the effectiveness of existing lighting policies and procedures.
- Identify concerns regarding work zone lighting, including the visual needs of workers and motorists.
- Identify technologies being utilized.

Researchers also contacted a sample of key work zone lighting industry representatives to obtain information regarding current and innovative work zone lighting technologies. The following sections describe the findings of these activities.

FIXED ROADWAY LIGHTING DESIGN

This section provides a general overview of fixed roadway lighting design. While the requirements for roadway lighting may differ from those for work zone lighting, there is some similarity in the design criteria, procedures, and parameters used that necessitates a discussion of roadway lighting herein.

Design Criteria

The quality of light represents the ability of observers to identify contrast differences and enables them to detect objects quickly, accurately, and comfortably. Quality of lighting is dependent upon the following (*3*):

- Illuminance.
- Uniformity.
- Luminance.
- Glare.

Lighting requirements are most easily defined in terms of illuminance. Illuminance is the amount of light falling on a surface and is measured in either lux (lx) or foot-candles (fc). Illuminance is an important criterion since it represents the quantity of lighting and significantly affects other lighting criteria. Illuminance may be increased by increasing the intensity of a light source, increasing the number of light sources, or decreasing the distance of light sources from the surface area (*3, 4*).

Uniformity is a design criterion that identifies how evenly light reaches the different parts of the target areas. The uniformity of illuminance is defined as the ratio of the average or maximum illuminance to the minimum illuminance over the work area. The average to minimum ratio is considered to be more practical for highway construction work areas since lighting is usually directed toward the pavement to avoid causing glare to workers and motorists; thus, yielding higher maximum to minimum ratios that do not practically represent the uniformity of the lighting in nighttime construction zones (*3, 4*).

Luminance is the measure of light reflected from a surface (e.g., the pavement) and is the quantitative measure of brightness. It is not affected by distance from the surface being measured and is expressed in candelas per square meter (cd/m^2) or foot lamberts. Pavement luminance depends on several factors including (*3*):

- The quantity of light reaching the pavement.
- Reflection characteristics of the pavement.
- Relative angle of incidence.
- Location of the observer.

Glare is another descriptor of light quality. Glare occurs when the luminance in the visual field is significantly greater than that to which the eyes are adapted. Glare can be direct (i.e., a light source shining directly into the eye) or reflected off the visual task being performed (e.g., pavement). There are two types of glare: discomfort and disability. Discomfort glare is measured subjectively and has no direct effect on vision. In contrast, disability glare (also known as veiling luminance) effectively reduces contrast and thus the visibility of objects (*3, 4*).

Design Procedures

The principal purpose of traditional fixed roadway lighting is to produce quick, accurate, and comfortable visibility at night for roadway users (e.g., motorists, pedestrians). The

Illuminating Engineering Society of North America (IESNA) has a standard practice (*5*) that serves as the basis for design of fixed lighting for roadways, adjacent bikeways, and pedestrian ways. This standard contains three main design procedures for roadway lighting design: 1) the illuminance of the road, 2) luminance of the road as seen by the driver, and 3) the small target visibility for the driver. IESNA recommends minimum maintained average illuminance levels between 3 and 17 lux and minimum illuminance uniformity ratios (minimum/average) between 0.17 and 0.33 for different types of roadways, pedestrian conflict classes, and pavements.

The second procedure (luminance) provides a better correlation for the visual inspection of the quality of roadway lighting design than the illuminance. IESNA recommends minimum maintained average road surface luminance levels between 0.3 and 1.2 cd/m^2 for different types of roadways and pedestrian conflict classes. The minimum luminance uniformity ratios can either be calculated as the minimum to the average or the minimum to the maximum. The recommended minimum luminance uniformity ratios (minimum/average) range between 0.17 and 0.33 and are similar to those for the illuminance procedure. The recommended minimum luminance uniformity ratios (minimum/maximum) range between 0.10 and 0.2.

Small target visibility is a newer procedure that was developed to improve motorist safety and incorporates recent studies of human visual processes. The small target visibility (STV) is the weighted average of the visibility levels of an array of targets on the roadway and the minimum maintained values range between 1.6 and 4.9 for different types of roadways and pedestrian conflict classes. STV assumes an empty road; however, where there is opposing traffic, disability glare from the approaching vehicle's headlamps can reduce the visibility of low-contrast objects. Minimum maintained average road surface luminance values and minimum luminance uniformity ratios (minimum/maximum) are provided, but the actual values are dependent on the separation between opposing traffic streams. The separation distance is important because increasing the separation distance decreases disability glare (*6*).

Disability glare from the luminaires is taken into account in all three procedures. For the STV criteria, disability glare from the road lighting luminaires is included in the calculation of visibility level. For the illuminance and luminance procedures, the maximum veiling luminance ratio, defined as the ratio of veiling luminance to the average road surface luminance, is used. For both procedures, the maximum veiling luminance ratio is 0.3 for freeways, expressways, and major roads, and 0.4 for collector and local roads (*6*).

Design Parameters

The main parameters in designing roadway lighting include: luminaire selection, luminaire mounting height, and luminaire spacing. In the process of luminaire selection, the designer chooses the type of lamp and its distribution characteristics. Each of the main groups of lamps is associated with different characteristics including: lamp life, efficacy, and light output. The other aspect of luminaire selection is the light distribution characteristics, which are controlled by the following three factors: vertical distribution, lateral distribution, and control of light distribution in the upper portion of the luminaire beam (cutoff) (*3, 7*).

The mounting height of the luminaire is another important parameter in designing lighting. In theory, increasing the mounting height of luminaires decreases discomfort and disability glare since it increases the angle between the luminaire and the line of sight (*3*). However, this also decreases the amount of light falling on the pavement surface (illumination) if the wattage or number of fixtures is not increased.

Spacing between luminaires is dependent on the vertical distribution of the luminaire (i.e., short, medium, or long) and its mounting height. In general, it is more economical and desirable to use high candle power luminaires at greater spacing to satisfy illuminance levels and uniformity requirements (*3*).

TYPES OF WORK ZONE LIGHTING

Typically, work zone illumination is provided by three types of lighting systems: temporary (fixed) systems, portable systems, or equipment-mounted systems. The most commonly used are portable systems, equipment-mounted systems, and some combination thereof.

Typically, temporary (fixed) systems use existing or temporary poles to mount standard roadway lighting luminaires such that the entire work zone area is lit. Temporary systems allow luminaires to be uniformly spaced at relatively high mounting heights that result in a uniform lighting with low glare. However, there is potential inefficiency due to illuminating areas of minimal or no activity (*4, 7*). There are also significant costs associated with installation and removal of these light poles.

Portable systems combine the luminaire, power supply, and pole into one device that can be easily moved from one location to another. Trailer-mounted light towers are the most common type of portable lighting system. The spacing, positioning, and low mounting height (12 to 30 ft) of portable systems can result in very non-uniform illumination and severe glare hazard (*4, 7*). Until recently, the limited ability to aim the fixtures on portable light towers also contributed to glare issues. Researchers identified one portable light tower vendor that manufactures a series of portable light towers that have the capability of directing all four floodlights straight down or at a slight angle to the side.

Another type of portable lighting recently available for nighttime highway construction and maintenance activities is balloon lights, which can be attached to towers. Balloon lights have been used by several states (California, Minnesota, and Pennsylvania) to help control glare by distributing the brilliance of visible light (i.e., luminous flux) over a relatively large area (*3, 4*).

Equipment-mounted systems offer better mobility and are useful to increase the level of lighting in front of or behind equipment. Suitable brackets and hardware must be provided to mount lighting fixtures and generators on equipment. Mountings should be designed so that light fixtures can be aimed and positioned as necessary to reduce glare and provide the required illuminance (*4, 7*). Balloon lights can also be mounted on equipment.

Two basic types of lamps are commonly used for work zone lighting: incandescent and electric discharge. Incandescent lamps include general service lamps and tungsten halogen lamps. Advantages of incandescent lights include low initial cost, good color rendering, good optical control capabilities, and instant start ability. Their main disadvantages are low efficacy and short life. In addition, a major concern when these lights are mounted on construction equipment is their sensitivity to vibration (*3, 7*).

Electric discharge lamps include: mercury vapor, metal halide, high-pressure sodium vapor, low-pressure sodium, and fluorescent. Their main advantages are lamp life and improved luminous efficiency. Their main disadvantage is a time delay and slow buildup of light output when the lamps are first turned on or restarted (*7*). Typically, balloon lights have a halogen incandescent or metal halide electrical system inside.

An innovative light source recently available for nighttime highway construction and maintenance activities utilizes solid-state lighting (more specifically light-emitting diodes [LEDs]). Researchers have identified one vendor that manufactures portable LED lighting that is self-sustained with auto solar charging. This portable system can include two or four fixtures, each with 48 LEDs and clear plastic optics. Currently, the mast height is limited to 12 ft.

The type of work zone illumination used is dependent upon the duration of the work activity and geometric constraints. For mobile, short-duration, and some short-term stationary operations, portable lighting may not be applicable since mobile operations can cover long distances during a single work period, and for shorter-duration activities the setup and removal of portable lighting can take longer than to perform the actual work or could considerably increase the amount of time it takes to complete the work activity. Thus, equipment-mounted lighting becomes more critical. For longer duration activities, both portable and equipment-mounted lighting systems may be used. Also, in some cases fixed temporary lighting may be used.

Geometric constraints such as limited or no shoulders, bridges, working adjacent to open lanes of traffic, horizontal and vertical curvature of the roadway, and intersections also affect the lighting design. Nighttime highway work on roadways with limited or no shoulders or on bridges may hinder or completely remove the ability to use portable light towers to illuminate the work area. In such instances, equipment-mounted lighting becomes critical. Glare to motorists is an issue, especially when the work activity is adjacent to open lanes of traffic. Glare is also an important consideration at intersections, since motorists are approaching the work area from multiple directions. Horizontal and vertical curvature may also increase glare to motorists, as well as decrease the illumination provided to the work area by portable lighting towers.

WORK ZONE LIGHTING ILLUMINATION REQUIREMENTS

Previous Research

Recently, illumination guidelines for nighttime highway work were developed as part of National Cooperative Research Program (NCHRP) Project 5-13 (*7*). Researchers recommended the three minimum illuminance levels shown in Table 1 in the work area. Category I (54 lux) is recommended for general illumination in the work zone primarily for safety in the area where the crew is expected to be. This minimum illumination is also recommended for tasks with large objects or low desired accuracy. Category II (108 lux) is recommended for illumination on and around construction equipment and for visual tasks associated with equipment. Category III (216 lux) is suggested for highway tasks that present higher levels of visual difficulty and require significant attention from the observer. Researchers choose to use illuminance criteria since work zone lighting systems are typically temporary and installed by non-engineers with no lighting background.

Table 1. NCHRP Project 5-13 Recommended Minimum Illuminance Levels for Nighttime Highway Construction and Maintenance (7).

Category	Minimum Illuminance Level lux (fc)	Area of Illumination	Type of Activity	Example of Areas and Activities to be Illuminated
I	54 (5)	General illumination throughout spaces	Performance of visual task of large size, medium contrast, low desired accuracy, or for general safety requirements	• Asphalt pavement rolling • Base course rolling • Embankment, fill and compaction • Excavation – regular, lateral ditch, channel • Landscaping, sod, and seeding • Maintenance of embankments • Reworking shoulders • Subgrade, stabilization, and construction • Sweeping and cleaning
II	108 (10)	General illumination of tasks and around equipment	Performance of visual task of medium size, low to medium contrast, medium desired accuracy, or for safety on and around equipment	• Asphalt paving and resurfacing • Barrier wall, traffic separators • Base course, grading, and shaping • Bridge deck • Concrete paving • Drainage structures and drainage piping • Guardrail and fencing • Highway signs • Milling, removal of pavement • Other concrete structures • Pothole filling • Repair of concrete pavement • Repair of guardrails and fencing • Sidewalk construction • Striping and pavement marking • Surface treatment • Waterproofing and sealing
III	216 (20)	Illuminance on task	Performance of visual task of small sizes, low contrast, or desired high accuracy and fine finish	• Crack filling • Highway lighting systems • Traffic signals

These illumination requirements cover the majority of the highway and bridge-related construction and maintenance operations. Determination of the three categories and their minimum illuminance values was influenced by several considerations including:

- IESNA recommended minimum levels for normal activity from the point of view of safety.

- IESNA recommended levels and uniformity ratios for construction activities.
- Occupational Safety and Health Administration (OSHA) required minimum illumination intensities for construction industry.
- Provisions for lighting requirements and guidelines as included in various state specifications for highway and bridge work.
- Opinions and views of various experts.
- Experience of the research team.

As shown in Table 1, researchers also recommended illuminance levels for 29 highway construction and maintenance tasks typically performed at night. These illuminance levels were based on a comparative analysis of typical highway tasks and non-highway tasks that included the following three steps:

1. Identifying factors affecting visual requirements of highway tasks.
2. Selecting a number of outdoor industrial tasks and assigning visual requirement factors to them.
3. Performing a correlation analysis for the different visual requirements and the lighting levels associated with them.

The first step focused on identifying factors that affect nighttime highway construction and maintenance task illumination requirements. These factors, grouped into four main categories, are shown in Figure 1. Based on the factors' significance (as determined through a literature review) and the practicality of assigning meaningful subjective levels, researchers compiled a list of five factors that significantly influence nighttime highway task visibility and their subjective levels (Table 2).

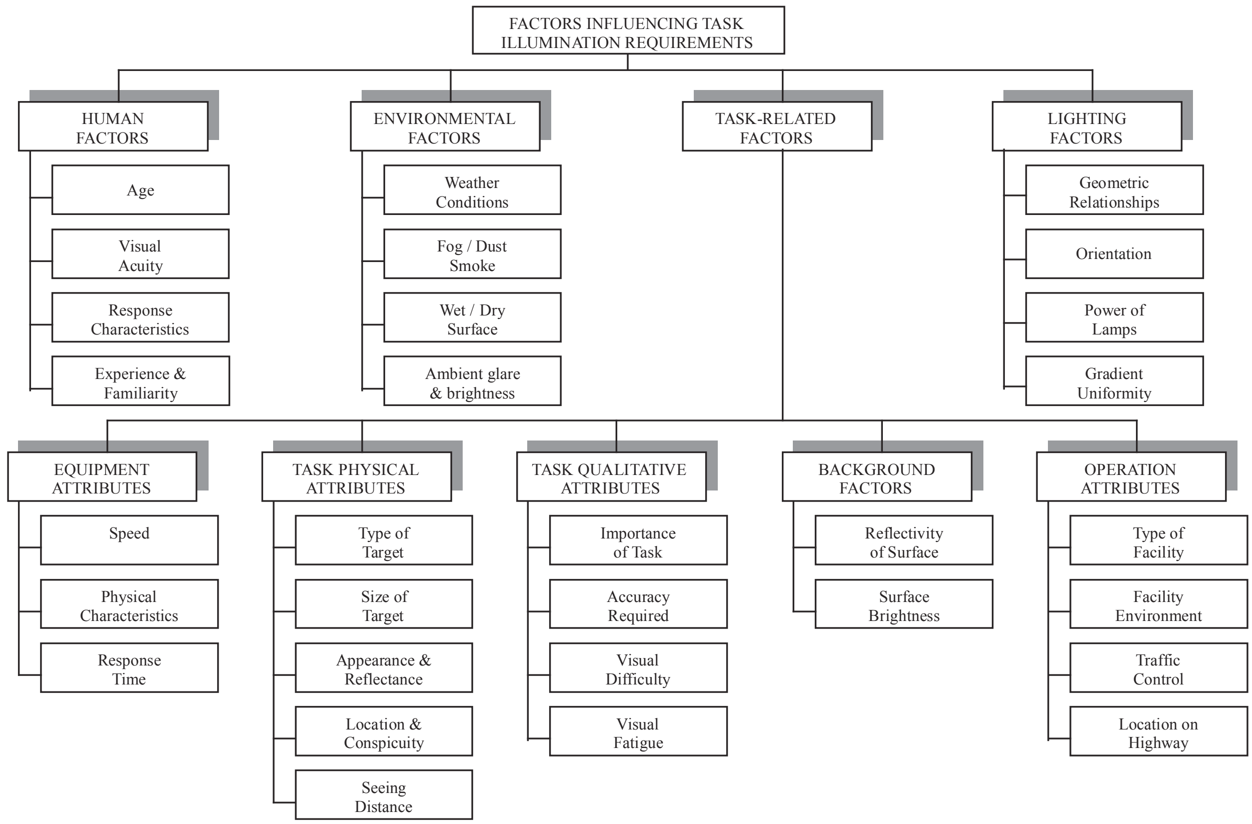


Figure 1. Summary of Factors Influencing Nighttime Task Illumination Requirements (7).

Table 2. Factors Influencing Task Illumination and Their Subjective Levels (7).

Factor	Subjective Level
Importance and accuracy of task	L – Low M – Medium H – High
Background reflection	L – Low M – Medium H – High
Speed	N – Not applicable L – Low M – Medium H – High
Relative size of object to be seen	F – Fine S – Small M – Medium L – Large
Seeing distance of the object from the observer	S – 1 to 5 ft M – 5 to 15 ft H – > 15 ft

Using the factors in Table 2, researchers matched established illumination standards for non-highway construction activities with highway construction activities that have similar visual task requirements. The recommended illumination values for highway tasks shown in Table 1 were based on the following:

- Computed averages of illumination for matching non-highway tasks.
- Current illumination standards and regulations for construction.
- Current state highway agency requirements for illumination.
- Researchers' observations of current practice on nighttime highway construction work.

According to the researchers, these average levels should be maintained over the specific visual task for desired visual performance. Although most tasks require maintenance of illuminance in the horizontal plane, some tasks such as bridge painting, concrete and steel repairs on bridges, and work on overhead signs and sign structures also require that illuminance in the vertical plane be maintained. Illuminance in the horizontal plane is measured with a photocell parallel to road surface, while illuminance in the vertical plane is measured with a photocell perpendicular to the road surface.

As shown in Table 3, researchers also recommended illumination areas for typical highway construction equipment based the equipment's characteristics, its application, and relevant Society of Automotive Engineers (SAE) current practices. Specifically, SAE-recommended practice J1024 (*8*) for forward lighting on construction and industrial machinery provides for adequate illumination for a distance that exceeds the vehicle stopping distance at its maximum operating speed. For simplification, the equipment was classified in two broad categories: slow moving equipment and fast moving equipment. The task illumination levels around the equipment should conform to the categories and minimum levels recommended for various tasks in Table 1. A maximum uniformity ratio of 10:1 in the work area was also recommended.

Work zone lighting can often cause discomfort and/or disability glare to motorists as well as workers. Thus, NCHRP 5-13 researchers also provided a glare control checklist (Table 4).

Table 3. Recommended Illumination Areas for Various Construction Equipment (*7*).

Provide minimum illumination levels over task working areas. This is the effective working width of the machine by approximately 16 ft. Maximum uniformity ratio of 10:1 in the work area. Minimum of average maintained illumination of 54 lux for all work areas.	
Minimum distance from machine to:	
Slow-moving equipment: Paver Milling machine	16 ft
Fast moving equipment: Backhoe loader Wheel loader Scraper Roller Motor grader	65 ft

Table 4. Glare Control Check List (*7*).

Factor	Control Requirement
Beam spread	Select vertical and horizontal beam spreads to minimize light spillage. Consider using cutoff luminaires.
Mounting height	Coordinate minimum mounting height with source lumens.
Location	Luminaire beam axis crosses normal lines of sight between 45 and 90 degrees.
Aiming	Angle between main beam axis and nadir (straight down) should be less than 60 degrees. Intensity at angles greater than 72 degrees from the nadir should be less than 20,000 candela.
Supplemental Hardware	Visors, louvers, shields, screens, and barriers.

After the development of the illumination requirements, NCHRP Project 5-13 researchers visited a nighttime highway construction site to evaluate the applicability of the guidelines. Overall, the three illumination levels appeared to successfully cover the work tasks. However, meeting the maximum uniformity ratio (average illuminance to minimum illuminance) of 10:1 was difficult in some cases.

The work zone lighting requirements recommended in NCHRP Project 17-17 (*4*) were based on the findings from NCHRP Project 5-13 and the *IES Lighting Handbook* (*9*); thus, they are similar to those discussed above (i.e., three levels of minimum average maintained illuminance [59 lux, 108 lux, and 215 lux] and 10:1 maximum uniformity ratio, with 5:1 being more desirable).

As part of the study conducted by El-Rayes et al. (*3*), researchers obtained field personnel's (Illinois DOT resident engineers and contractors) perceptions regarding required lighting levels for 27 possible nighttime highway construction activities. These activities were similar to those included in NCHRP Project 5-13 (*7*). Field personnel selected high, medium, or low lighting for each activity (i.e., specific illuminance criteria was not provided). Researchers computed the percentage of respondents selecting each lighting level for each activity. All of the percentages were then combined into a weighted average score for each activity. The calculated weighted average could range from 1 to 3 with low lighting values ranging from 1 to 1.5, medium lighting values ranging from 1.5 to 2.5, and high lighting levels ranging from 2.5 to 3. Researchers found relatively high agreement between resident engineers and contractors for a majority of the activities.

Based on this analysis, as well as information acquired from professional organizations, and state DOTs, El-Rayes et al. recommended minimum illuminance levels identical to those from NCHRP Project 5-13, except for the following activities:

- Rolling bituminous surfaces and pavements.
- Pavement patching.
- Shoulders: bituminous and Portland cement concrete.
- Sub-base and base courses.
- Work zone setup, take down, and revision.
- Work zone flagger station.
- Work zone access and material handling.

For the following activities El-Rayes et al. recommended a higher minimum illuminance level: rolling bituminous surfaces and pavements (108 lux), pavement patching (216 lux), and shoulder work on bituminous and Portland cement concrete surfaces (108 lux). For one activity (sub-base/base course work), El-Rayes et al. recommended a lower minimum illuminance level (54 lux). El-Rayes et al. also recommended minimum illuminance levels for several activities that were not considered in NCHRP Project 5-13: work zone setup, take down, and revision (54 lux); work zone flagger station (108 lux); and work zone access and material handling (54 lux). In addition to minimum illuminance levels, El-Rayes et al. recommended a lighting uniformity ratio of 6:1 (defined as the ratio of the average illuminance to the minimum illuminance over the work area) and a maximum glare ratio of 0.3 to 0.4 (defined as the ratio of the maximum veiling luminance to the average pavement luminance).

More recently, Hyari and El-Rayes (*10*) developed a framework for identifying the lighting requirements for nighttime highway construction activities. This framework, named *CONVISUAL*, integrates interdisciplinary concepts from construction engineering and vision science to ensure that the specified illuminance levels in a work area are adequate and enable construction workers to see all the critical work details needed to perform their tasks safely and productively. *CONVISUAL* utilizes the following five major phases to develop the required illuminance level for each highway construction activity:

1. Identify all work tasks associated with a construction activity.
2. Identify critical construction details that need to be seen by workers.
3. Field measure visual attributes for construction details.
4. Determine the required luminance levels.
5. Recommend the required illuminance level.

A prototype of *CONVISUAL* was implemented to illustrate its use in identifying the required illuminance level for pavement marking activity. The recommended illuminance level of 110 lux for this particular task is consistent with those recommended in previous research (*3, 7*). Hyari and El-Rayes recommended that *CONVISUAL* be used to determine illuminance requirements for other highway construction activities.

El-Rayes and Hyari (*11, 12*) also developed a decision support system to optimize the design of temporary lighting arrangements for nighttime highway construction projects. This decision support system is comprised of a lighting design model and a multi-objective optimization model. The lighting design model, *CONLIGHT,* is designed to evaluate the impact of all relevant lighting design parameters on the specified design criteria and thus support the development of a practical lighting plan. *CONLIGHT* includes the following lighting arrangement and lighting equipment parameters:

- Number of lighting equipment.
- Number of luminaires.
- Luminaire positioning.
- Mounting height of luminaire.
- Aiming angle of luminaire.

- Rotation angle of luminaire.
- Type of lamps.
- Lamp lumen output.
- Type of luminaire light distribution.
- Light depreciation.

In the decision support system, *CONLIGHT* is used to evaluate the fitness function for each lighting plan according to the three major lighting design criteria: average illuminance, lighting uniformity, and glare. The purpose of the multi-objective optimization model is to search for and identify near optimal lighting arrangements based on four major objectives:

- Maximize average illuminance.
- Maximize lighting uniformity.
- Minimize glare.
- Minimize lighting cost.

El-Rayes et al. (*3, 13*) conducted a number of field experiments to evaluate performance of various lighting arrangements in the following three typical highway construction zones: activity area, transition area, and flagger station. The results showed that commercially available lighting equipment was found to be capable of satisfying the lighting design criteria in existing standards. Researchers also found that setup of lighting equipment on-site had a significant impact on lighting performance, and thus lighting arrangements should be carefully designed and properly positioned on-site.

El-Rayes et al. (*14, 15, 16*) have also conducted research regarding lighting glare for highway construction projects. Researchers measured the levels of glare (i.e., veiling luminance ratio) and lighting performance caused by light towers in a select number of configurations. Tested parameters included the tower's height (vertical distance between center of the luminaries and the road surface), the rotation angle (represents rotation of light tower pole around the vertical axis), and the aiming angle of the four luminaries (vertical angle between the center of the luminaries' beam spread and the nadir. The main findings are as follows:

- The veiling luminance ratios (glare) exceeded the recommended 0.4 limit for roadway lighting design (*5*) in two cases.

- The veiling luminance ratio steadily increased for motorists as they approach the light source and reached a peak between 30 to 50 ft before the 16-ft height light tower and 65 to 80 ft before the 28-ft height light tower.
- The veiling luminance decreased as the height of the light tower increased.
- The rotation angle and aiming angle directly impacted the veiling luminance ratios.
- The average illuminance in the work area for all tested arrangements exceeded 216 lux.
- The lighting uniformity ratio in the work area exceeded the recommended 10:1 ratio in most cases tested (e.g., 13:1).

Based on these findings, the researchers recommended the following to reduce and control glare in and around nighttime work zones:

- Increase the height of light towers as much as practically feasible based on equipment capabilities and surrounding environment.
- The rotation angle and aiming angles should be kept as close to 0 degrees as possible.
- Evaluate glare in critical locations only. Critical in-lane locations appeared to be 30 to 80 ft before the light tower.

Researchers also measured the lighting characteristics of two types of balloon lights and compared them to a conventional light tower. Researchers found that the conventional light tower provided greater illuminance intensity on the ground near the light source than the balloon lights when mounted at the same height. However, disability glare was also greater for the conventional light tower. Again, researchers concluded that increasing the mounting height and reducing the aiming angle decreased glare.

This group of researchers also investigated the practicality of measuring the veiling luminance ratio (i.e., glare) in the field. The researchers found that measuring the components needed to compute the veiling luminance ratio experienced by motorists in the field was not practical since the measurement locations are constrained by safety considerations, the work zone layout, traffic control devices, and other work zone components (e.g., barrier). In addition, costly luminance meters are needed to measure pavement luminance. Thus, the research team developed a model for measuring and quantifying glare experienced by motorists that allowed workers to remain in safe locations within the work zone. However, this model still requires on-site personnel to measure vertical illuminance and enter data into a spreadsheet (requiring a laptop). In addition, the model was only calibrated to a select number of light configurations; thus, its ability to model the variety of lighting situations encountered in the field is a concern.

Federal and Professional Organization Standards

The lighting levels recommended in the 2009 *Manual on Uniform Traffic Control Devices* (MUTCD) (*17*) and 2011 *Texas Manual on Uniform Traffic Control Devices* (TMUTCD) (*18*) were based on the recommendations from NCHRP Project 5-13. Both manuals require that flagger stations be illuminated at night, except in emergency situations. Floodlights should be used to illuminate the work area, equipment crossings, and other areas, but they must be placed and aimed such that they will not produce disabling glare for approaching road users, flaggers, or workers. The adequacy of light placement and elimination of potential glare should be determined by driving through the lit area from each direction on all approaching roadways after the initial setup and periodically throughout the night. Desired illumination levels vary depending upon the nature of the task involved, but an average horizontal luminance of 54 lux can be adequate for general activities. An average horizontal luminance of 108 lux can be adequate for activities around equipment. Tasks requiring high levels of precision and extreme care can require an average horizontal luminance of 216 lux.

In a recent publication by NIOSH concerning work zone safety (*1*), illumination of the work zone was listed as an injury prevention measure. When installing lighting within a work zone, personnel should ensure proper illumination for the work space, while controlling glare so as not to blind workers and passing motorists. This can be accomplished by lowering the height of lighting equipment or considering the use of glare-free light balloons and glare screens. It is also recommended that federal, state, and local policy makers develop a comprehensive consensus standard for the illumination of work zones. The standard should include: 1) minimum lighting levels needed for each work task, 2) types of light sources recommended for both portable lighting and equipment-mounted lighting, 3) minimum area to be illuminated around each type of equipment, and 4) recommendations for placement of both portable lighting and equipment-mounted lighting. The publication then references the NCHRP Project 5-13 illumination recommendations.

OSHA regulations for minimum illuminance levels for different construction operations are shown in Table 5 (*19*). For some tasks, the OSHA standards are generally less than what has been recommended in previous highway work zone lighting research. Furthermore, the OSHA standard does not address lighting uniformity or glare.

Table 5. OSHA Minimum Illuminance Levels (*19*).

Area of Operation	Minimum Illuminance lux (fc)
General construction areas, concrete placement, excavation and waste areas, access ways, active storage areas, loading platforms, refueling, and field maintenance areas	32 (3)
General construction area lighting	54 (5)
Indoors: warehouses, corridors, hallways, and exitways	54 (5)
Tunnels, shafts, and general underground work areas (Exception: minimum of 108 lux is required at tunnel and shaft heading during drilling, mucking, and scaling)	54 (5)
General construction plant and shops (e.g., batch plants, screening plants, mechanical and electrical equipment rooms, carpenter shops, rigging lofts and active store rooms, mess halls, and indoor toilets and workrooms)	108 (10)
First aid stations, infirmaries, and offices	323 (30)

The International Commission on Illumination (CIE) has published recommendations for lighting external work areas including building sites which address illuminance levels, uniformity, and glare (*20*). As shown in Table 6, the CIE recommended values for illuminance vary by task as did previous highway work zone lighting research. However, CIE recommendations for uniformity ratios and glare rating vary by task as well. In general, the CIE recommendations tend to be similar to the recent highway work zone lighting recommendations.

In 2009, the American National Standard Institute (ANSI) released a new standard regarding work zone safety for highway construction (*21*). This standard requires all projects operating at night to have a nighttime operations illumination plan containing the following elements:

- Layout showing location of light towers or other light sources.
- Lighting calculations confirming the illumination requirements will be met by the layout.

- Description of light towers or other light source to be used and power source to provide uninterrupted power.
- Description of how glare will be controlled.

Table 6. CIE Recommended Illuminance and Uniformity Ratio Values (*20*).

Areas to be Lit	Operations Performed	Maintained Average Horizontal Illuminance Not Less Than (lux)	Uniformity Ratio Not Less Than		Glare Rating Not Greater Than
			Minimum/ Average	Maximum/ Minimum	
Work Area or Task	Very rough work	20	0, 25	8	55
	Rough work	50	0, 40	5	50
	Accurate work	100	0, 40	5	45
	Fine work	200	0, 50	3	45
Traffic Areas	Pedestrian passage, vehicle turning, loading and unloading points	50	0, 40	5	50
Safety and Security	General lighting on building site	50	0, 40	5	50

For minor night work, a written plan may not be necessary, but the relevant provision listed above should be addressed. The minimum illumination requirements shown in Table 7 must be met and the uniformity ratio (average illuminance to minimum illuminance) shall not exceed 5:1. In addition, all lighting shall be designed to minimize glare to oncoming traffic by extending tower lights to their full working height where feasible. The use of balloon lighting instead of light towers is encouraged to reduce glare.

Table 7. ANSI Minimum Illumination Requirements (*21*).

Operation	Minimum Illumination lux (fc)
All areas of the work zone, including tapers, at night during work time and during setup and removal of the traffic control devices	50 (5)
Flagging operations, paving operations, milling, concrete placement operations, and/or removal operations including bridge decks	100 (9)
Any tasks requiring fine detailed work (e.g., repair work or equipment installation)	200 (19)

IESNA is currently in the process of developing guidance on evaluating requirements for lighting the roadway in work zones to provide visibility for road users transiting through or adjacent to the work area (*22*). This draft guidance states that additional road lighting should be considered for roadway users under the following circumstances:

- Presence of adjacent high intensity work area lighting, relative to the surrounding ambient light levels.
- Abrupt changes in the roadway alignment; including lane reductions.
- The area in which the work area is located has a medium to high pedestrian conflict area classification.
- High traffic volumes.
- A fixed roadway lighting system already exists in the work area – the existing lighting levels should be maintained, and possibly augmented.
- The work area location is identified to have operational problems (e.g., high night time crash rate).

The draft document also contains the guidelines for lighting travel lanes in long duration work zones in Table 8. Long duration work zones are occupied for greater than three nights.

The draft document also addresses illumination of flagger stations. To make the flagger visible to approaching traffic, special attention should be paid to lighting the flagger station at night. Since positioning the flagger near permanent roadway lighting normally does not provide adequate illumination, it may be necessary to provide temporary lighting for the flagger station. The use of parked vehicle headlights to illuminate the flagger station is undesirable since it may create glare. The flagger should not be placed in a backlighted situation, since this configuration makes it difficult for the motorist to observe the flagger's instructions. Instead, lights used to illuminate the flagger station should be mounted high enough to light the flagger from the front or above and in such a manner that they do not create glare for approaching motorist or create shadows such that the flagger is not positively illuminated.

The draft document states that lighting for work areas can adversely impact the visual performance of all roadway users traveling through or adjacent to the work zone, even if the roadway itself is lighted. Thus, the impact of a work area lighting system on the driver's visual environment, and potential for adverse impacts on driver performance, must be considered.

Table 8. Draft IESNA Guidelines for Lighting Travel Lanes in Long Duration Work Zones (22).

Highway Type	Activity	Existing Lighting	Lighting Required	Maintain Lighting	Provide Lighting [a]
Rural Highway	No on-going work at night	No	No	NA	No
		Yes	Yes	Yes	NA
	Work on-going at night	No	Yes	NA	Yes
		Yes	Yes	Yes	NA
Urban Streets	No on-going work at night	No	No	NA	No
		Yes	Yes	Yes	NA
	No on-going work at night but major diversions in alignment	No	Yes	NA	Yes
	Work on-going at night	No	Yes	NA	Yes
		Yes	Yes	Yes	NA
Freeway	No on-going work at night	No	No	NA	No
		Yes	Yes	Yes	NA
	No on-going work at night but major diversions in alignment	No	Yes	NA	Yes
	Work on-going at night	No	Yes	NA	Yes
		Yes	Yes	Yes	NA

NA = Not Applicable
[a] Lighting should meet the relevant criteria established in the latest edition of RP-8 (*5*).

Inappropriate placement of high intensity lights may create disability glare and reduce visibility. Light trespass onto the travel lanes can also adversely affect the uniformity of the lighting design in the travel lanes. In addition, visual difficulties can extend beyond the immediate work zone due to abrupt changes in light levels.

The draft guidance recommends that the veiling luminance ratio should never be greater than 0.3 (maximum/average) (*5*). Glare from work area lighting experienced by motorists may be mitigated by the following:

- Not aiming lights upstream toward oncoming traffic.
- Ensuring that both the light source and any reflector in the optical system are not directly visible to the driver.
- Increasing the illumination levels in the travel lanes.

Transition lighting is not normally required for work zones. However, lighting levels in the travel lanes may be set above the lighting levels typically recommended (*5*) to reduce the veiling luminance ratio or because tasks being performed in the work area may require lighting levels significantly higher than existing roadway lighting levels and the same system is used to light the work area and travel lanes. The draft guidance recommends the following regarding transition lighting.

- If the lighting level in the work zone travel lanes is greater than three times the level outside the work zone, transition lighting should be installed using the guidance for departure zone lighting for toll plazas.
- If the roadway is not lighted beyond the work zone, transition lighting should be installed when the average illuminance level in the travel lanes within the work zone is greater than 10 lux.

Summary

Table 9 contains a summary of the general illumination guidance identified through a review of previous research and federal and professional organizations standards. Most of these recommendations include at least three minimum average illuminance levels based on the type of work activity, a maximum uniformity ratio, and address the issue of glare.

Table 9. Summary of Illumination Recommendations.

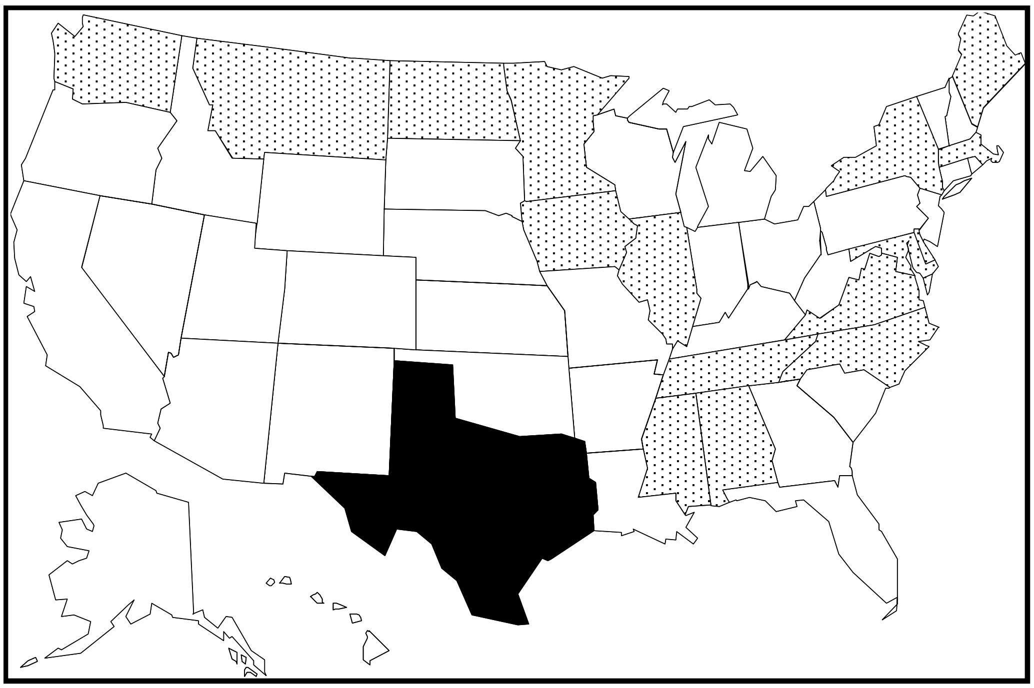
Reference	Minimum Average Illuminance Levels (lux)	Maximum Uniformity Ratio	Illumination Area Around Equipment	Glare Addressed
NCHRP 5-13 (*7*) and NIOSH (*1*)	Level I – 54 Level II – 108 Level III – 216	10:1	Slow moving – 16 ft Fast moving – 58 ft	Yes
NCHRP 17-17 (*4*)	Level I – 59 Level II – 108 Level III – 215	10:1	Not specified	Yes
Illinois Report (*3*)	Level I – 54 Level II – 108 Level III – 216	6:1	Not specified	Yes
MUTCD (*17*) and Texas MUTCD (*18*)	54, 108, & 216	Not specified	Not specified	Yes
OSHA (*19*)	32, 54, 108, & 323	Not specified	Not specified	No
CIE (*20*)	20, 50, 100, & 200	Varies by activity	Not specified	Yes
ANSI (*21*)	50, 100, & 200	5:1	Not specified	Yes

STATE AGENCY PRACTICES

In order to determine the state-of-the-practice regarding work zone lighting practices in the U.S., researchers conducted a survey of other state transportation agencies and obtained work zone lighting standards, specifications, and policies from other states (hereafter referred to specifications). The following sections describe the findings of these activities.

State Transportation Agency Survey

Researchers conducted interviews with 16 state transportation agency personnel regarding their work zone lighting specifications and any problems encountered while implementing their specifications. In addition, researchers identified concerns regarding work zone lighting and if any innovative work zone lighting devices have been used in their state. Figure 2 shows the state transportation agencies contacted.



Black dots = Completed survey and provided specification
White = No response
Black = Texas

Figure 2. Map of State Transportation Agency Survey Data.

All of the state transportation agencies contacted conduct night work, and 14 of the agencies have a work zone lighting specification. Most of the specifications apply to construction and contracted maintenance operations. Agency inspectors and/or resident engineers are primarily responsible for ensuring that the specification is followed in the field. A few states require detailed lighting plans be submitted and approved before beginning work. A few states also require that the contractor supply the agency inspector/engineer with a photometer capable of measuring illumination. Issues with regard to implementing work zone lighting specifications included:

- The term "adequate" is often interpreted differently by the contractor, field staff, and policy makers.
- Initial compliance with the specifications can be difficult, especially if some agency field personnel are more stringent than others.
- Although lighting plans may be approved prior to beginning work, field adjustments are often needed to ensure work is occurring in appropriately lit areas and glare is mitigated. Consequently, continual oversight is needed by agency field personnel. Thus, ensuring that the specification is followed in the field depends on the diligence of agency field personnel.
- Implementation of lighting in mobile and short duration work zones remains an issue.

Researchers also asked the state transportation agency personnel if they had experienced any problems with insufficient lighting, non-uniformity of the lighting, and glare from the lighting. Several states mentioned that insufficient lighting tends to occur most frequently at flagger stations. Also, sometimes contractors are found working in dark or dimly lit areas (e.g., staging areas that are separate from the primary work area, fringes of the work zone). With respect to non-uniformity of the lighting, some contractors illuminate only spot work locations instead of the entire work area. Shadows can also make it difficult for workers to see their work, especially around equipment.

Glare to motorists was the most prominent work zone lighting issue that state transportation agencies are still trying to address. Eight of the state transportation agencies interviewed have received complaints from motorists regarding glare in nighttime work zones. In most work zone lighting policies, glare is described in a qualitative manner; thus, it is measured subjectively in the field. Traditional lighting towers can create glare when they are not positioned correctly, which can occur if the contractors and agency field personnel do not consider the placement of lighting in relation to approaching vehicular traffic. Also, problems with traditional light towers are often not identified until after they have been erected and illuminated. However, once traditional light towers are in place and illuminated, it is time-consuming to make adjustments since the lamps get very hot and take time to warm up. Even if the lighting is positioned such that it is not creating glare for one direction of travel, it may be causing glare in the other direction of travel, especially on divided highways or roadways that differ in elevation.

To address the issues involved with implementing work zone lighting policies, state agencies have developed training to expand awareness of the specification, increase understanding of why the specification is needed, and emphasize specification expectations. Most states require contractors and agency field personnel to drive thru the work zone throughout the night to check for work zone lighting problems (e.g., personnel working in dark or dimly lit areas, glare). In addition, most agencies emphasize the need to drive thru the work zone in both directions to evaluate glare. State agencies also utilize existing work zone review teams to assess nighttime lighting in work zones.

The New York State Department of Transportation (NYSDOT) has purchased and supplied each region with photometric equipment to help quantify the measurement of light. NYSDOT personnel can use these measurements to ensure compliance and demonstrate problem areas to the contractors. In 2005, NYSDOT used temporary (semi-permanent) high mast lighting and mobile stadium lighting to illuminate a nighttime work zone on a major interstate project in an effort to provide more uniform light at sufficient lighting levels and to reduce glare (*23*, *24*). To address shadows around equipment, the Tennessee Department of Transportation (TDOT) now specifies lighting requirements based on the type of vehicle present in the work zone (e.g., asphalt spreaders, rollers, and sweepers).

Most of the states interviewed are also using balloon lights (tower and equipment mounted), which are designed to reduce glare. In Tennessee, balloon lights are the predominate nighttime lighting source and are required on all paving equipment (e.g., pavers, milling machines, material transfer devices, graders, rollers).

State Transportation Agency Specifications

Through the survey of state transportation agencies and an internet search, Texas A&M Transportation Institute (TTI) researchers obtained work zone policies and procedures from all but three states. In 2010, about one-third of the state DOTs had specific provisions included in their construction specifications that addressed nighttime work zone lighting requirements. Table 10 contains a summary of the general illumination guidance provided by a sample of state DOT policies, and Table 11 contains a summary of illumination guidance that is provided for specific equipment or work operations.

Table 10. Summary of State Agency Illumination Recommendations.

State	Minimum Average Illuminance Levels (lux)	Maximum Uniformity Ratio	Light Plan Required	Light Meter Provided or Used	Glare Addressed
California (25)	32, 54, 108, & 324	Not specified	No	No	No
Delaware (26)	50, 108, & 216	Not specified	No	No	Yes
Florida (27)	54	Not specified	Yes	Yes	No
Illinois (3, 28)	Level I – 54 Level II – 108 Level III – 216	10:1	No	Yes	Yes
Iowa (29)	54	Not specified	Yes	Yes	No
Louisiana (30)	Level I – 54 Level II – 108 Level III – 215	Not specified	Yes	Yes	Yes
Maine (31)	Level I – 54 Level II – 108 Level III – 215	Not specified	Yes	No	No
Maryland (32)	215	Not specified	Yes	No	Yes
Massachusetts (33)	105	4:1	No	Yes	No
Michigan (34)	54 & 108	Not specified	Yes	Yes	Yes
Mississippi (35)	108 & 216	10:1	Yes	Yes	Yes
Missouri (36)	54	Not specified	Yes	No	Yes
New Jersey (37)	54, 108, & 215	No specified	No	No	No
New York State (38)	Level I – 54 Level II – 108 Level III – 215	5:1	Yes	Yes	Yes
North Carolina (39)	108 & 215	Not specified	No	No	Yes

Table 11. State Agency Equipment Illumination Area Requirements.

Type of Equipment or Operation	Reference	Area to be Illuminated	Minimum Average Illuminance Level (lux)
Paving machine	Maine (31)	50 ft ahead/100 ft behind	108
	Massachusetts (33)	At screed area and immediately behind where manual raking is occurring (minimum 15 ft)	110
	Michigan (34)	Paver – 100 to 200 ft behind Roller – 50 to 100 ft ahead & behind	108
	New Jersey (37)	25 ft ahead/25 ft behind/ 10 ft to each side	108
		100 ft ahead & behind	54
	New York State (38)	50 ft ahead/100 ft behind	100
		400 ft ahead/800 ft behind	50
	Rhode Island (40)	At screed area and immediately behind where manual raking is occurring (minimum 15 ft)	108
	South Carolina (41)	50 ft ahead & behind	108
Milling machine	Maine (31)	50 ft ahead/100 ft behind	108
	New Jersey (37)	25 ft ahead/25 ft behind/ 10 ft to each side	108
		100 ft ahead & behind	54
	New York State (38)	50 ft ahead/100 ft behind	100
		400 ft ahead/800 ft behind	50
	South Carolina (41)	50 ft ahead & behind	108
Planing machine	Massachusetts (33)	20 ft ahead and behind	55

A comparison of these provisions reveals some consensus among state DOTs regarding the minimum average illuminance levels, with the minimum typically being 54 lux. In addition, most states with nighttime lighting policies require different minimum level based on the work activity. Among the state DOT standards reviewed, lighting uniformity requirements were only included in the Illinois, Massachusetts, Mississippi, and New York State DOT standards. In addition, the illumination area around equipment was only defined in seven of the state DOT standards. Approximately 60 percent of the state agencies that define minimum average illuminance levels require the contractor to submit a lighting plan. Similarly, approximately 50 percent require the use of an illuminance meter to check the illumination on-site, with most of these agencies requiring that the contractor provide the device. Most states acknowledge the need to minimize glare from nighttime work zone lighting, but few states provide specific, quantitative guidance on how to do so.

CHALLENGES AND RECOMMENDATIONS

Overall, previous research efforts have yielded similar recommendations for minimum average maintained illuminance levels, maximum uniformity ratios, required illumination areas around various construction equipment, and glare control measures. These recommendations are based on past practice, correlation to illumination standards for non-highway construction tasks, and subjective evaluations. Of course, it would be desirable to evaluate the visual needs of workers while completing various nighttime highway construction and maintenance activities; however, this would be an arduous undertaking, even with tools such as *CONVISUAL*, considering that each piece of equipment and each activity have unique task lighting requirements. Since the work zone illumination guidelines currently available do appear to be appropriately developed and defendable, researchers believe that further evaluation of the minimum illumination levels from a worker perspective was not needed.

While work zone illumination guidelines for nighttime highway work do exist, most of them only consider the visual needs of workers. However, as discussed, high intensity lights can create disability glare and reduce visibility for motorists. In addition, light trespass onto the travel lanes can adversely affect the uniformity of the lighting in the travel lanes. Therefore, researchers recommended the conduct of actual field studies and controlled-field (proving ground) studies to assess the impacts of work zone lighting on motorists' ability to safely navigate through the work zone and adequately detect workers. The actual field studies, documented in Chapter 3, provided insight into how drivers' eyes react to typical temporary work zone lighting configurations currently being used in Texas compared to standard lighting situations (e.g., no lighting and standard fixed lighting). The findings from the field studies were also used to help design the controlled-field studies, which evaluated the impact of various work zone lighting scenarios upon the ability of motorists to detect low-contrast objects (e.g., debris) and workers. The controlled-field studies are discussed in Chapter 4.

CHAPTER 3: FIELD STUDIES

INTRODUCTION

To provide insight into how drivers' eyes react to typical temporary work zone lighting configurations currently being used in Texas compared to standard lighting situations (i.e., no lighting and standard fixed lighting), researchers conducted field studies at two work zones. Researchers performed the field studies at night during summer 2011. The following background section briefly describes the human eye, night vision, and the impact of age on the eye. This section is followed by information regarding the experimental design and results of the field studies.

BACKGROUND

Nighttime driving is more difficult than daytime driving for various reasons that revolve around night vision, or the ability of drivers to see at night. This section includes a brief overview of the general physiology of the human eye and how it relates to nighttime driving.

The majority of people have stereoscopic vision, because they have two eyes. Each eye consists of rods and cones, where cones render images in color and rods provide gray scale images. The cones are concentrated on the center of the back of the eye and are associated with foveal vision. Foveal vision could be described as the high-resolution detailed vision and provides approximately two degrees of detailed viewing, about the width of a person's thumb extended out in front of him/her. Rods, on the other hand, provide lower resolution gray scale imagery information and are not present within the fovea but make the vast majority of the photoreceptors within the eye. To put this in perspective, there are over 100 million receptors in the eye with approximately 20 rods for every 1 cone. Peripheral viewing extends outside the foveal and primarily consists of rods with cones intermixed. Every person's vision blurs and color degrades as it moves into the periphery. The impact of rods and cones differ dependent on lighting conditions, which then relate us back to photopic, scotopic, and mesopic vision (*42*).

Photopic vision occurs in lighted conditions above approximately 10 cd/m^2 (*42*). Photopic vision is rich in color and resolution, but the quantity of light makes the eye less sensitive to lower lighting conditions. For instance, a person can clearly see the detail of the mountain on a sunny day, but the cave in the face of the mountain just appears as a dark hole.

Scotopic vision is the other extreme where there is little to no light, such as a starry night without any other light source (*42*). Depending on the source referenced, scotopic vision starts below either 0.1 or 0.001 cd/m^2 (*42, 43*). In nighttime driving, scotopic vision is not typically encountered due to the use of headlights by a driver, oncoming headlight glare, and other light sources and retroreflective objects within the nighttime driving scene. The lighting range between photopic and scotopic vision is referred to as mesopic vision.

Typically, a driver of a single vehicle on a rural road is using mesopic vision, obtaining lighting levels ranging from 0.01 to 10 cd/m^2 from vehicle headlight interaction with the roadway and various traffic control devices. When vehicle lighting from other traffic, street lighting, and other lighting sources along the roadway are incorporated into the driving scene, drivers will periodically transition between mesopic and photopic vision, depending on the proximity of their foveal viewing to bright light sources.

The importance of the above discussion is that the lighting levels under which drivers operate significantly affect pupil size and response. The average pupil diameter of the human eye ranges from 2 to 8 mm. For younger drivers (mid-20s), the minimum and maximum pupil size correlates to the overall average range. However, for older drivers (mid-60s), the minimum and maximum pupil size ranges from approximately 3 to 5 mm (*42*). This means that older drivers will have greater difficulty with seeing dim objects along the road and are more susceptible to glare.

Exposure to bright lights (i.e., glare) can create impairment in at least two ways through latency response and recovery. Latency response is the time duration prior to the pupil responding. While the human eye can constrict in the presence of bright light sources as quickly as 0.25 seconds and longer for lower intensity stimuli (*44*), latency by connotation means that the eye will have diminished capacity during that latency period before the eye starts to constrict. Older drivers will have an even longer latency response. A good example of latency would be when someone turns on the interior light in a vehicle, and it initially “shocks” the occupants’ eyes with the drastic change. Everyone’s eyes quickly adjust, but that adjustment takes time. Full adaptation from light to dark can take anywhere from 20 to 45 minutes, while fully adapting from dark to light only takes about 5 to 7 minutes, depending on the person and the conditions (i.e., 3 to 9 times faster).

Drivers that have been exposed to a bright light or glare source now must have their eyes adjust back to their previous state. The time to recovery depends on that previous state and what additional exposures may occur through recovery. During that recovery period, the driver's ability to distinguish dimmer objects is impaired (*43*), so the length of the recovery and the amount of the impairment can be critical in the nighttime driving environment. When considering age, older drivers can take as much as three times longer to recover (*45, 46*).

Another factor affecting nighttime vision while driving is that of veiling luminance. Veiling luminance is a term developed to quantify disability glare and results from additional light flooding into the eye that creates internal light scatter. This scatter diminishes a person's ability to see contrast between an object and its background (*47, 48*). The effect is like placing a thin veil in front of the driver's eye, allowing what is on the other side to still be seen, but the contrast between different objects is diminished.

When driving at night, a driver's eyes adjust to the ambient lighting condition by adjusting pupil size to control the amount of light entering the eye. The ability for a driver's eye to adjust is dependent on the amount of light, proximity of the light, and the driver's unique physiological capabilities. The latency response and veiling luminance can be impairments to drivers. Depending on the lighting conditions that are associated with the change, a driver's ability to detect dim objects may be impaired during the brighter conditions. For instance, driving from a rural unlit roadway into a lit urban roadway will provide overall improved ambient conditions, so this may not impair vision, but driving by an overly bright gas station along a rural road will impair a driver's ability to see into the dark roadway just past the gas station. This leads back to recovery where a driver's ability to see dimmer objects will be impaired for a period of time following exposure to brighter driving conditions. When considering nighttime work zone conditions, the impact of the ambient lighting conditions can be critical with the myriad of different changes to be expected within a work zone.

EXPERIMENTAL DESIGN

Researchers used in-vehicle equipment to document the site characteristics and reaction of drivers' eyes to temporary work zone lighting in two work zones. The following sections describe this equipment, the field data locations, participants, and study procedure.

Equipment

Through the use of the TTI instrumented vehicle (2006 Toyota Highlander) shown in Figure 3, researchers were able to collect the following data in the field:

- Vertical illuminance near the driver's eyes.
- Luminance of the forward facing scene.
- High-definition color video of the forward facing scene.
- Left and right eye pupil diameter.
- Where the driver was looking in the forward facing scene.
- Latitude and longitude.

Figure 3. TTI Instrumented Vehicle.

Researchers used a Minolta T-10 illuminance meter and the TTI mobile field luminance system to ambient lighting conditions with respect to time. The researchers placed the T-10 illuminance meter in the passenger seat near the driver eye height and oriented the meter to measure incoming light traveling parallel to the roadway in front of the vehicle. One field mobile luminance camera was placed on each side of the illuminance meter in a manner to avoid blocking incoming light, while accurately capturing what each driver viewed with respect to field luminance of objects within the forward driving environment. The mobile luminance system consisted of two V-Lambda-corrected, 12-bit gray scale cameras. Two cameras were used to ensure that a similar field of viewing to that of the forward scene camera used for tracking each driver's eyes was obtained. The illuminance meter reported at 1 Hz, and the mobile luminance system was set to report at 5 Hz. The high-definition (1080p) color video provided researchers with documentation of the study route, including temporary lighting, for each driver.

Figure 4 depicts the FaceLAB™ system used. This system includes two cameras and infrared pods used to track the driver's eyes and measure the diameter of their pupils. In addition, a forward facing scene camera was used in conjunction with the eye tracking system to document where the driver was looking.

Figure 4. Eye Tracking System on the TTI Instrumented Vehicle's Dash.

A global position system (GPS) was used to collect latitude, longitude, and speed data. GPS data were collected at 5 Hz. The researchers synchronized all data by time and in some cases also used the GPS data. Researchers also collected subjective opinion data from the participants as they traveled through the nighttime work zone.

Locations

Researchers collected driver eye, photometric, and site characteristic data at two work zones in Texas. The first work zone was in the Dallas-Fort Worth (DFW) area at the interchange of State Highway 114 and State Highway 121, known as the DFW Connector Project (*49*). Figure 5 shows that major reconstruction was taking place on several multi-lane highways (red, blue, green, and purple sections). Due to the nature of the work, the majority of the existing fixed roadway lighting was either removed or non-functional. During data collection, none of the temporary work zone lighting was in the traveled way. Instead, the majority of the temporary work zone lighting was offset from the traveled way. In a few locations, the temporary work zone lighting was immediately adjacent to the traveled way. Both portable light towers and balloon lighting were used. Since this work zone was in a major urban area, there was also various commercial lighting along the frontage road system.

Figure 5. DFW Connector Project Map (*49*).

The second work zone was in the Bryan-College Station (BCS) area on State Highway 6 between Harvey Mitchell Parkway (south) and Farm-to-Market (FM) 2818 (north). At this location, nighttime resurfacing required one travel lane to be closed each night. Figure 6 shows that the temporary work zone lighting consisted of balloon lighting on the paver and other equipment-mounted lighting on the paver and rollers (in addition to standard headlights). Portable light towers were not used since the work activity area was mobile within the lane closure. Fixed lighting was active, but only located at interchanges within the study corridor. There was also various commercial lighting along the frontage road system.

Figure 6. Paver and Roller in Bryan-College Station.

Participants

Research was conducted using a total of 12 human subjects as the driver of the TTI instrumented vehicle (five in DFW and seven in BCS). In order to have a representative sample, participants varied in gender and represented the following different age groups due to the previously discussed effects that age has on the eye:

- 18 to 34.
- 35 to 54.
- 55 or older.

Overall, half of the participants were male and half were female. Forty-two percent of the participants were in the 18 to 34 age category, 33 percent in the 35 to 54 age category, and 25 percent in the 55 or older age group. All participants had a visual acuity of at least 20/25 (normal or corrected) and were not color blind.

Study Procedure

Upon arrival, each participant checked in and a briefing took place. A researcher provided participants with an explanation of the study, which included that they would be driving a state-owned vehicle equipped with instrumentation that allowed researchers to measure various data, but operated and drove like a normal vehicle. Participants then read and signed an informed consent document. Participants had their visual abilities assessed through three tests: visual acuity, contrast sensitivity, and color blindness. These screenings provided comparison information for data reduction and ensured that all participants had at least minimal levels of acceptable vision prior to beginning the study. No participants were disqualified from the study based on these screenings.

Once in the vehicle, a researcher calibrated the eye-tracking equipment for each participant. Participants were then instructed to comment on anything, while driving, that helped or made it more difficult for them to travel through the work zone. Researchers did not specifically instruct participants to comment on the temporary work zone lighting, since this might have made the participants focus on the lighting (i.e., looked at more or longer than normal).

Participants then drove through the roadway sections shown in Table 12. In both cities, the first section was a dark section with no existing fixed lighting or temporary work zone lighting. The second section included only existing fixed lighting. In DFW, the existing fixed lighting was continuous throughout the section and mainly in the median. In BCS, the existing fixed lighting was intermittent and located mainly at entrance and exit ramps. The remaining sections in both cities contained temporary work zone lighting, as previously discussed.

After driving through each work zone section, participants were asked several questions regarding the design of the work zone. Upon completion of the driving task, participants were asked questions specifically about the work zone lighting.

DATA REDUCTION

First, researchers compiled all the raw output data files, except luminance data, into a spreadsheet for each participant. Through the use of time stamp and GPS data, the vertical illuminance and pupil diameter raw data were correlated. Within the study sections previously described, the dataset included 393,517 observations. According to the eye tracking system used, in order to obtain an accurate reading of the pupil diameter the gaze quality parameter must be a three. All data that had a gaze quality less than three were removed from the data set. As discussed previously, the pupil diameter typically ranges from 2 mm to 8 mm; hence all data that had a diameter less than 2 mm or greater than 8 mm were also eliminated from the data set. After these initial screenings, the data set included 313,759 observations (approximately 80 percent of the total observations).

Table 12. Field Study Roadway Sections.

City	Section	Average Length (miles)	Road	Description
Dallas-Fort Worth	1	1.9	IH 635 Southbound	No existing fixed lighting; some commercial lighting
	2	0.7	SH 114 Westbound	Continuous existing fixed lighting in the median; commercial lighting
	3	4.1	SH 114 Westbound to SH 121 Southbound	Temporary work zone lighting; commercial lighting
	4	5.8	SH 121 Northbound to SH 114 Eastbound	Temporary work zone lighting; commercial lighting
	5	6.6	SH 114 Westbound	Temporary work zone lighting; commercial lighting
	6	4.9	SH 114 Eastbound to SH 121 Northbound	Temporary work zone lighting; commercial lighting
Bryan-College Station	1	7.0	SH 6 Northbound and Southbound	No existing fixed lighting; very limited commercial lighting
	2	2.2	SH 6 Southbound	Intermittent existing fixed lighting in the median; some commercial lighting
	3	1.9	SH 6 Southbound	Temporary work zone lighting; commercial lighting
	4	1.3	SH 6 Northbound	Temporary work zone lighting; commercial lighting

IH = Interstate Highway; SH = State Highway

The eye tracking system measured the pupil diameter of each eye separately. A review of the pupil diameter for each eye revealed some large differences between the two measurements within one observation period (typically 0.033 seconds). Thus, researchers calculated the difference between the left and right pupil diameter for each observation period for each participant and plotted the data. The histograms revealed that the pupil size differences were normal distributions. Researchers then applied the following three interval limits to the aggregated data:

- 95th-percentile confidence interval.
- 15th and 85th percentiles.
- A range of all values within 1.96 standard deviations of the mean (a variation on the confidence interval, where the standard deviation is not divided by the square root of the sample size).

Researchers found that applying the 95th-percentile confidence intervals would exclude 99 percent of the observations. This interval was very narrow because of the large sample size. Conversely, the interval computed as mean ±1.96 times the standard deviation included 96.3 percent of the observations. In addition, the interval defined as mean ±1.96 times the standard deviation resulted in keeping all observations within the bell portion of the plot as well as the shoulders but excluded observations on the tails, which were believed to be anomalous. In contrast, the interval defined by the 15th and 85th percentiles excluded some observations on the shoulders of the distribution, which were thought to be accurate. Hence, researchers decided to screen all eye-tracker data such that observations with a pupil size difference in excess of 1.96 standard deviations away from the mean were excluded. A further comparison of the means for participant/study section combinations and the means for the data aggregated by study section revealed that it would be necessary to apply the pupil size difference screen using means and standard deviations that were computed separately for each combination of participant and study section to account for the effects of these variables on pupil size difference.

Researchers then verified that all of the vertical illuminance data were greater than zero. The device used to measure illuminance reported one data value per second. In contrast, the eye tracker device (which measured pupil size) reported 30 data values per second. To facilitate time-series trend comparisons between the pupil size and illuminance measurements, researchers linearly interpolated the illuminance data between actual illuminance measurements to yield illuminance values for every pupil size observation. In the final dataset, researchers averaged the right and left eye pupil diameter data for each observation period to yield an average pupil diameter for each illuminance value.

After these final screenings, the data set included 302,164 observations (approximately 77 percent of the total observations). The Statistical Analysis Software (SAS) program was then used to compute descriptive statistics for the illuminance and pupil size data for each combination of participant and study section, as well as for data aggregations across participants, across study sections, and across the entire data set. These statistics included:

- Mean.
- Standard deviation.
- Maximum.
- Minimum.

RESULTS

The data collected in Bryan-College Station and in Dallas did verify the effects of driver age on pupil size and ability of the pupil to change size. As shown in Figure 7 and Figure 8 for the entire data collection route, one sees a strong negative correlation in mean pupil size as a function of driver age and a less strong (but still evident) negative correlation in the standard deviation of pupil sizes. Mean pupil sizes for 20- to 30-year-old drivers were in the 6.0 to 7.5 millimeter (mm) range, as compared to 3.5 to 5.0 mean pupil sizes for the 50- to 60-year-old driver. Likewise, the standard deviation of pupil sizes decrease from approximately 0.7 mm at 20 years of age to around 0.3 mm at 60 years of age.

To mitigate the confounding effects of driver age and differences in the visual driving scene upon pupil size changes (a key variable of interest in this analysis), researchers then examined the correlation between participant age and the coefficient of variation in pupil size. The coefficient of variation (CV) essentially normalizes the magnitude of changes in a variable (i.e., its standard deviation σ) by the mean of that variable (μ):

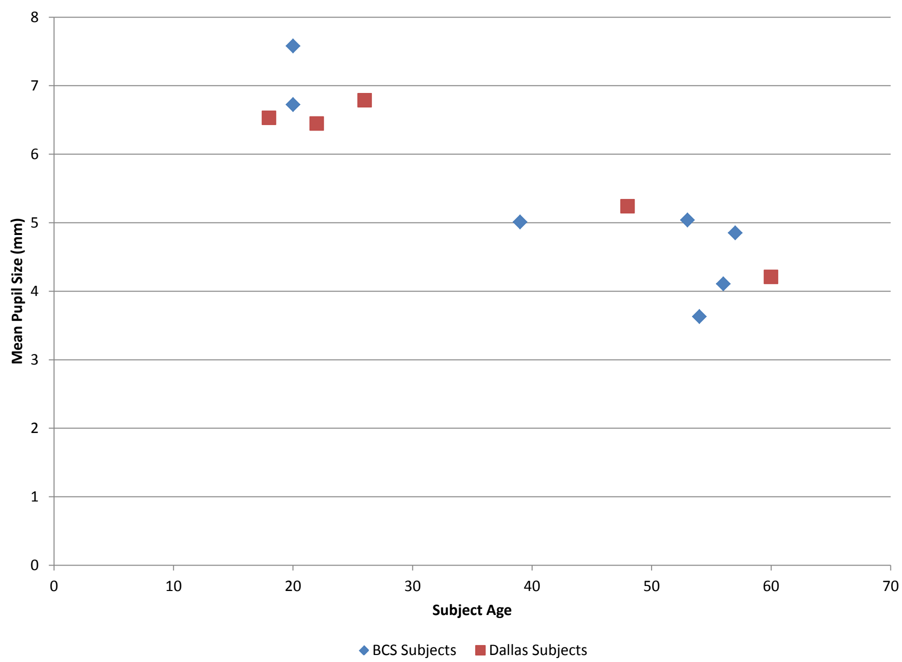


Figure 7. Mean Pupil Size as a Function of Age.

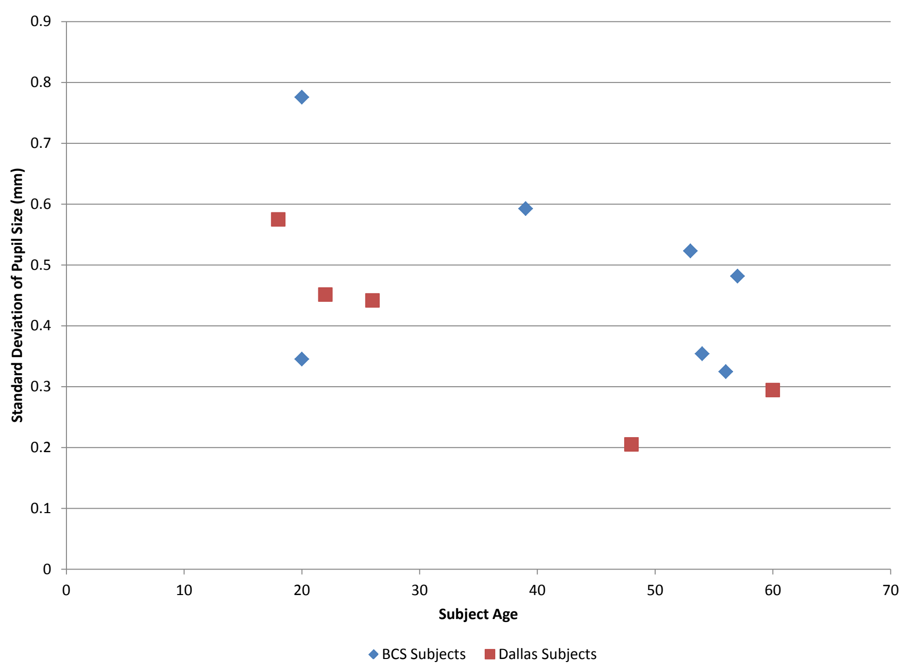


Figure 8. Standard Deviation of Pupil Size as a Function of Age.

As shown in Figure 9, participant age and pupil size CV over the entire data collection route have little, if any, correlation to each other. The pupil size CV for Dallas subjects does seem to be less than that of the BCS subjects, which could be a function of the higher traffic volumes present on the Dallas facilities. Greater volumes imply more frequent oncoming headlight illumination, which could keep pupil sizes reduced with less change in pupil size from point to point as the subjects traversed the study route.

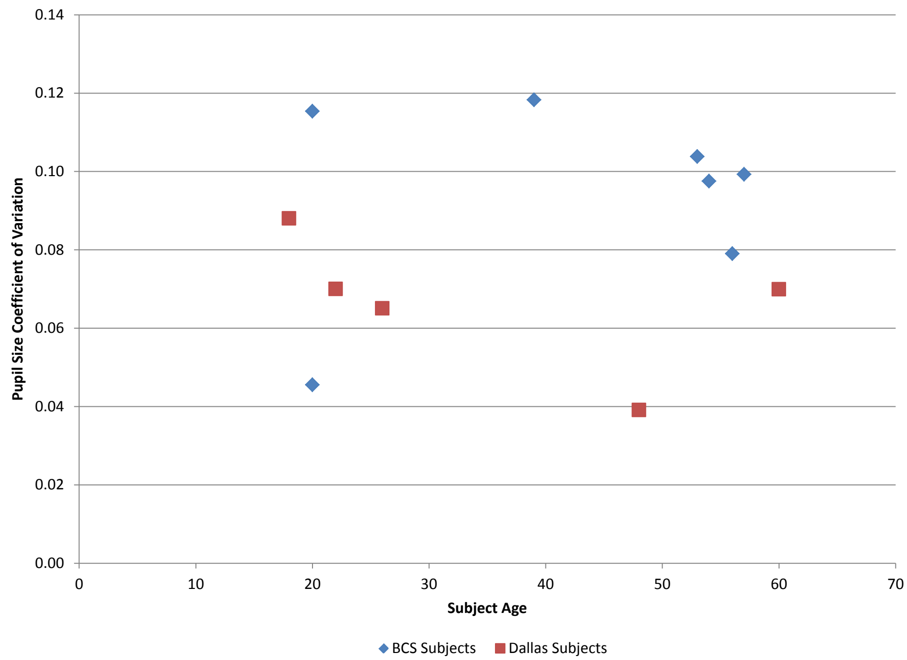


Figure 9. Pupil Size Coefficient of Variation as a Function of Age.

Considerable effort was then expended by the research team in assessing how participant pupil sizes adjusted as oncoming vehicle headlights, roadside and roadway lighting elements, and work zone lighting sections were encountered. Pupil sizes and changes in pupil size were compared to illumination values obtained point by point along the study travel route in the hope that illumination data and pupil size or pupil size changes could be correlated. Unfortunately, this was not found to be the case. Although pupil size is indeed influenced by the overall amount of light (illumination) falling upon the eye, the focus point (foveal length) also appears to significantly affect it as much if not more. As shown in Figure 10, a plot of participant pupil size versus illumination at the same point along the roadway does show segments of good correlation (e.g., between 0 and 7 seconds) where the pupil size is decreasing when the illuminance is increasing or vice versa. However, there are multiple locations where the pupil size and illumination both decrease or increase simultaneously (e.g., 8 seconds, 16 seconds). Referring back to the eye-tracker data at this point, one sees that the participant was actually focusing far downstream at an upcoming work zone light that caught the driver's attention (i.e., strobe on work truck and equipment-mounted roller/paver lights, respectively). The participant apparently focused on the lighting in the work space, resulting in a reduction in pupil size. Although the amount of light falling upon the pupil from that light source was fairly small due to the significant distance to the light source, the researchers believe that the focusing action of the eye on that source functioned in the same way that sunlight can be focused through a magnifying glass onto dry tinder to start a fire. The work zone lighting rays were, in effect, focused on the retina of the eye and caused a reduction in pupil size. This pattern was observed numerous times in the data, and precluded any direct attempts at developing predictive relationships of pupil size for an individual as a function of roadway illumination.

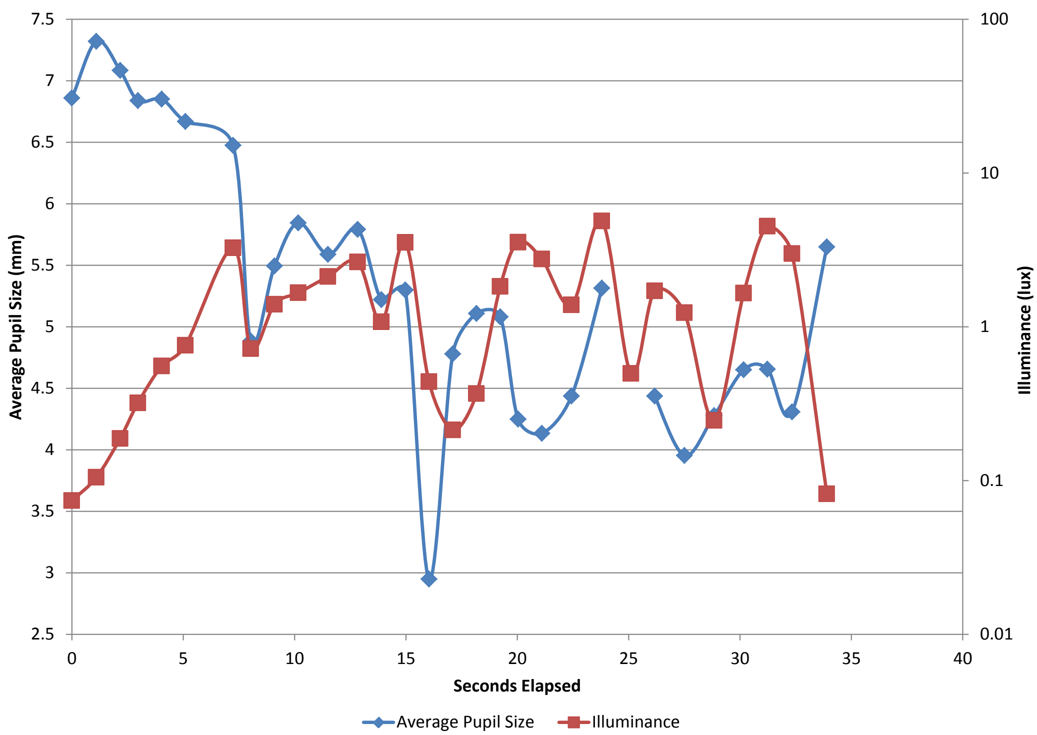


Figure 10. One Participant's Average Pupil Size versus Illumination.

Researchers then examined the relationship between pupil size and luminance values obtained point by point along the study travel route where the participant was looking in the hope that luminance data and pupil size or pupil size changes could be correlated. While pupil size and luminance appeared to be more strongly correlated than pupil size and illuminance, the post-processing of the data was extremely data-intensive as each still picture (collected five per second) had to be analyzed individually to calculate the luminance of the area where the participant was looking. Based upon this knowledge and experience with developing a mobile luminance system for static retroreflective traffic control devices, researchers determined that at this time a feasible tool to assess real-time illumination in nighttime work zones based on pupil size, illuminance, or luminance could not be developed.

Given that a point-by-point matching of illumination or luminance and pupil size as participants traversed the study route would not yield meaningful results, researchers turned to an overall assessment of the association between pupil size CV of each participant and the corresponding illumination CV in normal (non-work zone) and work zone segments along the driving route. Researchers hypothesized that higher normalized changes in illumination over a roadway segment, even if they could not be matched point by point along the segment to pupil size changes, might still be a reasonable predictor of higher levels of pupil size variation and support the contention that high levels of illumination provided at work zones for worker task performance may adversely affect driver nighttime vision capabilities. As Figure 11 illustrates, this was indeed found to be the case, with higher illumination CV associated with higher pupil size CV. The association between illumination and pupil size CV is not particularly strong, however, undoubtedly due to significant variation in pupil response from participant to participant. In addition, the overall trend does not provide a clear indication as to whether work zone illumination significantly adds to pupil workload, especially in environments with higher volumes, continuous roadway lighting, and/or frequent and intense off-roadway lighting for advertising, business frontage, etc. Therefore, researchers chose to pool the means and variances of the individual participants across the various field study sections of the driving routes (as defined in Table 12) and then develop pooled CVs of both pupil size and illumination. These results are illustrated in Figure 12 and Figure 13.

As Figure 12 illustrates, the same association trend between pupil size and illumination CVs was evident when both were pooled by field study section. More importantly, the pooled values in Figure 13 indicate that some (but not all) work zones do indeed result in higher variability in both illumination values and pupil sizes reacting to the illumination variability, even if the response between the two cannot be easily predicted at an individual driver level. This trend was evident even though much of the data under non-work zone conditions were collected in the Dallas region where roadway lighting, oncoming headlight glare, and roadside lighting is fairly high.

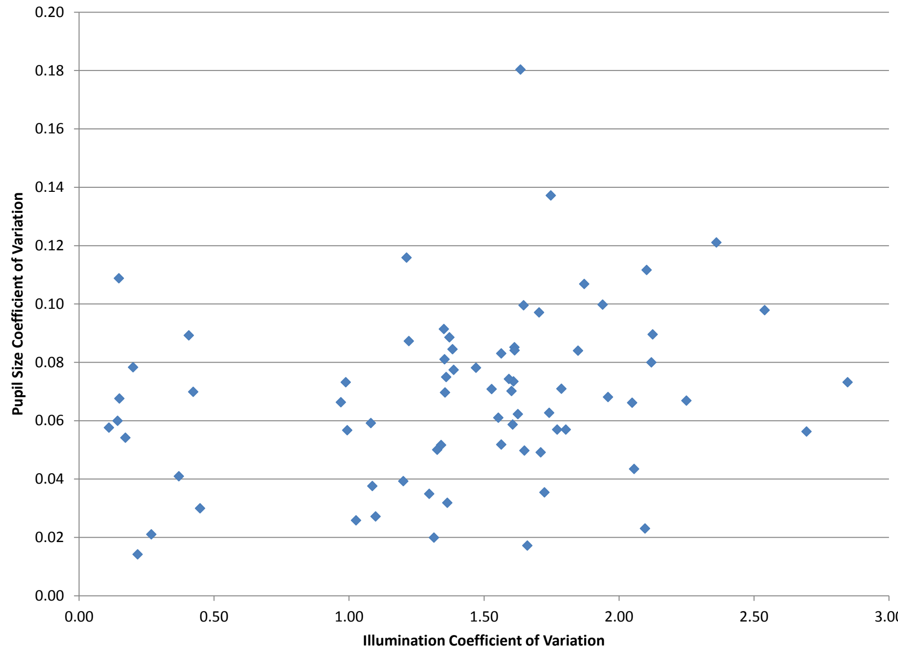


Figure 11. Pupil Size CV versus Illumination CV across All Participants and Field Study Sections.

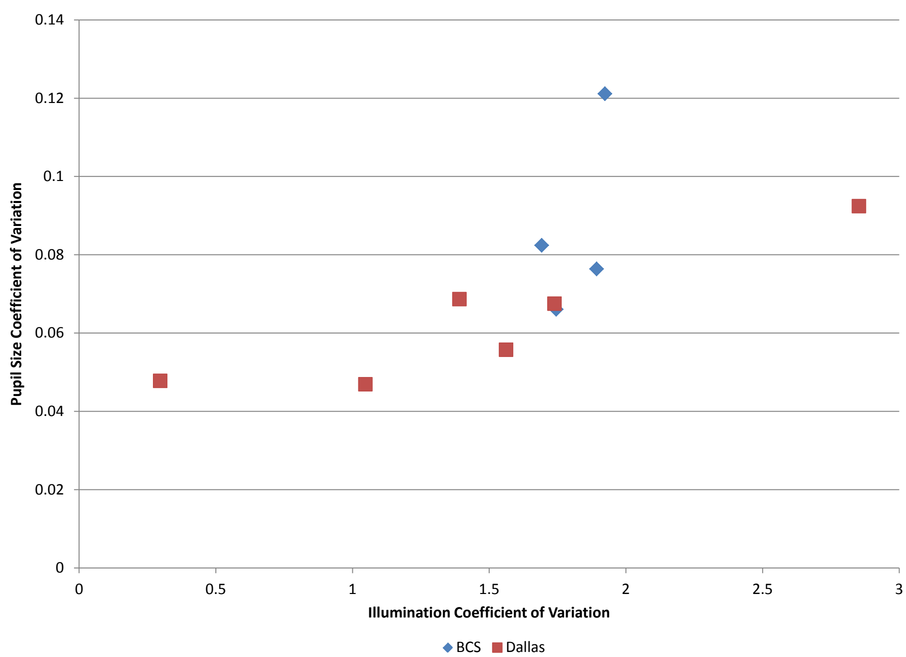


Figure 12. Pooled Pupil Size CV and Illumination CV for Each of the BCS and Dallas Field Study Sections.

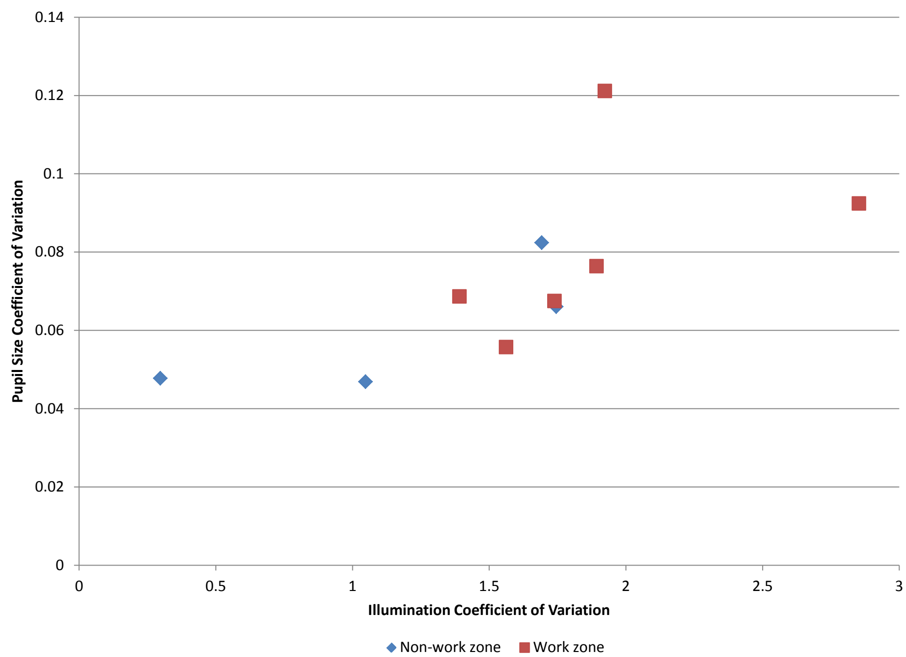


Figure 13. Pooled Pupil Size CV and Illumination CV according to Whether the Field Study Section Was in a Work Zone or Not.

SUMMARY AND CONCLUSIONS

Overall, the results of the field studies were somewhat mixed. On the one hand, researchers were unable to devise a mechanism that easily correlated pupil size changes to changes that occur in illumination or luminance as a driver traverses a roadway segment approaching and passing by an active nighttime work zone. It is believed that the continuous process of the driver eye focusing back and forth on both near and far-away illumination sources is not adequately captured through simply illumination measurement techniques such as was used in this study. While luminance may have been a better predictor of pupil size, the inability to post-process these data in a real-time environment currently limits its application. Consequently, it was not possible to devise a process to use illumination or luminance data obtained while driving through a work zone to indicate where pupil size changes were likely to occur so that some type of remedial action could be taken with the lighting sources to reduce such pupil size variability.

On the other hand, several general trends in terms of driver pupil size and pupil size variability either verified or uncovered as a result of these field studies. As expected, pupil sizes in general are correlated with participant age, with older drivers generally having small pupil sizes on average. Likewise, pupil size changes in response to different lighting levels as one traverses a roadway segment are also age-dependent. Normalizing those changes via the use of the coefficient of variation does appear to reduce these age-related effects. Furthermore, the pupil size CV was found to indeed be associated to illumination CV in the various field study sections and more importantly, that both the illumination and pupil size CVs tended to be higher than what is normally encountered by drivers even when traveling in urban environments with significant traffic volumes (and oncoming headlights), roadway lighting, and significant roadside business lighting.

Although the field studies were able to answer several key questions as to how work zone lighting affects driver pupil workload, it still was not able to determine at what level of workload does operational performance and safety become affected. At an even more fundamental level, it was not possible to determine if driver ability to detect and recognize hazards approaching, within, and even beyond the work space in the work zone was being adversely affected by the illumination changes and resulting pupil size changes occurring. Therefore, researchers initiated controlled-field studies to further examine the effects of work zone lighting on driver visual performance. These studies are described in the next chapter.

CHAPTER 4:
CLOSED-COURSE STUDIES

INTRODUCTION

The findings from the field studies were used to help design the controlled-field studies, which evaluated the impact of various work zone lighting scenarios upon the ability of motorists to detect low-contrast objects (e.g., debris) and workers wearing high-visibility vests. Researchers conducted the controlled-field studies at night during summer 2012. The following sections describe the experimental design, data reduction, and results of the controlled-field studies.

EXPERIMENTAL DESIGN

The study took place on a closed-course located at the Texas A&M University (TAMU) Riverside Campus in Bryan, Texas, over a nine-night period. The following sections describe the participants, treatments, vehicles and instrumentation, photometric data collected, and study procedure.

Participants

Researchers collected data for 30 participants from the Bryan-College Station, Texas, area. Participants varied in gender and represented two age groups, which characterized younger and older adult vision capabilities (i.e., 18 to 34 and 55 plus). Overall, half of the participants were male and half were female. In addition, half of the participants were 18 to 34 years old and half were at least 55 years old. All participants had a visual acuity of at least 20/40 (normal or corrected) and were not color blind.

Treatments

Participants were asked to identify four objects that were located 2 ft from the edge line of the simulated roadway: a gray visibility target (7 inches high by 7 inches wide by 0.5 inches deep), a brown box (6.5 inches high by 12 inches wide by 9.25 inches deep), a tire (75 R15, 8 inches high, 27 inches diameter), and a construction worker. The gray visibility target, small brown box and tire represented low-contrast debris that may be found in a work area (Figure 14).

Using three low-contrast objects also reduced the learning effect. The construction worker was dressed in blue scrubs, a Class 3 Level 2 vest, and no hardhat (Figure 15). Although this outfit represented a slightly worse-than typical viewing condition (without hardhat), it did allow the researchers to assess the detection and effectiveness of a high-visibility vest design at nighttime work zones. For safety reasons the objects could not be located any closer to or in the travel lane.

a) Gray Visibility Target.

b) Small Brown Box.

c) Tire.

Figure 14. Low-Contrast Objects.

Figure 15. High-Contrast Worker.

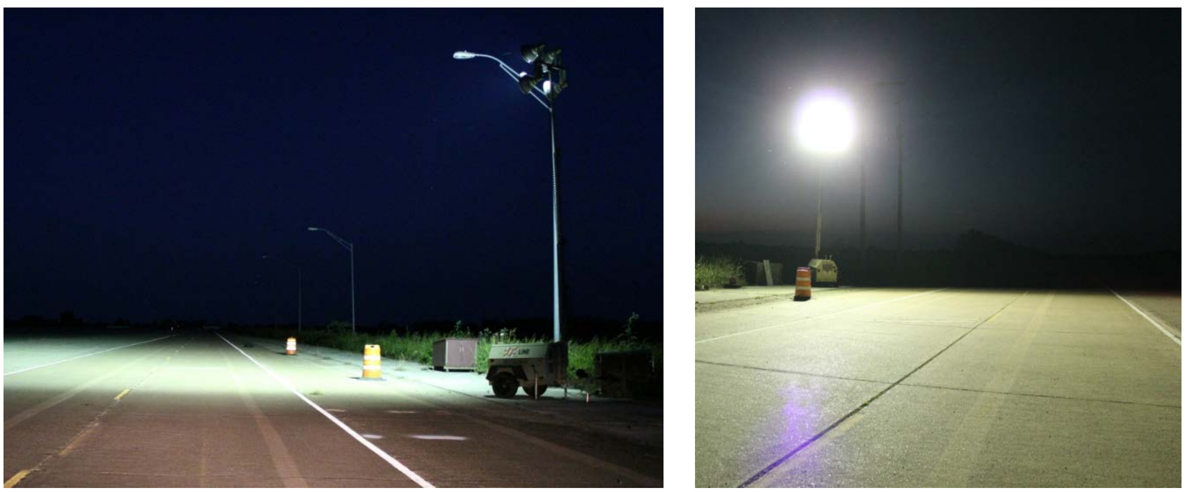
Three lighting conditions were set up on the course on separate runways: a dark region (no lights), a portable, trailer-mounted light tower rented from a local traffic control company (Figure 16), and a portable balloon light borrowed from a vendor (Figure 17). The dark condition provided data regarding detection distances with only the vehicle's headlights and thus was considered the base condition. In order to produce an intentional glare situation, the portable light tower was aimed down the simulated roadway in the southbound direction.

Participants drove both northbound and southbound along the course past both temporary work zone lighting conditions. Since balloon lights evenly distribute light over an area, the light emitted from the device was similar in both directions (Figure 18). Figure 19 shows that for the portable light tower, participants driving southbound traveled with the direction of the lights (no glare), while participants driving northbound traveled against the direction of the lights (glare).

Figure 16. Trailer-Mounted Light Tower.

Figure 17. Balloon Light.

Figure 18. Northbound Approach to Balloon Light.



a) Southbound (No Glare). **b) Northbound (Glare).**

Figure 19. Approach to Portable Light Tower.

Under each temporary work zone lighting condition, there were three possible positions for the objects: positions 1, 2, and 3. Figure 20 and Figure 21 show the locations of these three positions with respect to the balloon light and portable light tower, respectively. Position 2 was located near the light where there was an illuminance level of approximately 54 lux (minimum illuminance level recommended for general construction and maintenance work). Position 1 and position 3 were located where participants would be entering and leaving the lit areas, and the illuminance level was approximately 2 lux at these locations. Since the balloon light provided a more uniformly distributed light, position 1 and position 3 were positioned at equal distances from the light support (60 ft). With the portable light tower, however, the light was angled in such a way that resulted in position 1 being much closer to the portable light tower than position 3 (10 ft and 165 ft, respectively). One standard construction barrel was located approximately halfway between each object position (two total) to replicate work zone traffic control devices that could be found in nighttime work zones.

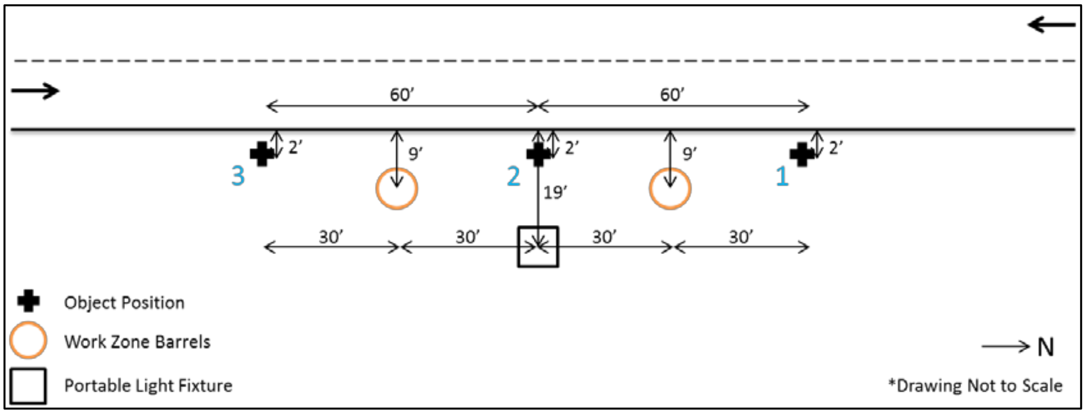


Figure 20. Dimensions and Layout for Balloon Light.

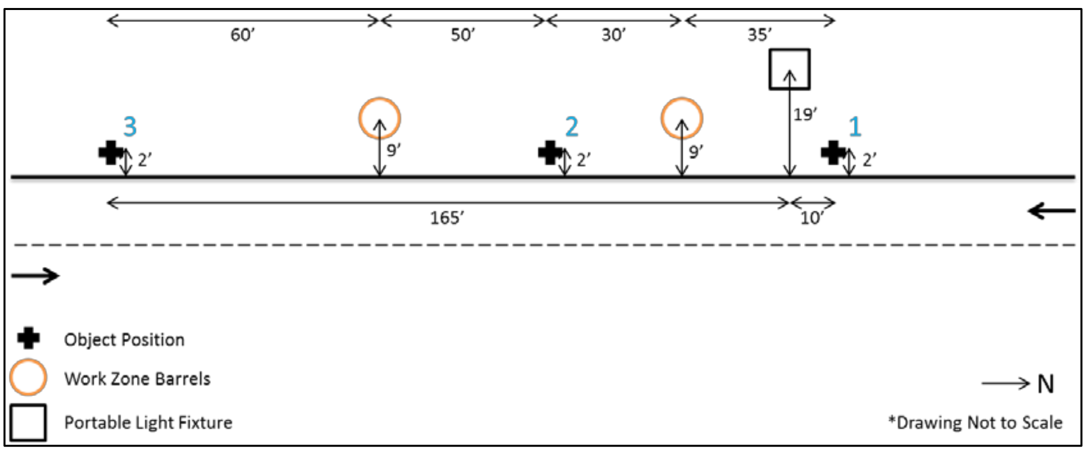


Figure 21. Dimensions and Layout for Portable Light Tower.

Overall, there were 52 treatments used, separated into three treatment orders. Each treatment order consisted of the four base treatments (i.e., each object under dark conditions) and 16 different temporary work zone lighting treatments (object, lighting, and position varied). To reduce learning effects and to keep the duration of the study reasonable, each participant saw only one treatment order.

Vehicles and Instrumentation

The study utilized two state-owned vehicles, both 2009 Ford Explorers, with the headlights aimed according to the manufacturer's instructions. A GPS was mounted on the windshield and connected to a laptop with data collection software. A researcher was present in the back seat of the vehicle at all times with two primary goals: 1) safely navigate each participant through the course, and 2) operate the data collection equipment during testing. Using an ASCII tag system in the software, the researchers indicated when the participant began a course run and when the participant identified an object.

Photometric Data

Each night, at the beginning of the study, staff took horizontal illuminance measurements on the pavement at each of the three object positions for each lighting condition. Table 13 shows the averages and standard deviations of the horizontal illuminance values collected each night of the study. As previously stated, when the object was placed at the light, the horizontal illuminance value should have been approximately 54 lux; however, due to natural conditions that changed from night to night (e.g., wind), the actual values for each position 2 varied. The horizontal illuminance value at each position 1 and 3 also varied from the planned 2 lux.

Table 13. Horizontal Illuminance Descriptive Statistics.

Light Type	Position	Sample Size	Average (lux)	Standard Deviation (lux)	Minimum (lux)	Maximum (lux)
Portable Light Tower	1	9	2.93	1.37	1.15	4.94
	2	9	49.30	4.46	44.80	56.80
	3	9	2.41	0.33	1.77	2.87
Portable Balloon Light	1	9	2.09	0.11	1.94	2.28
	2	9	65.07	2.30	61.80	69.40
	3	9	2.14	0.13	1.92	2.36

Study Procedure

Upon arrival at Riverside Campus, each participant checked in, and a briefing took place. A researcher presented the participants with an explanation of the study, including what objects they would be looking for (i.e., a picture of each object as well as its name were shown to participants), and asked them to read and sign an informed consent document. Participants then had their visual abilities assessed through three tests: visual acuity, contrast sensitivity, and color blindness. These screenings provided comparison information for data reduction and ensured that all participants had at least minimal levels of acceptable vision prior to beginning the study. No participants were disqualified from the study based on these screenings.

Once in the vehicle, the researcher checked to ensure that all equipment was running properly and went over more detailed directions. Participants were asked to verbally state out loud as soon as they could correctly identify an object using the previously discussed object names. Participants were informed that if they realized they misidentified an object, they should restate the correct object as soon as they noticed. In addition to identifying the objects, participants were asked to rate how easy or hard it was to identify the object correctly on a scale from 1 to 5, where 1 was very easy, 3 was neither easy nor hard, and 5 was very hard. The researcher marked the participant's response on a standard data collection sheet, while also noting any other relevant comments or explanations the participants offered. After reviewing the instructions, the researcher directed the participant toward the course. Participants drove the vehicles at approximately 40 mph.

Two participants, one in each vehicle, drove through the course simultaneously, one after another, with designated points in the course for each vehicle to stop and allow the other vehicle to complete a run. The study always began with the base treatments. The base treatments presented each object without any lighting (i.e., dark). So initially, participants were asked to detect and identify each object with just the vehicle's headlights, which remained on low beams for the entire study. After the base treatments, the participants were directed toward the first lit treatment. The participants continued through a series of lit treatments, which varied in object, object position, light type, and travel direction. When completed with the 16 lit treatments, the researcher asked the participant final, follow-up questions about the different lighting conditions.

DATA REDUCTION

While a participant drove through the course, the researcher in the vehicle used the ASCII tag system in the GPS software to indicate when the participant began a course run and when the participant identified an object. After the study was completed, all GPS data collected for each participant were imported into a spreadsheet and reduced to the points of interest (i.e., any point marked with an ASCII tag).

Utilizing the GPS software, researchers drove through the course once without any participants, denoting the start location of each lap and each object position under the temporary work zone lights and under the dark condition. These data were reduced as well and used to determine the actual travel distance between the lap start and each object position. Detection distances were calculated by subtracting the participants' object identification distance (from the lap start to the identification of the object) from the object distance (from the lap start to the actual object position).

For analysis, researchers considered one response variable (detection distance) to assess the impact of the temporary work zone lighting scenarios studied. Since the base treatments were all located in the dark (one light type) and did not include multiple positions, researchers used the object variable as the only factor. For the lit treatments, the factors included in the analyses were light type and object position. Researchers did not consider travel direction as a separate factor since they intentionally designed the portable light tower to produce glare in one direction but not the other. Instead, travel direction was incorporated into the light type factor yielding four light types: balloon northbound, balloon southbound, light tower northbound, and light tower southbound. For the lit treatments, the three object positions were at, before, and after the temporary work zone lighting.

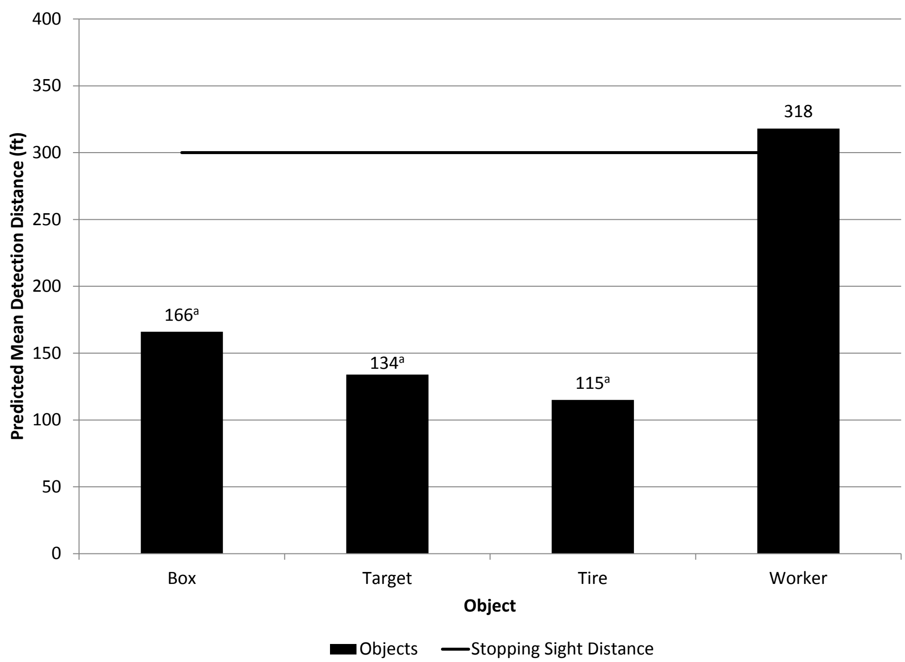
Researchers initially fit a model with all main effects and possible two-way interactions. While researchers did not design the study to investigate the impact of the demographic variables (gender and age), they were considered in the model for completeness. As expected, gender was not found to be a significant factor, and thus was removed from the final models. Aware of the fact that older adults typically have shorter detection distances than younger adults due to age-related effects on eyesight, researchers considered age group (18 to 34 and 55 plus) as a covariate factor. This allowed researchers to adjust the results for the potential difference among the age groups, which could influence the response variable, before the start of the experiment. A 5-percent significance level (α=0.05) was used for all statistical analyses.

RESULTS

This section describes the results and analyses of the different treatments. Researchers used the predicted values (estimated marginal means) for the mean detection distances to compare different treatments. When there are multiple factors in the model, it is not fair to make comparisons between raw cell means in data because raw cell means do not compensate for other factors in the model. The estimated marginal means are the predicted values of the response variable for each level of a factor that have been adjusted for the other factors in the model.

Base Treatments

Each participant started the study with the base treatments. In these scenarios, the only light surrounding the objects was that contributed by the vehicle headlights. The statistical analysis results showed that the main effect (i.e., object) was statistically significant (α=0.05). As shown in Figure 22, the predicted mean detection distances for the box, target, and tire (i.e., low-contrast objects) were consistently lower and significantly different than the predicted mean detection distances for the worker (i.e., high-contrast object). Due to the retroreflective components of the vest, this difference was expected. The predicted mean detection distance for the worker (318 ft) was practically the same as the stopping sight distance for the conditions studied (300 ft at 40 mph), showing the benefit of retroreflective material. In contrast, the predicted mean detection distances for the three low-contrast objects (166 ft, 134 ft, and 115 ft) were all less than stopping sight distance for the conditions studied (300 ft at 40 mph). This illustrates a fairly well-known fact that drivers tend to overdrive their headlights, especially in rural, dark scenarios. Since no significant differences were found among the three low-contrast objects, the further lighting analyses were separated into high-contrast (worker) and low-contrast (box, target, and tire) groups.



[a] The box, target, and tire treatments were significantly different from the worker treatment.

Figure 22. Mean Detection Distances for Base Treatments.

Worker Treatments

For the high-contrast or worker treatments, the statistical analysis results showed that light type and object position, as well as the two-way interaction between these main effects, were statistically significant (α=0.05). Based on these data, researchers further examined the interaction of the two main effect variables.

Figure 23 shows the predicted mean detection distances for the worker at each position under the balloon light based on travel direction. At each position, the difference in the predicted mean detection distance for each travel direction varied by up to approximately 150 ft (or 2.6 seconds traveling at 40 mph), but there were no significant differences in the predicted mean detection distances between the two directions, verifying the expectations. Although the contribution from headlights differed with travel direction (i.e., worker always on the east side of the road near balloon light), the impact was minimal compared to the light distribution from the balloon light at and after the light. At the before position, the headlight contribution was more evident and resulted in a longer predicted mean detection distance in the northbound direction than in the southbound direction.

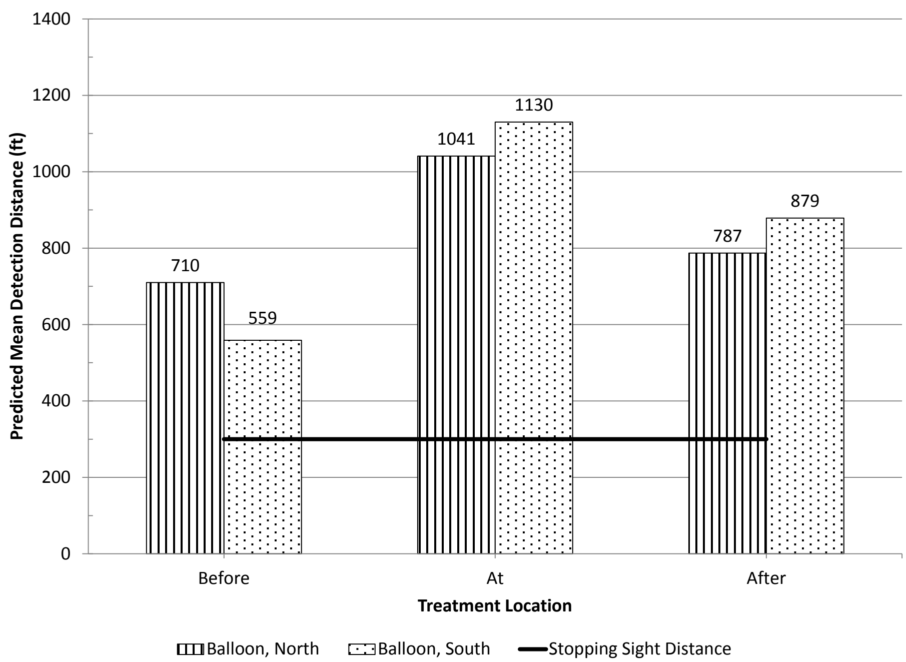


Figure 23. Mean Detection Distances for Worker, Balloon Light Treatments.

General trends show that the at position, which was under the light (position 2), yielded the longest detection distances. The after and before positions produced similar mean detection distances; however the mean detection distances for the before position were slightly less since the worker was backlit in this position (i.e., negative contrast), so detection relied more heavily on the headlights. Overall, at each position, the predicted mean detection distances under the balloon light were all longer than stopping sight distance (300 ft at 40 mph) and the predicted mean detection distance with no illumination (318 ft), showing that the balloon light did increase the detection distance of the worker.

As expected with the light tower, travel direction had a larger impact on the predicted mean detection distances (Figure 24). When traveling northbound, participants drove into the light or intentional glare. This glare was not present when traveling southbound as the participants were driving in the same direction as the light. Due to the impact of glare, the detection distances when traveling north were consistently shorter than the detection distances obtained when traveling south (differences of approximately 300 ft or 5 seconds traveling at 40 mph). While these larger differences in the predicted mean detection distances were not found to be statistically significant (probably due to the small sample size), the trend does show the impact of glare throughout the simulated work area.

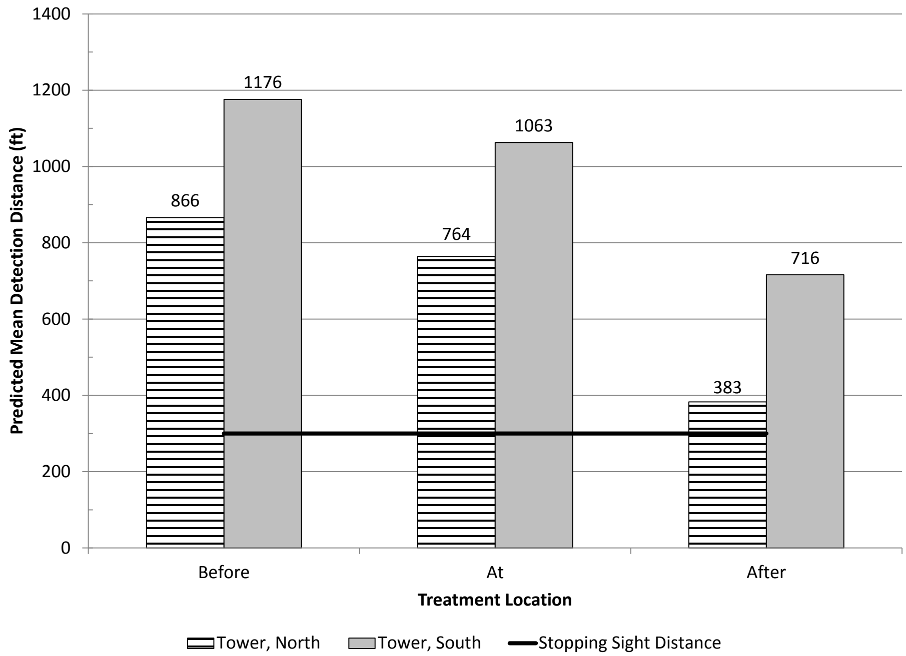


Figure 24. Mean Detection Distances for Worker, Light Tower Treatments.

In addition, because of the angled nature of the light tower, the predicted mean detection distances at the before position were the longest and became shorter as participants progressed through the simulated work area (decreasing by about 470 ft). At the before position in both directions, the worker was darker than the illuminated pavement in the background (i.e., backlit or negative contrast) and the retroreflective components on the vest reacted to the headlight contribution, yielding longer detection distances. In contrast, in the southbound direction after the light tower the worker, as well as the pavement, was illuminated by the light tower. Thus, the worker was washed out by the light tower illumination, making it more difficult to detect the worker against the illuminated pavement. In the northbound direction after the light tower, the worker was located in a very dark environment immediately following the illuminated section. In this direction, the participants had to deal with significant glare, making it more difficult to detect the worker.

While most light tower scenarios increased the detection distance of the worker above the dark condition (318 ft), at the location immediately following the light that produced glare (northbound) the predicted mean detection distance was practically the same as the dark condition (383 ft). Even so, the predicted mean detection distance for the worker (383 ft) was longer than stopping sight distance (300 ft at 40 mph). Overall, these data show the negative impact improper positioning of temporary work zone lighting can have on worker detection but also demonstrate the advantage of retroreflective vests even in less than ideal conditions.

Low Contrast Treatments

Based on the analysis of the dark treatments, the three low-contrast objects had detection distances that were statistically the same, therefore, all of the low-contrast treatments were analyzed as one object. Just as with the worker, the statistical analysis results indicated that light type and object position, as well as the two-way interaction between them, were statistically significant for the low contrast treatments. So as before, researchers further examined the interaction of the two main effect variables.

Figure 25 shows the predicted mean detection distances for the low-contrast objects at each position under the balloon light based on travel direction. At each position, the difference in the predicted mean detection distance for each travel direction varied by up to approximately 70 ft (or 1 second traveling at 40 mph). Again, there were no significant differences in the predicted mean detection distances between the two directions. Researchers believe that the before position yielded the shortest detection distance because at this position the low-contrast objects were backlit; thus, the only light falling on the face of the objects was from the vehicle headlights. Unexpectedly, this condition yielded predicted mean detection distances (137 and 94, respectively) below the predicted mean detection distance found in the dark scenario (138 ft). While at the other positions the predicted mean detection distances were longer than in the dark scenario, they were all shorter than stopping sight distance.

Again the light tower travel direction had an impact on the predicted mean detection distance (Figure 26). As with the worker, due to the impact of glare, the predicted mean detection distances when traveling north were shorter than the predicated mean detection distances obtained when traveling south. However with the low-contrast objects, the difference in the predicted means by travel direction was statistically significant for the at and after positions, again showing the impact of the glare as participants traveled through the work area. In addition, since the low-contrast objects did not include retroreflective components, the longest predicted mean detection distances were actually near the light where the face of the object was continually illuminated by the light.

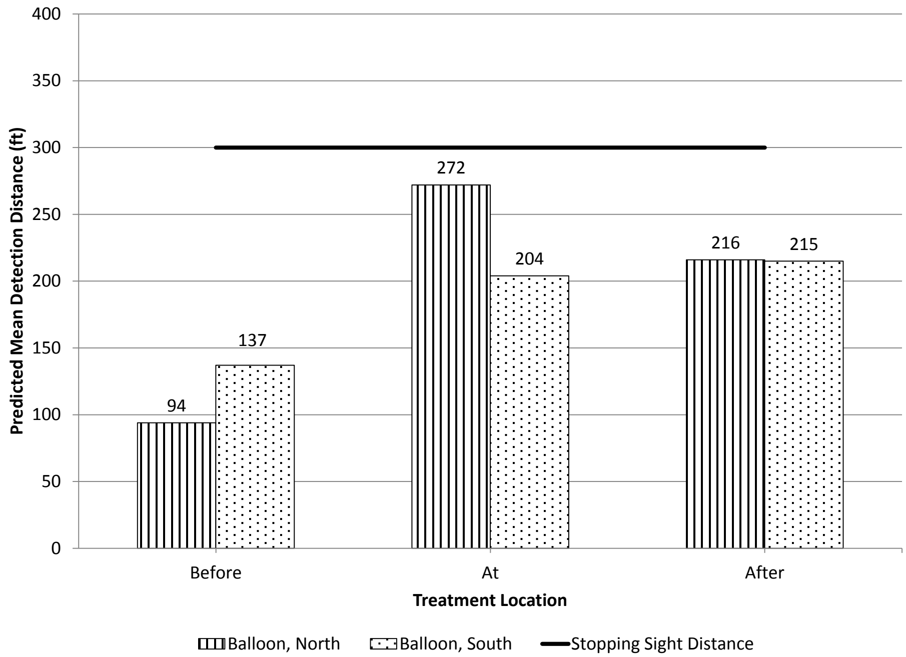


Figure 25. Mean Detection Distances for Low-Contrast, Balloon Light Treatments.

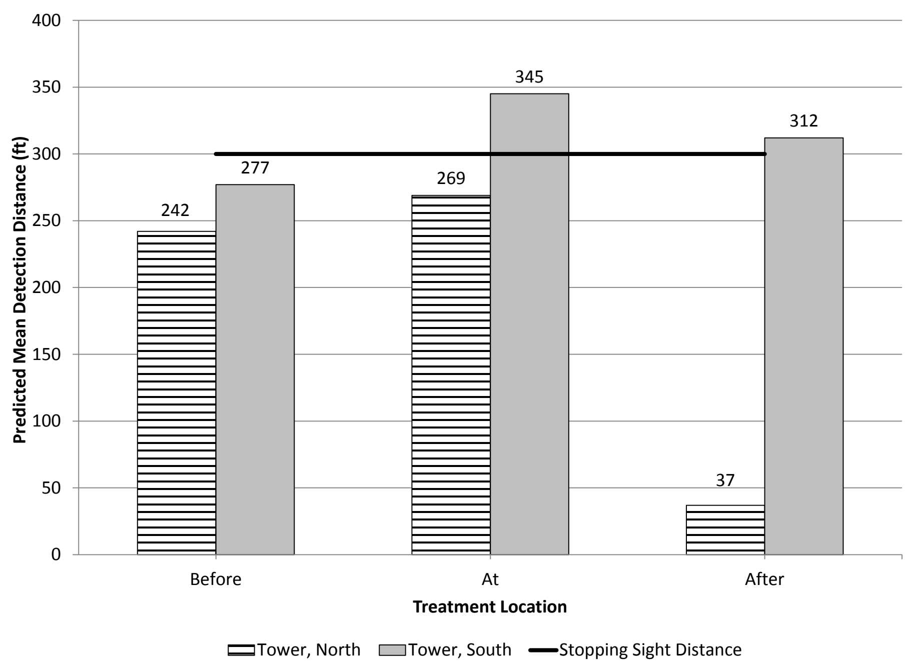


Figure 26. Mean Detection Distances for Low-Contrast, Light Tower Treatments.

The impact of the glare is evident in the northbound direction immediately after the light tower. Here the predicted mean detection distance was only 37 ft (275 ft less than in the southbound direction and approximately 100 ft less than in the dark scenario). In addition, 45 percent of the participants were either past the low-contrast object before they correctly identified it or did not even see the low-contrast object. As with the balloon light, at all the other travel direction/position combinations the predicted mean detection distances were longer than in the dark scenario (138 ft); however, only two positions in the southbound direction yielded predicted mean detection distances longer than stopping sight distance.

SUMMARY AND CONCLUSIONS

Summary

Researchers conducted the controlled-field studies to evaluate the impact of various work zone lighting scenarios upon the ability of motorists to detect low contrast objects (e.g., debris) and workers. The dark scenario treatments (base conditions) confirmed that a worker wearing a retroreflective vest could be detected at significantly longer distances than low-contrast objects (i.e., box, target, and tire). Researchers also confirmed that drivers tend to overdrive their headlights, especially in rural, dark scenarios.

Compared to the dark scenarios, the illuminated roadway section results showed that properly installed temporary work zone lighting can increase worker and low-contrast object detection distances. The results also confirmed a negative impact on worker and low-contrast object detection distances from improper positioning of portable light towers, and supported the theory that workers can be washed out visually when directly illuminated by portable light towers, making them more difficult to detect. Overall, all of the temporary work zone lighting conditions (even those with glare) resulted in worker detection distances greater than the stopping sight distance for the conditions studied. In contrast, only two of the temporary work zone lighting conditions resulted in low-contrast object detection distances greater than stopping sight distance for the conditions studied. So, improperly implemented lighting that produces glare conditions for motorists can severely limit the ability of drivers to detect low-contrast objects immediately after the light source.

CHAPTER 5:
SUMMARY, RECOMMENDATIONS, AND GUIDELINES

The objectives of this research project were to: 1) assess the impact of work zone lighting on motorists, and 2) develop work zone lighting guidelines for nighttime operations, considering both worker and motorist needs. To do this, researchers conducted field studies to provide insight into how drivers' eyes react to typical temporary work zone lighting configurations in Texas compared to standard lighting situations (i.e., no lighting and standard fixed lighting). Researchers also conducted closed-course studies to evaluate the impact of various work zone lighting scenarios upon the ability of drivers to detect low-contrast objects (e.g., debris) and workers. The findings from these studies, as well as information from a literature review and review of other state agency specifications, were then used to develop work zone guidelines for nighttime operations that considered both worker and motorist needs.

Field Study Summary

Several general trends in terms of driver pupil size and pupil size variability were either verified or uncovered as a result of the field studies. As expected, pupil sizes in general are correlated with participant age, with older drivers generally having small pupil sizes on average. Likewise, pupil size changes in response to different lighting levels as one traverses a roadway segment are also age-dependent. Normalizing those changes via the use of the coefficient of variation does appear to reduce these age-related effects. Furthermore, the pupil size CV was found to indeed be associated with illumination CV in the various field study sections and more importantly, that both the illumination and pupil size CVs tended to be higher than what is normally encountered by drivers even when traveling in urban environments with significant traffic volumes (and oncoming headlights), roadway lighting, and significant roadside business lighting. However, it is believed that the continuous process of the driver's eye focusing back and forth on both near and far-away illumination sources is not adequately captured through simply illumination measurement techniques such as was used in this study. In addition, while luminance may be a better predictor of pupil size, the inability to post-process these data in a real-time environment currently limits its application. Consequently, it was not possible to devise a process to use illumination or luminance data obtained while driving through a work zone to indicate where pupil size changes were likely to occur so that some type of remedial action could be taken with the lighting sources to reduce such pupil size variability.

Closed-Course Study Summary

The dark scenario treatments (base conditions) confirmed that a worker wearing a retroreflective vest could be detected at significantly longer distances than low-contrast objects (i.e., box, target, and tire). Researchers also confirmed that drivers tend to overdrive their headlights, especially in rural, dark scenarios.

Compared to the dark scenarios, the illuminated roadway section results showed that properly installed temporary work zone lighting can increase worker and low-contrast object detection distances. The results also confirmed a negative impact on worker and low-contrast object detection distances from improper positioning of portable light towers, and supported the theory that workers can be washed out visually when directly illuminated by portable light towers, making them more difficult to detect. Overall, all of the temporary work zone lighting conditions (even those with glare) resulted in worker detection distances greater than the stopping sight distance for the conditions studied. In contrast, only two of the temporary work zone lighting conditions resulted in low-contrast object detection distances greater than stopping sight distance for the conditions studied. So, improperly implemented lighting that produces glare conditions for motorists can severely limit the ability of drivers to detect low-contrast objects immediately after the light source.

Recommendations

Improvements to Construction Specifications

Based on the review of previous literature and state agency nighttime work zone lighting policies, field study findings, and closed-course study findings, the researchers recommend that TxDOT develop nighttime work zone lighting specifications to be included in their construction standards and/or barricade and construction standard sheets. The specifications should include the following at a minimum:

- *Definition of nighttime work.* Nighttime work is defined as work performed one-half hour after sunset to one-half hour before sunrise.

- *Minimum lighting levels.* The lighting system shall provide an average minimum of 5 fc (54 lux) throughout the work area and 10 fc (108 lux) around equipment. Tasks requiring high levels of precision and extreme care shall require an average minimum of 20 fc (216 lux). Existing street and highway lighting shall not eliminate the need for the contractor to provide lighting. Conventional vehicle headlights on construction vehicles and equipment shall not be permitted as the sole means of illumination while working. If the lighting system does not meet the minimum illumination levels, the contractor shall make necessary adjustments before any work proceeds.
- *Glare control.* The lighting system shall be designed and operated to avoid glare that interferes with traffic and workers. The contractor shall locate, aim, and adjust lighting equipment and/or provide glare control hardware as necessary to reduce objectionable levels of glare. Conventional vehicle headlights on construction vehicles and equipment shall never be used when facing oncoming traffic in order to avoid glare and confusion to drivers. The engineer or inspector shall determine when glare exceeds acceptable levels, either for traffic or workers. If objectionable glare exists, the contractor shall make necessary adjustments before any work proceeds.
- *Light trespass.* The lighting system shall be designed and operated to minimize light trespass out of the work area. The engineer or inspector shall determine when light trespass exceeds acceptable levels for adjoining residences or traffic. If objectionable light trespass exists, the contractor shall make necessary adjustments before any work proceeds.
- *Provision of a light meter.* A light meter that is capable of measuring illuminance in foot candles and lux shall be provided by the contractor to on-site TxDOT personnel (e.g., project engineer or inspector), along with instructions on how to use the meter. The light meter and instructions shall become the property of the contractor after final acceptance.

Guidelines for TxDOT Field Personnel

The following are guidelines for the on-site TxDOT personnel (e.g., project engineer or inspector) that will be checking the adequacy of the nighttime operation illumination.

- *Light measurement.* The first night of operation, installed lighting should be checked using a light meter. The light meter should be held such that the sensor is facing up (i.e., parallel to the roadway) and at the height of the intended work (e.g., ground for general illumination and at task height for specific activities). If multiple work locations exist, measurements should be taken at each work location. A summary of these measurements should be noted in the inspection records, along with a summary of the specific tasks being performed at each location. If the required illuminance levels are not met, the contractor shall be instructed to make necessary adjustments before any work proceeds. Operational checks of the lighting should also be made when construction phasing is changed or other major changes are made to the operation that may impact the lighting levels, focusing on light levels where work activity is occurring.
- *Glare control.* Glare should be assessed by driving through the nighttime work zone operation and observing the lighting systems from all directions (including entrance and exit ramps, overpasses, flyovers, etc.). Temporary lights in the immediate vicinity of the roadway, especially those near driver eye height, can produce glare for motorists (critical glare locations for motorists appear to be 30 to 80 ft before a light). At a minimum, the following checks should be made by on-site TxDOT personnel each night:
    - ✓ At least one drive-thru should occur. Additional drive-thrus should also occur anytime the lighting system is significantly altered. Drive-thrus should be performed in both directions of travel (even on divided roadway sections). Any light sources creating discomforting glare to approaching vehicles from either direction of travel should be adjusted. Portable lighting towers that cannot be aimed downward ± 30 degrees should be particularly checked. Such towers have significant glare potential, and their use may need to be limited to work spaces far away from travel lanes (i.e., at the project staging area).

- ✓ Travel on all entrance, exit, and connector ramps, as well as overpasses, within the project should also be checked to ensure that the lighting used does not create glare conditions on those ramps.
- ✓ The positioning of temporary lighting near critical roadway features (signing, geometric features, crosswalks, etc.) should also be checked. If a critical roadway feature is located just before or beyond temporary lighting, a second light source may be needed before or beyond the work space, respectively to provide adequate visibility of the critical feature. Critical features that should be checked include but are not limited to:
    - o Roadside signing (e.g., guide signing, exit ramp signing, warning signing, etc.).
    - o Geometric features (e.g., exit ramps, changes in alignment, lane closures, lane reductions).
    - o Pedestrian crosswalks.
- ✓ No work tasks should be allowed to be accomplished strictly through the use of work vehicle or equipment headlights. Special task lighting should be provided by the contractor prior to starting work. Also, check to ensure that any special task lighting is not oriented towards approaching traffic.
- ✓ Any work vehicles or equipment facing approaching traffic should not have their headlights on, as this can create glare problems and also confuse drivers at night.

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