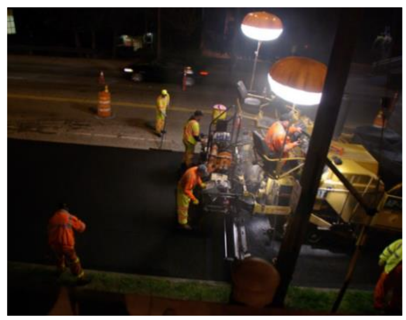
Guidelines

For Work Zone Designers



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16. Abstract

Most State and many other transportation departments in the U.S. maintain roadway and/or work zone design manuals containing State specific regulations, policies, and design guidance for their designers and consultants to use. However, those manuals vary widely in the depth of coverage and the work zone design topics offered. National work zone design guidelines are lacking. This series of guidelines for work zone designers covers various work zone safety design topics for states, design manual decision makers, editors, and subject matter experts to develop or enhance their own guidance materials.

"Guidelines for Work Zone Designers – Illumination for Night Construction" provides guidance covering the topic of safely lighting work zones at night and is not intended to be a stand-alone document for designing work zone traffic control plans. State, county, local, and tribal transportation agency subject matter experts, should use this material as reference material to augment their own work zone design policies and guidance.

The material in this guide was gathered from existing State design manuals, considered as best state-of-the-practice by the authors and worthy of sharing with other states, and from state-of-the-art work zone safety and traffic management research documents developed by the Transportation Research Board, the FHWA and other institutions.

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Table of Contents

List of Figures

List of Tables

List of Appendices

Cover & Back Page Photograph Sources

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0. Foreword

Designing highways, bridges, and other transportation infrastructure is both a science and an art. Good design requires careful balancing of a wide range of technical, social, financial, and environmental considerations, many of which affect road user safety. To guide staff and consultants on agency design policies, highway and bridge design manuals are issued by many State Departments of Transportation (DOTs). Design manuals are also issued by some county, municipal, and tribal transportation departments and by other highway agencies such as tollway authorities.

This document is part of a series of prototypical work zone design guidelines developed by the Traffic Operations and Safety Laboratory (TOPS Lab) at the University of Wisconsin through a grant provided by the Federal Highway Administration (FHWA). The documents in this series are not intended for use directly by designers. Instead, they are intended to serve as a framework to assist agency technical editors in preparing relevant sections of their design manuals. It is anticipated that the material in this document will be augmented with agency-specific policy and procedural information. Highway agencies should adapt and modify the information in this document based on their own operational experiences, traffic conditions, terrain, climate, organizational structures, risk management policies, legislation, and case law.

Guidance included in this document represents the authors' opinions of good practices. This document is not intended to serve as a national standard, policy, or regulation. Reference in this document to any specific commercial products, processes, or services, or the use of any trade, firm, or corporation name is for the information and convenience of the reader and does not constitute endorsement, recommendation, or favoring by FHWA or the authors.

Two font colors are used in this document to assist agency design manual editors in adapting the prototypical guideline material for their state-specific guidelines:

Black color normal text identifies narrative, text, and other materials ready for consideration for incorporation into agency-specific guidelines, with relatively little revision.

Italicized purple color text identifies commentary material and other issues that are likely to need modification to reflect agency-specific policies, organizational structures and choices, and require further considerations.

Note: Blue color is used to designate section heading numbers and titles in this Guide.

1. Introduction

Night construction is an increasingly popular method for reducing the traffic impacts of lane closures, expediting project completion dates, and (in hot climates) providing a more comfortable environment for road workers. A discussion about when to use night construction is included in the Guidelines for Work Zone Designers – Traffic Control Design Overview procedure. This document discusses selecting and positioning work zone illumination devices.

This document was written to introduce highway designers who are unfamiliar with illumination design to the basic concepts of temporary lighting for highway construction operations. It has two objectives:

- To provide designers with an overview of the main design considerations related to work zone illumination.
- To assist designers specifying appropriate work zone lighting systems using Standard Detail Drawings, shop drawings, and project specifications.

Definition of terms used in this document:

- **Luminaire** is a complete lighting unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply. This definition is from the Illuminating Engineers Society (IES). Some other documents, such as supply catalogs, may refer to luminaires as light fixtures and the terms are considered interchangeable.
- **Lamp** is the device that emits light from within the luminaire.
- **Luminance** describes the measurement of the amount of light emitting, passing through, or reflected from a particular surface from a solid angle. It also indicates how much luminous power can be perceived by the human eye. This means that luminance indicates the brightness of light emitted or reflected off of a surface. The SI unit for luminance is candela/square meter (cd/m2) and the U.S. unit is the foot-lambert (fL).
- **Illuminance** describes the measurement of the amount of light falling onto (illuminating) and spreading over a given surface area. The SI unit for illuminance is lux (lx) and the U.S. unit is foot-candle.

Additional discussion about these terms and other lighting concepts are discussed in Section 2 and a more complete list of definitions is included in the Section 9 Glossary.

Ordinary roadway lighting is intended to provide illumination for vehicles during normal street and highway operations. The illumination levels are usually less than 20% of what is required for work operations. In addition, many permanent highway lighting systems use high pressure sodium lamps that produce pinkish-yellow light that is not well suited to construction work. Due to their angle, the headlamps on motor vehicles are also generally unsuitable for production lighting. As a result, it is nearly always necessary to illuminate the night time work zone with supplemental lighting provided by contractors.

Well-designed work zone lighting can contribute to worker safety, the safety of drivers and other road users, worker morale, productivity, work quality, and the ability to inspect the work (Figure

1. Conversely, poorly designed work zone lighting can create situations that are hazardous for workers, drivers, and other road users (Figure 2).

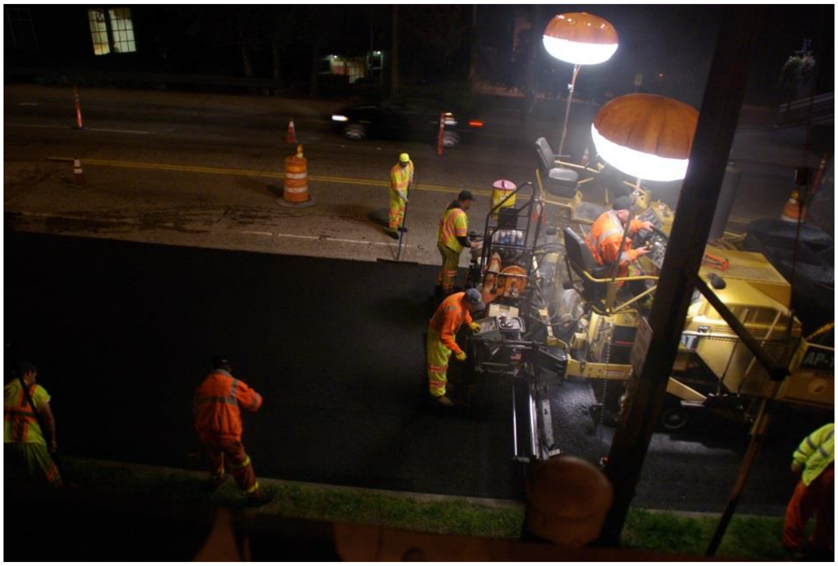


Figure 1. Well-designed lighting for a night paving operation.
Source: Pavement Interactive

a. Approximately ½ mile upstream of luminaire.
Source: Susan Paulus/Lakeside Engineers

b. Approaching luminaire.
Source: Susan Paulus/Lakeside Engineers

Figure 2. Blinding glare caused by poorly positioned work zone illumination at a freeway work zone. For drivers the light was so intense that it completely obscured the workers and equipment that are partially visible in the left lane of Figure b.

This document is organized as follows:

- *Section 1 introduces the functional requirements of work zone lighting and discusses common mistakes and pitfalls involving work zone lighting systems.*
- *Section 2 provides an overview of the fundamental concepts required for illumination design. It is intended to introduce highway designers to the key concepts and terminology necessary to interact with lighting designers and apply lighting design principles.*

- *Section 3 describes the work zone lighting technologies and equipment currently available in the United States.*
- *Section 4 provides information about methods for minimizing physical, electrical, and chemical hazards related to work zone lighting systems.*
- *Section 5 presents key design criteria for work zone lighting systems: meeting the functional needs of highway workers without creating optical hazards for drivers or other road users.*
- *Section 6 provides detailed information about lighting system design including the use of lighting analysis software.*
- *Section 7 provides lighting design examples for typical work operations such as a flagger station, a paving operation, and a bridge deck repair.*
- *Section 8 discusses methods for evaluating the performance of work zone lighting systems in the field.*
- *Section 9 provides a glossary of frequently used lighting terms. For example, illumination engineers use the term luminaire to refer to a lighting fixture and the term lamp to refer to the light source within a luminaire. (A layperson or highway contractor might be inclined to call the former a "light" and the latter a "bulb"). The terminology recommended by the major illumination engineering societies is used in this publication.*

1.1. Hazards of Improperly Designed Work Zone Lighting

Lighting design is an engineering specialty that is unfamiliar to most highway designers. Although illumination engineers are often consulted for permanent highway lighting design, in the past highway designers often left the selection of temporary work zone lighting systems to the discretion of the contractor or field engineering staff—who are also unfamiliar with illumination design in most cases. Too often, the result has been deficient work zone lighting that can be hazardous for workers, drivers, and other road users. Typical problems include:

- Excessive glare that creates a serious driving safety hazard (Figure 2).
- Uneven patterns of light and darkness that make it difficult for drivers to see where the workers are.
- Strong shadows that increase the risk of worker injuries and make it difficult for workers to see what they are doing.
- Excessively bright areas that force workers to squint, obscure details, make it difficult to see into trenches and manholes, and downgrade workmanship.
- Intense task lighting surrounded by darkness that can affect worker morale by creating a psychological perception of gloom[1].
- Physical and electrical hazards due to careless wiring placement often accompanied by lighting disruptions and lost production.

To avoid these problems, work zone illumination should be considered during the design phase whenever night construction would be required or allowed. For most projects this requires the following actions during the project design phase:

- Minimum, maximum, and preferred illumination levels should be specified in the contractual documents.

- Contractual provisions should be established to require the contractor to modify the lighting system if it is deemed deficient in any way, such as presenting a safety hazard to workers, drivers, or other road users.
- A Standard Detail Drawing should be included in the plans to show an approved illumination layout relevant to the type(s) of construction operation that are expected for the proposed project.
- At the designer's discretion, the contractual documents could allow the contractor to deviate from the Standard Detail subject to agency approval. This gives the contractor flexibility in the selection of lighting equipment. Typically, the approval process will be based on a contractor-supplied shop drawing illustrating the proposed lighting layout along with an analysis of a representative part of the construction scene prepared using approved lighting software. The analysis should include both the horizontal illuminance levels at the working plane and a glare check based on the perspective of an approaching truck driver.

1.2. The Safe System Approach

The Safe System approach is a relatively new way of thinking about the interaction of roads, road user behavior, vehicles, and speeds. It was published in 2008 as the result of a three-year cooperative effort by an international group of safety experts representing 22 countries [2]. The United States was represented in this effort by high-ranking officials from the Federal Highway Administration (FHWA), the Federal Motor Carrier Safety Administration (FMCSA), and the National Highway Traffic Safety Administration (NHTSA).

In the past, transportation safety efforts were often fragmented due to the difficulty of coordinating engineering, enforcement, and educational efforts overseen by various agencies and organizations. The Safe System approach is intended to overcome these difficulties. It states that improving roadway safety is a responsibility everyone shares, which includes designers, contractors, and users of the transportation system. To reduce casualties, safer roads and roadsides, safer vehicles, safer speeds, and safer road user behavior are needed (Figure 3).

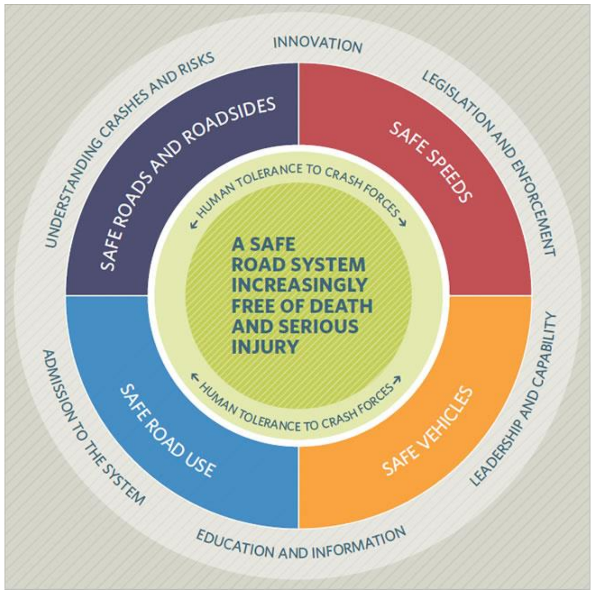


Figure 3. Elements of the Safe System.
Source: © 2017 New Zealand Transport Agency

Night work operations pose special challenges due to reduced visibility. Adding to this challenge, adverse atmospheric conditions such as fog and wet pavement can exacerbate the risk of night work. Although traffic volumes are usually relatively low, night traffic often includes a high proportion of heavy trucks which are more susceptible to glare than cars because of their higher seating position. Older road users often lack the visual acuity to see clearly at night and are more susceptible to glare than their young counterparts are. Drunk driving and drug-impaired driving are more prevalent at night and there is increased potential for impaired pedestrians.

Road user and worker fatigue also factor into night work zone safety. Driving or working at night runs counter to the human body's natural circadian rhythm which controls mood, alertness, body temperature, and other aspects of the body's daily cycle. Drivers' symptoms of fatigue can include: loss of alertness, difficulty keeping eyes in focus, frequent yawning, distraction (wandering thoughts and loss of concentration), memory lapses, reduced awareness of surroundings (e.g., "suddenly" seeing another vehicle), missing turn-offs or exits, failure to check rear view mirrors as frequently as normal, unconscious variations in speed, driving too slow or too fast, drifting out of the lane, and erratic lane changing.

Because of these risk factors, it is doubly important that the design of the night work zones contribute to safe driving and safe work. The goal is to design a system that minimizes the crash risks and attenuates the consequences of a crash, no matter whether it results from misbehavior, drowsiness, or a simple mistake by a road user or a worker.

1.3. Work Zone Lighting Design Parameters

In priority order, the primary design considerations for work zone lighting are as follows:

1. **Glare Control:** Assuring the safety of drivers and other road users by avoiding glare and intense shadows in all lanes that remain open to traffic (a formal definition of glare is provided in Section 5.2).
2. **Code Compliance:** Meeting all relevant electrical codes to assure the safety of workers and the public.
3. **Intensity:** Providing sufficient (but not excessive) illumination in the areas occupied by the workforce.
4. **Shadow Control:** Minimizing harsh shadows that could adversely affect work quality by hiding surface texture and other important details.
5. **Spillover Control:** Avoiding excessive illumination of residential properties adjoining the work zone.

Table 1 lists these design parameters and corresponding performance criteria. These parameters are defined and discussed in more detail in subsequent sections of this document.

Table 1. Key design parameters for work zone illumination.

Priority	Design Consideration	Performance Measures and Criteria (See referenced sections for additional details)	Relevant Sections of this Document
1	Glare Control	Maximum Veiling Luminance Ratio less than 0.4 *or* Maximum Threshold Increment less than 15%.	5.3
2	Code Compliance	All elements of system compliant with National Electrical Code (or relevant state/local electrical codes) *or* low voltage system used to limit shock and fire risks.	4.3
3	Min and Max Intensity Levels	Horizontal illuminance measured at work surface 4 to 45 foot-candles depending on type of work.	5.1
4	Shadow Control	Task areas should be illuminated from at least two directions to avoid hard shadows that mask work details.	2.4
5	Spillover Control	Use proper shielding and aiming to minimize light spillover off right-of-way, especially residential areas.	5.5

1.4. Lighting Design and Equipment

Developing lighting designs that meet the criteria outlined in Section 1.3 requires a combined evaluation of several factors:

- The type of lighting equipment that will be used at the site.
- The way the equipment is physically positioned (such as the height, angle, and spacing of luminaires).
- Shadows cast by construction equipment, work vehicles, and fixed objects.
- The condition of the lighting equipment (e.g., light loss due to dust and dirt).

Relatively small changes in the height, spacing, and angle of luminaires can greatly affect the suitability of an arrangement. Every lighting problem will have multiple solutions. For example, a designer might choose to use several small lights mounted relatively low or a few larger lights mounted high.

A number of specialty lighting products are marketed to the construction industry, but simply specifying a certain type of equipment does not assure that all five design criteria will be met. The way the equipment is deployed in the field is at least as important as the hardware itself. A work zone lighting field study found that "the use of low-glare light sources such as balloon lights can contribute to the reduction of glare however it does not guarantee that the intensity and type of utilized lights do not cause glare conditions that exceed the acceptable limits in and around the construction site"[3]. Therefore, careful selection and aiming of all luminaires is necessary to assure that the light output pattern matches the functional requirements of the work operation while minimizing glare, shadows, and spillover.

1.5. The Role of Lighting Software in the Design Process

Meeting the requirements outlined in Section 1.3 generally requires a pre-deployment lighting analysis. This is preferable to relying solely on field demonstrations because it provides more time to obtain different equipment or revise the lighting layout before work begins. Pre-deployment analysis also reduces the potential for lost production and resulting conflict between contractors and the agency staff.

Although outdoor lighting can be analyzed by hand, it is generally faster and easier to use lighting analysis software. The software can be used in two ways:

- By an agency to establish Standard Detail Drawings (SDDs) for typical situations such as flagger stations and paving operations.
- By a contractor to prepare a report showing that a proposed lighting arrangement is safe and effective if it differs from an agency-approved SDD or addresses a situation that is not covered by an SDD.

Lighting analysis requires two inputs:

- A scaled drawing with a plan view of the anticipated typical locations of workers, equipment, and lighting devices in relation to the traffic lanes.
- Photometric data file(s) for the proposed lighting equipment.

Photometric files (also called IES files) show how much light is produced by the proposed lighting devices and the spatial pattern of their light output. For example, some devices send light in all directions while others produce a focused beam that goes only in certain directions. IES files can typically be downloaded at no cost from the lighting equipment manufacturer's website.

An on-site field test should always be conducted at least 24 hours prior to the start of work. Results can be used to fine-tune the installation, such as adjusting the height and angle of the luminaires. This also provides a measure of protection against any issues that were not captured in the computer analysis such as variations in curvature and grade, reflections from nearby buildings and waterways, and existing permanent light sources.

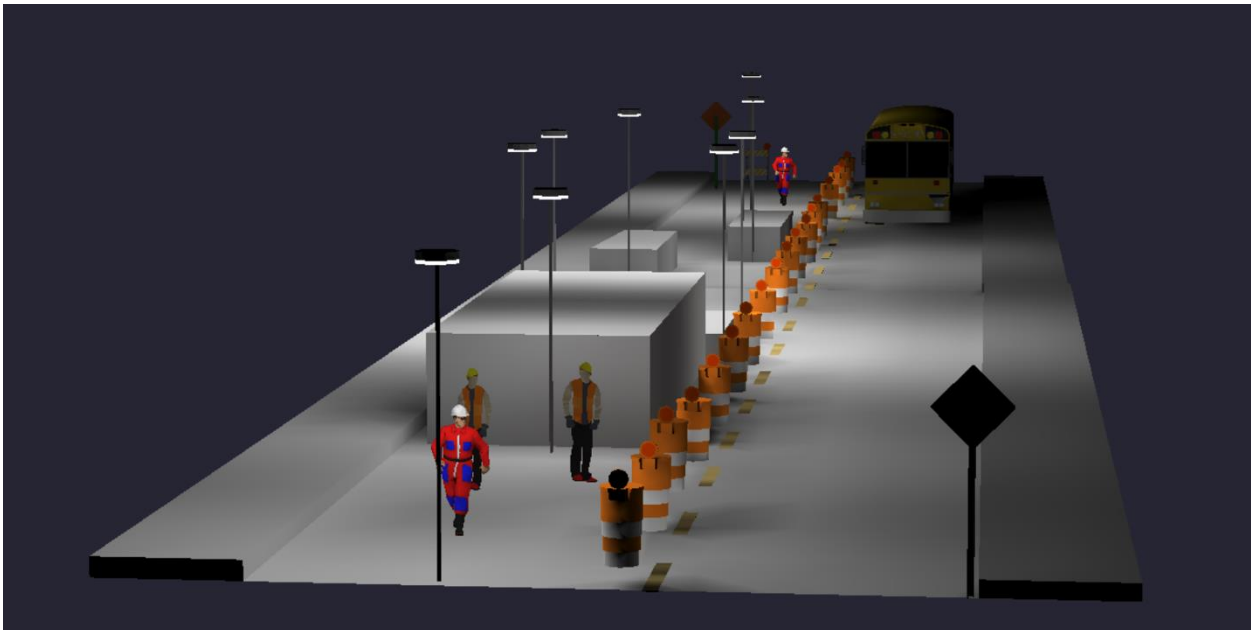


Figure 4. Computer rendering of an asphalt paving scene. To reduce runtime, the paver and asphalt rollers were represented by rectangular boxes.

Note: To provide realistic examples, commercial software was also used to prepare analyses and renderings for this document. The renderings were prepared using IES data files for typical commercial lighting products from various manufacturers. *Reference in this document to any specific commercial products, processes, or services, or the use of any trade, firm, or corporation name is for the information and convenience of the reader, and does not constitute endorsement, recommendation, or favoring by FHWA or the authors.* The lighting industry frequently introduces new models to take advantage of technological advances. Consequently, devices used as examples in this document could be discontinued or superseded at any time by their manufacturers.

1.6. Alternatives to Software-Based Lighting Design

Although not recommended, an alternative to a formal lighting analysis is to require the contractor to conduct a field demonstration of the proposed lighting layout prior to the start of work. If this option is allowed, the demonstration should be done **several business days** prior to the start of each new lighting set-up to allow time for different equipment to be brought to the site if the proposed layout is deemed unacceptable by the agency. This option should only be used in lower-risk situations such as low-speed or low-volume roads.

1.7. Legal, Regulatory and Standards Issues

MUTCD. The U.S. national Manual on Uniform Traffic Control Devices (MUTCD) provides night lighting standards and guidance information in Section 6F.82, Floodlights, and in 6G.19, Temporary Traffic Control During Nighttime Hours [4]. The standards requirements are as follows:

- Except in emergencies, flagger stations shall be illuminated at night.
- Except in emergencies, temporary lighting shall be provided at all flagger stations.
- Floodlighting shall not produce a disabling glare condition for approaching road users, flaggers, or workers.

The MUTCD also includes the following guidance recommendations:

- When night work is being performed, floodlights should be used to illuminate the work area, equipment crossings, and other areas.
- The adequacy of the floodlight placement and elimination of potential glare should be determined by driving through and observing the floodlighted area from each direction on all approaching roadways after the initial floodlight setup, at night, and periodically.

MUTCD Section 6G.19 provides information about desirable illumination levels. *This topic is discussed in Section 5.1 of this document.*

NEC and Local Electrical Codes. The National Electrical Code (NEC) published by the National Fire Protection Association (NFPA) establishes electrical safety standards to prevent shock, arc flash, and fire. *As of 2015, the NEC had been adopted in all U.S. states except Arizona, Mississippi, and Missouri. State and local codes (including NEC supplements) also influence electrical safety requirements in many jurisdictions.*

IES and CIE Guidelines. Two international organizations publish extensive technical standards, guidelines, and research related to illumination. Recommended practices for the United States are based primarily on the recommendations of the Illumination Engineering Society of North America (IES). Lighting terminology has been standardized internationally by the International Commission on Illumination, known by its French initials CIE (Commission Internationale de l'Eclairage). Certain CIE guidelines are also applied in North America, particularly when no equivalent IES guidance has been published.

2. Lighting Concepts

This section introduces fundamental lighting concepts and explains several lighting terms that are used in this document. *Definitions of terms and units to measure the terms are included in Section 1 and additional glossary of terms are provided in Section 9. Experienced lighting designers can proceed to Section 3 (work zone lighting equipment) or Section 4 (work zone lighting design parameters).*

2.1. Measuring Light Intensity

There are several methods for describing the intensity of a lighting source. It is perhaps easiest to explain these terms by example. Although production of traditional "light bulbs" (tungsten-filament incandescent lamps) has been phased out due to their low efficiency, they are probably familiar to most readers. A tungsten lamp consumes a certain amount of electrical **power** (perhaps 60 watts) and produces a certain amount of light (perhaps 800 lumens). More precisely, it emits a **luminous flux** of 800 lumens, which is the total amount of light going in all directions. Luminous flux is denoted by the symbol Φ (phi). (As discussed in Section 3.1, light output per watt depends on the lighting technology).

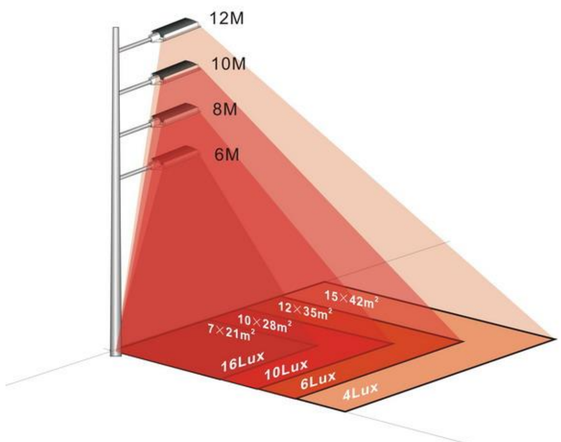


Figure 5. Illuminance decreases as the distance between the light source and the work surface increases

Source: WikiMedia Commons/Allenlinroman

If a white card is held a certain distance away from a lamp, the amount of light falling on the card is the **illuminance**. Notably, the amount of light falling on the card depends on the distance between the card and the lamp: as the card is moved closer to the lamp, the illuminance increases (Figure 5). Illuminance is denoted by the symbol *E*.

In U.S. customary units, illuminance is measured in **foot-candles**; in the metric system it is measured in *lux*. Although the exact conversion is 1 foot-candle = 10.76 lux, it is often approximated as 1 foot-candle = 10 lux (this approximation is of little practical significance for illuminance levels below 50 fc).

The amount of light that reflects off a white card is called **luminance.** Luminance is usually measured in **candelas per square meter** (cd/m^2), also informally called a **nit** (the U.S. customary unit is the foot-lambert: 1 cd/m^2 = 1 nit = 0.292 foot-lamberts). Luminance is denoted by the symbol *L*.

Luminance is the measurable quantity that most resembles a person's perception of brightness, but they are not quite the same. This is because human perception depends partly on the color of the light (human eyes are most sensitive to yellow-green).

If two adjacent parts of a scene have very different luminance levels, it is perceived as **glare**. In high-glare situations, workers, drivers, and other road users have difficulty seeing one another because the human eye cannot adjust to a bright and a dim lighting level at the same time. In other words, both light intensity and light uniformity are important in human perception and comprehension of a scene.

Figure 6. Portable illuminance meters are available online and from specialty retailers for $25 to $250 depending on quality and features.
Photo: Wikimedia Commons/Hankwang

Figure 7. Luminance photometers are specialty instruments that generally cost $750 to $2500.
Source: National Research Council of Canada

Illuminance can be measured easily in the field using a light meter (Figure 6) so the standards for horizontal illumination of work zones and other work environments are generally based on **illuminance**. Illuminance can be increased by increasing the intensity of a light source, increasing the number of light sources, or decreasing the distance of the light sources from the work surface.

Table 2 provides some examples to familiarize the reader with typical illuminance levels. Luminance is measured using specialty instruments called photometers (Figure 7).

Table 2. Examples of Illuminance Levels.

Situation	Illuminance (Foot-Candles)	Illuminance (lux)
Full Moon on Clear Night	0.025	0.27
Civil Twilight	0.3	3.4
Permanent Roadway Lighting	0.25 to 1.5	3 to 16
Residential Living Room	4.6	50
60 watt incandescent bulb 20 inches away	9 to 12	100 to 125
Office Interior	30	320
Sunrise on Clear Day	37	400
Hospital Operating Room	1675	18,000
Direct Sunlight	3,000 to 12,000	32,000 to 130,000

Figure 8 is a false-color image showing the illuminance levels of a work zone scene similar to the true-color scene in Figure 4. Note that the light is brightest near the middle of the scene due to the combined effect of several luminaires. Figure 9 shows the same scene viewed by an approaching driver. Notably, even when the **illuminance** is the same, reflections off light-colored objects (such as the white parts of the traffic control drums) produce greater **luminance** than reflections from dark-colored objects (such as the orange parts of the drums).

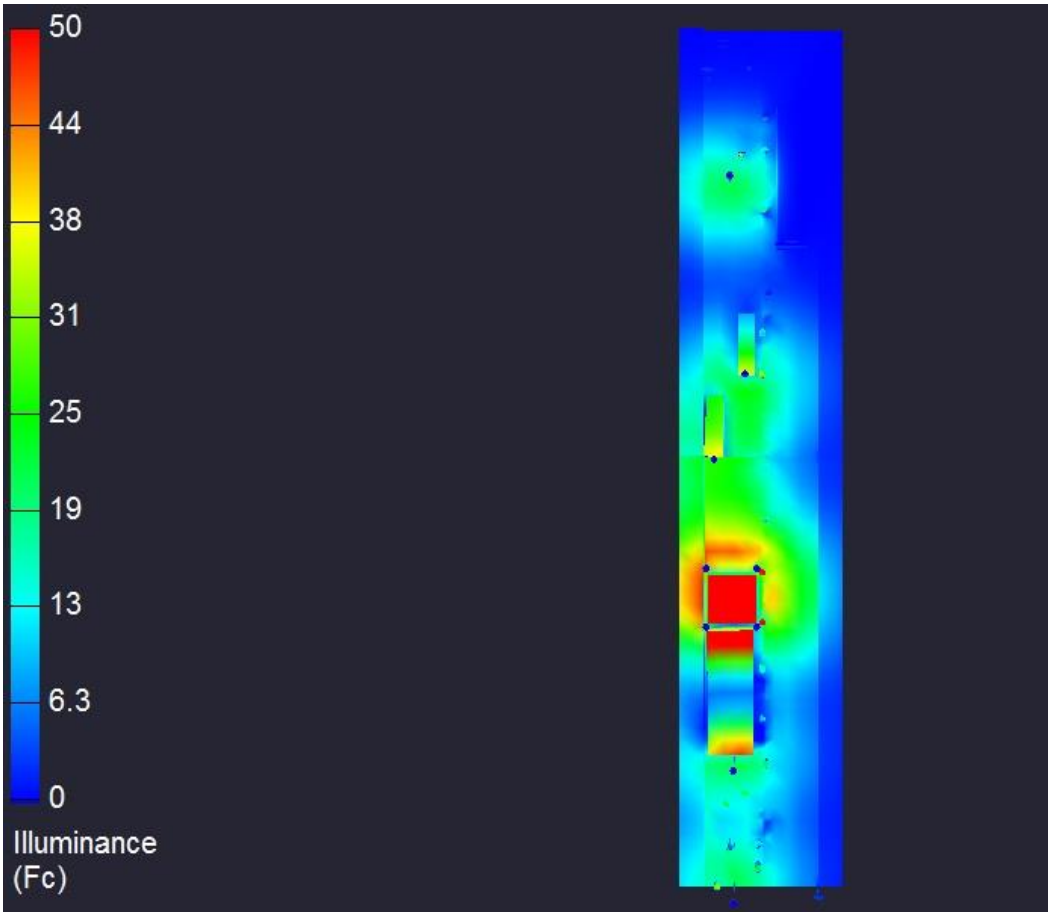


Figure 8. False color image illustrating the illuminance levels of a work zone scene.

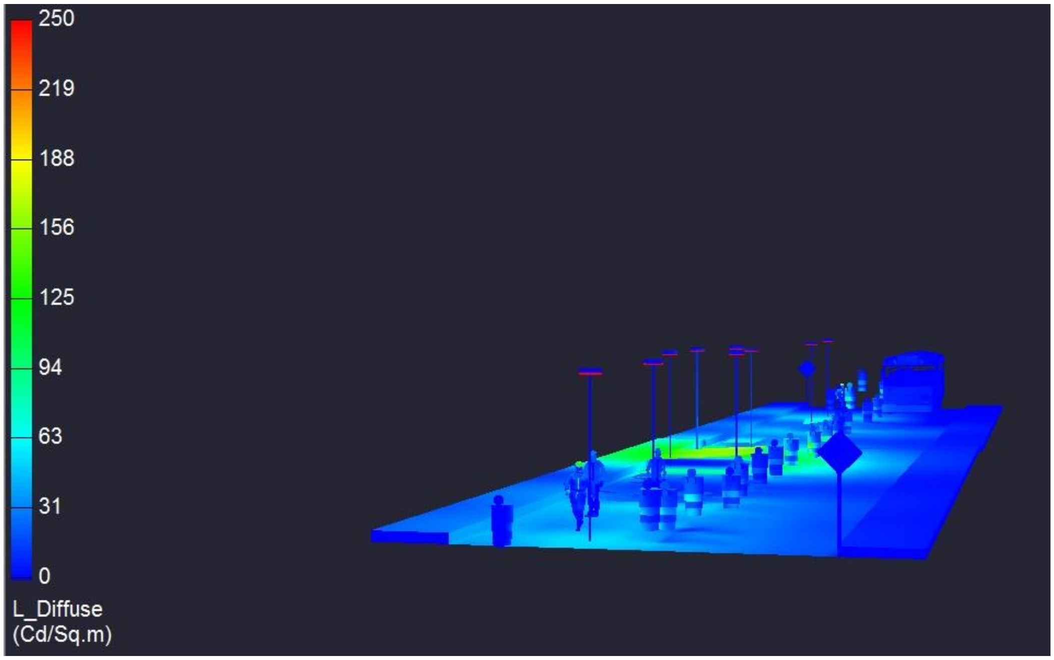


Figure 9. False color image illustrating the luminance levels of a work zone scene.

2.2. Vertical and Horizontal Illumination

Like luminance and illuminance, the concepts of vertical and horizontal illumination are perhaps best explained by example. Imagine a warehouse worker whose job is to select the correct box amongst many products that are stacked on a tall array of shelves. This task requires good **vertical** illumination: ideally, each shelf should be lighted in such a way that the front of each box is readable and the upper shelves do not shadow the products stacked lower down. The amount of light that falls on the floor is of lesser importance.

Next, consider the case of a group of highway workers whose job is to assure that newly laid pavement has the correct surface finish. This task requires good **horizontal** illumination: ideally, the entire pavement surface should be lighted in such a way that the workers and their equipment will not shadow the roadway surface they are trying to see. This task requires some light on vertical surfaces such as the sides of the paving machine, but the pavement surface itself is of primary importance. Luminaires can use the same lamps and other electrical components, but have completely different reflector-diffuser internal systems.

As the example above suggests, the selection of work zone lighting systems should take into consideration the tasks that are being performed. Flatwork primarily requires horizontal illumination, while building a retaining wall requires vertical illumination. Some tasks require both. For example, a flagger station requires some vertical illumination so that the stop/slow paddle and the flagger’s face and hands are clearly visible to drivers and horizontal illumination to allow drivers identify their correct driving path. In most cases, highway construction primarily requires horizontal illumination, so it is generally possible to select lighting equipment that can be mounted overhead to direct predominantly downward (this helps control driver glare and spillover into areas beyond the work site).

2.3. Beam Spread.

Outdoor lighting equipment can be broadly classified as symmetric or asymmetric. Symmetric luminaires produce a circular lighting pattern while asymmetric luminaires typically emit an oval, rectangular, or crescent-shaped pattern.

Using luminaires with asymmetric beam patterns is often desirable for work zone applications because it allows the luminaires and their power supplies to be positioned on the shoulder where they are less likely to interfere with the work operations (Figure 10).

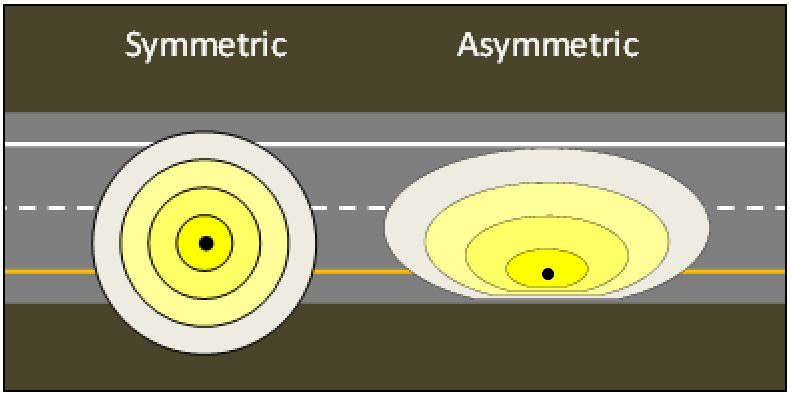


Figure 10. Asymmetric luminaires can often be positioned on the roadway shoulder where they are less likely to be in the way of workers and equipment.

The lighting products industry has developed a system for describing the illumination pattern of various types of luminaires. This is referred to as **beam spread** and is traditionally indicated by the **NEMA Type**[1]. Type 1 is a very narrow spotlight and Type 7 is a very wide floodlight. Asymmetrical (oval) beam spreads are identified by two numbers, for example NEMA Type 6 × 3.

Table 3. NEMA Beam Spread Classifications.

NEMA Type	Beam Spread	Description
1	10° to 18°	Very Narrow
2	18° to 29°	Narrow
3	29° to 46°	Medium Narrow
4	46° to 70°	Medium
5	70° to 100°	Medium Wide
6	100° to 130°	Wide
7	130° and up	Very Wide

The NEMA designations were developed at a time when circular or oval beam patterns were typical. Modern LED luminaires are not limited to these shapes: square, rectangular, and crescent-shaped patterns are increasingly popular and merit consideration in work zone applications. For example, a rectangular or crescent-shaped pattern rotated to match the cone taper can be useful when lighting a flagger station.

[1] NEMA is the National Electrical Manufacturers Association. Note that NEMA also has a separate set of "type" numbers describing different kinds of electrical enclosures (e.g. indoor vs waterproof electrical boxes).

Detailed information about beam spread is embedded in machine-readable format in each luminaire's IES file. The information can be visualized using free software. It is common for manufacturers to use the same external housing, but by changing the shape of the reflector and LED arrangements inside the fixture, are able to offer many different lighting patterns, and all with the same power consumption.

2.4. Key Light, Fill Light, and Shadows

The terms **key light** and **fill light** refer to the predominant and secondary sources of light when there are two or more luminaires at a scene. As shown in Figure 2 and Figure 36, a common past practice was to light work zones using a single source, typically a 30-foot high portable light tower topped with 4 × 1000 watt high intensity discharge lamps. This arrangement produces extremely bright light—but only from one direction (all the light is key light): harsh shadowing occurs obscuring areas in the field of view; objects will look flat making it difficult for workers to see small defects and distinguish details. In addition, without fill light, reflections from wet surfaces (such as freshly placed concrete) can be problematic.

Using two or more luminaires spaced several feet apart provides both key light and fill light (Figure 11). An additional fill light placed behind the object, sometimes called a **back light**, can further enhance object details. The portrait photos in Figure 12 compare the effects of single-point and multi-point lighting: note the additional details visible in the right photo, such as the subject's hair and beard. In work zones, multi-point lighting softens shadows and makes it easier to see three-dimensional details such as pavement texture. When feasible, placing the lights at different heights can also be helpful.

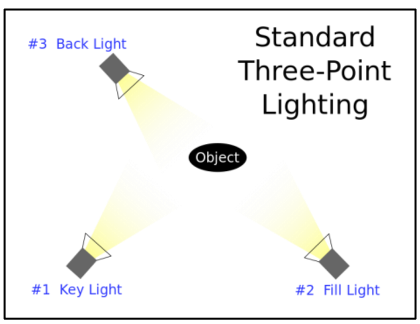


Figure 11. Three-point lighting setup.
Source: WikiMediaCommons/Theonlysilentbob

Source: WikiMedia Commons (Public Domain)/Warner Brothers

Photo: WikiMedia Commons/ Robert Judge

Figure 12. Comparison of single-point lighting (left) and three-point lighting (right) effects.

3. Work Zone Lighting Equipment

3.1. Lamp Types

The following types of electric lamps were in common use for wide-area outdoor lighting in the United States as of 2016:

Light Emitting Diode (LED)

- Typically comprised of multiple semiconductor modules.
- Each emitter is usually encapsulated in a clear plastic lens that focuses or disperses the light.
- Lightweight, long life, directional.
- Resistant to vibration and physical damage.
- Low power consumption: energy efficiencies of up to 300 lumens per watt expected to be commercially available by 2016 [5].
- No warm-up time, instant re-strike when turned off.
- Objects appear in their true colors; most manufacturers provide a Color Rendering Index [CRI] close to 100, mimicking sunlight.
- Do not burn out suddenly – gradually become dim with age.
- Individual diodes generally not replaceable.

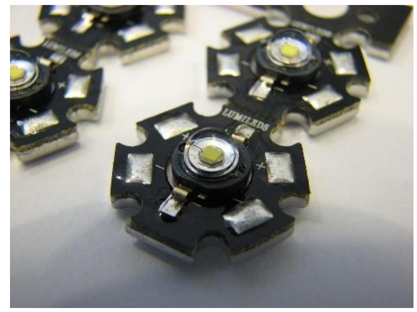


Figure 13. High-power light emitting diode modules
Source: WikiMedia Commons/Gophi

Metal Halide

- Quartz discharge tube with mercury and metal halides (usually sodium iodine).
- Energy-efficient.
- Typical lamp life 6,000 to 15,000 hours.
- Good color rendering.
- Requires 1 to 15 minutes to reach full brightness.
- When turned off, a cool-down period of 2 to 20 minutes is required before the lamp will re-strike (re-illuminate). In applications where luminaires must be moved frequently, this can delay and frustrate workers.

Figure 14. 400 watt metal halide lamp (36,000 lumens) with 100 watt incandescent lamp (1600 lumens).
Photo: WikiMedia Commons/JoeX

Halogen

- Tungsten filament surrounded by halogen fill gas (typically iodine or bromine).
- Generate considerable heat; poor energy-efficiency.
- Very good color rendering (100 CRI)
- No warm-up time, no re-strike time.
- Low up-front cost.
- Short lamp life; fragile filament can break if bumped or dropped.

Figure 15. 500 watt halogen lamp (11,000 lumens).
Source: WikiMedia Commons/Hundehalter

High Pressure Sodium (HPS)

- Quartz discharge tube with sodium and mercury.
- Energy-efficient, long service life.
- Warm-up time approximately 5 minutes, long re-strike time.
- Produces pinkish-orange light with low CRI (about 25).
- Unsuitable for work operations that require accurate color recognition, such as electrical wiring (for example, yellow and orange objects look almost the same under HPS light).

Figure 16. 600 watt high pressure sodium lamp (90,000 lumens)
Source: WikiMedia Commons/Skatebiker

Low Pressure Sodium (LPS or SOX)

- Quartz discharge tube with sodium.
- Very energy-efficient, long service life, vibration resistant.
- Long warm-up and re-strike times.
- Produces monochromatic yellow light with a CRI of -44.
- Unsuitable for work operations that require accurate color recognition, such as electrical wiring.

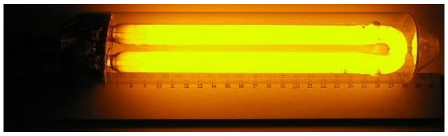


Figure 17. 35 watt low pressure sodium lamp (4550 lumens).
Source: WikiMedia Commons/Proton02

Mercury Vapor

- Quartz discharge tube with mercury.
- Low energy efficiency compared to LED, metal halide, and HPS.
- 4 to 7 minutes warm-up time to reach full intensity.
- The light has a peculiar combination of violet and green hues with a very poor CRI of about 17.
- Not recommended for night highway work, but could be present on site as part of permanent street lighting system.

Figure 18. 80 watt mercury vapor lamp
(2700 lumens).
Source: WikiMedia Commons/Ulfbastel

Figure 19 compares the color and effect of three different lamp technologies that were in use at the same intersection (low pressure sodium, mercury vapor, and LED).

Figure 19. Comparison of lighting sources: high pressure sodium (pinkish-yellow light in foreground), mercury vapor (greenish light alongside street in background) and LED (pure white light on crosswalk at left and corner at right) at an intersection in Alessandria, Italy.
Source: WikiMedia Commons/GiancarloGotta

Incandescent lamps and fluorescent tubes are generally too fragile for work zone lighting applications.

3.2. Luminaire Configurations

Many types of outdoor luminaires are potentially adaptable to work zone applications. Commercial/industrial lighting fixtures that use discharge lamps typically include reflectors to direct the light and prismatic diffusers to make the light softer and more uniform. LED fixtures generally have clear plastic lenses molded directly over each individual LED; the shape of the lens determines the direction of the emitted light. Beam patterns vary depending on configuration of the lamps, reflectors, diffusers, and lenses.

Another designation relates to the extent to which luminaires are designed to reduce the amount of light that spills onto adjacent areas. The Illuminating Engineering Society (IES) defines fixtures as full cutoff, cutoff, semi-cutoff, or non-cutoff (Figure 20).

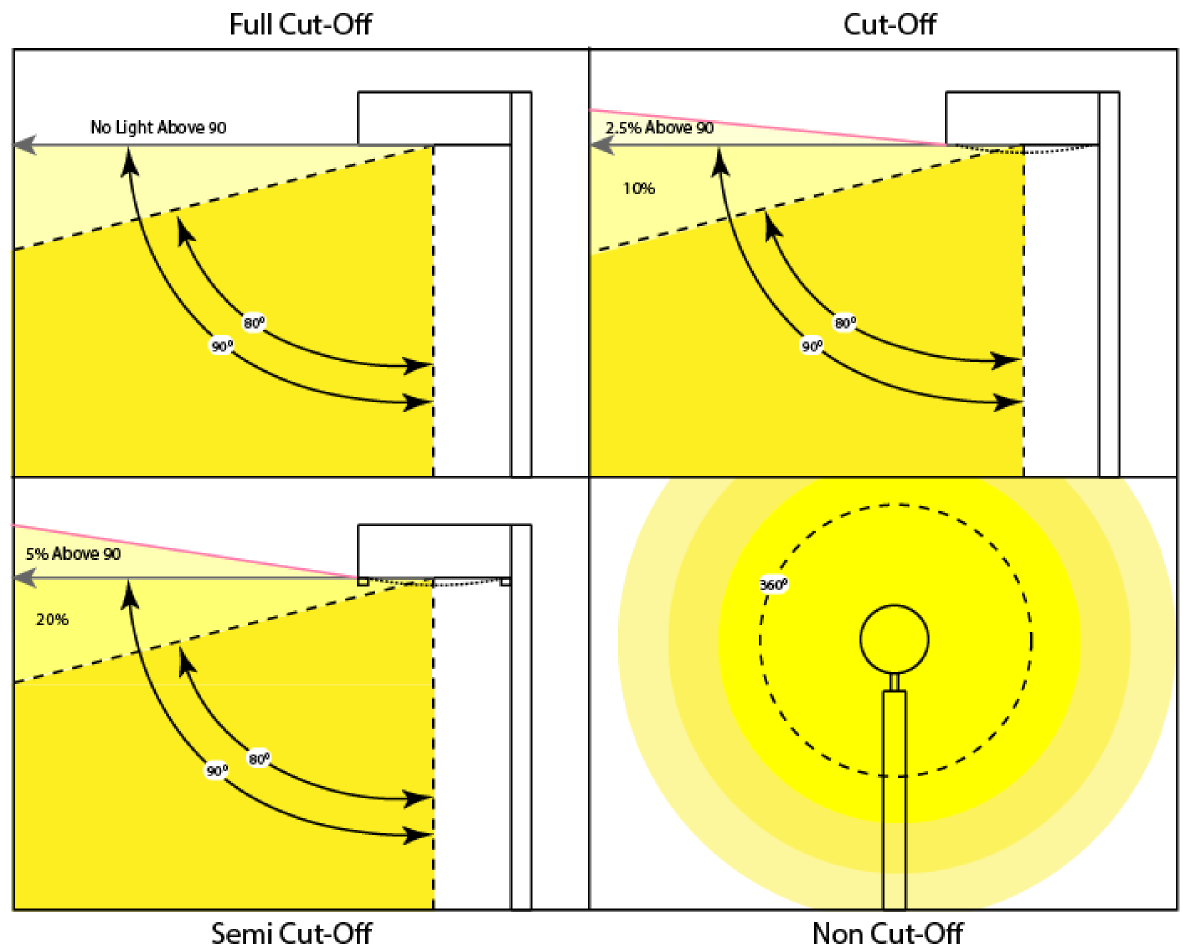


Figure 20. Full cutoff, cutoff, semi-cutoff, and non-cutoff luminaires.
Source: UW-TOPS Lab

3.3. Balloon Lights.

Balloon lights are a specialty luminaire originally developed for the film and video industry (Figure 21). The design is essentially an industrial version of the traditional Japanese paper lantern. These luminaires typically consist of one or more high-intensity lamps surrounded by a translucent fabric balloon that softens and disperses the light. The upper portion of the balloon often has a reflective inner coating to direct some of the light downward. Some commercial products use a blower to expand the balloon, while others have an umbrella-like internal wire frame. Various light sources are available including halogen, metal halide, and LED. The balloon helps reduce glare, but the non-cutoff fixture makes spillover control difficult. Systems are typically supplied with a special carrying case to minimize the risk of damaging the fabric during transport. Balloon lights are substantially more expensive than other luminaries with comparable output.

Figure 21.Tripod-mounted balloon light.
Source: WikiMedia Commons/Thiemo Schuff

3.4. Portable Light Towers

Portable light towers (Figure 22 and Figure 23) are one of the most widely available work zone lighting systems. The equipment typically consists of a trailer-mounted diesel engine with a generator and four high-intensity lights on a telescoping mast. Most commercially available units extend up to 30 feet high. This configuration is popular with contractors due to portability, low up-front cost, and relatively fast set-up time. Typically, the generator has reserve capacity to power auxiliary lamps or other tools. Engine noise can generate complaints near residential areas.

The most widely used configuration has 4 x 1000 watt halogen or metal-halide lamps which is sufficient to illuminate several acres. LED based systems are also available; the greater efficiency of LED lamps allows the lights to operate for several hours using battery power or multiple towers can be connected and operated from a single generator.

Tower lights are a very intense light source and must be aimed with utmost caution. Pointed downward such a system can produce well over 200 foot-candles in the immediate vicinity of the tower, but it is difficult to achieve uniformity because the light drops off to less than 2 foot-candles at a distance of 50 feet from the tower [6]. With a typical output of 400,000 to 500,000 lumens, the systems can create blinding glare and serious traffic safety hazards if improperly aimed. Glare problems are especially likely if the vertical lamp tilt angle exceeds 45 degrees [3].

Figure 22. Portable light tower.
Source: WikiMedia Commons/Shisheng Xuan

Figure 23. Two portable light towers shining directly at camera (note the glare).
Source: Pavement Interactive

As shown in Figure 24, kits are available for retrofitting portable light towers with balloon lights. This provides a uniform light distribution and spreads the light over a wider area, which can be helpful in managing glare.

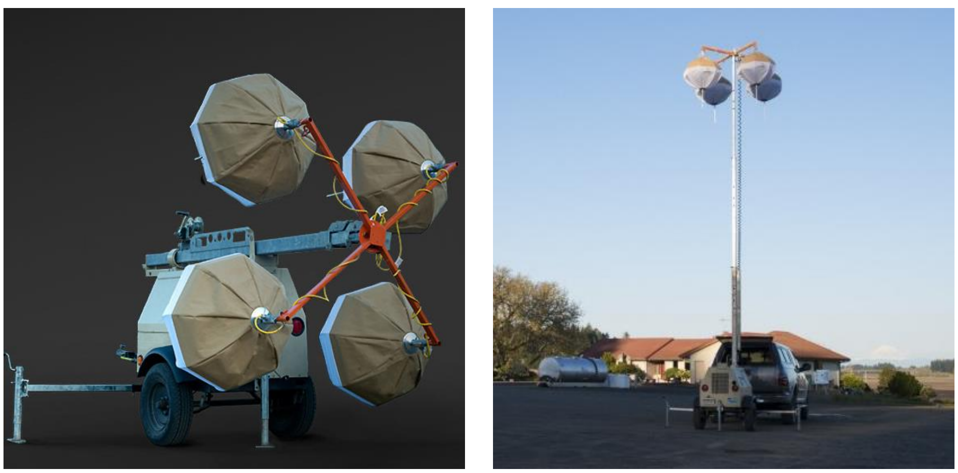


Figure 24. Balloon light adapter for portable light towers.
Source: MoonGlo Work Light LLC/moongloworklightusa.com

3.5. Tripod-Mounted Floodlights

Tripods are a popular means of mounting portable work lights (Figure 25). Typically, the maximum height is 14 to 16 feet. Tripods are portable and lightweight, but can tip over in high wind.

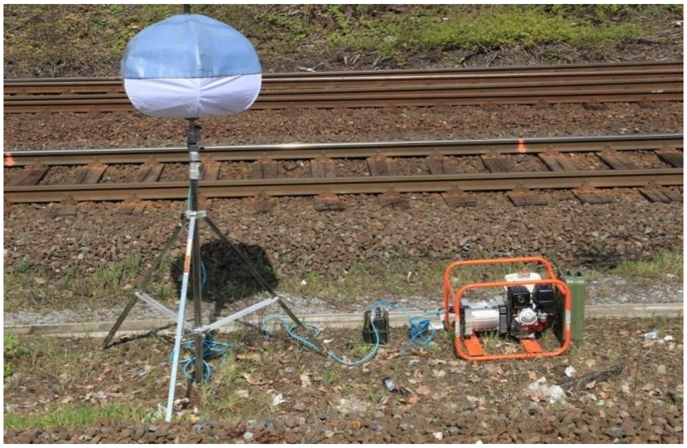


Figure 25. Tripod-mounted balloon light with generator.
Source: Frank Vincentz/WikiMedia Commons

3.6. Equipment-Mounted Lights

As shown in Figure 26 through Figure 29, some types of lighting luminaires can be mounted directly on construction equipment. Since the lights move with the equipment, this can reduce the effort required to set up activity area lighting. Another advantage is that the lights can be powered by the construction equipment's electrical system which is increasingly practical with energy-efficient lamp technologies such as LED.

Figure 26. Sketch of an equipment-mounted LED downlight attached to an asphalt paver.
Source: Modified photo by UW-TOPS Lab. Base photo: WikiMedia Commons/AlvfanBeem

Figure 27. Sketch of equipment-mounted LED downlights attached to an asphalt roller.
Source: Modified photo by UW-TOPS Lab. Base photo: WikiMedia Commons/Ellin Beltz

Figure 28. Floodlight attached to equipment to provide task lighting.
Source: Pavement Interactive

Figure 29. Balloon lights attached to an asphalt paving machine.
Source: National Cooperative Highway Research Program Report 476

3.7. Pushcart-Mounted Lights

Luminaires can be mounted on various types of pushcarts:

- **Hand Trucks.** A pole-mounted luminaire attached to a two-wheeled hand truck is a practical solution for flagger station lighting (Figure 30). The generator or battery is usually mounted on the parcel shelf to counterweight the luminaire. This configuration is well suited to paving operations since the flagger can roll the hand truck along as work progresses.

- **Small pushcarts** (Figure 31) are an alternative to tripod mounting. The entire apparatus can be rolled as a single unit for ease of repositioning. The cart's castors (wheels) should be equipped with brakes to prevent rollaway. The energy source (generator or battery) can be placed on the parcel shelf to counterweight the luminaire. When used with asymmetric luminaries, the cart can usually be placed on the roadway shoulder where it is less likely to interfere with work operations.

Figure 30. Flagger station balloon light and generator mounted on a hand truck.
Source: Airstar Safety

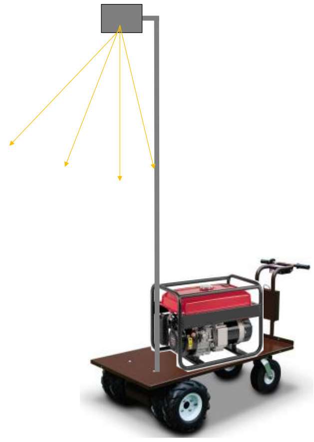


Figure 31. Sketch of an LED downlight mounted on a pushcart.
Source: TOPS Lab

3.8. Other Mounting Options

Some other mounting configurations are potentially useful in work zone environments.

- **Backpack lights.** Battery-powered backpack lights can provide hands-free task lighting in the immediate vicinity of a worker or inspector.

- **Catenary lighting** refers to any type of luminaire suspended from on an overhead cable (Figure 32). This can be a practical solution for longer-term work operations such as bridge construction.

Figure 32. Catenary lighting-suspending luminaires from a cable-is sometimes a practical means of illuminating long-term work zones.
Source: WikiMedia Commons/Holger Ellgaard

4. Health, Safety, and Operational Considerations

4.1. Contrast Panels

Although artificial lighting and high-visibility apparel help improve the visibility of flagger stations, there is often limited visual contrast between flaggers and the background environment to return light toward a source, such as headlights (Figure 33). The use of contrast panels can improve flagger station visibility as illustrated in Figure 34.

Figure 33. There is often limited visual contrast between flaggers and the surrounding environment.
Source: rvecafe.com

A contrast panel typically consists of a roughly four foot by four foot piece of plywood, corrugated plastic, or fabric positioned behind the flagger (Figure 34). The color of the panel should be unreflectorized matte white. To avoid impeding the flagger’s ability to see traffic and the work operations, the height should not exceed approximately 4 feet. The panel can be mounted on an approved crashworthy base, but it is often simplest to place it on a hand truck or cart that can be moved as the work location changes. A contrast panel can also be improvised by putting a white tarp over a sawhorse, barricade, etc.

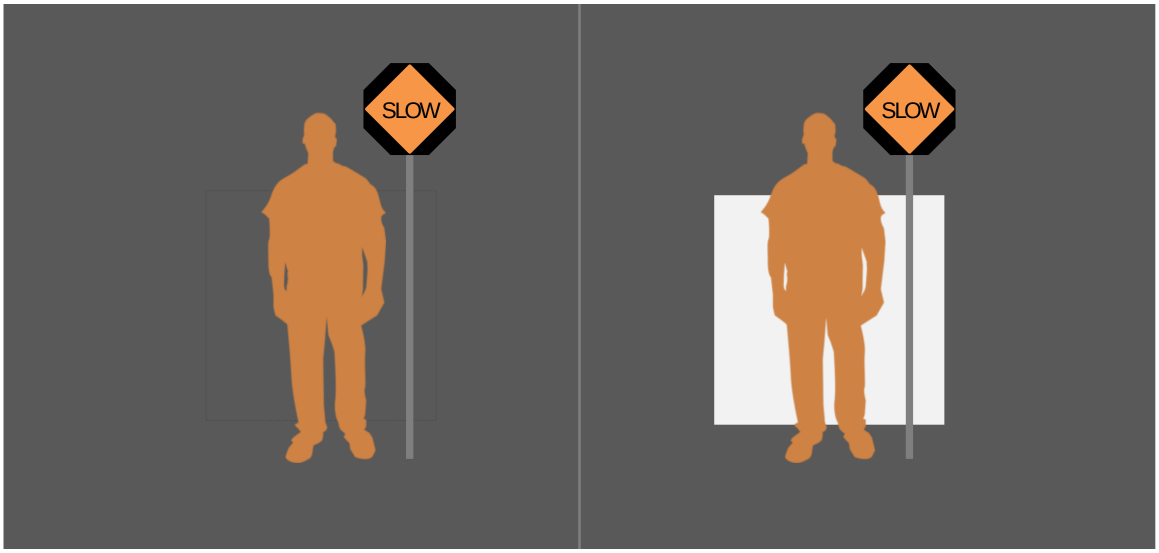


Figure 34. A matte white panel positioned behind the flagger can help improve the night visibility of the flagger station.
Source: Modified image by UW-TOPS Lab. Base image by WikiMedia Commons/rejon

4.2. Minimizing Driver Distraction from Work Vehicle Lighting

The more objects there are in a driving scene, the mental effort increases for drivers to process incoming visual information and decide which objects are important to the driving task. During night work operations, the number of light sources and objects (workers, vehicles, etc.) can sometimes be overwhelming. As a result, drivers (especially those travelling at high speed) will tend to ignore objects in their peripheral vision. Visual overload is particularly likely if there are large variations in lighting intensity in different parts of the scene.

Flashing Lights. Flashing amber lights are intended to draw attention to work vehicles. When used indiscriminately, they can inadvertently pull attention away from other work zone hazards, such as workers on foot. When several work vehicles are clustered in one area, the combination of multiple flashing lights can encourage drivers to direct their attention to parts of the scene that are not relevant to navigating safely through the site. In addition, excessively bright flashing vehicle lights can leave after-images that interfere with seeing other parts of the scene.

Figure 35. Amber beacon.
Wikimedia Commons/ Ehsnils - Eget arbete.

The vehicle equipment industry produces many types of flashing vehicle lights ranging from simple beacons with a single flash pattern at moderate intensity (Figure 35) to elaborate light bars that produce very intense light and offer dozens of complex flash patterns. In general, a simple beacon is sufficient to warn workers within a closed area about approaching vehicles. While brighter light bars could be appropriate for daytime operations, their light levels (and flash rates) are often excessive for night operations.

The MUTCD requires arrow boards and portable changeable message signs (PCMS) to be dimmed at night, and this is also appropriate for flashing amber lights on work vehicles. To avoid damage to night vision, the brightness of flashing amber lights should not exceed 400 to 600 effective candelas [7], [8]. High flash rates convey a sense of urgency that is generally appropriate for emergency vehicles, but not for work vehicles. As a result, flash rates should be limited during night work. Table 4 provides recommended specifications for flashing lights used at night in a lane or area that is closed to general traffic when it is equipped with work zone lighting providing an average illuminance of 5 foot-candles or more.

Table 4. Recommended specifications for flashing amber lights on work vehicles used in illuminated work zones.

Parameter	Minimum	Maximum
Luminous Intensity (effective candelas)	40	400
Flash Rate (flashes per minute)	60	90

Source: FAA Advisory Circular AC 150/5210-5D.

Headlights. Due to their almost horizontal position, vehicle headlights are not good sources for production lighting. They can also be a major distraction to oncoming vehicles especially if the work operation involves counter-directional travel on a divided highway. Therefore, the following contractual provisions are recommended:

- **Turn off headlights when not needed.** When operating in an area that is closed to traffic and has temporary work zone lighting with an average intensity of 5 foot-candles or more, work vehicles should turn off their headlights. Low-intensity parking lamps should remain illuminated.
- **Avoid counter-directional travel.** Counter-directional travel by work vehicles on a divided highway can distract and confuse drivers and should be avoided whenever possible. When counter-directional travel is necessary, headlights should be cleaned frequently to minimize halo effects and the vehicle should operate at low speed with headlights dimmed. If available, daytime running lamps should be used in lieu of headlights during counter-directional running.

Example. Asphalt paving is being done at night in an area illuminated to the levels recommended in Table 4. This is done using downward-focused lights mounted above the paving machine and on similar equipment. A loaded asphalt truck approaches the work zone and drives through the transition area with its headlights on. As the vehicle reaches the portion of the activity area where supplemental work zone lighting has been provided, it reduces speed to approximately 10 mph. The vehicle operator turns off the high-intensity "general purpose" flashing amber lights and turns on the medium-intensity "night work" flashing amber beacon. The operator then turns off the headlights, leaving the vehicle's low-intensity marker lamps (parking lamps) illuminated. The headlights remain off until the truck has discharged its load into the paving machine. When unloading is completed, the driver slowly pulls forward, turns on the headlights, switches to general-purpose flashing amber lights, and the empty truck leaves the activity area.

4.3. Electrical Safety

A number of design details can help protect the general health and safety of workers using work zone illumination equipment, along with the safety of pedestrians and others who might be exposed to temporary wiring.

Electrical Code Compliance. *Contractual provisions should be put in place to assure that all work zone lighting complies with relevant provisions of the NEC or other applicable state and local codes. As of mid-2015, all U.S. states except Arizona, Mississippi, and Missouri had adopted the National Electrical Code (NEC). The NEC allows slight relaxations of certain electrical standards for temporary installations, but these are not an excuse for haphazard wiring practices such as frayed cords, loose connections, or non-weatherproof splices in outdoor environments.* Many work zone lighting systems are designed to operate on 120-volt 60 Hz alternating current. All such devices must be protected by circuit breakers and Ground Fault Circuit Interrupters (GFCIs), even if powered by a generator. Suitable luminaires must be used—not bare lamps without guards. To reduce the likelihood of loss of lighting in the event that another tool or device trips a circuit breaker or GFCI, the NEC requires lighting and receptacles (outlets) to be on different circuits.

Equipment Voltage.
One of the best ways to reduce the risk of injury when using electrical equipment is to limit the supply voltage to the lowest needed to get the job done [9]. Specifying the use of low-voltage (12 volt DC or 24 volt DC) devices can reduce the risk of shock, spark, or fire in the event temporary wiring is cut or damaged by work operations. This is particularly advantageous in wet environments and can make it easier to comply with electrical codes. In some cases, 12-volt DC devices can be powered directly from vehicle or equipment alternators or using deep-cycle batteries.

Another method for reducing electrical hazards is to specify the use of center-tapped isolation transformers (known as 55-0-55 transformers) [10]. These devices take a standard 120-volt AC input and convert it to two 55-volt feeds that are 180° out of phase. Connecting across both phases allows the use of standard 110-120 volt devices, but the voltage-to-ground is limited to 55 volts to reduce shock and fire risks.

The use of higher voltage equipment (such as 208 or 240-volt systems) is not recommended for work zone lighting.

Physical Protection of Lighting Equipment. Contract specifications should ensure that electrical cords and cables are carefully routed to avoid tripping hazards for workers and the public. Cables and lamps should be protected from breakage and wire damage. To prevent temporary lights from being blown over by the wind, they should be firmly anchored or weighted. If a lamp breaks, the exposed filament could present a hazard. Contract specifications should also ensure the contractor inspects luminaries, lamps, cables, generators, batteries, and other electrical equipment regularly to maintain electrical safety and to keep the site properly illuminated.

4.4. Chemical Safety

Many outdoor lighting systems use lamps that contain mercury, metallic sodium, lead, or other hazardous chemicals. In work zones, there is always a risk of physical damage to lamps due to a knock-down or similar mishap, potentially exposing workers and the public to these substances. Specifying lamps that are certified as compliant with the European RoHS (Reduction of Hazardous Substances) directive can help reduce chemical hazards. Many LED lighting products are RoHS compliant.

Small portable generators are usually fueled by gasoline while larger generators usually use diesel fuel. Extra fuel should be stored well away from sources of ignition. Battery-powered systems typically use deep-cycle lead-acid batteries; consideration should be given to specifying the use of gel cell batteries which are less likely to cause a hazardous spill if tipped or damaged.

4.5. Edge Marking

Although the presence of properly designed work zone lighting can enhance the overall safety of the work site, during night work it is especially important that workers can readily locate and identify hazards such as trenches, open manholes, and the edges of elevated work platforms. In many cases, this can be accomplished by marking edges and boundaries using fences, paint, or retro-reflective tape. In some instances, it is appropriate to provide secondary lighting to reduce hazards at areas that would otherwise be concealed by shadows (for example a trench in a shadowed area might not be visible to a person approaching on foot). Increasing overall illuminance levels is sometimes helpful, but this must be done carefully to assure that it does not increase glare, shadowing, or contrast problems.

4.6. Maintaining the Work Zone Lighting System

Dirt significantly reduces the amount of useful light produced by a lighting system and work zones are often dusty environments. Low-mounted luminaires can become splashed with asphalt tack, concrete paste, paint, etc. As a result, contractual provisions should assure that lamps, reflectors, and diffusers used in work zone lighting systems are cleaned and inspected regularly. Lighting systems should also be inspected regularly for frayed wiring, loose connections, and missing or damaged heat shields and guards. Where the designer has reason to believe that the work zone will be unusually dusty or cleaning will not be completed regularly, the light loss factors used in analytical computations should be adjusted accordingly.

5. Lighting Design Criteria

5.1. The Workers' Perspective: Measuring and Specifying Illumination Levels

Target illuminance levels are important work zone lighting design parameters. Since illuminance decreases with distance from the lighting source, it should be measured (or computed) at the actual height where the work will be taking place. For most paving operations, this will be the top of the subgrade or (in the case of an overlay) the surface of the existing pavement. For work operations involving excavation, the lighting intensity should be measured at the bottom of the trench. (This differs from typical practice for interior lighting where intensity is usually measured at desktop height.)

Maximum and minimum illuminance levels should be established by the designer based on the anticipated type of work operations. The smaller that the object to be seen is and the less contrast the object has with its background, the more light is needed [4]. As shown in Table 5, three general categories have been established based on the difficulty of the work task and how much visibility is required to perform the task. (Note that in addition to this general work zone illumination, small task lights might be required for shadowed areas such as the interior of manholes, pull boxes, and electrical cabinets.)

Table 5. Recommended illuminance levels for highway worker task areas.

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

* Note: Maximum illuminance to be measured in conditions of full darkness and subject to further limits based on glare control.

The MUTCD indicates that an average horizontal luminance of 5 foot candles can be adequate for general construction, while tasks requiring high levels of precision and extreme care can require an average horizontal luminance of 20 foot candles [4]. Similar guidance was provided in NCHRP Report 476 [11]. For simplicity in field implementation, these averages have been adapted into minimum and maximum levels for the **task area of each individual worker** (adaptation is necessary due to practical considerations associated with lighting an outdoor area with indefinite boundaries). In the past, some work zones have been illuminated to levels far in excess of the Level 3 criteria which can be problematic for drivers. As a result, suggested maximum levels are also provided in Table 5.

These levels are for ordinary atmospheric conditions; higher illuminance could be necessary under extraordinary conditions such as excessive dust or mist. Brighter lighting might also be justified if it is known that the majority of the workforce will consist of older employees (as they age, people need more light to accomplish the same task).

Methods for measuring illuminance in the field (and determining compliance with these criteria) are discussed in Section 8.2. The rationale for using maximum and minimum levels is discussed in Appendix A.

In the past, work zone lighting systems were sometimes specified based on the power consumption of the lamps, for example in watts per square meter of work area. With the transition to high-efficiency light sources, these computation methods are no longer meaningful.

5.2. The Drivers' Perspective: Contrast and Glare

Contractors often have a "brighter is better" mindset about work zone lighting. This overlooks an important fact: human vision works best when lighting levels are relatively uniform. As discussed in Section 2.1, excessive differences in contrast or illumination levels are called **glare.** Simply put, when part of a scene is very bright and part is very dark, the human eye struggles to make the entire scene viewable:

- Mild to moderate glare is uncomfortable.
- Severe glare causes people to look away, try to shield their eyes, squint, or close their eyes. These instinctive behaviors are clearly undesirable while driving.
- In extreme glare, the fluid inside the eye scatters the light and the brain is unable to process the incoming visual information: the driver is temporarily blinded.


Source: Photo reproduced with the permission of the American Traffic Safety Services Association (ATSSA)


Source: National Cooperative Highway Research Program Report 476

Figure 36. Flagger stations obscured by glare.

While there are no distinct cut-off points for various glare levels, for the purposes of lighting design glare severity is often categorized as follows:

- **Discomfort Glare** is distracting or uncomfortable, but does not significantly reduce the ability to see the information needed for driving (or a similar task).
- **Disability Glare** reduces the ability to perceive the visual information needed for the task. Light is scattered within the eye causing a haze of **veiling luminance** that decreases contrast and reduces visibility. The greater the intensity of the glare light and the closer the glare light is to where one is looking, the greater the disability glare.
- **Blinding Glare** is so intense that no visual perception is possible for an appreciable length of time after the light source has been removed from the field of view.

Disability glare can lead to the following effects:

- **Reduced visibility distance.** The distance at which an object can be seen is known as the “visibility distance.” This distance is reduced when disability glare is present.
- **Increased reaction times.** As the intensity of oncoming headlamps increases, drivers’ reaction times to objects in and along the roadway become longer.
- **Increased recovery time.** Even after drivers pass the light source that is causing the glare, it has a lasting effect that increases the time required for drivers’ eyes to recover their ability to detect objects. During that time, the visibility distance is reduced and reaction times are increased.

Older people are more susceptible to glare and take longer to recover from its effects. Even for young drivers, fully adapting to a sudden change in lighting levels requires several minutes. The adjustment process is not symmetrical: the eye adapts more quickly to an increase in brightness than to a decrease. As discussed in Section 5.5, avoiding abrupt luminous intensity changes should be considered in work zone lighting design.

Contractors tend to think about work zone lighting in terms of workers and their tasks which usually require a pool of light in the immediate vicinity of each work operation. This perspective is very different from what is seen by drivers moving through the work zone at speed or flaggers and other workers needing to view oncoming vehicles as shown in Figure 37, which often consists of a dynamic series of bright and dark areas. If drivers’ eyes adjust to relatively bright lighting near the main work operation (such as paving), they may not clearly see dimmer secondary work operations downstream (such as saw cutting in advance of the paver). As shown in Figure 36, a related problem is lighting layouts that leave workers silhouetted against a bright background. Therefore, lights need to be aimed carefully and lighting levels throughout the entire activity area need to be relatively uniform to minimize the risk of vehicle-worker collisions.

Figure 37. Glare from these floodlights made it necessary for flaggers to shield their eyes to distinguish oncoming traffic.
Source: http://onlinepubs.trb.org/onlinepubs/trnews/trnews260RPO.pdf

5.3. Quantifying Glare

Several methods for measuring glare have been developed. For outdoor lighting, the two most commonly used methods are **Veiling Luminance (VL) ratio** and **Threshold Increment (TI)**. Both are based on the concept of veiling luminance: as the intensity of a glare source reaches a critical value, its light begins to obscure the scene like a veil that has been placed in front of the driver's eyes and, at this point, the driver is no longer able to distinguish the visual information necessary for the driving task.

- **VL ratio** is reported as a decimal. Specifically, it is computed as the maximum value of Veiling Luminance ($L_{v,\,max}$) divided by the Average Pavement Luminance (L_{avg}). Typical maximum VL ratios for roadways are 0.3 to 0.4. As a point of reference, on a two-lane roadway in level terrain the headlight glare from an oncoming vehicle with its low beam lights on produces a VL ratio of approximately 1.7 and the high beams produce a VL ratio of approximately 5.6 [3].
- **TI** is reported as a percentage. Specifically, it is computed as the percentage increase in the luminance of the road surface required to render an object just visible under the proposed lighting system (with glare present) as compared to the luminance required to render the object just visible in the absence of glare. Typical TI limits for roadways are 10% to 15%.

Glare computations are usually performed using 3D lighting analysis software.

5.4. Controlling Glare.

There are a number of strategies for controlling glare. These include:

- Using multiple luminaires to achieve a uniform lighting level and reduce shadows.
- Using diffusers to spread the light from each lamp more uniformly.
- Avoiding sending light directly into the eyes of drivers and other road users by selecting luminaires that send light in only the directions where it is needed (Figure 38).
- Using luminaire housings that limit the amount of light emitted in undesired directions (these fixtures are called “cut-off luminaires”).
- Using glare screens or walls to block the view of undesired light sources.
- Mounting the luminaire high (around 40 feet) to keep the lamp out of the normal field of view or mounting it so low that it is below eye level.
- Aiming intense light sources (such as tower lights) directly downward or as close to downward as possible.
- Aiming intense light sources (such as tower lights) away from the direction of traffic if possible (note that this may conflict with the goal of minimizing spillover lighting).
- Keeping existing street/highway lighting illuminated (in addition to floodlighting) to improve the overall uniformity of lighting levels (general light reduces the veiling luminance ratio).

As the mounting height of a luminaire is lowered, the vertical component of the light increases resulting in increased risk of glare. For a mounting height of about 40 feet, light reaching the driver’s eyes at vertical angles of 60 to 90 degrees is perceived as glare and light in the 80 to 90 degree range is especially problematic (Figure 41).

Figure 38. Industrial exterior luminaires are available in models that provide a focused beam to help manage spillover and glare.
Source: Hubbell Industrial

5.5. Lighting Uniformity.

Uniformity ratios are frequently used as design criteria for lighting systems, but their use in work zone environments is somewhat difficult. There are two ways of defining the uniformity of an illuminated scene. The first is to compare the luminance of the **brightest area** to the luminance of the **darkest area**. The second is to compare the average illuminance with the illuminance in the darkest area. Both values can be expressed as ratios greater than one, or as decimals less than one. For the purposes of this document, the latter approach has been used:

$$U_0 = E_{min} / E_{ave}$$

Where:
E_{min} is the minimum illuminance in the room or area
E_{ave} is the average illuminance in the room or area

A number closer to 1.0 indicates more uniform light levels. Typical minimum U_0 targets are 0.40 to 0.70 for building interiors and 0.17 to 0.33 for parking lots, roadways, and exterior walkways [1], [12].

The concept of uniformity is important in all work environments. If a uniformity ratio is to be contractually stipulated for work zone lighting, the boundaries of the "work area" need to be clearly defined. When lighting is provided only in the immediate vicinity of tasks, such as milling or paving, the uniformity ratio measured across the entire MUTCD "project area" can fall to as little as 0.01 [3]. If the contractor is required to provide uniformity throughout the entire MUTCD project area, lighting will be required in portions of the work zone where neither workers nor equipment are present. A more pragmatic approach is to aim for uniformity in the immediate vicinity of the workforce.

When there are two or more active task areas, consideration should also be given to lighting continuity for any workers who need to travel between the areas. A minimum illuminance of 0.5 to 1.0 foot-candles is recommended in the intervening space to reduce the risk of trip/fall type injuries, especially if the workers need to traverse uneven surfaces or areas where construction debris are present.

5.6. Spillover Lighting

As shown in Figure 39, some types of luminaires send light in directions where it is rarely needed. For example, except in the case of tunnel work or repairs on the underside of bridges, it is seldom necessary to provide upward illumination.

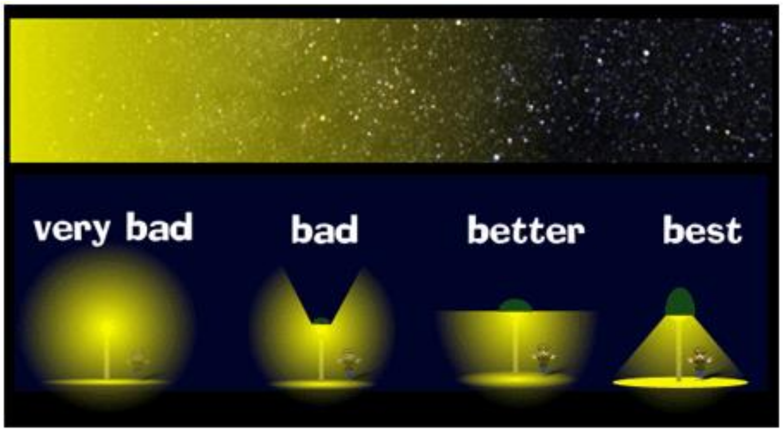


Figure 39. Control of spillover light.
Source: International Dark-Sky Association

When luminaires without reflectors are used for paving operations or similar flatwork, about half of the light goes into the sky, where it is of no benefit to the workforce. The Upward Waste Light Ratio (UWLR) quantifies the amount of undesired up light; it is defined as the proportion of the luminous flux emitted by the luminaire above the horizontal in the installed position.

Light emitted horizontally contributes to glare for drivers and can be a nuisance for second- and third-floor occupants of buildings adjacent to the work zone. Reflector-diffuser systems (Figure 40) allow light to be directed and utilized efficiently, reducing the required number of luminaires, generators, cords, and other electrical apparatus. The position of the lamp within the reflector-diffuser assembly is an important factor in controlling glare and limiting spillover, sky glow, and light trespass.

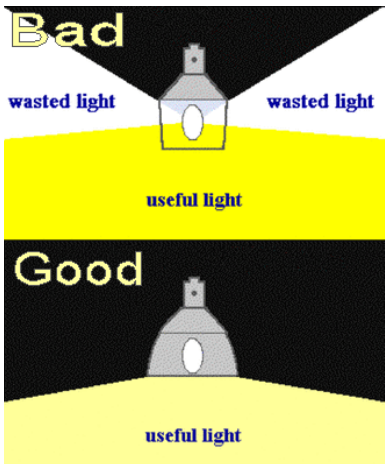


Figure 40. Reflector-Diffuser.
Source: International Dark-Sky Association

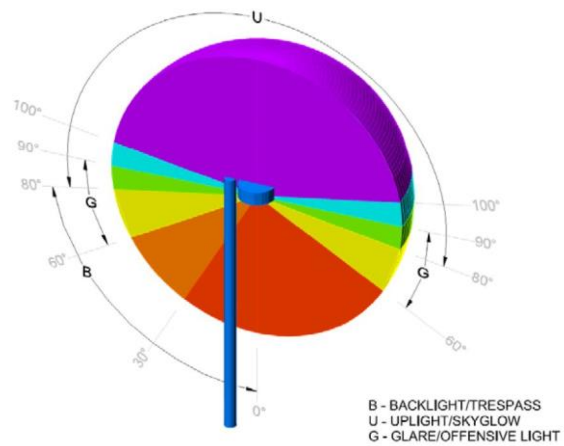


Figure 41. Spillover and glare angles for a luminaire mounted at 40 feet.
Source: FHWA Lighting Handbook (August 2012)

5.7. Use of Existing Highway Lighting

Typical design standards for permanent street and highway lighting call for average maintained illuminance levels of 0.25 to 1.5 foot-candles (3 to 17 lux) depending on the roadway classification and traffic volume [1]. The lowest values are generally found on residential streets and the highest on suburban arterials adjacent to commercial development. Where provided, freeway lighting is usually in the range of 0.50 to 0.75 foot-candles (5 to 9 lux).

Although these levels are generally not sufficient for work operations, keeping existing roadway lighting in service during construction can be helpful in limiting glare from work zone floodlighting by providing a uniform overall illuminance level.

A field survey should be used to determine the existing illuminance levels and luminaire spacing for use in the work zone lighting analysis. This can be done by taking readings with an illuminance meter in a grid pattern throughout the work zone, taking care to assure that the grid spacing differs from the center-to-center distance between existing luminaires. In some cases, early-stage installation of new permanent lighting systems can contribute to the light available for subsequent night construction tasks.

6. Analyzing Work Zone Lighting

Illumination engineering has several sub-specialties. Building interiors, building exteriors, parking lots, highways, sports venues, airfields, and vehicle interiors all require specific types of lighting equipment and lighting design procedures. Lighting engineers who are experienced in highway lighting design are not always experts in the design of work zone lighting, which is more similar to designing the lighting for an exterior industrial operation such as a quarry, railroad switching yard, or refinery. A key difference is that many work zones are industrial operations that move continuously. In addition, glare control in industrial operations is often accomplished by mounting the luminaries very high or screening the site with walls or opaque fences—options that are seldom practical in work zones.

6.1. Software

Exterior lighting analysis can be done by hand, but the process is tedious because it is necessary to add up all of the light coming from each lighting device at multiple angles. More often, the lighting analysis process is automated using specialty software. While 2D lighting analysis packages can provide insight about the lighting levels available to workers, only 3D rendering packages such as AGi32, Relux, and Radiance are suitable for determining the way the lighting layout will look to drivers (See Section 7). These three examples also represent different business models: AGi32 is commercial software available for purchase, Relux is a commercial product that can be downloaded at no charge (the company charges for training and other services), and Radiance is an open source project supported by the U.S. Department of Energy. Some of the available packages are stand-alone software, while others operate as plugins for popular CADD packages.

The analysis process begins by laying out a roadway segment that represents a typical condition for the work operations. This includes:

- establishing the overall length of the task area (plus a suitable buffer for analyzing approaching traffic),
- positions of work vehicles and workers-on-foot,
- stylized representation of the temporary traffic control devices that will be present at the site,
- lateral spacing between work operations and adjoining traffic in both travel dimensions,
- any relevant major terrain features such as large trees,
- if applicable, existing permanent roadway lighting luminaires are added to the scene, and finally
- add proposed work zone floodlighting apparatus in its proposed locations.

Next, the software is used to render and analyze the scene. Relevant outputs include visual representations of the illuminance as it appears to workers, the luminance as it appears to drivers approaching the work zone from all relevant travel directions (including turning movements at intersections), and a plot of the Veiling Luminance Ratio and/or Threshold Index for drivers in the lanes adjoining the work zone.

Luminaire data files are an essential element of the computer-based design process. These files are usually supplied by lighting equipment manufacturers. They provide detailed machine-readable information about how much light is produced by a lighting device, how concentrated or diffused the light is, and the directional pattern of the light. These characteristics depend on the design of the luminaire itself, such as the type of the lamp and the shape of the reflector and diffuser. In the United States, the IES file format is the most frequently used; many software packages also accept the European ELUMDAT format.

Required Data. The following parameters are needed for the analysis:

- Geometry of the road system (lane width, shoulder width, median width, etc.).
- Dimensions and typical positions of the anticipated work vehicles and workers-on-foot.
- IES files for the proposed work zone luminaires and any existing highway lighting.
- Best-available information about existing pavement type and condition so that appropriate reflectance values can be selected.
- Eye height values for lighting analysis are usually 4.75 to 4.92 feet for drivers in automobiles and 5.5 feet for pedestrians. Note: eye height values are recommended by IES and CIE for lighting analysis differ from those recommended for geometric design in the AASHTO Green Book.
- Lumen depreciation factors for lighting device specifications are based on "initial lumens" which represent the light output when the device is clean and new. Dirt and age can reduce this output. A depreciation value of 0.7 to 0.9 is recommended to account for this effect. Values as low as 0.5 may be necessary for sites with extremely dusty conditions.

6.2. Software Runtime.

As computers become faster, the runtime for lighting analysis is becoming less and less of an issue. Most 3D rendering packages use the ray tracing method. This involves generating a large number of light rays and following their path as they are emitted from each luminaire and bounce off or are absorbed by surfaces such as the pavement, work equipment, etc. The time required for ray tracing analysis depends on the complexity of the shapes that are modeled and the speed of the computer that is running the software.

While there are a several online libraries with 3D PMX models for various types of construction equipment, these photo-realistic models have very complex shapes that add a considerable amount of computation to the ray tracing process. Modeling the work equipment as simple blocks in realistic colors is generally sufficient for analytical purposes and will expedite the runtime considerably. *With 2015 vintage computers, work zone renderings with "block" style vehicles can generally be completed in less than 5 minutes.* If a photorealistic image is desired for a public meeting exhibit or other display, the rendering can be re-run using detailed PMX models and this could take an hour or more.

In general, the runtime computers that use Microsoft Windows operating systems will be accelerated if the computer is booted in "safe mode." Safe mode turns off various services that run in the background, such as periodically checking for new e-mail.

7. Work Zone Lighting Plan Examples

This section provides worked examples that demonstrate how to achieve the target lighting levels with readily available equipment while maintaining acceptable glare and uniformity.

7.1. Case 1: Flagger Station

The first step in developing a lighting analysis for a flagger station is to prepare a plan view sketch illustrating the position of the flagger with respect to traffic lanes and lighting equipment. Figure 42 (based in part on MUTCD Figure 6H-10) provides an example for flagging a two-way one-lane operation.

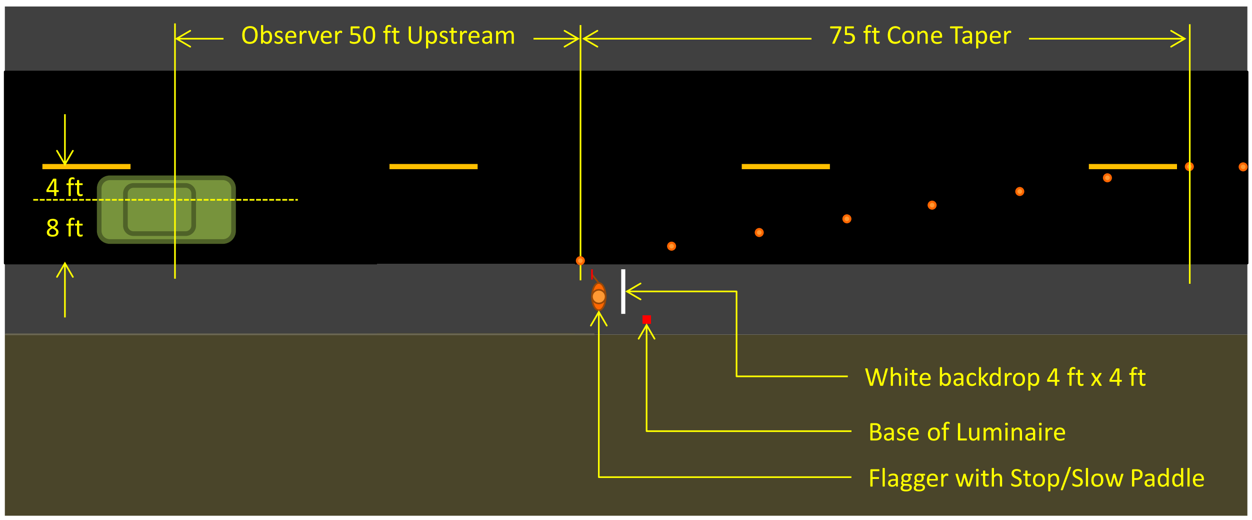
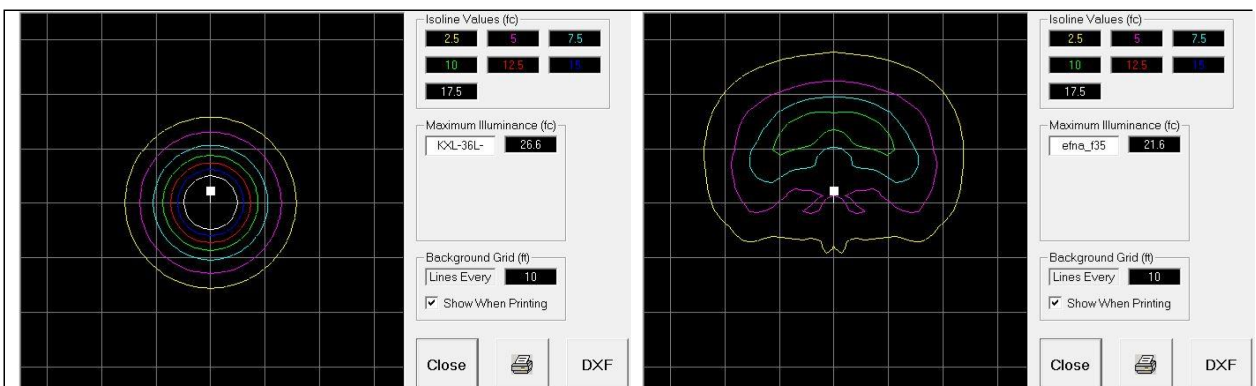


Figure 42. Plan sketch for flagger station lighting analysis.

The second step in the analysis is to identify one or more luminaires that are potentially suitable for the site. A 2D lighting software can be used for a quick comparison of the beam spread as shown in Figure 43.

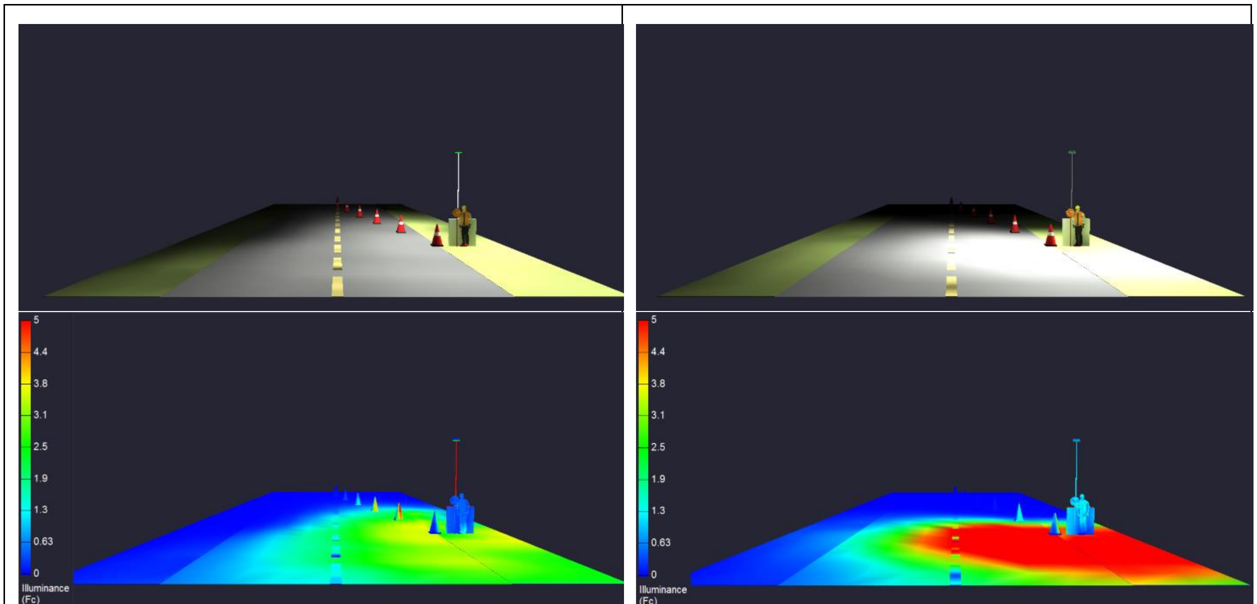


Hubbell Kemlux KXL-36L-X-5K-N (85 watts, 8700 lumens)
Height 14 ft., Light Loss Factor 0.8

GE Evolve EFNA 3540 (148 watts, 13450 lumens)
Height 14 ft., Light Loss Factor 0.8

Figure 43. Isoline charts for two industrial LED luminaires.

Next, the scene is rendered in 3D using the lighting analysis software. The upper half of Figure 44 provides a true-color visual comparison of the lighting effects generated by the two products. The false-color images in the lower half of the figure quantify the illuminance levels. In this case, the asymmetric beam pattern of the EFNA product shown on the right is advantageous because most of the light falls in front of flagger even though it the luminaire is behind the flagger station where it is less likely to be struck by an errant vehicle. (With the symmetric KXL luminaire, the stop/slow paddle and the flagger's face are partially in their own shadows.) Based on the rendering, it is evident that horizontally rotating the luminaire about 30 degrees clockwise would further improve the illumination by shining nearly all of the light on the flagger and the cone taper (in this situation, not much is gained by lighting the roadside beyond the shoulder).



Hubbell Kemlux KXL-36L-X-5K-N (85 watts, 8700 lumens)
Height 14 ft., Light Loss Factor 0.8

GE Evolve EFNA 3540 (148 watts, 13450 lumens)
Height 14 ft., Light Loss Factor 0.8

Figure 44. Comparison of two luminaires at a flagger station- true color rendering version on top and false color rendering version on bottom for two different types of LED lighting products.

7.2. Case 2: Asphalt Paving on a Two-Lane Rural Highway

The previous example of a flagger station illustrates a simple case where the lighting is required at one stationary location. A more involved example for lighting analysis would be a paving operation on a two-lane rural highway. Figure 45 illustrates a plan sketch for an asphalt paving operation where lights are mounted on both sides and behind the paver to enable proper and safe operation of the paver as well as allow the workers performing raking and levelling behind the paver sufficient light to perform their tasks. Lights are mounted in the front and back of the rollers to provide lighting for the operator to move the roller forward and backward to compact the asphalt mat. Finally, portable lights on push carts can be used for other workers, upstream and downstream of the paving operation. Following the steps described in Section 7.1, lighting analysis is performed for two types of luminaires: Balloon lights (Airstar Sirocco) and LED downlights (GE EFNA). Figure 46 and Figure 47 show the true color renderings and Figure 48 and Figure 49 show false color illuminance levels of the paving train operation using balloon lights and LED downlights. The recommended minimum and maximum illuminance levels for a paving operation are 8 Fc and 35 Fc respectively, while the targeted range is 10 to 15 Fc. For the lighting configurations analyzed, the illuminance levels in the work area range from about 15 to 40 Fc for balloon lights, while they range from about 10 to 30 Fc for LED downlights.

For this example, the LED light package produces an illuminance pattern closest to the targeted overall light level range for this night paving operation design. While the balloon lights produce a maximum illuminance level slightly higher than the desired maximum level for paving work, the balloon lights higher illuminance levels may be preferred by the contractor for economical and production reasons. Running this type of analysis with different luminaire types and outputs allows the differences to be examined and tradeoffs to be evaluated.

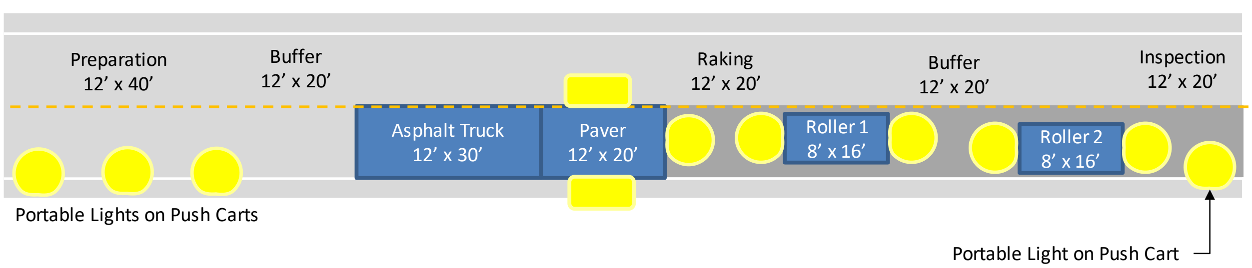


Figure 45. Plan sketch for asphalt paving train analysis.

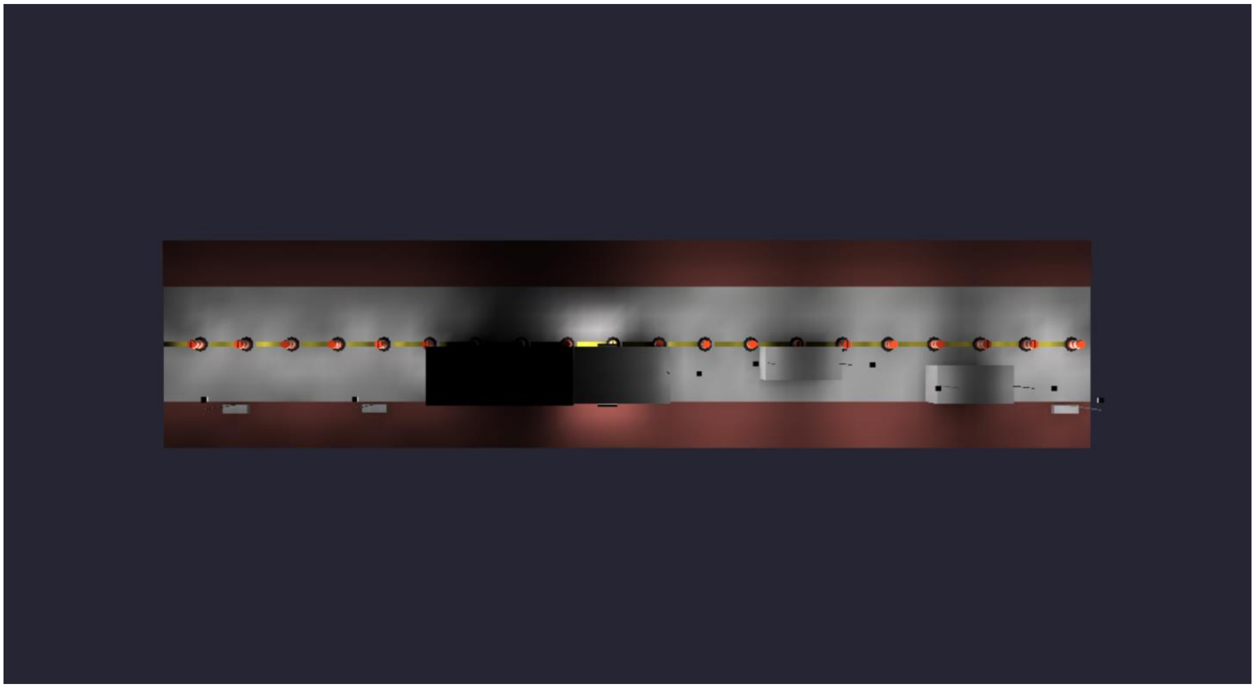


Figure 46. True-color rendering results of the paving operation with LED downlighting (GE EFNA).

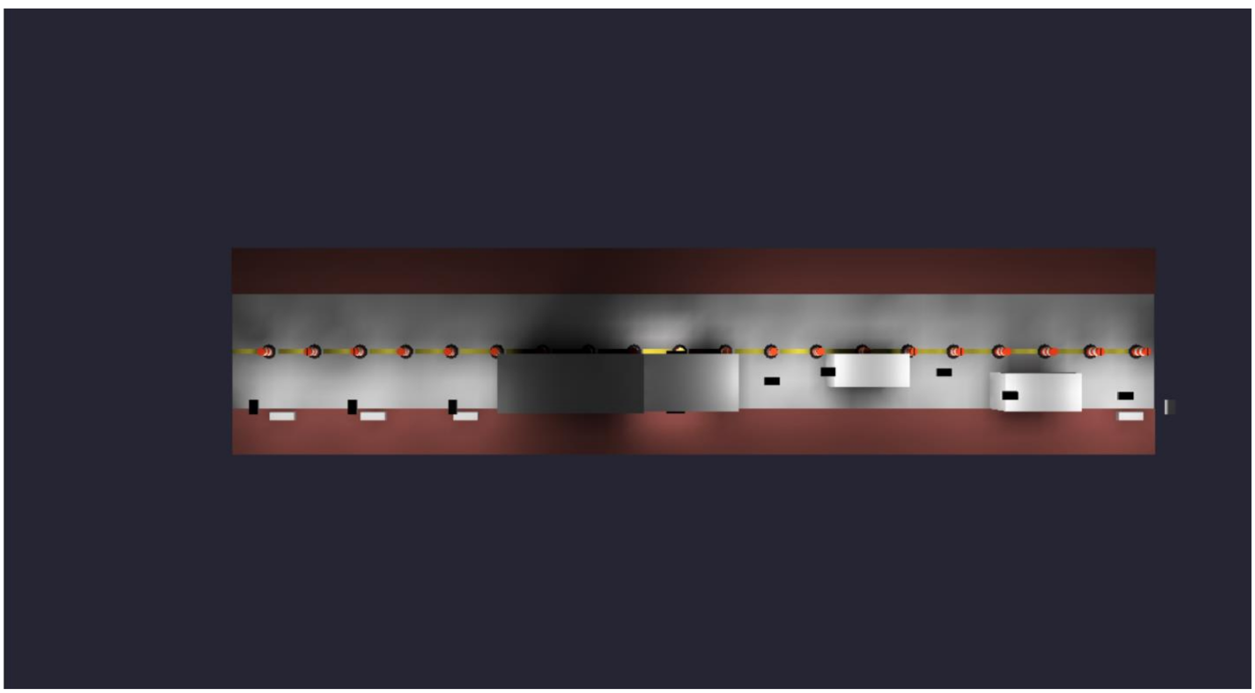


Figure 47. True-color rendering results of paving operation: Balloon Lights (Airstar Sirocco)

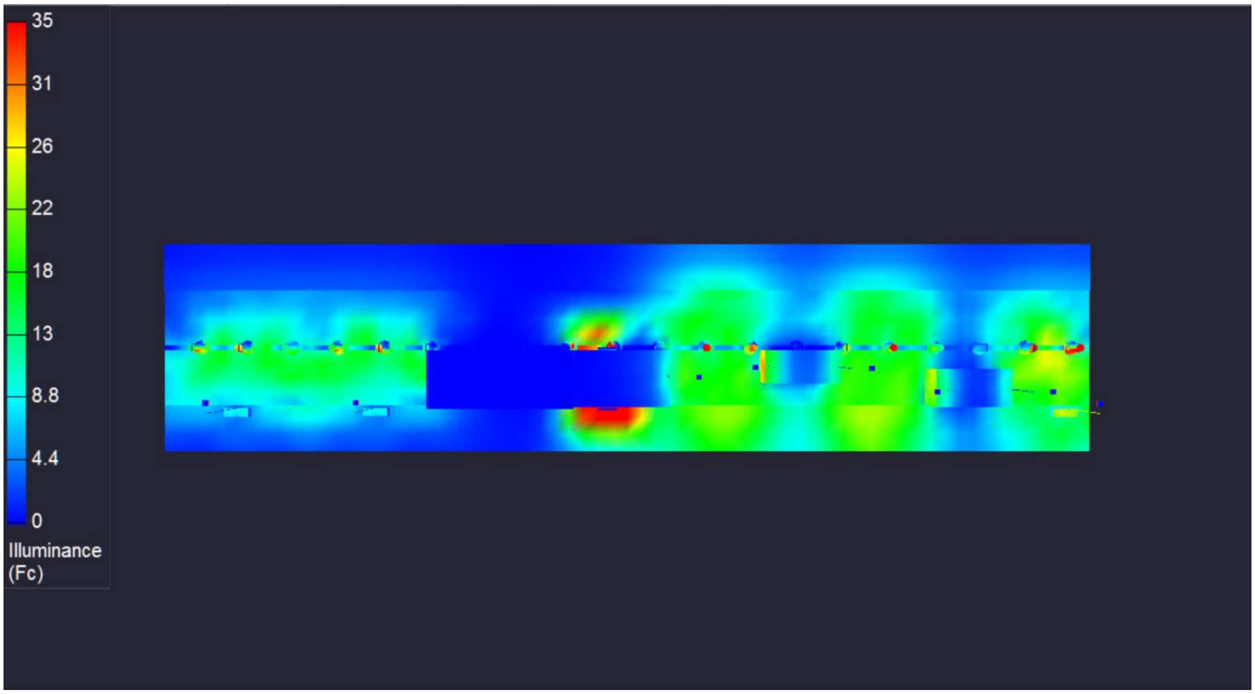


Figure 48. False-color illuminance levels obtained using LED downlighting products (GE EFNA).

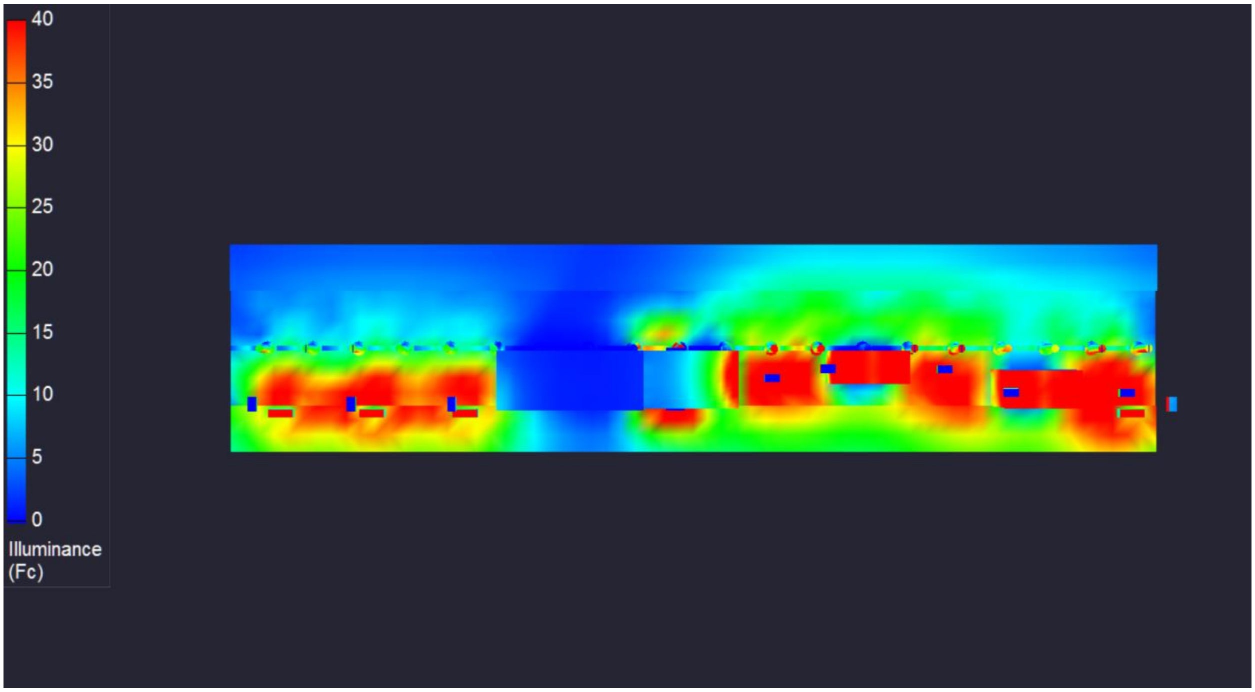


Figure 49. False-color illuminance levels obtained using Balloon Lights (Airstar Sirocco).

7.3. Case 3: Bridge Deck Repair

Using only one light source creates strong shadows, limits visibility in excavations, causes difficulty in seeing surfaces, and causes harsh reflections from wet/shiny surfaces. Considering the nature of bridge deck repair and the precision required, a three-light setup such as the one shown in Figure 50 would be more appropriate to reduce shadows and light the work zone more uniformly. Following the steps described in Section 7.1, lighting analysis is performed for two types of luminaires: Balloon lights (Airstar Sirocco) and LED downlights (GE EFNA). Figure 51 and Figure 52 show the true color rendering results and false color illuminance levels of bridge deck repair scene illuminated by balloon lights while Figure 53 and Figure 54 show the true color rendering and false color illuminance levels for LED downlights. For the lighting configurations analyzed, the illuminance levels in the work area range from about 5 to 35 Fc for balloon lights while they range from about 5 to 20 Fc for LED downlights.

Therefore, both lighting systems appear to produce acceptable lighting results. Examining the results shows the illuminance levels using balloon lights has a wider range compared to the LED downlights.

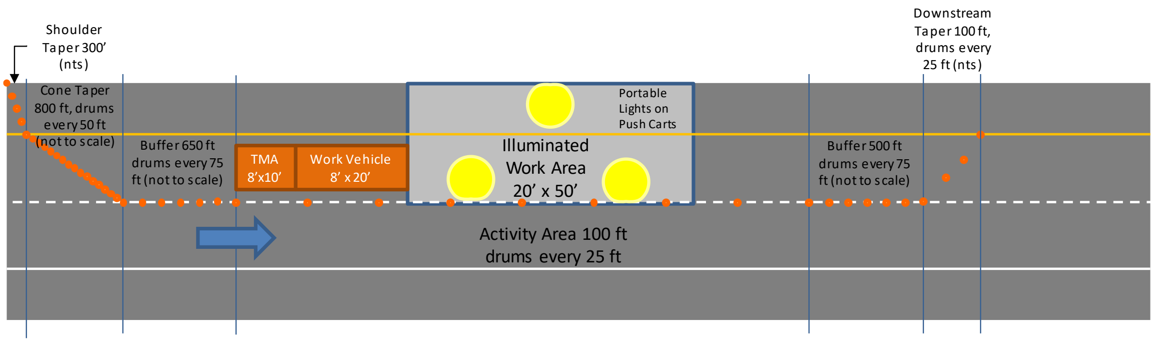


Figure 50. Plan sketch for bridge deck repair with a three light setup for developing lighting analysis.

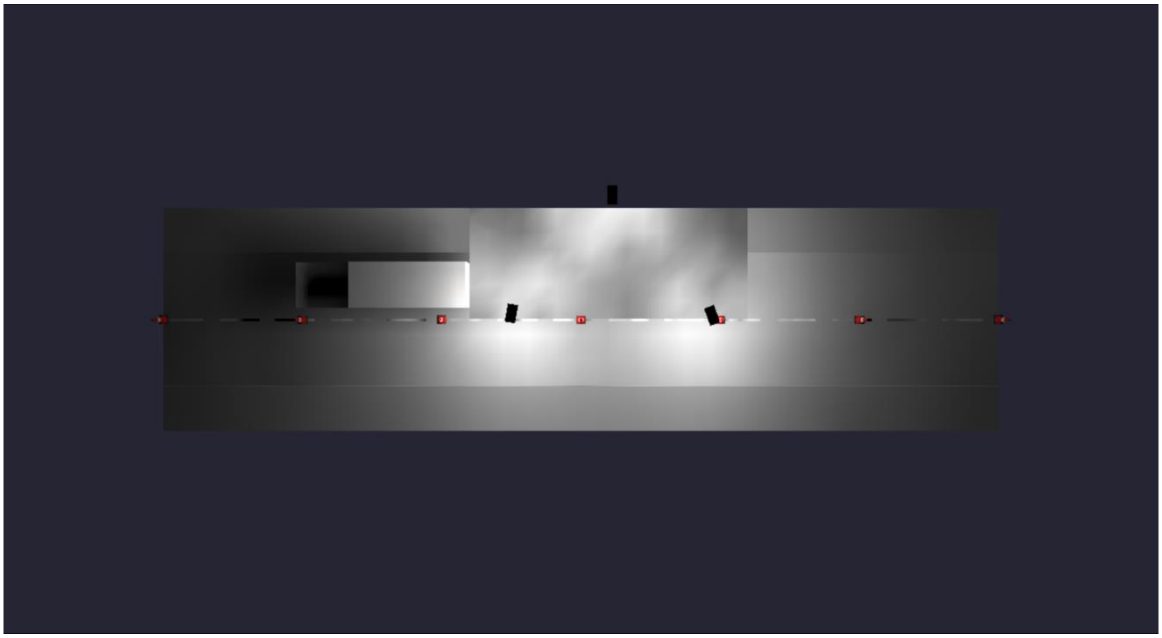


Figure 51. Bridge deck repair true color rendering scene illuminated by balloon lights (Airstar Sirocco).

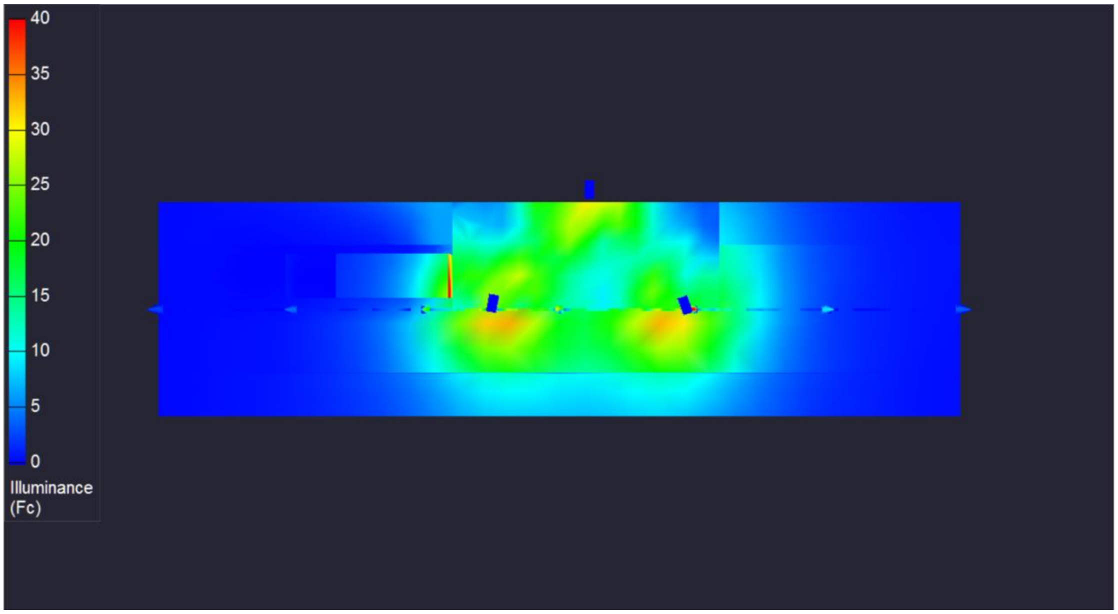


Figure 52. False color illuminance levels for balloon lights.

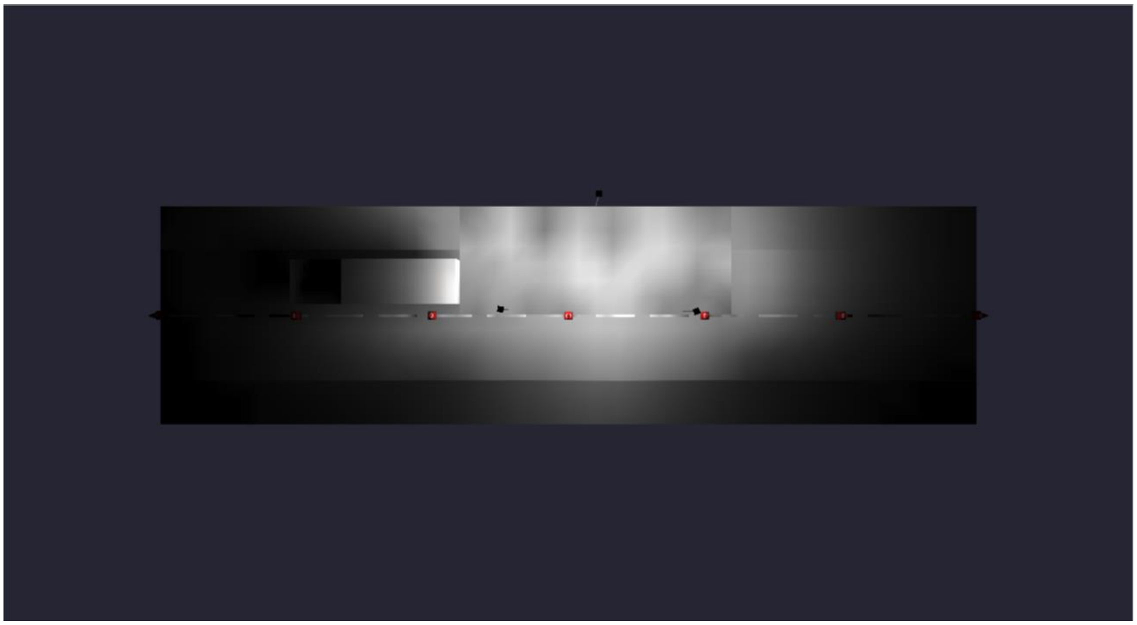


Figure 53. Bridge deck repair true color rendering illuminated by LED downlights (GE EFNA).

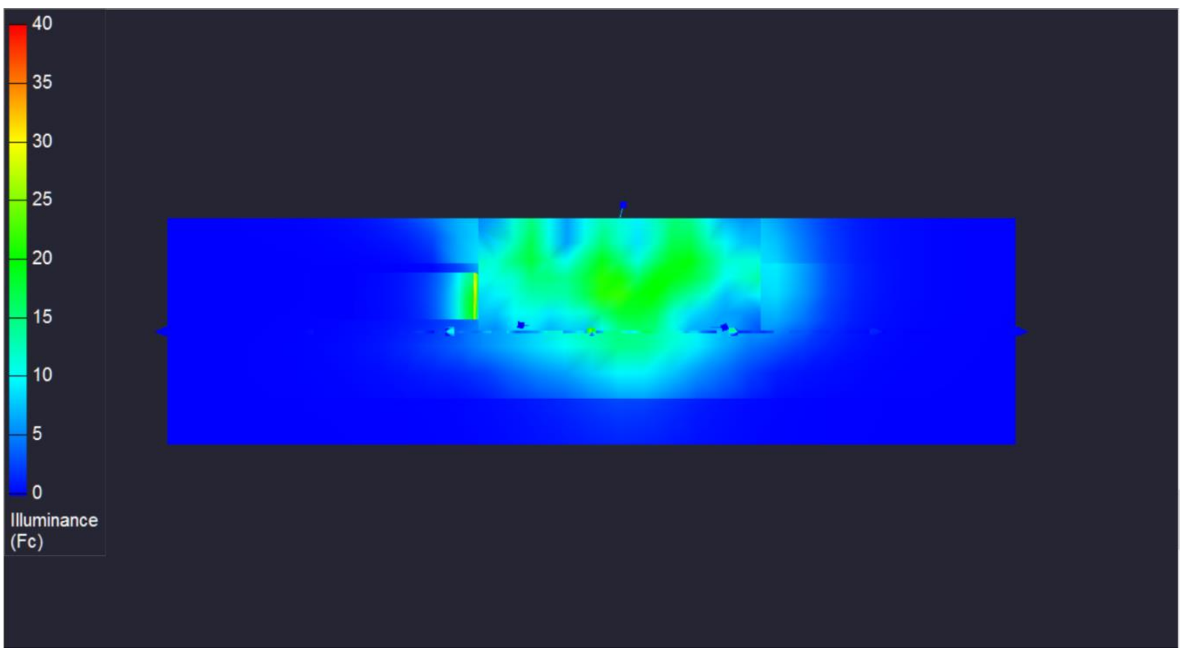


Figure 54. False color illuminance levels for LED downlight.

7.4. Case Study Results.

These case study examples illustrate the tradeoffs that occur when using different luminaire types, luminaire placement, and output levels. Using the lighting analysis procedure described, designers can explore different lighting configurations for the type of construction to obtain the desired illuminance levels, more uniformly in the work area, and at an optimal cost.

8. Performing a Lighting Field Review

Many agencies have traditionally relied solely on field evaluations to determine the suitability of work zone lighting systems. As noted earlier in this document, these evaluations have often been subjective in nature, leaving much potential for disputes between the field engineer and the contractor. In addition, field demonstrations typically occur quite late in the lighting implementation process, when it can be difficult to make major changes in the lighting equipment or layout without delaying the work. Therefore, pre-deployment computer modeling of the proposed work zone lighting layout is recommended to minimize the risks to agencies, contractors, and the public. Post-deployment field evaluations should still be conducted to assure that devices have been correctly installed properly aimed, and that there are no inadvertent equipment swaps (as noted in Section 2.3, different versions of the same lighting product can have identical physical appearance but very different light output patterns). Field reviews also help assure that there are no problems attributable to issues that were not modelled, such as variations in grade, variations in pavement color/texture, or reflections from adjoining buildings. Results of field evaluations should be used to fine-tune the lighting in the field to minimize glare and optimize the usable light available to road users and workers.

8.1. Driving and Walking Through

A work zone field lighting review should include drive-throughs in all lanes and all permitted travel directions, including all legal turning movements at intersections. The vehicle used for the field review should be equipped with ordinary (not heavily tinted) window glass. The use of a pick-up or SUV with high ground clearance is preferable, as glare is usually a greater problem in vehicles with a high driver eye height. In general the most critical condition will be complete darkness; problems identified early in the night (e.g. during twilight) are likely to be become worse as the sky darkens. Although the basis of analysis and evaluation is usually dry pavement conditions, a wet pavement should be conducted if the work zone lighting system will be in use during those conditions.

If the work zone serves pedestrian or bicycle traffic, a walk-through (or bike-through) field inspection should also be conducted to assure that there is adequate illumination for pedestrians and cyclists. Particular attention should be given to crosswalks and other points of conflict between motorized and non-motorized traffic. The inspection should also check for any locations where non-motorized road users and work vehicles would have difficulty seeing each other due to glare and/or the absence of sufficient illumination. Other locations meriting special attention include ramps, steps, transit stops, broken pavement, trenches, open holes, and places where there are construction materials or debris on or near the walkway.

8.2. Field Measurement of Horizontal Illuminance

Section 5.1 establishes suggested maximum and minimum illuminance levels for various categories of work activities. An illuminance meter (Figure 6) is essential for measuring illuminance in the field and determining compliance with these requirements. Meters are can be purchased online for $25 to $250 depending on quality and features. Although there are illuminance meter apps for smartphones, independent testing in 2016 found that the apps are not accurate mainly because the small sensors in phones cannot accurately adjust for light entering at shallow angles [13].

Figure 55 illustrates the measurement of illuminance levels for three workers who are positioned near a specific luminaire. Trapezoids identify each worker's task area. Notably, the size of each task area will vary depending on the specific activities; for example, Worker G is doing tasks that are relatively close to where she is standing, while Worker H might be operating a piece of equipment that requires him to look further away. In this example, lighting levels are adequate for Workers G and H, but inadequate for Worker I.

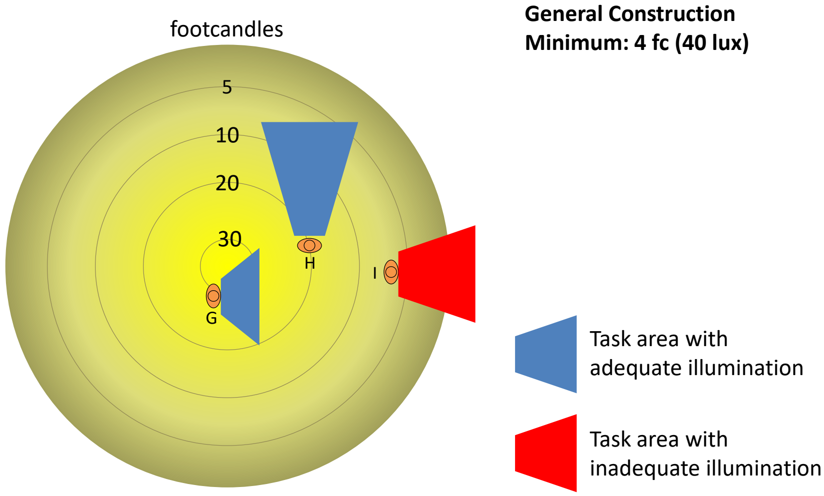


Figure 55. Application of minimum illuminance concept.

8.3. Field Measurement of Glare

There are three methods for conducting an objective field assessment of glare:

- Detailed automated glare analysis can be prepared using a video photometer and specialized software [14]. Currently, most of the software available for this purpose is designed around European standard EN13201 so the outputs are expressed in terms of the Threshold Index (TI).

- A procedure for accurately estimating glare using vertical illuminance readings can be found in the report, "Nighttime Construction: Evaluation of Lighting Glare for Highway Construction in Illinois" at http://apps.ict.illinois.edu/projects/getfile.asp?id=2973. This procedure is equipment-specific; it was calibrated for configurations with one, two, or three 2 × 1000 watt halogen balloon lights (most likely Airstar Sirocco model 2K HA) or a single light tower with 4 × 1000 watt circular metal halide lamps positioned at vertical and horizontal angles of 0° to 45°.

- A quick estimate of the glare can be done manually if it is feasible to walk through the work zone in a closed area that is close to the open traffic lanes. Ideally, the illuminance readings should be collected one-third of the distance into the driving lane closest to the glare source, if the traffic volume is light enough to do so safely. The observer will first record the horizontal illuminance at the pavement surface preferably at intervals of approximately every 15 feet (5 meters) throughout the work activity area. Next, the observer will record the vertical illuminance at driver-eye level as close as safely possible to the driving position at the point where the glare is worst (typically this is 25 to 100 feet upstream of the brightest luminaire in the lane closest to the glare source [3]). A quick estimate of the VL Ratio can then be estimated computed using the following equation:

$$Quick\ Veiling\ Luminance\ Ratio\ Estimate = \frac{12\pi \times E_{Vg}}{\theta^n \times E_{Have}}$$

Where:
E_{Vg} = Maximum vertical Illuminance at point of maximum glare
E_{Have} = Average horizontal illuminance for the work activity area
θ = Vertical angle between road surface and light source at the point of maximum glare
$n = 2.3 - 0.7 \times log_{10}(\theta)$ For $\theta < 2°$
$n = 2$ For $\theta > 2°$

Worked Example

The resident engineer is concerned that a portable light tower illuminating a freeway work zone is producing excessive glare. The glare is worst approximately 75 feet upstream of the light tower where the vertical illuminance is 48 foot-candles. The height of the light tower is 35 feet. The horizontal illuminance on the pavement was measured every 250 feet beginning 2750 feet upstream of the light tower and ending 250 feet upstream of the tower; readings were 0.2, 0.6, 0.9, 1.2, 1.6, 1.7, 1.8, 2.1, 2.3, 2.1, 2.5, and 3.8 foot-candles. Estimate the glare ratio at approaching the light tower.

Solution: First, compute the average horizontal pavement illuminance at the approach to the tower:

$E_{Vg} = 48$ fc
$E_{Have} = (0.9 + 1.2 + 1.6 + 1.7 + 1.8 + 2.1 + 2.3 + 2.1 + 2.5 + 3.8) \div 10 = 2.0$ fc
$\theta = \arctan(35 \div 75) = 25°$
$n = 2$

$$Quick\ Veiling\ Luminance\ Ratio\ Estimate = \frac{10\pi \times 48}{25^2 \times 2} = 1.20$$

Conclusion: The estimated VL Ratio is 1.20. This is three times the acceptable limit of 0.4. The illumination setup should be modified to reduce glare.

9. Glossary

Color Rendering Index (CRI): A quantitative measure of the ability of a light source to reveal the colors of various objects faithfully. Sunlight has a CRI of 100.

Glare: A condition of vision in which there is discomfort or a reduction in the ability to see details or objects caused by an unsuitable distribution or range of illuminance or by extreme contrasts.

Glare Ratio: Glare is the ratio of luminaire luminous intensity to background luminous intensity.

Brightness: Luminance as perceived by the human eye.

Illuminance: The amount of light falling on a surface. Illuminance is measured in foot-candles (fc) (US customary units) or lux (metric units). 1 fc = 10.764 lux.

Luminance: The amount of light reflected off a surface or the amount of light a viewer sees. Luminance is measured in candelas per square meter (cd/m²).

Lamp: A bulb or other device that produces light.

Luminaire: A light fixture.

Luminous Flux: The amount of light given off by a source in all directions, measured in lumens.

Threshold Increment (TI): a measure of glare for street lighting, specifically the loss of visibility caused by disability glare.

Tilt: The angle of a luminaire is measured from vertical, as shown in Figure 56. For example, a luminaire that points straight down is mounted at 0 degrees.

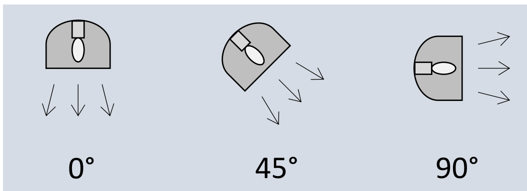


Figure 56. Measurement of luminaire tilt angle.

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Appendix A. Derivation of Maximum/Minimum Illuminance Levels for Work Zones

The traditional approach for specifying area illuminance levels is based on a combination of the average horizontal illuminance and a specified illuminance uniformity ratio. This is logical in indoor workplaces (such as an office or factory production floor) where the boundaries of the workspace are clearly defined by walls. In such cases, the average illuminance is computed by taking light meter readings at multiple locations and averaging the results over the entire floor area, and the uniformity ratio is computed by dividing the illuminance in the darkest part of the room by the average illuminance for the entire area. Similar computation methods can be used for outdoor areas with well-defined boundaries such as parking lots and athletic fields.

Most highway work zones do not have well-defined boundaries. For example, workers could be spread over an area 1000 to 2500 feet long with the positions of personnel and equipment changing frequently. Applying fixed-area computation methods to such areas is often impractical and, when attempted, can result in unnecessary lighting of inactive areas, excessive spillover to adjoining properties, and considerable expenditure to provide a large number of luminaires.

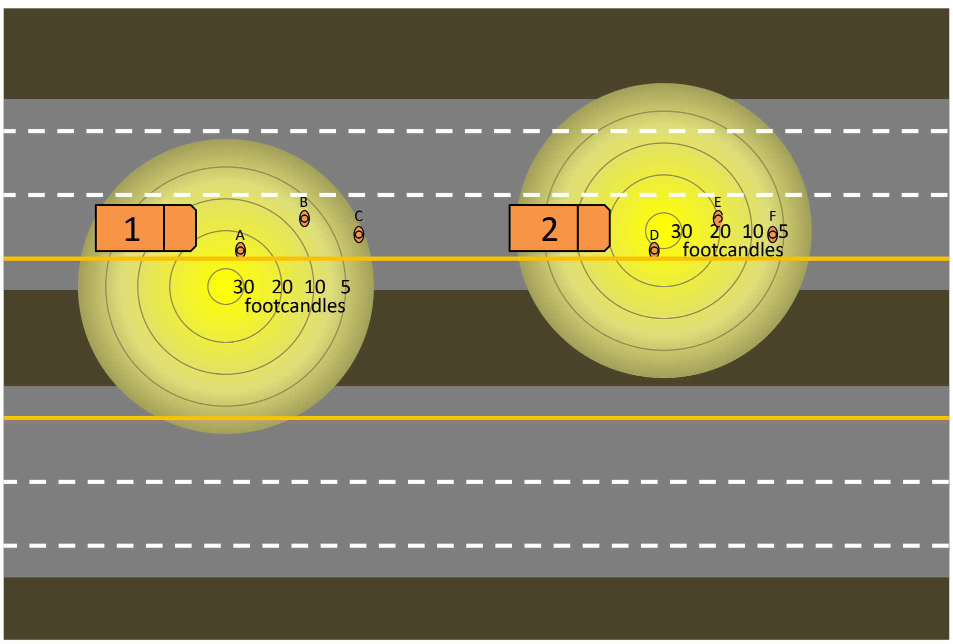

Figure 57. Examples of illumination levels at a work zone scene.

The difficulty of measuring average illuminance for a work zone scene is illustrated in Figure 57. For example, in the vicinity of Truck 1 worker A has about 25 foot-candles of light in all directions, worker B has 5 to 10 fc (depending on which way the worker is facing), and worker C is dimly lit with less than 5 fc. The positions of the workers near Truck 2 are identical to those around Truck 1, but the base of the luminaire has been moved from the shoulder to the center of the lane. The workers in the Truck 2 area have more light than their counterparts near Truck 1, but the luminaire blocks the path of Truck 2. Worker D has about 30 fc and worker E has about 20 fc in all directions. Worker F has more than 10 fc when looking upstream and less than 5 fc when looking downstream. As this example illustrates, **small changes in the locations of lights and workers can radically change any computation of the average illuminance.**

Another consideration is the distance each worker needs to look—some of the tasks could be right at the worker's feet, while other tasks could require looking several yards away. Similarly, light falling outside the lane where work activity is taking place is often irrelevant to the useful light available to the workers. Finally, it is important to recognize that when a work zone is illuminated by a single device it is not possible to compute a uniformity ratio: the light trails off gradually with increasing distance from the luminaire.

To avoid these complexities, maximum and minimum illuminance levels are presented in Section 5.1. These values were derived from the MUTCD and NCHRP 476 and converted to maximum/minimum point values. The conversion assumes a **minimum** illuminance of 75% of the average values suggested in the MUTCD.

Figure 58 shows the application of the minimum illuminance concept for a work scene. Note that using this method, lighting levels are measured for each worker's task area. The location of the task area will change as workers move around the site and its size depends on the nature of the task. For example, assuming general construction with a minimum illuminance of 4 fc, there is more than enough light for Worker G. Most of Worker H's task area is acceptable, but the light at the upper-right corner is marginal. The light for Worker I is inadequate. As further discussed in Section 8.2, a field inspector would need to consider the various locations that workers might occupy throughout the operation rather than their positions at one moment in time.

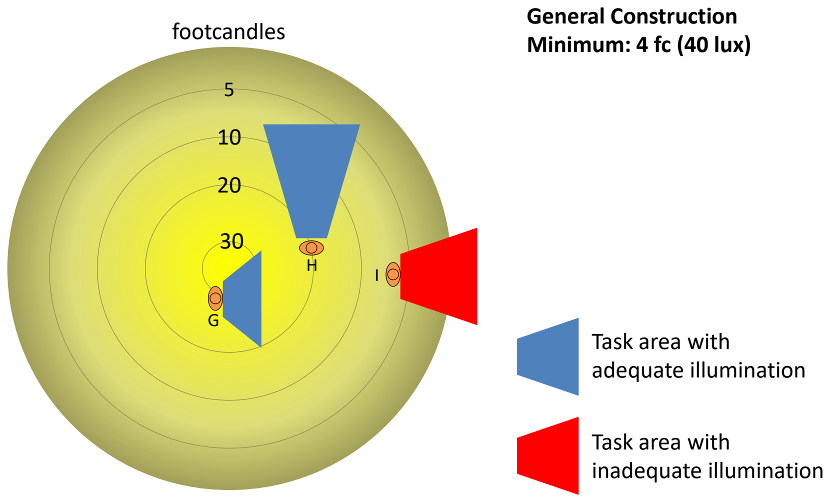

Figure 58. Application of minimum illuminance concept.

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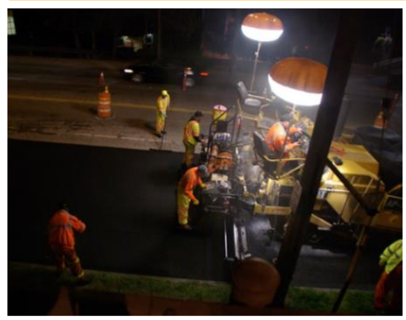


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