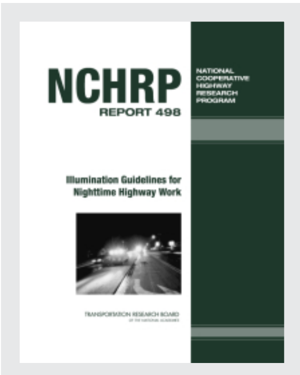

Illumination Guidelines for Nighttime Highway Work (2003)

DETAILS

0 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-43128-6 | DOI 10.17226/21955

CONTRIBUTORS

Transportation Research Board; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine 2003. *Illumination Guidelines for Nighttime Highway Work*. Washington, DC: The National Academies Press. https://doi.org/10.17226/21955.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 498

Illumination Guidelines for Nighttime Highway Work

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Gainesville, FL

SUBJECT AREAS
Materials and Construction • Maintenance • Safety and Human Performance

Research Sponsored by the American Association of State Highway and Transportation Officials
in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2003
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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NCHRP REPORT 498

Project G5-13(2) FY1996

ISSN 0077-5614

ISBN 0-309-08780-5

Library of Congress Control Number 2003114933

Price $20.00

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

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Business Office
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Washington, DC 20001

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Printed in the United States of America

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AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 5-13(2) by the Department of Civil Engineering, University of Florida.

Ralph D. Ellis, Jr., Associate Professor of Civil Engineering, University of Florida, was the Principal Investigator. Other contributors to this report were Zohar Herbsman, Professor of Civil Engineering, University of Florida; Scott Amos, former graduate research assistant, now Assistant Professor, Pittsburgh State University; and Ashish Kumar, former graduate research assistant.

The work on this project was performed under the general supervision of Professor Ellis with assistance from Scott Amos and Ashish Kumar, research assistants.

FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report provides guidelines for illumination for nighttime highway work, work zone illumination design, and use of temporary roadway lighting for construction and maintenance work. These guidelines will help highway agencies and the public accrue the benefits of nighttime highway work while ensuring a safe environment for motorists and workers. The report is a useful resource for state construction engineers and others involved in nighttime construction and maintenance work on highways.

An increasing amount of nighttime highway work is being performed on both divided and undivided highways in urban and rural settings to minimize the congestion effects of daytime reductions in capacity and/or to accelerate the work. This often necessitates the use of illumination to facilitate the work while maintaining a safe work area for motorists and workers. As nighttime work continues to increase in frequency, illumination guidelines that identify the types of light sources and the minimum and maximum levels of illumination required for a variety of nighttime work in typical situations need to be developed and made available to public agencies and contractors. Without such guidelines, illumination will continue to be provided on a trial and error basis, which can be costly in both time and safety. NCHRP Project 5-13 and subsequently Project 5-13(2) were conducted to address this need. Project 5-13 produced preliminary illumination guidelines for construction and maintenance activities.

Under NCHRP Project 5-13(2), “Illumination Guidelines for Nighttime Highway Work,” The University of Florida was assigned the objectives of (1) developing illumination guidelines for nighttime highway work, (2) developing guidelines for work zone illumination design, and (3) developing guidelines for the use of temporary roadway lighting for construction and maintenance work. To accomplish these objectives, the researchers reviewed relevant domestic and foreign literature, surveyed state departments of transportation (DOTs) to establish the extent of use of nighttime construction and maintenance work, and adapted illumination guidelines developed by other industry sectors to the specific needs of transportation construction and maintenance. Also, the researchers conducted field visits and monitored nighttime highway construction and maintenance activities on several projects to assess the suitability of the preliminary guidelines developed in the initial phase of research and to provide a basis for developing improved guidelines.

The survey of transportation agencies revealed that nighttime construction and maintenance work is performed by at least 28 state DOTs. The construction activities most commonly performed at night are resurfacing, barrier walls and traffic separators, milling and surface removal, marking and stripe painting, bridge deck construction, concrete pavement construction, base course construction, ditch and channel excavation, embankment filling and compaction, and highway signing. The maintenance activities most commonly performed at night are sweeping and cleanup, concrete pavement repair, bridge deck rehabilitation and maintenance, resurfacing, milling and surface removal, lighting system repair, traffic signal maintenance, marking and stripe painting, surface treatment, and barrier walls.

The research concluded that nighttime highway work can be performed safely and with a level of quality and economy comparable to that achieved from daytime construction, and the study produced three stand-alone sets of guidelines: (1) “Illumination Guidelines for Nighttime Highway Work,” (2) “Guidelines for Work Zone Illumination Design,” and (3) “Guidelines for the Use of Temporary Roadway Lighting.” These guidelines address relevant topics, including visibility requirements, lighting equipment, lighting configuration and arrangement, lighting system design, system operation and maintenance, and economic considerations. The guidelines will assist in planning, designing, and operating nighttime highway work zone lighting and should, therefore, be particularly useful to highway agencies and contracting firms involved in nighttime construction and maintenance work.

CONTENTS

ILLUMINATION GUIDELINES FOR NIGHTTIME HIGHWAY WORK

SUMMARY

An increasing amount of highway construction is being performed at night to avoid daytime congestion. Lighting is a key factor in performing construction at night. Illumination levels and lighting configuration directly affect the safety, quality, and cost efficiency of the project.

The objective of this study was to develop suggested illumination guidelines for nighttime highway construction work. These guidelines can be used by public agencies and construction contractors in determining the appropriate levels of illumination and the proper configuration of the light sources.

The guidelines were developed based on a comparison of established illumination standards for nonhighway construction activities with highway construction activities that have similar seeing task requirements. Field observations of nighttime highway construction work were made. Input was obtained from construction equipment manufacturers and lighting manufacturers. A field demonstration was conducted to determine constructability and validity of the suggested guidelines.

The resulting illumination guidelines present three illumination requirement categories with suggested target illumination values. These illumination categories are as follows:

Category I 54 lx (5 ft-candles)

Recommended for the general illumination in the work zone primarily from the safety point of view in the area where crew movement is expected or taking place. This category is also for tasks requiring low accuracy, involving slow-moving equipment, and having large-sized objects to be seen.

Category II 108 lx (10 ft-candles)

Recommended for illumination on and around construction equipment and the visual tasks associated with the equipment, such as resurfacing.

Category III 216 lx (20 ft-candles)

Recommended for tasks that present higher visual difficulty and require increased attention from the observer, such as crack filling, critical connections and maintenance of electrical devices, or moving machinery.

Typical highway construction activities are identified and assigned to an illumination category on the basis of the visual requirements of the tasks. Additionally, suggested lighted area limits were developed for moving work activities.

Controlling hazard glare is a critical issue in lighting highway work zones. Glare control countermeasures were developed and are included with the illumination guidelines.

In addition to this report, a separate document titled “Guidelines for Work Zone Illumination Design” was prepared as an aid for the practitioner in designing and implementing work zone illumination plans.

Finally, a third separate document titled “Guidelines for the Use of Temporary Roadway Lighting” was developed. This document covers the relevant issues with regard to using temporary roadway lighting.

These two guidance documents are published herein.

SECTION ONE

BACKGROUND, RESEARCH APPROACH, AND RECOMMENDATIONS

CHAPTER 1

BACKGROUND AND RESEARCH APPROACH

BACKGROUND

Recently many states have shifted their priority from building new facilities to maintaining and improving those already in existence. Daytime lane closures for rehabilitation work results in heavy congestion on roads already loaded to capacity. The daytime lane closures are also hazardous, costly, and inconvenient for the traveling public. As a result, more construction and rehabilitation work is being performed at night when traffic flow is minimal. In addition to several obvious advantages of nighttime work—such as cooler temperatures for equipment and material and fewer traffic problems and delays—there may also be certain disadvantages. Night work comprises many complex issues and a variety of problems, which include lighting conditions, safety, and effect on quality, worker availability, and administrative decisions.

Recent research conducted at the University of Florida has shown lighting as one of the most important factors for nighttime construction (*1*). It has been found that safety in the work zone, traffic control, quality of work, and workers' morale are directly related to work zone lighting. Limited or restricted visibility is an obvious drawback of nighttime construction. However, with adequate levels of light, construction operations can be performed as well at night as they can be during the day. Likewise, the key factors that influence accident rates are the physical conditions of drivers and the light conditions of the environment. The physical conditions of the driver may include conditions such as drowsiness and sensitivity to light glare. Worker injury rate also increases because of the inherent vision impairment associated with nighttime lighting conditions (*2*). Sufficient lighting of the work area is also important from the point of view of quality. Standard highway lighting, or light from nearby businesses or residences, is generally inadequate to properly light the areas where work is performed. Inadequate lighting results in problems with proper inspection. Work quality is affected because many defect causes, such as shadows, tack spread, and asphalt droppings, cannot be properly controlled (*3*).

In the specifications of many state highway agencies (SHAs), present lighting requirements are minimally defined (e.g., minimum intensity level of 54 lumens per square meter (lx) or 5 ft-candles (fc), sufficient light to permit good workmanship and proper inspection, etc.). Most of these specifications are not only inadequate but also are not standardized. Decisions pertaining to work zone lighting are left to the discretion of the site engineer and the contractor. Moreover, due to the lack of criteria related to average illumination levels and uniformity of illumination, lighting systems cannot be designed satisfactorily.

RESEARCH OBJECTIVES

Although lighting is the single-most important factor in nighttime construction, it is the least studied. Very little research has been done concerning the proper lighting of construction sites. This research effort aims not only to suggest the design of a lighting system based on current site conditions, but also to facilitate developing a set of standard guidelines and specifications. The objectives of this proposed research effort are as follows:

- To develop guidelines that can be used by public agencies and contractors in determining: (a) the types of light sources and (b) the minimum and maximum levels of illumination for a variety of nighttime work in typical highway situations;
- To develop guidelines for work zone lighting design; and
- To develop guidelines for the use of temporary roadway lighting to provide work zone lighting.

RESEARCH APPROACH

This study was conducted in two phases. Phase I focused on the development of the Guidelines for Work Zone Illumination and on the Design Guidelines for Work Zone Lighting. Phase II was performed to obtain additional validation of the guidelines developed in Phase I and to investigate the possibility of using temporary roadway lighting as a source for work zone lighting.

The general strategy for developing the illumination guidelines was to transfer established illumination guidelines from other well-established industry areas to the specific area of transportation construction and maintenance. This was accomplished by defining the seeing task characteristics of the different operations within highway construction and maintenance.

Work activities with similar seeing tasks from other industries were matched with the highway tasks. Recommended illumination levels were assigned to the highway activities. Field visits and monitoring of nighttime highway construction and maintenance activities provided data to refine and validate the guidelines for work zone illumination. Design guidelines were developed with the project-level user in mind. Simplicity and ease of use were favored over more complicated approaches.

In Phase I, a literature review and a survey of industry practice was conducted. Additionally, field visits to nighttime highway projects were performed. The objective was to obtain an accurate assessment of the current practices for lighting nighttime highway projects. Of particular interest were existing specifications or standards used by SHAs for specifying the lighting to be used for night work.

Phase I also involved the development of guidelines for illuminating nighttime highway work projects. The seeing task requirements for various highway maintenance and construction activities were identified and compared with established lighting standards for other industries and national standards. Illumination requirements for highway activities were developed from this analysis. A lighting design manual of practice was prepared as an aid to the highway construction or maintenance professional for configuring proper work area lighting.

The key issues in Phase I were

- Understanding the state of current practice of nighttime highway project activity,
- Developing illumination requirements for highway project activities, and
- Developing design procedures for configuring highway project work area lighting systems.

In Phase II, there were two primary objectives:

1. To expand and validate the findings of Phase I with additional field reviews and contacts with SHAs in various geographic regions and
2. To investigate and develop guidelines for the use of temporary lighting as a source of work area lighting for highway projects.

Additional visits to different states were conducted, including visits to nighttime projects. Draft illumination guidelines were reviewed with state and contractor personnel, and draft standards were checked against current project situations. Design procedures were also reviewed and input was solicited. The use of temporary roadway lighting for work area lighting was investigated. The investigation revealed that the use of temporary roadway lighting was extremely limited. However, one project was identified and a site visit was made to the project. Nevertheless, guidelines for the use of temporary roadway lighting were developed as a part of Phase II.

CHAPTER 2
SUMMARY OF FINDINGS AND RECOMMENDATIONS

SUMMARY OF FINDINGS

The purpose of this research was to develop guidelines for the illumination of nighttime highway work including both construction and maintenance activities. Additionally, the research developed guidelines for highway work area lighting design and investigated the use of temporary roadway lighting in connection with highway construction. These objectives were accomplished by performing a comprehensive literature review and conducting surveys to obtain information on current practice. On-site field visits to nighttime construction projects were also made to many projects located in 11 states. During the field visits, observations of lighting practice and illumination measurements were made. Interviews and discussions with field personnel of the SHAs and the contractors also contributed to the research results. Illumination level guidelines were developed for nighttime highway work activities by comparing the seeing tasks associated with highway work activities with the seeing tasks of other industry activities with established illumination standards. Design procedures were developed for the design of temporary work lighting. The subject of using temporary roadway lighting was also researched.

The research team defined work zone illumination requirements in three categories depending on the visibility requirements of the work tasks. Minimum average illumination levels were suggested for each category. Additionally, lighted area requirements were suggested for slow- and fast-moving construction equipment. Glare control guidelines and countermeasures were also developed as an integral part of the illumination guidelines. The recommendations were field tested in a demonstration project that validated that the illumination standards were achievable with little additional cost to the project.

A simplified design approach was developed for the design of work zone lighting systems. Standard lighting configurations were also developed to assist field personnel in setting up appropriate work area illumination and for configuring equipment lighting.

The subject of using temporary roadway lighting to illuminate highway construction work areas was researched to the extent possible. Limited project examples were found but did indicate the basic design and implementation considerations.

The conclusion of this study is that nighttime highway work can be performed safely and with economy and quality comparable to that performed in the daytime. The essential critical factor is proper illumination. This study offers information that can assist highway agencies in establishing standards and procedures for illumination of nighttime highway work activities. The two keys to implementation are as follows:

1. Establishing organizational standards and
2. Training SHA and contractor personnel.

RECOMMENDATIONS

The following baseline recommendations have emerged as a result of this study:

1. There is a need for a uniform national standard for highway work area illumination. AASHTO should consider developing this study based on the findings of a recommended illumination standard that could be adopted by its member states.
2. There is a real need for improvements in manufacturer-installed equipment lighting. AASHTO should encourage equipment manufacturers to offer appropriate nighttime operational lighting as optional equipment.
3. The use of temporary roadway lighting may grow. The Roadway Lighting Committee of the Illuminating Engineering Society (IES) of North America should consider including a discussion of temporary roadway lighting in the Roadway Lighting Practice Manual (*4*).
4. AASHTO or the FHWA should consider sponsoring the development of a basic course on Work Area Illumination. The course content could be used by SHAs as a basic training tool for their own personnel and for contractor personnel.

ORGANIZATION OF THE REPORT

This report presents research findings in four separate and distinct sections:

- SECTION ONE: Background, Research Approach, and Recommendations

- SECTION TWO: Illumination Guidelines for Nighttime Highway Work
- SECTION THREE: Guidelines for Work Zone Illumination Design
- SECTION FOUR: Guidelines for the Use of Temporary Roadway Lighting

Sections One, Two, and Three focus on different aspects of the general topic of lighting nighttime highway work activities. To facilitate the use of these individual sections, they have been structured more or less as "stand-alone" documents within this report.

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SECTION TWO

ILLUMINATION GUIDELINES FOR NIGHTTIME HIGHWAY WORK

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

The objective of this research effort was to develop illumination guidelines for nighttime highway work. Nighttime highway work operations are becoming more common because of the need to avoid daytime congestion and traffic delays. The quality of the work area lighting is a major factor influencing project safety, work efficiency, and work quality. Although lighting standards exist for other industries, no national guidelines have existed for the illumination of nighttime highway work.

RESEARCH APPROACH

Literature Review and State of Current Practice

A comprehensive literature review was performed to obtain the most up-to-date and relevant information concerning the illumination of construction work zones. Very few publications were found that dealt directly with lighting for construction work. However, much information was found concerning the general subject of lighting work areas. Additionally, an industry survey was conducted to learn the state of current practice.

Field Reviews

A number of field visits were made to investigate the current nighttime highway construction and maintenance practices. The selection of projects was based on their geographical location and diversity, substantial experience with night work, and utilization of different construction practices (e.g., use of screens and barriers to avoid glare). In selecting projects, not only was an effort made to select representative kinds of typical highway projects, but care was taken to avoid repetition and a variety of projects covering nearly all the operations were chosen.

A field review form was prepared to record all relevant information as observed on site. The form included pertinent information such as project information and location; tasks information, lighting equipment, and configuration; quantity of light and illumination levels; uniformity, direction, and glare of light; and general information about workers and power sources.

During field reviews, several projects with different nighttime operations were visited. These reviews included projects in rural, urban, and semi-urban environments on limited access, primary, and other types of roadways. Various types of operations included replacing concrete barrier walls to separate traffic from work zone; asphalt concrete paving of intersections; in-situ concrete construction of bridge decks; excavation, filling, and embankment construction; and milling, repaving, and marking of limited-access highways. Projects were visited in the following locations: Jacksonville, Florida; Orlando, Florida; Tampa, Florida; Gainesville, Florida; Los Angeles, California; Dallas, Texas; Charlotte, North Carolina; Buffalo, New York; Harrisburg, Pennsylvania; Grand Rapids, South Dakota; and Salt Lake City, Utah.

Various tasks identified were related to all the observed operations. Other information such as background reflectance, importance and speed required, and seeing distance for the tasks were collected. The most difficult and fatiguing tasks in each operation were also identified. Most of the observed tasks had low or medium background reflectance owing to low reflectivity of the pavement and other concrete and soil structures. Importance, speed, and accuracy of the tasks also varied from low for excavation to high for paving and finishing works. Seeing distances of the tasks were categorized into four main categories: (1) less than 0.31 m (1 ft); (2) 0.31 to 1.5 m (1 to 5 ft); (3) 1.5 to 4.6 m (5 to 15 ft); and (4) more than 4.6 m (15 ft).

For construction lighting, equipment-mounted lights, portable light plants, and their combinations were most commonly used. Some equipment such as pavers and rollers were equipped with custom-made retrofit lights. Pavers usually had six or more lights: two lights at the front, two lights at the rear, two lights aiming at the screed, and the rest of the lights illuminating the sides of the equipment. Figure 1 shows a typical pavement roller in use on a Charlotte, North Carolina, project site. Compacting rollers and brushing rollers usually had two to four sealed lamps and sometimes additional mounted lights. However, wheel loaders, dump trucks, and flat-beds were equipped with manufactured conventional equipment lights. For bridge deck construction, the crane, conveyor system, and screed were equipped with several mounted lights. Milling

Figure 1. Pavement roller operation (Charlotte, North Carolina).

machines had sealed beam units, which were manufactured and installed at the factory. Relatively stationary work zones were usually supplemented by portable light plants, which were also used for general lighting of the area.

Most of the mounted lights were 500-W tungsten-halogen lamps powered by diesel generators. The generators, in most areas, were installed on the construction equipment. These halogen lights were mounted on custom-made brackets and poles and provided sufficient flexibility to change lamp height and aim as desired. Figure 2 shows a typical asphalt paver operating with contractor-installed auxiliary lighting.

Most of the fixed lights were 75- to 100-W conventional automobile lamps and had fixed aim and light positions. The most common portable light found during field reviews was a light trailer equipped with four high-intensity discharge (HID) lamps of 1,000 W each. Trailers were also equipped with diesel generators and 9.2 m (30 ft) maximum height adjustable towers. These light plants used metal halide, one of the most common lamps enclosed in a parabolic reflective cover to provide a uniform narrow beam of light. These light towers provided sufficient uniform flood light for the work zone; however, in some instances, they also caused severe discomfort glare and sometimes disability glare to the motorists, especially when installed against the moving traffic. Figure 3 shows a typical portable light plant tower.

For the bridge deck construction project, the concrete barge and chute were illuminated with 1,000-W sodium vapor lamps enclosed in a rectangular reflective covering. Lights on the crane were 1,000-W metal halide lamps spaced at 9.2 m (30 ft) and oriented toward the hoist. For the milling-repaving project, lights on the milling machine were fixed and oriented to illuminate the critical areas such as the conveyor, milling edge, and rear and all sides of the equipment.

Quantity of light was found to be sufficient for most of the tasks; however, some tasks were not adequately illuminated, and reasons for this were attributed partly to the inadequacy of light plants and partly to their improper orientation. Particularly for compacting rollers, lighting was not sufficient and the operator was moving the equipment broadly in a pattern based on experience instead of vision. Similarly, illuminance levels were not enough for sweeping brush rollers and asphalt spreaders applying tack coats. The operators essentially moved in a certain predefined pattern and sometimes failed to notice missed spots. For intersection paving and bridge construction jobs, illuminance levels for hand spreading of the mix also were less than satisfactory. In most cases, illumination of the general area was found to be adequate;

Figure 2. Typical paver operating with contractor-installed lighting (Buffalo, New York).

Figure 3. Typical portable light plant tower.

however, in many cases, task illumination was not adequately emphasized.

Factors that were observed to evaluate quality of light included uniformity, direction, diffusion, and direct and veiling glare. Lighting for nearly all the observed operations was adequately uniform. In the milling and repaving operation, uniformity of light was difficult to maintain because of the continuous movement of the operation. Good uniformity was possible with the use of well-diffused luminaires. Regarding flood light towers, light was well diffused and uniform as compared with equipment-mounted lights, which provided more spot and task illumination.

The direction of lighting was found objectionable in many cases, particularly for tower lighting plants. In one case, the plant was placed in close proximity to the travel lane facing oncoming traffic, the result of which was nearly blinding disability glare to the motorists. In other cases, light plants were situated at locations creating a shadow zone on the tasks. Because of inappropriate directivity of lights, on several occasions tasks were performed in a negative contrast instead of a positive one. Shadows of defects aided their identification. Spotlights mounted on various equipment, in general, had better directivity. Lights on some of the compaction rollers were not mounted high enough; as a result most, of the light fell on the wheels instead of the pavement. Spotlights on milling machines were factory installed and had better directivity.

Veiling glare was negligible for all the observed operations because of the low reflectivity of pavement and other construction surfaces. Direct glare to workers was, in general, more common in the case of highway operations than for bridge construction. The problem of glare to motorists was found to be acute for highway operations in which adjacent lanes were opened to traffic. In urban and semi-urban environments, particularly where roadway lights were available, there were fewer glare problems because there was reduced background contrast. It was noted during field investigation that lighting design and provision were essentially based on the contractor's discretion and, in some cases, little or no thought was given to location, positioning, and orientation of the light plants.

Summary of Survey

A preliminary list of construction and maintenance tasks was identified and sent to all the SHAs. In the survey, respondents were asked to identify the construction and maintenance tasks performed in their states during nighttime. They were also asked to indicate the frequency of these nighttime tasks. Out of 52 agencies, a total of 33 responded, of which 28 respondents indicated some nighttime construction and maintenance work in their states.

APPROACH TO DEVELOPMENT OF ILLUMINATION REQUIREMENTS

Identification and Classification of Nighttime Work Activities

In order to categorize typical highway nighttime work, various highway operations were identified. Interviews with DOT personnel, opinions of various knowledgeable individuals, and review of standard specifications for road and bridge construction resulted in a preliminary list of the most commonly performed highway operations (*1*). These operations were categorized into highway maintenance and highway construction tasks. Both lists also included activities on bridges, signalization, and other highway facilities. A brief description of these tasks is presented in Table 1. The tasks in each list represent various operations and activities, which are categorized according to their similarities in visual requirements.

Table 2 shows some of these task categories, typical operations represented by them, and various activities involved in the operation. Although all the activities in a particular operation (as shown in Table 2) may not have similar visual requirements, they are grouped together for practical reasons. Compliance is more realistic if a single lighting standard is specified for one operation rather than a different standard for each activity in the operation. However, the task category representing several operations is based on the similarity of visual requirements of those operations.

The results of responses obtained from the survey regarding construction and maintenance tasks during nighttime are summarized in Tables 3 and 4, respectively. Tables 3 and 4 give the relative frequency of night work as reported by SHAs. To identify the most commonly performed maintenance and construction tasks, both the lists are sorted in a decreasing order of the task frequency. Resurfacing, barrier wall placement, milling, and pavement marking appear to be the most common construction tasks performed at night. On the other hand, traffic signaling, lighting systems, landscaping, riprap, and sidewalks are the least preferred tasks for nighttime construction.

Table 4 shows cleanup, concrete pavement repair, and bridge deck rehabilitation as frequent maintenance activities during nighttime. In the survey, many respondents indicated that a significant amount of nighttime maintenance is attributed to emergency work in addition to regular required maintenance. Earthwork, landscaping, and rip rap are the least common maintenance activities conducted at night.

Factors Influencing Illumination Requirements

Identification of Key Factors

From literature review and discussion with experts on lighting and illumination, a number of factors affecting

TABLE 1 Highway maintenance and construction tasks performed at night

Task No.	Maintenance Tasks Performed at Night	Construction Tasks Performed at Night
1	Maintenance of earthwork/embankment	Excavation—regular, lateral ditch, channel
2	Reworking shoulders	Embankment, filling and compaction
3	Barrier wall or traffic separator	Barrier walls, traffic separators
4	Milling and removal	Milling and removal
5	Resurfacing	Resurfacing
6	Repair of concrete pavement	Concrete pavement construction
7	Crack filling	Subgrade stabilization and construction
8	Pot filling	Base courses—clay, cement, asphalt
9	Surface treatment	Surface treatment
10	Waterproofing/sealing	Waterproofing/sealing
11	Sidewalks repair and maintenance	Sidewalks construction
12	Riprap maintenance	Riprap placement
13	Resetting guardrail/fencing	Guardrail/fencing
14	Painting stripes/pavement markers	Painting stripes/pavement markers/metal buttons
15	Landscaping/grassing/sodding	Landscaping/grassing/sodding
16	Highway signing for maintenance works	Highway signing for construction
17	Traffic signals maintenance	Traffic signal construction
18	Highway lighting system—repair and maintenance	Highway lighting system construction
19	Bridge decks rehabilitation and maintenance	Bridge decks construction
20	Drainage structures maintenance and rehabilitation	Drainage structures, culverts and sewers construction
21	Sweeping and cleanup	Construction of other concrete structures

illumination requirements were identified. During the process of identification, only those factors that are related with outdoors and nighttime highway type situations were selected. They are categorized in four categories, which include:

1. Human factors,
2. Environmental factors,
3. Task-related factors, and
4. Lighting factors.

Further classification was done for the task-related factors because of their varying characteristics. Figure 4 summarizes all the factors and categories. These categories are explained in greater detail in the following sections.

Human and Cognitive Factors

Visibility detection and recognition are greatly affected by various human physical, physiological, and psychological factors. The important human factors affecting vision and perception are as follows:

1. Age,
2. Visual acuity,
3. Response characteristics,
4. Attention,
5. Expectation,
6. Experience, and
7. Familiarity.

Many studies have indicated that there is a correlation between age and visual acuity. Ability to detect targets tends to decrease for the observers belonging to a older age group. Similarly, the effect of visual acuity, which is influenced by several human visual functions such as glare sensitivity and transient adaptation, on an individual's perception and recognition varies depending on the individual's age.

On the other hand, response characteristics and cognitive behavior of an individual's experience and familiarity with a particular object also affect the process of recognizing and perceiving that object. For example, an experienced operator can identify defects on a newly paved road surface even under reduced illumination levels as compared to one having less experience with the work environment.

Environmental Factors

In this category, factors such as weather conditions, fog, surface condition, and ambient brightness are included. The literature review indicated that ambient brightness helps reduce the relative contrast of the object and the background, which is crucial in detecting an object. However, for night work conditions, ambient brightness helps increase the illu-

TABLE 2 Categorization of typical highway construction tasks

Task Category	Type of Operation	Activities
Excavation	Regular excavation Subsoil excavation Lateral ditch excavation Channel excavation	
Embankment	Dry fill method Hydraulic method	
Backfilling	Pipe culverts Storm sewers Other structures	
Subgrade	Stabilization of subbase Lime-treated Cement-treated	
Base Courses	Limerock base Graded aggregate base Sand-clay base Shell stabilized base Soil-cement base Asphalt base	Composition of mixes Preparation of subgrade Spreading the mix Compacting and finishing Correcting defects and thickness Priming, curing or maintaining
Surface Treatment	Prime coat Tack coat	Preparation of surface Distribution of material Spreading cover material Rolling and curing
Cement-Concrete	Pavement Sidewalk	Subgrade preparation Setting forms Placing reinforcement Placing concrete Consolidating and finishing Straightedging and surface correction Joints and curing
Fencing	Guardrail Fencing	Setting timber and steel posts Placing rail or fabric Reflector elements
Highway Lighting		Excavation and backfilling Trenches for cable Concrete base for light poles Erecting light poles Installation of luminaires

mination level of the task and requires less additional light for adequate illumination.

Atmospheric losses may have a significant effect upon the illuminance at the observer's eye level unless the viewing distance is short. In fog, the law of diminishing returns takes effect at relatively short distances. Since for nearly all the highway construction and maintenance work, distances are relatively short and the visual field is more or less limited to the work zone, weather conditions and atmospheric losses may not contribute significantly to the losses in object visibility.

Task-Related Factors

Task-related factors, owing to their characteristics and variations, are further subcategorized into the following five categories.

Equipment Attributes. Use of different types of construction equipment adds another dimension to nighttime highway work compared with other external night work situations. Factors related to construction equipment influencing task illumination requirements include:

1. Speed,
2. Physical characteristics, and
3. Response time.

Speed of equipment governs the exposure time or the duration of seeing. To some extent, higher speed of a particular piece of equipment can be compensated for by increased illumination for adequate visibility. Physical characteristics of some equipment may restrict the vision of the operator, and some of the targets may not be detectable irrespective of the quantity of illumination. For example, in a roller, the operator's vision is restricted by

TABLE 3 Number of states performing various nighttime highway construction tasks

Task No.	Construction Tasks Performed at Night	Frequency of Tasks		
		Frequently	Occasionally	Rarely
1	Resurfacing	7	8	12
2	Barrier walls, traffic separators	7	8	3
3	Milling and removal	6	11	9
4	Painting stripes, pavement markers, metal buttons	4	8	4
5	Bridge decks construction	3	16	7
6	Concrete pavement construction	3	9	12
7	Base courses—clay, cement, asphalt	3	6	8
8	Excavation—regular, lateral ditch, channel	3	5	10
9	Embankment, filling and compaction	2	6	10
10	Highway signing for construction	2	6	8
11	Subgrade stabilization and construction	2	5	10
12	Surface treatment	2	1	5
13	Drainage structures, culverts & sewers construction	1	5	13
14	Waterproofing/sealing	1	4	6
15	Construction of other concrete structures	0	6	13
16	Guardrail, fencing	0	4	5
17	Highway lighting system construction	0	3	7
18	Traffic signals construction	0	1	9
19	Landscaping, grassing, sodding	0	0	9
20	Riprap placement	0	0	6
21	Sidewalks construction	0	0	4
	Total Number of Responses	28		

NOTE: Tasks are arranged in the decreasing order of their frequencies.

the presence of drums in the visual field. Similarly, for loaders and pavers, detection of targets near the equipment is determined by its position. However, for far targets, quantity of illumination increases the detection distance. Required detection distance also depends on the response characteristics of the equipment. Equipment with low response time, low maneuverability, or high speeds requires greater detection distance and hence increased illumination.

Physical Attributes of the Task. Physical characteristics of the task or the target have significant effects on the quantity and quality of illumination required for detection. Size, type, appearance, and reflectance targets and their relationship with luminance values for their identification have been discussed in detail in existing literature. Lower luminance levels are required for larger targets. Similarly, location and level of conspicuousness of the target also helps its identification. For the same illumination level, detection of any target in the middle of the work zone is faster than the ones on the sides. Minimum distance of seeing a target from the observer's perspective also affects its identification. A defect on the road surface is more likely to be detected by a ground crew than an operator on the equipment for the same illumination level.

Task Qualitative Attributes. The qualitative factors associated with nighttime highway construction tasks include:

- Importance of the task,
- Accuracy desired,
- Visual difficulty in performing the task, and
- Visual fatigue as a result of performance.

TABLE 4 Number of states performing various nighttime highway maintenance tasks

Task No.	Maintenance Tasks Performed at Night	Frequency of Tasks		
		Frequently	Occasionally	Rarely
1	Sweeping and cleanup	7	8	3
2	Repair of concrete pavement	6	2	12
3	Bridge decks rehabilitation and maintenance	4	4	8
4	Resurfacing	3	7	9
5	Milling and removal	2	8	7
6	Highway lighting system—repair and maintenance	2	8	4
7	Traffic signals maintenance	2	7	7
8	Painting stripes/pavement markers	2	5	7
9	Surface treatment	2	1	2
10	Barrier wall or traffic separator	1	4	8
11	Crack filling	1	3	6
12	Pot filling	1	3	5
13	Resetting guardrail/fencing	1	3	3
14	Waterproofing/sealing	1	2	3
15	Highway signing for maintenance and works	0	3	11
16	Drainage structure maintenance and rehabilitation	0	3	3
17	Sidewalks repair and maintenance	0	2	3
18	Reworking shoulders	0	1	6
19	Riprap maintenance	0	1	5
20	Landscaping/grassing/sodding	0	1	3
21	Maintenance of earthwork/embankment	0	0	7
Total Number of Responses		27		

As indicated in the literature review, performance increases with the level of illumination until an optimum level. Beyond this point, further increases do not necessarily deteriorate performance. From the conclusion of previous studies, it can be inferred that visually difficult and visually fatiguing tasks may be performed better with an increase in the illumination level. Similarly, for the tasks requiring higher accuracy and additional attention, increased illumination is desired.

Background Factors. Background factors include the characteristics of the surface on which a task needs to be performed or a target needs to be detected. Surface brightness, which also depends on background illumination, reduces the positive relative contrast for the task. Particularly when the degrees of reflectivity of the background surface and the task are in the same range, detection and recognition becomes difficult.

Operation Attributes. These factors are essentially associated with the type of highway construction operation and the location where it is performed. These factors include:

- Type of facility,
- Facility environment,
- Traffic control, and
- Location on the highway.

These factors influence task illumination requirements for the same task in varying capacity.

Type of facility determines classification of the highway (i.e., limited access highways, other arterials, collectors, or local roads). Any construction or maintenance operation on limited access highways requires increased attention in forms of quality, safety, and traffic control. Glare problems due to excessive illumination are more severe on

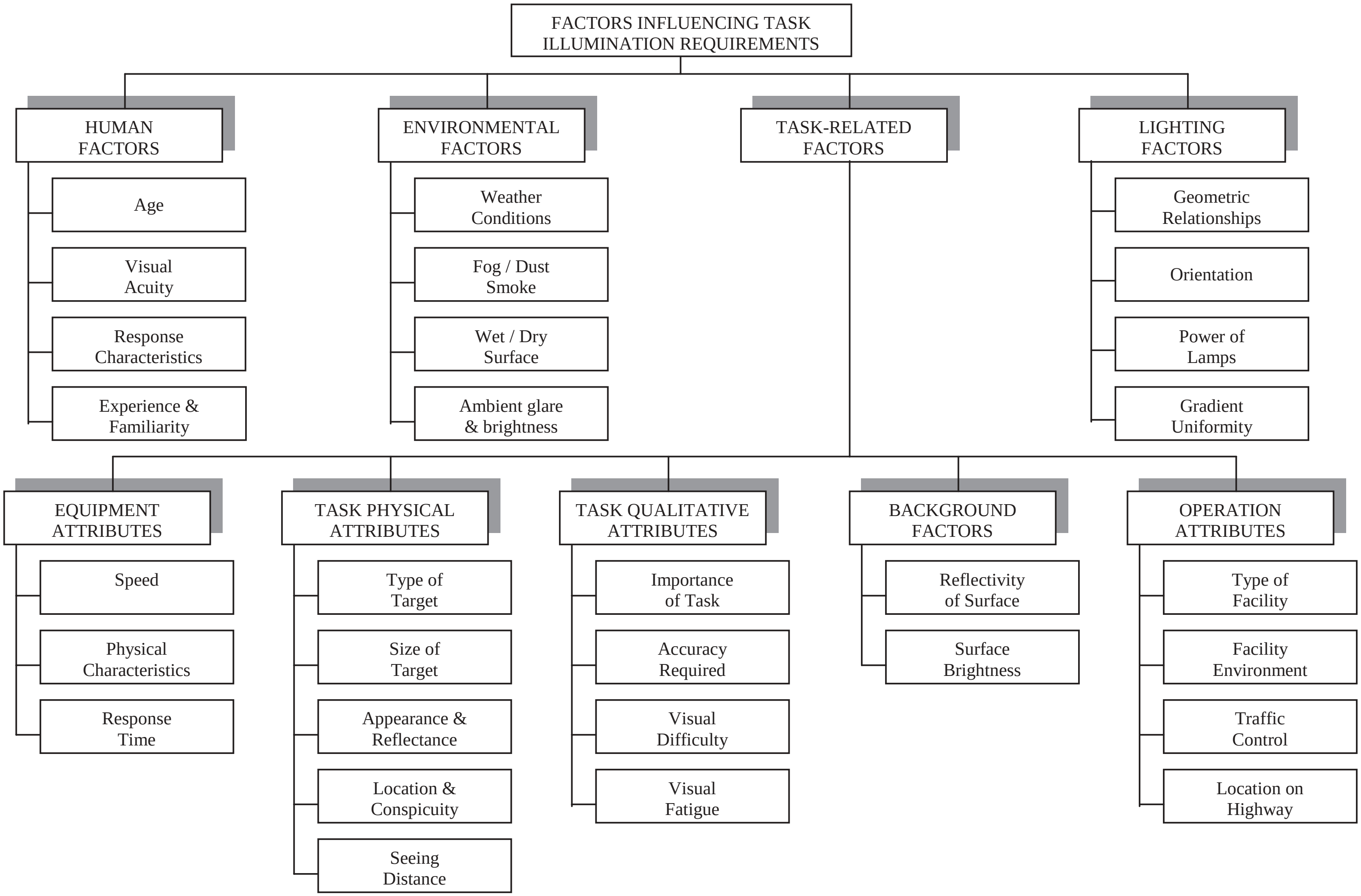


Figure 4. Summary of factors influencing task illumination requirements.

these highways because the speed of vehicles is higher and drivers do not expect any interference. Facility environment includes the geographical area of the operation such as urban, semi-urban, or rural. For urban areas, street lights and roadway lighting may provide sufficient illumination to perform common highway construction tasks. The problem of glare is also limited in the urban areas because of considerable ambient brightness. However, for rural areas, adaptation and glare are serious problems because of the sudden shift from darkness to a brightly lit environment and then back to darkness for motorists passing through the work zone.

Illumination requirements for highway operations are also affected by the traffic control plan designed for the operation. Complete road closure or detour for bridge or highway construction may eliminate the problem of glare to the motorists. Similarly, traffic control plans may depend on the duration of the project. For example, a short-term project may need different types of lights and illumination levels than a long-term project. Location of the work area on the highway or bridge, such as on the right-of-way, median, shoulder, ramp, or intersection, also affects the illumination specification and requirements. Since reflectivity of the background surface depends on the location on the highway, illuminance values to facilitate detection of a target may vary with the location of the task. Therefore, illuminance values for gravel shoulder, asphalt pavement, concrete pavement, and concrete deck are different and vary with the distance from the lamp. As a result, illuminance values for the same surface luminance will be different.

Lighting Factors

Factors associated with lighting provisions that can influence task illumination requirements include:

1. Geometric relationship,
2. Orientation,
3. Power and type of lamps,
4. Gradient uniformity, and
5. Glare.

Geometric relationships among light plant, observer, and location of the object sometimes affect the amount of illumination required because the reflectance of background surfaces varies with different positions. Similarly, orientation, power, and types of lamps also affect reflectance and contrast. Uniformity is associated with the quality of illumination, which is important for seeing detail in the work area. Uniformity, depending on the task characteristics, also affects the quantity of illumination required to perform the task. Glare of both types, discomfort and disability, is a direct result of the quantity of illumination. Glare is not only affected by the power and type of lamps but also by the size and orientation of the light source and the reflectance of the background surface.

Identification of Significant Factors

From the literature review and discussion with experts on lighting and illumination, the factors affecting illumination requirements have been identified and summarized in Figure 4. Although all of the identified factors influence task illumination requirements, the degree of influence varies. A list of factors that significantly affect the illuminance levels for highway construction tasks is given in Table 5. The factors in the table have been selected specifically for highway construction-related visual tasks from the factors described in Figure 4 and as a result of the literature review. Selection of these factors was based on (1) their significance as addressed in a number of technical articles pertaining to roadway and outdoor lighting and (2) the practicality of assigning meaningful subjective levels. The factors that were not suitable for quantifying were not included in the list since they would have affected the proper comparison of nonhighway and highway tasks. Various measurement levels are assigned to the factors in Table 6. A number of these levels are subjective in nature because it is not feasible to introduce objective levels for all the factors, particularly keeping construction activities in view. There has been no priority or significance level associated with these factors. All the factors in the table are not assigned a significance level or degree of influence although they affect illumination requirements identically and vary in their degree of influence. Some factors are envisaged to have a direct and consistent effect on the lighting levels required for seeing. These conclusions are drawn from the findings of the literature review and experienced personnel. The primary sources of literature in determining these factors were IES of North America publications and standards. According to one IES publication for industrial lighting, the main factors affecting industrial seeing tasks include:

1. Size of object,
2. Contrast or reflection,
3. Time spent to evaluate and to complete the task,
4. Luminance,
5. Accuracy to be achieved in the task, and
6. Age.

Based on the IES recommendations, the following factors were included in the data analysis and model development:

TABLE 5 Factors significantly affecting nighttime highway task visibility

Factor	Suggested Factor Levels
Size of the objects to be seen	very fine, small, medium, large
Shape of the objects to be seen	flat, 1-dimensional, 3-dimensional
Contrast of object & background	<30%, 30–70%, >70%
Age of workers	under 40, 40–55, over 55 years
Reflectance of the surface	<30%, 30–70%, >70%
Time spent in seeing	few seconds, 1–5 min, half hr +
Importance of task	low, medium, high
Importance of speed	low, medium, high
Importance of accuracy	low, medium, high
Visual difficulty in seeing	low, medium, high
Visual fatigue experienced	low, medium, high
Seeing distance of the object	1–5 ft, 5–15 ft, >15 ft
Safety and glare considerations	non-critical, moderately important, critical
Importance of uniformity	non-critical, moderately important, critical

TABLE 6 Factors influencing task illumination requirements and their subjective levels

Task No.	Factors	Subjective Levels
1	Importance and accuracy of the task	L – Low M – Medium H – High
2	Background reflection	L – Low M – Medium H – High
3	Speed	N – Not applicable L – Low M – Medium H – High
4	Size of the object to be seen	F – Fine S – Small M – Medium L – Large
5	Distance of seeing	S – 1 to 5 ft M – 5 to 15 ft H – > 15 ft

1. Speed associated with the task,
2. Accuracy or importance desired for the task,
3. Reflectance of the background surface,
4. Seeing distance of the object from the observer, and
5. Relative size of object to be seen.

None of the human factors is included in the list because of the presumption that every crew or operator is a normal attentive observer in a given age group. Moreover, during field investigation, it was determined that on highway construction projects in general, equipment operators belong to one age group. Visual and other variations among crew members for highway construction work do exist. However, recommended lighting guidelines are based on normal visual capacity with sufficient allowance for individual variation. The factor of time spent on the task has been interpreted as speed associated with possible movement. Hence, it has been substituted by a factor of speed in the list. The dynamic nature of a construction project also introduces the factor of visual distance for the operator and the crew, namely, the seeing distance within the same work zone and for the same task may vary. As a result, another factor on seeing distance has been added to the list.

For comparison purposes, it was considered necessary to quantify these selected factors. Since determining and assigning number values to the factors was found difficult in actual field conditions, certain subjective levels were assigned to these factors from practical considerations. Table 6 provides the factors and their subjective levels.

CHAPTER **2**

DEVELOPMENT OF ILLUMINATION REQUIREMENTS

ILLUMINANCE LEVEL CATEGORIES

The prime requirement for highway construction lighting is to facilitate the performance of construction-related visual tasks in the work zone through high-quality illumination. Correct lighting can enable the crew to observe and effectively control various equipment and processes in highway operations. Based on the appraisal of findings, recommendations for illuminance categories and values are provided in Table 7. The three categories, which provide for minimum illuminance levels at 54 lx (5 fc), 108 lx (10 fc), and 216 lx (20 fc) for various tasks, cover the majority of the highway- and bridge-related construction and maintenance operations. Although the recommended levels satisfy safety requirements, they are also intended to provide a guide for efficient visual performance. For this reason, they may not be interpreted as recommended requirements for regulatory minimum illuminance.

Determination of the three categories and their minimum illuminance values was influenced by several considerations. The significant considerations include

1. IES-recommended minimum levels for normal activity from the point of view of safety. For visual detection in high hazard situations, this value is 54 lx (5 fc).
2. IES-recommended levels and uniformity ratios for construction activities, which are 108 lx (10 fc) for general construction and 22 lx (2 fc) for excavation work.
3. Occupational Safety and Health Administration (OSHA)-required minimum illumination intensities for construction industry, which range from 33 lx (3 fc) to 108 lx (10 fc) for various construction activities. Proposed Code of Federal Regulations (CFR) 30 for illumination requirements for draglines, shovels and wheel excavators, which range from 54 lx (5 fc) to 108 lx (10 fc) for various parts of the equipment.
4. Provisions for lighting requirements and guidelines as included in various state specifications for highway and bridge work. Minimum of 54 lx (5 fc) in Florida, 108 lx (10 fc) in Michigan, 108 to 216 lx (10 to 20 fc) in North Carolina, and 216 lx (20 fc) in Maryland are some of the provisions.
5. Opinions and views of various experts as obtained from the survey and literature review concerning comfortable and practical minimum illuminance values and categories for nighttime highway work.
6. Experiences of the research team as obtained from the field reviews and interviewing crew personnel.

In contrast to IES illuminance ranges and weighting-factor system, the suggested categories in Table 7 recommend only the minimum illuminance values. In 1979, IES shifted from a single-value recommendation to the range system in order to reflect lighting-performance trends found in research. It was intended that the new procedure would allow the designer flexibility in determining illuminance levels depending on lighting task characteristics. The characteristics for lighting tasks included

1. Visual display or details to be seen,
2. Age of the observers,
3. Importance of speed or accuracy for visual performance, and
4. Reflectance of the task and background.

The object in the visual display offers some inherent visual difficulty and affects the illuminance value required to perform the visual task. As pointed out in the findings, the age of the observer reflects the condition of visual system. For typical highway operations, nearly all the crew and equipment operators can be classified in one broad age category and, therefore, age is assumed to cause no additional variations on the illuminance values other than the ones selected for that age group. The importance of speed and accuracy depends on the seeing requirements, whether casual, important, or critical. The reflectance of the object and background in a task determines luminance caused by the illuminance. However, from the analysis of findings it was found that reflectances for various road and other construction surfaces do not vary significantly.

As a result, the three recommended categories were found to be adequate to account for differences in visual display and variations in accuracy and speed for the majority of the highway construction tasks. Another reason to

TABLE 7 Recommended minimum illuminance levels and categories for nighttime highway construction and maintenance

Category	Min. Illuminance Level lx (fc)	Area of Illumination	Type of Activity	Example of Areas and Activities to be Illuminated
I	54 (5 fc)	general illumination throughout spaces	performance of visual task of large size; or medium contrast; or low desired accuracy; or for general safety requirements	• Excavation • Sweeping and cleanup • Movement area in the work zone • Movement between two tasks
II	108 (10 fc)	general illumination of tasks and around equipment	performance of visual task of medium sizes; or low to medium contrast; or medium desired accuracy; or for safety on and around equipment	• Paving • Milling • Concrete work • Around paver, miller, and other construction equipment
III	216 (20 fc)	illuminance on task	performance of visual task of small sizes; or low contrast; or desired high accuracy and fine finish	• Crack filling • Pot filling • Signalization or similar work requiring extreme caution and attention

limit the number of categories or illuminance levels to three is attributed to the feasibility of attaining one or more levels in one operation.

Category I is recommended for the general illumination in the work zone primarily from the safety point of view in the area where crew movement is expected or taking place. This category is also recommended for tasks requiring low accuracy, involving slow-moving equipment, and having large-sized objects to be seen.

Category II is recommended for illumination on and around construction equipment and the visual tasks associated with the equipment. The primary concern in suggesting the minimum illuminance value for this category is equipment safety and medium accuracy desired for the task. For certain tasks (e.g., resurfacing), not only is the safety around the paver and roller crucial but quality of the finished surface is also important.

Category III is suggested mainly because of the efficient visual performance required for certain tasks. Highway tasks which present higher visual difficulty and require increased attention from the observer include crack and pothole filling, joint sealing, critical connections, and tasks involving maintenance of electrical connections and moving mechanical parts. Table 7 includes other examples for each of the three categories.

COMPARISON OF NONHIGHWAY AND HIGHWAY WORK TASKS

The visual requirements in a typical highway construction task are similar to the visual requirements of certain outdoor industrial tasks. For comparison with highway tasks, a list of equivalent nonhighway tasks was identified and their required illuminance levels were obtained from ANSI/IES recommendations for outdoor industrial spaces (*2*). Based on the characteristics of these tasks, they were assigned different levels of the various factors as determined in the earlier section. Table 8 provides the list of selected nonhighway outdoor tasks, area, factor descriptions, and recommended illuminance levels.

A statistical analysis of the nonhighway matrix revealed a correlation between the factors and their effect on illumination

TABLE 8 Illuminance levels of outdoor industrial tasks and spaces

Task No.	Area	Name of the Activity	Factors					Recommended Illuminance Level lx(fc)
			Importance	Reflection	Speed	Size	Distance	
1	Automotive Industry	Frame assembly	H	M	L	S	S	50 (540)
2		Welding area	H	H	N	S	S	50 (540)
3		Machining operations	H	H	H	F	S	75 (810)
4		Coal yards & oil storage	L	L	N	L	L	0.5 (5.4)
5		Outdoor substation, parking	L	L	N	L	L	1.5 (16.2)
6		Entrance, truck maneuverability	L	L	L	L	L	5 (54)
7		Furnace area, sheet rolling	H	M	N	M	S	30 (324)
8	Iron & Steel Industry	Mold yard	L	L	N	M	L	5 (54)
9		Scrap stock yard	M	M	N	M	L	10 (108)
10		Hot top storage	M	H	M	M	L	10 (108)
11	Petrochemical Industry	Pump rows, valves, manifolds	L	L	N	M	L	5 (54)
12		Heat exchangers	L	L	N	M	L	3 (32.4)
13		Maintenance platforms	L	L	N	L	L	1 (10.8)
14		Operating platforms	L	L	N	M	L	5 (54)
15		Cooling towers, equipment	L	L	N	M	L	5 (54)
16		Furnaces	L	L	N	M	L	3 (32.4)
17		Active ladder, stairs	L	L	L	L	L	5 (54)
18		General area	L	L	N	L	L	1 (10.8)
19		Extruders and mixers	M	M	L	M	M	20 (216)
20		Conveyors	L	L	M	L	L	2 (21.6)
21		Outdoor plants, equipment	L	L	N	S	M	5 (54)
22		Outdoor substation	L	L	N	L	M	2 (21.6)
23		Plant road: Frequent use	L	L	M	L	L	0.4 (4.3)
24		Plant road: Infrequent use	L	L	L	L	L	0.2 (2.2)
25		Plant parking lots	L	L	L	L	L	0.1 (1.1)
26		Outdoor bulk storage	L	L	N	L	L	0.5 (5.4)
27		Large bin storage	L	L	N	L	M	5 (54)
28		Small bin storage	M	M	N	S	M	10 (108)
29		Small parts storage	M	M	N	F	M	20 (216)
30	Pulp and Paper Industry	Groundwood mill grinder	H	M	H	S	M	70 (756)
31		Beater room	H	M	L	M	M	30 (324)
32		Roll dryer	H	M	M	S	M	50 (540)
33		Cutting and sorting	H	M	H	S	S	70 (756)
34		Active warehouse	M	M	L	M	M	20 (216)
35		Shipping truck shed	M	M	L	M	M	20 (216)
36		Roadways	L	L	M	L	L	0.4 (4.3)
37		Log pile	L	L	N	M	L	3 (32.4)
38		Log unloading	L	L	L	M	M	5 (54)
39	Industrial Outdoors	Excavation	L	L	N	L	M	2 (21.6)
40		General construction	M	M	N	M	M	10 (108)
41		Active entrance	L	L	L	L	L	5 (54)
42		Inactive entrance	L	L	N	M	L	1 (10.8)

levels. The main statistical procedures used were (1) correlation coefficients and (2) determination of mean. Correlation analysis was performed to examine the extent of the relationship between the selected factors and illuminance levels. The accuracy and importance of the factors were given the highest priority during the comparison of nonhighway work tasks with highway work tasks.

Nonhighway tasks were matched with equivalent highway tasks. As a result of the analysis, it was determined that if four or more factors including importance and accuracy match, then the illumination level recommended for the first task may be suggested for the second task also.

DEVELOPMENT OF RECOMMENDED ILLUMINATION CRITERIA

Illumination Levels

As described in the previous section, a similar assignment of factor levels was also performed for all the identified highway construction and maintenance tasks. For each of the highway tasks, four or more factors from the nonhighway matrix were matched. A list of nonhighway tasks was prepared for all highway tasks. An average of illumination levels specified for all matching nonhighway tasks was used to suggest illumination categories for highway tasks. Table 8 shows the typical industrial tasks, their factor descriptions, and specified illumination requirements.

Suggested illumination values (see Table 9) for highway tasks were based on the following: (1) compared averages of illumination for matching nonhighway tasks; (2) current illumination standards and regulations for construction; (3) current SHA requirements for illumination; and (4) researchers' observations of current practice on nighttime highway construction work. In some cases, the suggested illumination value was less than the compared average illumination for a nonhighway task because of these considerations.

In order to recommend guidelines for equipment lighting, a set of construction equipment most commonly used for highway work was selected. Based on the equipment's characteristics, its application, and relevant Society of Automotive Engineers (SAE) current practices, a minimum area to be illuminated in front and back of the equipment is recommended.

The current SAE-recommended practice J1024 for forward lighting on construction and industrial machinery provides for adequate illumination for a distance that exceeds the vehicle stopping distance (D) at its maximum operating speed (*3*). This stopping distance includes a 1.5-sec operator reaction time interval and can be computed by the following formula (where H is the speed):

D (ft) = 2.2 H mph

D (m) = 0.4167 H km/h

The actual stopping distance is a function of machine mass and speed. Braking performance for rubber-tired construction machines is provided as a recommended practice in SAE J1142 (*3*). At typical working speeds on the order of 16.1 to 24.2 km/h (10 to 15 mph), braking distances are approximately 4.6 to 6.1 m (15 to 20 ft) plus the reaction distance of 10.1 m (33 ft). The illuminated area in the direction of travel should, therefore, be approximately 17.7 m (58 ft) ahead and behind the equipment. Although SAE standards do not provide an illumination level for this point, it is estimated that at the maximum range, the illumination should be at least 10.8 lx (1 fc).

The suggested minimum area to be illuminated for each piece of equipment is presented in Table 10. For practical reasons, most of the equipment is classified in two broad categories: slow-moving equipment and fast-moving equipment. Although the illumination level at the maximum range

TABLE 9 Suggested illumination categories and levels for typical highway construction and maintenance tasks

Task No.	Task Description (Construction)	Factors					Compared Averages	Suggested Illumination	
		Importance	Reflection	Speed	Size	Distance		Category	Level lx (fc)
1	Excavation—regular, lateral ditch, channel	L	L	N	L	L	1.3	I	54 (5)
2	Embankment, filling and compaction	L	L	M	L	L	0.6	I	54 (5)
3	Barrier walls, traffic separators	M	M	N	M	L	10	II	108 (10)
4	Milling and removal	M	M	M	M	L	10	II	108 (10)
5	Resurfacing	M	H	M	L	L	10	II	108 (10)
6	Concrete pavement construction	M	H	L	M	L	10	II	108 (10)
7	Subgrade stabilization and construction	L	L	L	L	M	1.86	I	54 (5)
8	Base courses—clay, cement, asphalt	M	L	M	M	L	10	II	108 (10)
9	Surface treatment	M	H	M	L	L	10	II	108 (10)
10	Waterproofing/sealing	M	H	M	M	M	10	II	108 (10)
11	Sidewalks	M	M	L	L	M	20	II	108 (10)
12	Riprap	M	M	L	M	M	17.5	II	108 (10)
13	Guardrail, fencing	M	M	N	M	M	15.7	II	108 (10)
14	Painting stripes/markers/metal buttons	M	H	M	S	L	10	II	108 (10)
15	Landscaping, grassing, sodding	L	L	N	L	L	1.3	I	54 (5)
16	Highway signing	M	M	N	M	M	15.7	II	108 (10)
17	Traffic signals	H	M	N	S	S	43.3	III	216 (20)
18	Highway lighting system	H	M	N	S	M	70	III	216 (20)
19	Bridge decks	M	L	N	M	M	10	II	108 (10)
20	Drainage structures, culverts, storm sewer	M	M	N	L	M	13.3	II	108 (10)
21	Other concrete structures	M	H	L	M	L	10	II	108 (10)
	(Maintenance)								
22	Maintenance of earthwork/embankment	L	L	M	L	L	0.6	I	54 (5)
23	Reworking shoulders	L	H	M	L	L	0.4	I	54 (5)
24	Repair of concrete pavement	M	M	M	S	M	10	II	108 (10)
25	Cracking filling	H	M	L	F	M	30	III	216 (20)
26	Pot filling	M	M	N	F	M	13.3	II	108 (10)
27	Resetting guardrail/fencing	M	M	N	M	M	15.7	II	108 (10)

TABLE 10 Recommended illuminated distance in the direction of travel for various types of construction equipment

Type of Equipment	Working Speed, mph (km/h)	Reaction Distance [a], ft (m)	Braking Distance, ft (m)	Distance to be Illuminated in Front and Back of Equipment [b,c], ft (m)
Slow-moving Equipment Paver Milling Machine	4–5 (6.4–8)	11 (3.4)	5 (1.5)	16 (4.9)
Fast-moving Equipment Backhoe Loader Wheel Tractor Scraper Wheel Loader Compactor/Roller Motor Grader	10–15 (16.1–24.2)	33 (10.1)	15–25 (4.6–7.6)	58 (17.7)

[a] Reaction distance = 2.2 x working speed
[b] Distance to be illuminated = reaction distance + braking distance
[c] Minimum illumination level of 10.8 lx (1 fc) at maximum distance

provided in the Table 9 should not be less than 10.8 lx (1 fc), the task illumination levels around the equipment should conform to the categories and minimum levels recommended for various tasks.

Assessment of Glare Hazard

Glare hazard, both disability and discomfort, is a serious problem on highways. The various sources of glare affecting the work crew and the motorist include:

1. Glare from passing vehicles,
2. Glare from temporary work area lighting, and
3. Glare from lighting on construction equipment.

The intensity levels for organic lighting on construction equipment were not found to be high. However, retrofitted equipment lighting installed after manufacture was often high intensity and could cause glare problems. Glare resulting from stationary light plants is potentially the most severe for motorists and workers.

There are several methods which have been suggested to evaluate and quantify glare:

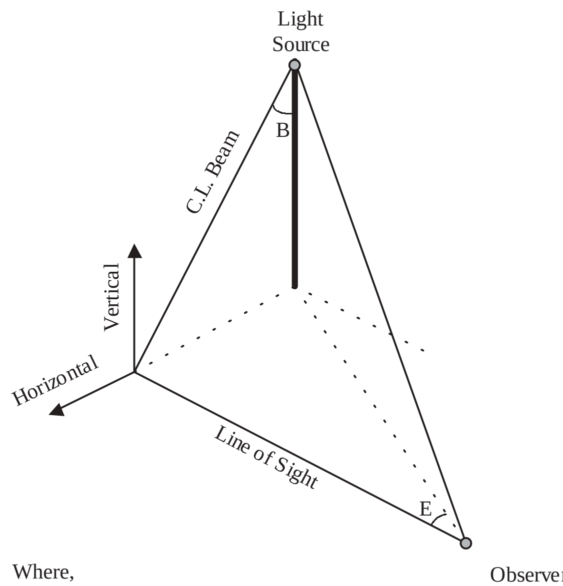
1. Between comfort and discomfort (BCD) illuminance levels,
2. Glare control mark, and
3. Visual comfort probability.

These methods are useful for fixed or stationary situations. However, it is difficult to specify and achieve such levels considering the dynamics of highway construction work zones. Instead, a more practical approach of controlling glare has been adopted in this study. This approach includes (1) avoiding glare to the workers from the headlights of the traveling vehicles and (2) reducing glare from the light plants to the motorists.

To avoid glare to the workers from the headlights of the traveling vehicles, several measures can be taken. Glare avoidance screens or barrier walls are usually used as a measure to protect workers from outside glare. Often height of the barrier walls was not thought to be sufficient to completely protect the work zone from vehicle lights. As a result, additional screens, panels, or paddles were mounted on the barrier walls to help separate the lanes and reduce glare.

In order to limit the glare from stationary tower light plants to the motorists, appropriate lighting configuration was determined to be a viable solution. In some cases, the motorist may be protected from the work zone lighting by providing screens on top or by mounting lamps below the top edge of the barrier wall. However, in the most general case where light sources are elevated, the glare hazard can be most efficiently controlled by selecting an appropriate configuration and controlling the beam angle. Figure 5 illustrates the relevant geometry between light source and the observer. Beam angle is measured as the angle between the center-line of the beam and vertical and eccentricity are given by angular distance of the light source from the line of sight of the observer. According to one study, the amount of glare decreases or BCD luminance increases as beam angle decreases and eccentricity increases (*4*). However, for a typical highway work zone situation, maximum eccentricity is limited and cannot exceed the total width of a few lanes. As a result, beam angle is the only controlling factor available for glare control.

Beam angle, if reduced substantially, can cause significant adverse effects on beam spread, area of illumination, and uniformity. A beam angle of not more than 60 degrees for elevated flood lights is most appropriate and also appears to agree with several SHA specifications. The maximum height of the tower for this beam angle was limited to 9.2 m (30 ft).



Where,

B: Beam angle with vertical

E: Eccentricity of observer's position

Figure 5. Effect of beam angle and eccentricity in reducing glare.

CHAPTER **3**

FIELD DEMONSTRATION OF ILLUMINATION GUIDELINES

INTRODUCTION

This study has focused on the subject of lighting construction work zones during nighttime highway construction. The primary objectives have been to develop guidelines that can be used by the practitioner to safely and efficiently design and maintain work zone lighting systems. Candidate guidelines were developed based on the best currently available science and were presented in Chapter 2. However, to evaluate the applicability of these guidelines, the construction job site may be the ultimate test of engineering theory. Trial of the proposed guidelines on an actual construction site was considered to be essential. Consequently, the research team undertook a field demonstration of the guidelines as a part of Phase I of the project.

DEMONSTRATION OBJECTIVES

The overall objective of this field research was to validate the proposed guidelines. The following specific objectives have been identified:

1. Evaluate the adequacy of the format and user understanding of the work zone lighting design procedures presented in the guidelines.
2. Evaluate the constructability and feasibility of the lighting configuration and systems suggested by the guidelines.
3. Evaluate the performance effectiveness of the lighting plan suggested by the guidelines.
4. Evaluate the cost of designing and implementing a lighting plan in accordance with the guidelines.

DEMONSTRATION PROCEDURE

The investigators obtained agreement from the Florida Department of Transportation (FDOT) and Hubbard Construction Corporation, an FDOT contractor, to participate in the field trial. Although FDOT's current lighting specification is substantially different from the proposed guidelines, both parties agreed to try to provide lighting on a specific project according to the proposed guidelines. The research procedure consisted of the following tasks.

Task 1. Project Selection and Development of Lighting Design

An FDOT project was selected because its work schedule fit within the time limitations available for this research study and because it was expected to involve some work activities in all three illumination levels specified in the guidelines. The project, titled Resurfacing University Boulevard, located in Jacksonville, consisted of the asphalt pavement resurfacing of an existing approximately 3.2-km (2-mi) four-lane arterial road.

Working with the contractor's supervisory personnel, the research team developed a lighting design and a lighting plan for the project. This design is included in Appendix for Section Two: Lighting Design for Demonstration. During the design and planning process, the research team accessed the suitability of the guidelines as a design tool to be used by contractor personnel.

Task 2. Implementation of the Design

Implementation of the design consisted of the following lighting modifications to the contractor's equipment.

Asphalt Paver—Cedar Rapids 451. Figure 6 provides the detail of the lighting arrangement on the paver. The design modification consisted of adding one 1,000-W metal halide luminaire mounted in the center of the rear side of the paver to provide lighting to the finished pavement area directly behind the paver. The luminaire was mounted with an adjustable yoke mount and provided with a cutoff baffle. Power was supplied by portable gasoline powered generators mounted on the deck of the paver.

Pavement Rollers—Galion and Hyster. Figures 7 and 8 give the details of the lighting arrangements on the pavement rollers, respectively. The design improvement consisted of adding two additional 55-W quartz halogen lamps to the Galion machine and one additional quartz halogen lamp to the Hyster machine. These additional luminaires were mounted on a bracket bar installed on the front of the machine. Power was supplied by the internal DC alternator.

Portable Light Tower—Four 1,000-W MH. The portable light tower was modified by adding cutoff shades to each of

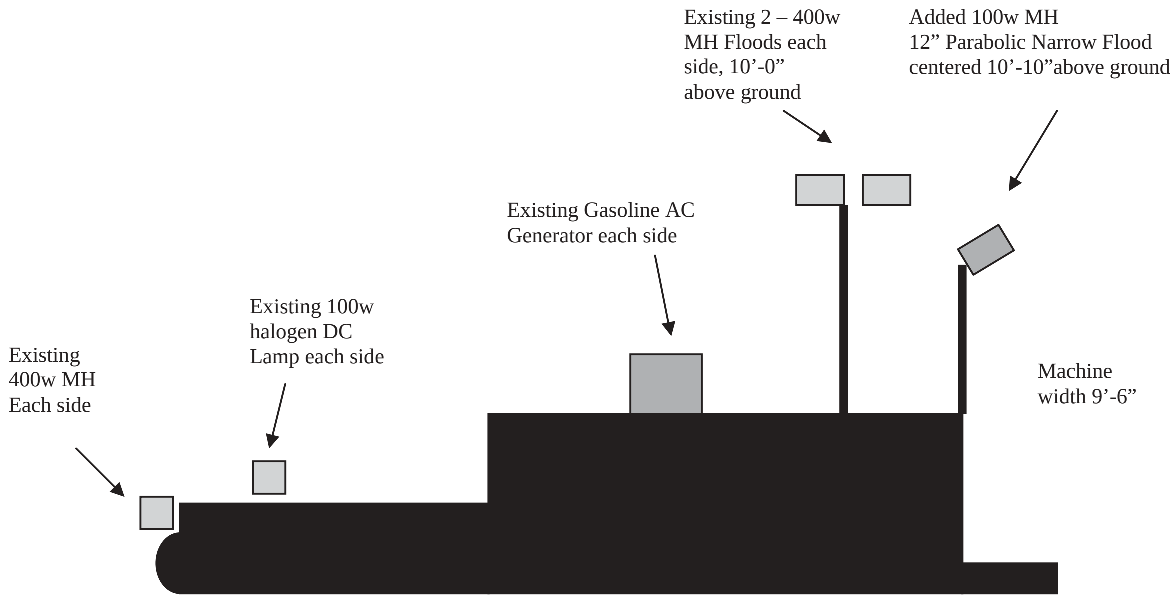


Figure 6. Detail of lighting configuration on asphalt paver.

the four flood lights. These glare control shades were easily attached with spring clips provided with the shades.

Task 3. Performance Observations

Construction of the project was performed by the contractor with the modified equipment lighting. The research team made observations regarding the following:

1. Actual illumination as compared with the lighting plan and guidelines.
2. Suitability of the lighting in terms of work performance and opinions of the participants.

Design Guidelines. Contractor's supervisory personnel were able to follow the procedures in the guidelines with the assistance of the research team. However, this experience suggests that training would be required in most cases prior to a contractor's successful use of the design procedure.

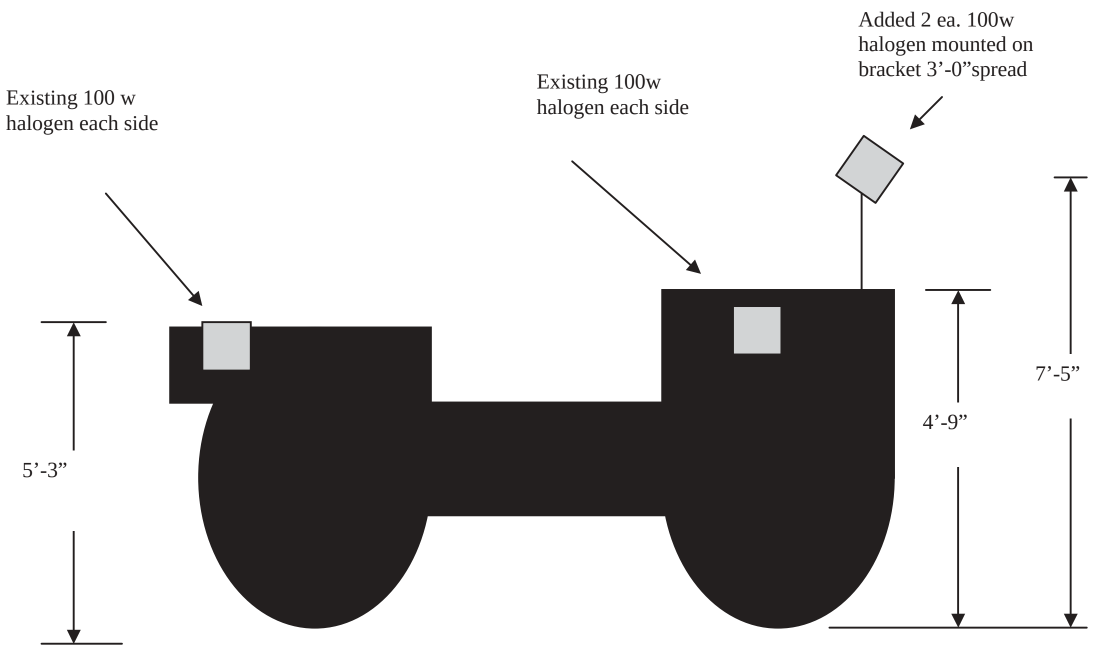


Figure 7. Detail of lighting configuration on Galion Roller.

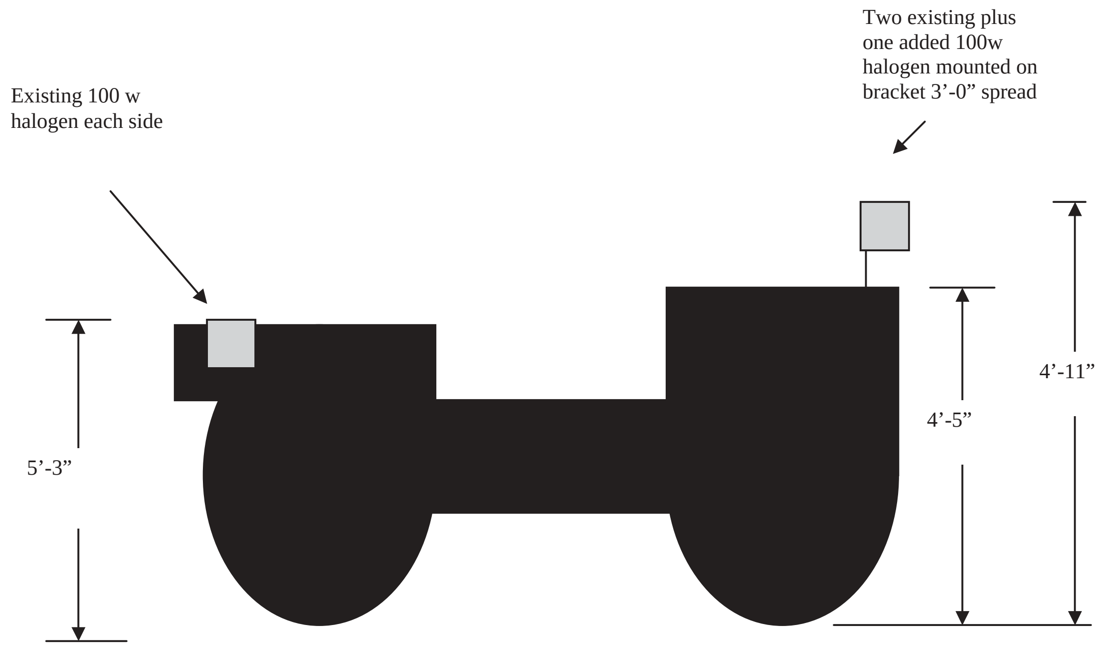


Figure 8. Detail of lighting configuration on Hyster Roller.

Lighting Equipment Availability, Installation, and Cost. All of the additional luminaires added to the project were readily available from retail suppliers. The contractor’s normal equipment maintenance personnel accomplished mounting of the luminaires with minimal labor.

The total cost of all modifications was approximately $1,628. This is clearly a small cost increase on a project with a total budget exceeding 1 million dollars. Table 11 summarizes the additional lighting costs.

Lighting and Work Performance. The research team measured actual illumination. The results of the illumination measurements are summarized in Figure 9. Target illumination levels were obtained in the design work area in all cases. Uniformity ratios exceeded the target value in the case of the asphalt paver and with the portable light tower. A summary of the illumination results by work task is provided in Table 12.

Work performance was observed to meet or exceed the project quality requirements and the contractor’s production expectations. No significant safety or quality control incidents occurred. It was reported that this achieved performance level is typical for this contractor and cannot necessarily be related to the project’s lighting upgrade. Nevertheless, the majority of the working participants did agree that the improved lighting made their jobs easier. A summary of the participants’ survey is presented in Table 13.

Analysis, Appraisal, Application. The design procedures suggested in the Guidelines for Work Zone Illumination Design were successfully used to design the lighting systems for the demonstration project. Area lighting was not the only design requirement. Each task and each piece of construction equipment required unique task lighting in addition to the general area lighting.

Task 4. Evaluation and Summary

The research team evaluated and summarized the results of the demonstration project. Appropriate modifications to the guidelines are suggested. In addition, the following “lessons learned” were obtained from the demonstration project:

1. Each piece of equipment and each task has unique task lighting requirements in addition to general area lighting requirements.
2. Equipment operators are a good source of information about areas they need to see while performing tasks.
3. Experienced night workers adapt to varying lighting situations and use indicators other than light to perform their tasks, such as sound.
4. The lighting of construction equipment could be very much facilitated if equipment manufactures would provide lighting or at least increase amp capacity.
5. The use of glare control shades on luminaires is an inexpensive and effective glare counter measure.

The three categories of illumination levels appeared to successfully cover the work tasks in the demonstration project. A listing of the tasks performed under each illumination level category was previously given in Table 10.

Pavement rolling was changed from Category II (108 lx, 10 fc) to Category I (54 lx, 5 fc). This change was made during

TABLE 11 Summary of lighting upgrade costs

EQUIPMENT	LIGHTING ADDITIONS	MATERIALS AND LABOR	COST
Asphalt Paver—Cedar Rapids 451	Added 1 ea. 100 w metal Halide Flood – Ruud No. 4410-D 1 ea. Spare Replacement Luminaire	Luminaires $462.00 Pipe support $3.00 Wiring $12.00 Installation Labor $18.00	$495.00
Pavement Roller—Gallion Dresser	Added 2 ra. 55 w Qtz Halogen Lamps, CAT 8180 1 ea. Spare Replacement Luminaire	Luminaires $117.00 Bracket Bar $22.00 Wiring $10.00 Installation Labor $36.00	$185.00
Pavement Roller—Hyster	Added 3 ea. 55 w Qtz Halogen Lamps, CAT 8180 2 ea. Spare Replacement Luminaire	Luminaires $156.00 Bracket Bar $18.00 Wiring $10.00 Installation Labor $36.00	$220.00
Portable Light Tower	Added 4 ea. Glare Control Shades General Elec. PSON34	Glare Control Shades $728.00 Installation Labor $0.00	$728.00

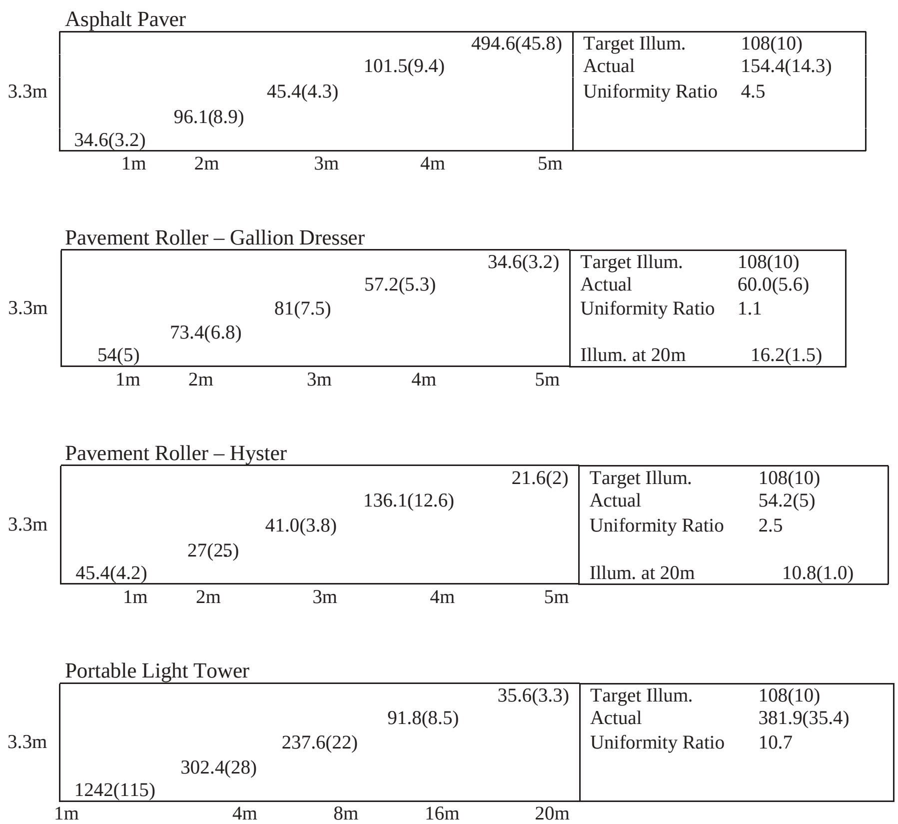


Figure 9. Illumination of measurement results.

TABLE 12 Summary of illumination measurements by work task

Category Target Illumination Level	Task	Measured Illumination (Average)
I 54 lx (5 fc)	Water movement Sweeping Clean up Pavement rolling	54 – 60.4 lx (5.0 – 5.6 fc)
II 108 lx (10 fc)	Asphalt Paving Worker activity around paver Racking, shoveling asphalt	154.4 lx (14.3 fc)
III 216 lx (20 fc)	Maintenance of equipment Set up of asphalt distributor	382.3 lx (35.4 fc)

TABLE 13 Summary of participants' survey

How does the lighting on this project compare with last project you worked on?	Very Much Better 2	Somewhat Better 6	About the Same 2	Not as Good 1
How would you rate the lighting on this project with regard to your ability to do your job?	Very Good 1	Good 3	Just O.K. 6	Poor 1
Indicate whether or not this project should have more or less light in the work area.	Much More	A Little More 4	About the Same 7	Less Light
Indicate your job classification.	Supervisor 1	Engineer/ Inspector 1	Equipment Operator 3	Workman 6

the design process based on consultation with the FDOT field engineer and the contractor's field supervisors. Additionally, the lighted work area for the roller was set as an area 3.3 m by 6.1 m (11 ft by 20 ft). Both of these changes appear to have worked well.

Meeting the suggested maximum uniformity ratio of 10.0 was difficult in some cases. For example, the illumination level directly adjacent to the asphalt paver was 494.6 lx (45.8 fc). This hot spot was the result of focusing the additional 100-W metal halide lamp at an angle of approximately 60 degrees with the vertical to control glare. The actual uniformity ratio of 14.3 was not detrimental to the performance of the work.

Maintaining the 10.8 lx (1 fc) levels at the seeing horizon distances for moving equipment was also successful. This requirement was obtainable and appeared to match the work requirements.

The use of glare control shades on the portable light tower worked well. These devices are easily attached to the luminaires with spring clips. Their use significantly reduced glare from the tower lamps.

All of the lighting hardware used was readily obtainable. No special or unusual luminaires were used. Costs were minimal. Neither costs nor availability of equipment were obstacles to implementing the proposed illumination guidelines.

In summary, the Guidelines for Work Zone Illumination Design provided a simple, straight-forward procedure for designing work zone lighting. However, the guidelines could be enhanced by including a discussion of the need to consider the unique requirements of each task.

CHAPTER **4**

RECOMMENDED ILLUMINATION GUIDELINES

INTRODUCTION

This chapter presents a summary of the findings and recommended guidelines for illumination of nighttime highway work resulting from this study. The content of the guidelines includes recommended minimum illumination levels for different nighttime highway work tasks, glare control requirements, and implementation considerations. These guidelines may be used by specifying agencies such as SHAs when developing standards for nighttime highway work and may provide guidance for professionals in the design and implementation of work zone lighting.

Minimum Illumination Requirements

Suggested minimum illumination requirements are presented in Table 14. Typical night work activities are assigned to one of three lighting requirement categories:

Category I	Minimum illumination of 54 lx
Category II	Minimum illumination of 108 lx
Category III	Minimum illumination of 216 lx

Table 14 also provides guidance with regard to the minimum illuminated area for different stationary and moving tasks.

Glare Control Requirements

Suggested requirements for glare control and avoidance are presented in Table 15. Of the recommendations, proper aiming and the use of glare control shading hardware appear to be the most effective countermeasures.

Related Implementation Issues

Training

Field reviews at numerous projects in many states suggest that the technical aspects of work area lighting are relatively new to both SHA and contractor field personnel. Clearly there is a need for basic training with regard to properly configuring and maintaining the lighting of a nighttime highway work area. Suggested subject areas are

- Review of specified lighting standards,
- Minimum levels of illumination,
- Glare control requirements,
- Lighting hardware options and characteristics, and
- Proper equipment mounting of luminaires.

More advance training may be appropriate for designers of work area lighting plans and for those persons responsible for reviewing lighting plans.

Adjusting Lighting Requirements to Specific Tasks

The recommended minimum illumination requirements are general in nature. A review of the specific task should be performed to determine task-specific lighting requirements. This examination of the work process and detail may indicate additional specific lighting needs related to the performance of the task. This review of the task seeing requirements should include experienced equipment operators and workers. For example, the operator of a pavement roller normally is looking at the pavement surface in advance of the machine; however, if the pavement is being placed against a concrete curb, the operator must also be able to see the edge of the roller wheel. Input from the field work force is an important factor in successful lighting design and implementation.

Avoid Omitting Ancillary Activities

Normally, attention is focused on the primary construction or maintenance activities. Lighting plans and configurations are established to accommodate these key production activities, such as the placement and compaction of asphalt pavement. Care must be taken to ensure that other ancillary activities also have adequate lighting. For example, inspection of asphalt pavement typically occurs at a considerable distance from the location of the paver and the following rollers. Provisions must be made so that the quality control and acceptance activities are also properly lighted.

Another example occurs in the construction of portland cement concrete pavements. Management attention generally focuses on the paving operation receiving adequate lighting. However, several hours after the paving operation has passed,

TABLE 14 Recommended target illumination levels and lighting guidelines

Description of Construction and Maintenance Task	Average Maintained Illumination	
	Category	Target Level lux (fc)
Excavation – Regular, Lateral Ditch, Channel	I	54 (5)
Embankment, Fill and Compaction	I	54 (5)
Barrier wall, Traffic Separators	II	108 (10)
Milling, Removal of Pavement	II	108 (10)
Asphalt Paving and Resurfacing	II	108 (10)
Concrete Pavement	II	108 (10)
Asphalt Pavement Rolling	I	54 (5)
Subgrade, Stabilization, and Construction	I	54 (5)
Base Course Grading and Shaping	II	108 (10)
Surface Treatment	II	108 (10)
Base Course Rolling	I	54 (5)
Waterproofing and Sealing	II	108 (10)
Sidewalk Construction	II	108 (10)
Sweeping and Cleaning	I	54 (5)
Guard Rails and Fencing	II	108 (10)
Striping and Pavement Marking	II	108 (10)
Landscaping, Sod and Seeding	I	54 (5)
Highway Signs	II	108 (10)
Traffic Signals	III	216 (20)
Highway Lighting Systems	III	216 (20)
Bridge Decks	II	108 (10)
Drainage Structures and Drainage Piping	II	108 (10)
Other Concrete Structures	II	108 (10)
Maintenance of Embankments	I	54 (5)
Reworking Shoulders	I	54 (5)
Repair of Concrete Pavement	II	108 (10)
Crack Filling	III	216 (210)
Pot Hole Filling	II	108 (10)
Repair of Guardrails and Fencing	II	108 (10)
Implement Glare Control Measures. (See Table 15 for Glare Control Check List.)		

Recommended Illumination Areas for Typical Highway Construction Equipment	
Provide target illumination over task working area. This is the effective working width of the machine by approximately 5 meters.	
Minimum distance from machine to	
Slow Moving Equipment: Paver Milling Machine	5 meters
Fast Moving Equipment: Backhoe Loader Wheel Loader Scraper Roller Motor Grader	20 meters
Other Equipment: Maximum uniformity ratio of 10:1 in the work area. Minimum of average maintained illumination of 54 lx (5 fc) for all work areas.	

TABLE 15 Glare control check list

Beam Spread	Select vertical and horizontal beam spreads to minimize light spillage. Consider using cutoff luminaires.
Mounting Height	Coordinate minimum mounting height with source lumens (see Figure A-2).
Location	Luminaire beam axis crosses normal lines of sight between 45° and 90°.
Aiming	Angle between main beam axis and nadir less than 60° (see Figure 5). Intensity at angles greater than 72° from the vertical less than 20,000 candela.
Supplemental Hardware	Visors Louvers Shields Screens Barriers

joints must be cut in the pavement; the saw cutting crew may be left without adequate lighting.

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APPENDIX FOR SECTION TWO

LIGHTING DESIGN FOR DEMONSTRATION

ROLLERS

Based on the design criteria, rollers were classified as a Category II with an average illuminance of 108 lx (10 fc), a uniformity ratio of 10 : 1, and an illumination area of 17.7 m by 3.3 m (58′ × 11′) at each end of the equipment. After meeting with the contractor and equipment operators, it was determined that the work zone could be reduced to 6 m (20′) and that 54 lx (5 fc) would be sufficient illumination. This effectively reclassifies the equipment as Category I. Since there is limited mounting space to support a tower, 55-W incandescent, sealed beam lamps will be mounted on the frame for this equipment.

Given an area of 19.8 m^2 (220 sf) and a required illumination level of 54 lx (5 fc), the necessary wattage can be found as follows:

Recommended watts/m^2: 12 (Figure A-1)

$$\text{Total wattage: } \frac{12\text{w}}{\text{m}^2} \times 19.8\text{m} = 238 \text{ watts}$$

$$\text{Number of lamps: } \frac{238 \text{ watts}}{55 \text{ watts / lamp}} = 4.3 \text{ lamps (use 4)}$$

The recommended headlamp is a Caterpillar composite halogen lamp assembly. A high beam lamp is selected for extended throw. Four will be required in each direction (front and rear).

Project results for the roller indicate the validity of the simplified design procedure. The Gallon Dresser roller equipped with four lamps achieved the desired 54 lx (5 fc) with an excellent uniformity ratio.

As a result of the demonstration, the lighting criteria for roller operations were revised to be a Category I requirement at 54 lux (5fc). Because of the rolling patterns used by the roller operators, the seeing task is performed adequately at Category I illumination level. Inspection and quality control activities are likely to require additional task-specific illumination.

PAVER

Based on the design criteria, pavers are classified as a Category II with an average illuminance of 108 lx (10 fc), a uniformity ratio of 10 : 1, and an illumination area of 4.9 m by 3.3 m (16′ × 11″) at the back end of the equipment. After meeting with the contractor and equipment operators, it was determined that in addition to the work zone lighting, it would be beneficial to provide task lighting for moving parts such as the screed.

Since this lighting is highly directional, it will not be considered in the determination of the work zone lighting requirements. The required area of illumination was extended by 1.2 m due to the mounting position of the light on the paver. For this application, a post mounted metal halide fixture is recommended.

Given an area of 19.8 m^2 (176 sf) and a required illumination level of 108 lx (10 fc), the necessary wattage can be found as follows:

Recommended watts/m^2: 4 (Figure A-1)

$$\text{Total wattage: } \frac{4\text{w}}{\text{m}^2} \times 19.8\text{m}^2 = 79 \text{ watts}$$

From manufacturers' literature (RUUD Lighting), a narrow parabolic luminaire is selected to minimize light spillage to the sides of the work zone. A 100-W metal halide lamp is selected as the next available size (50, 70, 100, 175). From Figure A-2, it is then determined that there are no constraints on the mounting height for this wattage. The light will be mounted at 3.3 m (11′).

Since the supplemental task lighting installed by the contractor is directed on the screed, it does not play a significant role in the work zone calculation. Comparison of the actual results with those simulated using AGI lighting software is again favorable. The required average work zone illumination is achieved with uniformity ratios within acceptable limits.

PORTABLE LIGHT TOWER

Commercially available portable light towers are usually equipped with four 1000-W metal halide lamps and have a maximum extended height of 9 m (30′). Based on the relationship between mounting height and source lumens, it is evident that this equipment will be a tremendous source of glare since the minimum acceptance mounting height for a 1,000-W metal halide is approximately 14 m (46′). This phase of the demonstration determines the effectiveness of glare control devices while maintaining adequate illumination levels.

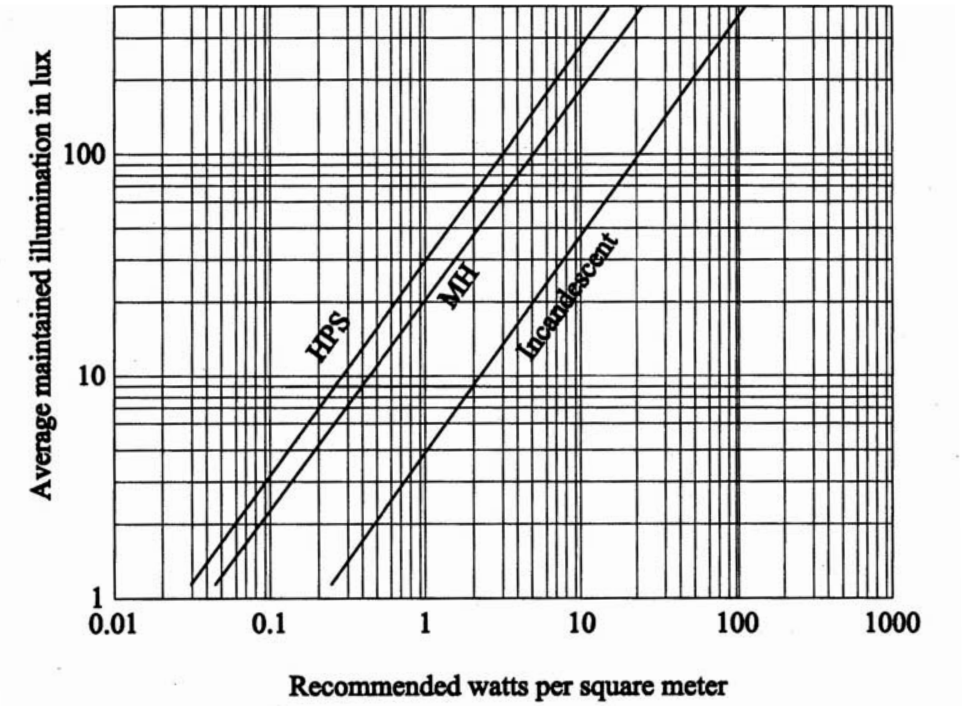


Figure A-1. Recommended watts/m^2 for different illumination levels.

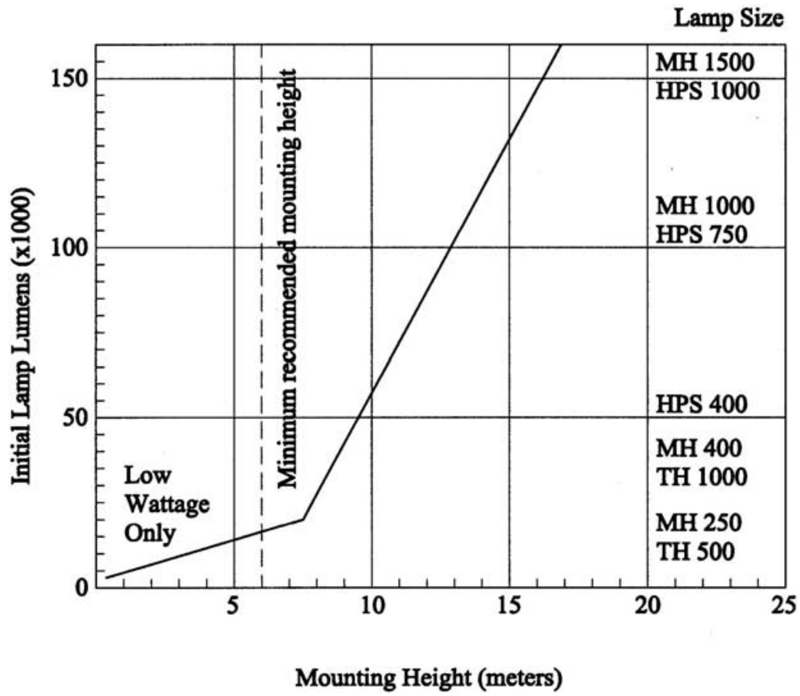


Figure A-2. Recommended relationship between mounting height and source lumens.

Assuming the work zone to be illuminated has an area of 56 m^2 (600 sf) and a required illumination level of 108 lx (10 fc) the necessary wattage can be found as follows:

Recommended watts/m^2: 4 (Figure A-1)

Total wattage: $\frac{4w}{m^2} \times 56m^2 = 238$ watts

Although only 224 W are necessary, the equipment in common use operates at 4,000 W. For the demonstration, a mounting height of 3.7 m (12′) was selected due to equipment constraints.

AGI software molding of the illumination levels indicated illumination levels far exceeding required results. Based on a simple visual analysis, the reduction in glare was significant.

SECTION THREE

GUIDELINES FOR WORK ZONE ILLUMINATION DESIGN

CHAPTER 1

INTRODUCTION TO DESIGN GUIDELINES

PURPOSE OF GUIDELINES

These guidelines have been prepared to assist SHAs and other public agencies' personnel in determining illumination requirements and provisions based on site conditions and in developing their own set of specifications and standards for compliance during nighttime highway related maintenance and construction operations. These guidelines resulted from a study by the University of Florida for TRB (*1*). Recommendations in the guidelines are largely based on the findings of the study.

These guidelines are intended for use as a guide in planning, design, operations and maintenance of work zone lighting systems during nighttime operations. Average maintained illuminance levels are recommended for a variety of nighttime work on highways. The guidelines also assist in selecting the appropriate lighting hardware and equipment, in determining the configuration of the lighting system, and in designing the lighting systems. The guidelines address the issues related to economic considerations and operation and maintenance of lighting systems. Criteria for glare avoidance by the passing motorists were also developed and have been incorporated in the guidelines in the form of specified luminances and their arrangement, sizing the sources of light, and configuring the system. The format of the guidelines is designed to ensure practicality for both the construction and the public agency administrating the construction project. The material in this document is presented in such a way that it may be used by lighting designers, engineers, contractors, and other public officials as a reference document for work zone lighting design. Although this document is intended to provide basic tools to the lighting designer to develop a functional and acceptable lighting system, it does not set any regulatory requirements or national policies. The recommendations are intended to satisfy safety requirements and to be interpreted as an informational guide for efficient visual performance for working crew, equipment operators, and inspectors and for reducing discomfort glare to passing motorists.

NIGHTTIME HIGHWAY CONSTRUCTION

From construction literature and surveys, it is evident that night work is common on many highway projects across the country. According to a study (*1*), out of 52 states surveyed, 28 respondents indicated some nighttime construction and maintenance work in their states. It was also indicated that night work is increasing and is being performed on more and more construction and maintenance projects. Table 1 shows the 10 most commonly performed nighttime construction and maintenance tasks as obtained from the survey. Survey results also showed that most of the highway agencies, with a few exceptions, do not have detailed specifications pertaining specifically to nighttime construction. Only some of the states have certain provisions included in their specifications that address lighting requirements.

To investigate the current nighttime highway construction and maintenance practices, a review of representative types of typical highway projects was also done in the study (*1*).

This review included projects in rural, urban, and semiurban environments on limited access, primary, and other types of roadways. It was found that equipment-mounted custom-made lights and portable light plants were most commonly used for construction lighting. Lighting design and provision were essentially based on the contractor's discretion; in some cases, little or no thought was given to location, positioning, and orientation of the light plants.

ORGANIZATION OF THE GUIDELINES

These guidelines are designed to assist in planning, designing, and operating nighttime highway work zone lighting systems. The overall process of designing and operating a work zone lighting system consists of the following six steps:

1. Understanding visibility requirements and determining average illuminance levels for various tasks that optimize safety of passing motorists and visual performance of workers.
2. Selecting appropriate lighting equipment including light sources, luminaires, and mounting arrangements.
3. Determining the lighting configuration and arrangement for portable, equipment retrofit, and fixed light plants.
4. Designing the lighting system, including controlling glare.
5. Operating and maintaining the lighting system.
6. Analyzing the economics and costs of the lighting system.

All these steps are discussed in the following chapters, beginning with Chapter 2.

TABLE 1 Ten most common work tasks performed at night

Construction Tasks	Maintenance Tasks
Resurfacing	Sweeping and cleanup
Barrier walls, traffic separators	Repair of concrete pavement
Milling and removal	Bridge deck rehab. and maint.
Painting stripes and markers	Resurfacing
Bridge deck construction	Milling and removal
Concrete pavement construction	Highway lighting system repair
Base courses—day, cement, asphalt	Traffic signal maintenance
Excavation—regular, ditch, channel	Painting stripes and markers
Embankment, filling, and compaction	Surface treatment
Highway signing	Barrier walls

CHAPTER 2

VISIBILITY REQUIREMENTS

INTRODUCTION

Because vision depends on light, the primary goal of any lighting design is to provide an environment in which people, through their sense of vision, can function effectively, efficiently, and comfortably. In the case of the highway construction work zone, visual performance considerations should not only be limited to the construction workers but also include quality assurance personnel and passing motorists. Unless adequate care is taken, a suitable lighting situation might exist for one group yet pose serious hazards for another. Ideal lighting systems strike a balance between all groups involved in or affected by the construction process.

With respect to visual performance, three basic areas are discussed in this chapter: visual task, lighting conditions, and human factors. These areas are traditionally considered as primary factors in visual acuity. Table 2 summarizes variables affecting each of these components. Although these variables are very often discussed individually, many interrelationships exist among them.

Visual Task

In analyzing the visual task, the most important influencing variables are luminance of the object, luminance of the background, contrast, size, and duration. These variables are all quantifiable and have found application in analytic models.

Luminance is often referred to as photometric brightness and is by definition the luminous flux (light) being emitted, transmitted, or reflected from a surface. It depends both on the intensity of the light striking an object and the proportion of that light reflected in the direction of the eye.

Visual perception tends to improve with apparent size of the visual task, its contrast to background, and average luminance level of the visual field. In practice, the only factor that can be controlled is luminance.

Studies have shown that as background luminance increased, performance as measured by speed and accuracy increased at a decreasing rate until a point was reached where large changes in the background luminance resulted in only small changes in performance (*2*).

The duration variable is related to the time it takes for the human eye to register a meaningful visual image. Given enough time, fine detail can be distinguished in poor light. The principle of diminishing returns is also evident with this variable.

Tasks showing high contrast between the task target or critical detail and its background results in good visibility with relatively lower illumination levels. The opposite is also true: low contrast results in low visibility and higher levels of required illuminance.

LIGHTING CONDITIONS

Sometimes referred to as quantity and quality of lighting, the influencing variables for lighting conditions are illuminance, veiling luminance (disability glare), discomfort glare, luminance ratios, brightness patterns, and chromaticity.

Quantity of lighting refers to illuminance, the illuminous flux density measured in lumens per square meter (lx) or square foot (foot-candles). Usually illuminance is given in the horizontal plane; however, it can also be measured in the vertical plane.

Quality of lighting relates to the relative ability of available light to provide the contrast differences so that people can make quick, accurate, and comfortable recognition of cues required for the seeing task. Variables most often associated with quality are glare, uniformity, and chromaticity. It should be recognized that, in many instances, changes intended to optimize one variable will adversely affect another, and the resultant total quality of the configuration may be degraded. A good lighting layout is the result of compromise among variables.

By definition glare is the sensation of discomfort and interference with vision produced by visual field luminance sufficiently greater than that to which eyes are adapted. It arises because of an unsuitable luminance distribution or extreme luminance contrasts in space or time. Two types of glare are discussed in the literature, disability glare and discomfort glare.

Uniformity is a measure of relationships of illuminance over an area, such as brightness ratios and patterns of luminance. Poor uniformity may distort visual perception of the work zone. For industrial lighting, it is typically expressed as the ratio of the average illuminance to the minimum illuminance over the relevant area. Acceptable values range from

TABLE 2 Primary factors in visual acuity

Visual Task	Lighting Conditions	Human Factors
Size Luminance Contrast Exposure time Type of object Degree of accuracy required Task motion Peripheral patterns	Illumination Glare Uniformity	Condition of the eyes Adaptation level Fatigue level Subjective impressions

10 : 1 to 2 : 1, with 5 : 1 generally considered suitable for construction activities. Uniformity depends on luminous intensity distribution, spacing/mounting height ratio, and direction of the luminaire beams.

Since brightness attracts the eye's attention, all individual sources in the field of view produce an overall impression. If there is a lack of harmony or order among sources, the overall impression can be annoying to observers. Visual clutter, which is referred to as "noise," results in losses in productivity due to fatigue. Positioning of light sources is therefore very important.

HUMAN FACTORS

Issues of illumination problems introduced by human factors, both physical and psychological, are most complex. On the physical side, primary variables are condition of eyes, adaptation level, and fatigue level, all of which are extremely difficult to quantify.

Adaptation refers to the ability of the visual system to change its sensitivity to light. Transient adaptation is the phenomenon of reduced visibility after viewing a higher or lower luminance than that of the task. In a construction work zone, this could be related to an equipment operator whose scan might move from well-illuminated nearby tasks to more distant tasks that have little or no lighting. For this reason, existing illumination in areas adjacent to the work zone need to be considered when optimizing the lighting environment. A recent study concluded that as motorists passed from dark areas to an illuminated area, their visual performance can be measurably impaired by work zone lights (*3*).

There is growing evidence that perceived quality of lighting systems relates to more than task visibility. Subjective impressions or psychological reactions have been evaluated with respect to illuminance, spatial distribution, and color.

A general trend replicated in numerous studies is for increased satisfaction with higher illuminance, followed by a decrease in satisfaction at the highest illuminance.

RECOMMENDED ILLUMINATION LEVEL CATEGORIES

To facilitate highway construction lighting design, three illuminance categories are recommended for various tasks covering the majority of the highway- and bridge-related maintenance and construction operations. The three categories require average maintained illuminance levels of 54 lx (5 fc), 108 lx (10 fc), and 216 lx (20 fc), respectively. Although the recommended levels satisfy safety requirements, they are also intended to provide a guide for efficient visual performance. For this reason, they may not be interpreted as recommended requirements for regulatory minimum illuminance. Determination of the three categories and their illuminance values is based on several factors, including IES recommendations, OSHA requirements, provisions in state specifications, and opinions and views of various experts. The three recommended categories are found to be adequate to account for differences in visual display and variations in speed and accuracy for the majority of the highway construction tasks.

Category I is recommended for the general illumination in the work zone, primarily from the safety point of view, in the area where crew movement is expected or taking place. This category is also recommended for tasks requiring low accuracy, involving slow-moving equipment, and having large-sized objects to be seen.

Category II is recommended for illumination on and around construction equipment and the visual tasks associated with the equipment. The primary concern in suggesting the minimum illuminance value for this category is equipment safety and medium accuracy desired for the task. For certain tasks, such as resurfacing, not only is the safety around the paver and roller crucial but quality of the finished surface is also important.

Category III is suggested mainly because of the efficient visual performance required for certain tasks. Highway tasks which present higher visual difficulty and require increased attention from the observer include crack and pothole filling, joint sealing, critical connections, and tasks involving maintenance of electrical connections and moving mechanical parts.

RECOMMENDED ILLUMINATION LEVELS

Table 3 provides the recommended illuminance levels and categories for some of the most commonly performed nighttime construction and maintenance operations. The work activities are identified as a result of survey of SHAs (*4*). These activities are compared with visually similar nonhighway activities and the recommended illuminance levels are

TABLE 3 Recommended minimum illuminance levels and categories for nighttime highway construction and maintenance tasks

Description of Construction and Maintenance Task	Average Maintained Illumination	
	Category	Target Level lux (fc)
Excavation – Regular, Lateral Ditch, Channel	I	54 (5)
Embankment, Fill and Compaction	I	54 (5)
Barrier wall, Traffic Separators	II	108 (10)
Milling, Removal of Pavement	II	108 (10)
Asphalt Paving and Resurfacing	II	108 (10)
Concrete Pavement	II	108 (10)
Asphalt Pavement Rolling	I	54 (5)
Subgrade, Stabilization, and Construction	I	54 (5)
Base Course Grading and Shaping	II	108 (10)
Surface Treatment	II	108 (10)
Base Course Rolling	I	54 (5)
Waterproofing and Sealing	II	108 (10)
Sidewalk Construction	II	108 (10)
Sweeping and Cleaning	I	54 (5)
Guard Rails and Fencing	II	108 (10)
Striping and Pavement Marking	II	108 (10)
Landscaping, Sod and Seeding	I	54 (5)
Highway Signs	II	108 (10)
Traffic Signals	III	216 (20)
Highway Lighting Systems	III	216 (20)
Bridge Decks	II	108 (10)
Drainage Structures and Drainage Piping	II	108 (10)
Other Concrete Structures	II	108 (10)
Maintenance of Embankments	I	54 (5)
Reworking Shoulders	I	54 (5)
Repair of Concrete Pavement	II	108 (10)
Crack Filling	III	216 (210)
Pot Hole Filling	II	108 (10)
Repair of Guardrails and Fencing	II	108 (10)
Implement Glare Control Measures. (See Table 4 for Glare Control Check List.)		

Recommended Illumination Areas for Typical Highway Construction Equipment	
Provide target illumination over task working area. This is the effective working width of the machine by approximately 5 meters.	
Minimum distance from machine to	
Slow Moving Equipment: Paver Milling Machine	5 meters
Fast Moving Equipment: Backhoe Loader Wheel Loader Scraper Roller Motor Grader	20 meters
Other Equipment: Maximum uniformity ratio of 10:1 in the work area. Minimum of average maintained illumination of 54 lx (5 fc) for all work areas.	

TABLE 4 Glare control check list

Beam Spread	Select vertical and horizontal beam spreads to minimize light spillage. Consider using cutoff luminaires.
Mounting Height	Coordinate minimum mounting height with source lumens (see Figure 2).
Location	Luminaire beam axis crosses normal lines of sight between 45° and 90°.
Aiming	Angle between main beam axis and nadir less than 60° (see Figure 5). Intensity at angles greater than 72° from the vertical less than 20,000 candela.
Supplemental Hardware	Visors Louvers Shields Screens Barriers

adopted. The illuminance levels provided in Table 3 are the recommended average levels that should be maintained over the specific visual task for desired visual performance. As a safety requirement, a minimum of 54 lx (5 fc) in the immediate areas of work is recommended. A uniformity ratio of 10 : 1 should be maintained in accordance with the target illuminance levels for specific tasks.

Guidelines for equipment lighting are recommended for a set of construction equipment most commonly used for highway work. Based on the equipment's characteristics and its application and relevant SAE current practices, a minimum area to be illuminated in front and back of the equipment is recommended and provided in Table 3. For simplification, most of the equipment is classified in two broad categories: (1) slow-moving equipment and (2) fast-moving equipment. The illumination level at the maximum range provided in Table 3 should not be less than 10.8 lx (1 fc). However, the illumination levels around the equipment should conform to the illuminance categories and target levels recommended for the specific tasks. Also, the glare control measures suggested in Table 4 should be considered.

Visual Requirements of the Task

Each work activity may have unique task lighting requirements in addition to the requirement for area illumination. Providing good work zone lighting involves an understanding of the work task and identification of any special seeing requirements. The following visual requirements are included here as examples:

Asphalt Paving Operations

- The push bar in the front of the machine and the screed board at the rear of the machine must have task lighting.
- Elevated lighting may produce a glare hazard for the truck drivers who must back up to the front of the paving machine.

Pavement Rollers

- When rolling adjacent to curbs, the operator must be able to see the edge of the front roller.
- When water is used with the roller, lamps must be cleaned often.

SUMMARY

There are many complex and interrelated factors contributing to the lighting environment. However, only a few of them are within the control of the lighting designer. The visual task is fixed by the nature of the construction, and most of the variables relating to human factors are not controllable because of the diversity of the population that will be affected. The primary influence is within the variables of the lighting condition.

CHAPTER 3

SELECTING LIGHTING EQUIPMENT

INTRODUCTION

Proper selection of lighting equipment along with its correct application is essential if a lighting system is to serve its intended purpose efficiently and economically. Knowledge of fundamental characteristics of lighting equipment and familiarity with current hardware and developments within the industry is one of the first steps toward an effective lighting system. Prior to designing a lighting system, current product information should be obtained from lighting equipment manufacturers or their product line representatives.

This chapter describes major components of a lighting system and introduces how system performance is described in photometric test reports. For purposes of clarity, it has been divided into three basic elements:

1. Light sources,
2. Luminaires, and
3. Photometric data.

LIGHT SOURCES

The purpose of this section is to review relevant lamp types and their main characteristics. The most important element of illumination systems is the light source. It is the principal determinant of visual quality, economy, and efficiency.

Two basic types of light sources are commonly used for construction work zone lighting: incandescent and electric discharge. Each light source type has inherent advantages and disadvantages. A summary of important lamp characteristics is provided in Table 5; recommendations for applications are provided in Table 6.

Incandescent Lamps

Incandescent lamps include general service lamps and tungsten halogen lamps. Their chief advantages are low initial cost, good color rendering, and good optical control capabilities. Their instant start ability is also important for construction applications. Their primary disadvantages are the low efficacy and short life of these lamps. However, they are considered quite useful as temporary or portable lighting. A major concern when mounted on construction equipment is their sensitivity to vibration. Incandescent lamps are normally made smaller for vibration service (up to 150 W) and for rough service (up to 500 W).

Discharge Lamps

The electric discharge family of lighting source includes metal halide, mercury, high-pressure sodium, low-pressure sodium, and fluorescent lamps. In general, they all have long lamp life and improved luminous efficiency. There is a time delay and slow buildup of light output when the lamps are first energized or after restart. A properly designed discharge system typically requires fewer luminaires than an incandescent system. However, it does require a current limiting device, called a ballast, that is not necessary with incandescent systems. High-intensity discharge lamps are less fragile than most incandescent lamps and will stand up to more vibration. The lumen output of metal halide lamps is sensitive to the operating position of the lamp. The highest output is obtained with the lamp operating in the vertical position. The lowest output is usually obtained with the lamp tilted 60 to 75 degrees off vertical. Manufacturers' data usually include a de-rating factor for tilted operation.

Luminaires

Photometric characteristics are largely determined by the luminaire. It is composed of one or more lamps together with parts designed to distribute light, to position and protect lamps, and to connect lamps to the power supply. One of the first steps in glare control is in selection of a luminaire with proper distribution characteristics or shielding. Luminaires can also serve as shock absorbers to minimize the effects of vibration.

Flood Lighting

Flood lights are one of the most common luminaires used in construction lighting. Some of the types of floodlights available are as follows:

1. Enclosed rectangular, where the reflector and lamp assembly is enclosed in a weatherproof housing.

TABLE 5 Important lamp characteristics (IES Lighting Handbook, 1993)

Light Source	Lumen Output per Lamp	Efficacy (Lumens per Watt)	Life (hrs)	Color Adaptability	Degree of Light Control	Maintenance of Lumen Output
Incandescent Tungsten Halogen	Fair	Low (24)	Low (2000)	High (Daylight White)	High	Fair
Mercury Vapor	Good	Fair (63)	High (24000)	Fair to Good (Medium White)	Fair	Fair
Metal Halide	High	Good (110)	Good (10000)	Good (Bright White)	Good	Good
High Pressure Sodium	High	High (140)	High (24000)	Fair (Soft Orange)	Good	High
Fluorescent	Low	Fair to Good (85)	Fair (7500)	Fair to High (Daylight White)	Fair	High

2. Enclosed round, where the housing forms a weatherproof reflecting surface.
3. Shielded or cutoff, where the luminaire is designed to shield the light at some angle, usually above 72 degrees from the vertical.
4. Reflectorized, where the reflector is an integral part of the lamp.

Shielded luminaires generate very distinctive light patterns. Their main advantage is in glare control and light control. Knowledge of a particular pattern is useful for preliminary design selections. Detailed design can be accomplished with photometric data provided by the manufacturers of the specific luminaires to be used.

Photometric Data

Photometric data is used to accurately describe performance of luminaires in terms of light distribution. Characteristics such as candlepower distribution, zonal lumens, efficiency, luminance, beam widths, and typing are provided for use in design, specification, and selection of lighting equipment. Data are typically provided in either tabular or graphical formats.

TABLE 6 Lamp applications

Light Source	Recommended Applications
Incandescent Tungsten Halogen	Task-oriented lighting Equipment-mounted lights Small areas Low mounting heights
Mercury Vapor	Not recommended
Metal Halide	Medium-sized areas Good color rendition required Varied mounting heights
High Pressure Sodium	Large areas Color rendition not important Varied mounting heights
Fluorescent	Not recommended

Understanding the presentation of horizontal and vertical angles is required for comprehension of the luminaire light distribution. Horizontal angle ranges describe the level of symmetry that a light distribution possesses, while the range of vertical angles indicates distribution of light in an upward or downward direction.

Horizontal angles are described as if the luminaire is viewed from above and angles are measured in a counterclockwise direction. Within each horizontal plane, there is a series of vertical angles. At each of these vertical positions, light intensity is measured beginning directly below the luminaire at the photometric nadir. Viewing light intensity at each vertical angle within a single horizontal angle results in a curve, which can be represented graphically. Lamp manufactures provide both graphic and tabular photometric information for their products. Candela distributions can also be presented graphically. Isofootcandle charts are useful in determining direct components of illuminance for a particular luminaire.

IES has developed a standard format tabular report that summarizes essential data. Often data are used to represent an entire family of lamps having the same light center. In this case, the report lumen basis is established as 1,000 or some multiple thereof, and tabulated data can be adjusted for specific lamp lumens by multiplying each point by the ratio of actual lamp rated lumens to the report lumen basis.

SUMMARY

Selection of lighting equipment is complicated by the wide variety of sources and luminaires available. There is no one-best solution for a given application. With performance requirements in mind, characteristics of the luminaire should be reviewed and those that are unsuitable should be eliminated. Accurate engineering and design of the overall illumination system is dependent on the availability and use of current photometric data.

CHAPTER **4**

CONFIGURATION OF THE LIGHTING SYSTEM

INTRODUCTION

An important consideration prior to designing the lighting system is the desired system configuration. Factors affecting this decision include work zone size, required mobility, duration of work, required illuminance levels, and cost. There are three basic options for configuring illumination systems: temporary, portable, or equipment mounted. Advantages and disadvantages for each option are discussed in this chapter.

TEMPORARY SYSTEMS

A temporary system is defined as a fixed lighting system intended to illuminate an entire work zone or some large portion thereof using luminaires mounted on either existing poles or poles that have been temporarily placed at the site. Initial costs for this type of system should include purchasing and installing poles, foundations, mounting hardware, luminaires, and wiring. Costs of energy and removal of poles should also be taken into consideration.

Primary advantages of a temporary system are in the high quality of illumination that can be achieved. Luminaires can be spaced uniformly, subject to any work zone physical constraints, and at relatively high mounting heights. This flexibility serves to provide uniform illumination with minimal glare and eliminates unnecessary equipment from within the work zone.

Disadvantages of temporary lighting are in the cost and potential inefficiency due to illuminating areas of minimal or no activity. There may also be some difficulty in providing adequate power.

A variation of this temporary scheme that merits consideration relies on the use of existing street lighting systems. A typical roadway lighting design would provide for 6.5 average maintained lx (0.6 fc). Most roadway lighting is designed for approximately one or two footcandles of illumination. If adequate power is available, it might be possible to retrofit existing luminaires with higher wattage lamps. This technique requires familiarity with existing hardware and power distribution systems and should only be considered after consulting both the equipment manufacturer and the owner of the system.

PORTABLE SYSTEMS

An illumination system designed in such a manner that it can be easily moved from one location to another will be classified as a portable system. Trailer-mounted systems are most often used on job sites. A necessary feature of this type of system is the power supply or generator which eliminates reliance on existing utility service. Commercially available systems have a wide variety of features, such as hydraulic or electric controls, to enhance or simplify their use. Tower heights range from 1.8 m (6 ft) to a full 9.1 m (30 ft) and are usually rotatable 360 degrees for easy floodlight aiming. Figure 1 is a photograph of a portable light tower being used to illuminate a fixed drainage installation activity.

Luminaires generally provided with portable systems are round spun general-purpose floodlights with a 1,000- to 1,500-W metal halide or high-pressure sodium lamp. Smaller systems are equipped with tungsten halogen floodlights rated at 500 to 1,500 W. This type of system is self-contained, easily moved about the jobsite (thus providing flexibility in the illumination design), very reliable, and easy to operate and maintain. However, units available for rental are typically equipped with much more light than would be desired under most circumstances. In addition to being not very cost effective, these units tend to create a tremendous glare hazard on jobsites. Because of the high luminance sources and low mounting heights, extreme care must be taken in the positioning and aiming of these lights.

EQUIPMENT-MOUNTED SYSTEMS

A survey of current practice found a frequent reliance on construction equipment-mounted light systems. This raises a question regarding intent and capability of installed lights. None of the manufacturers indicated that the factory-integrated lights are actually engineered to provide predetermined task-specific lighting levels.

Discussions with engineers pointed out the use of SAE criteria as the basis for lighting systems on most construction equipment. SAE standards have been developed to provide specifications for lighting and marking of industrial wheeled equipment whenever such equipment is

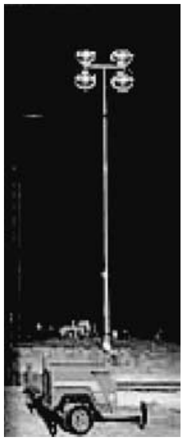


Figure 1. Trailer-mounted portable light plant.

operating on or traveling on a highway (*5*). As such, these standards do not actually pertain to work zone lighting. There are however, SAE-recommended practices suggesting the use of particular floodlamps for the illumination of work areas close to equipment (*5*). These recommendations give no indication of the expected illuminance levels.

A study sponsored by the U.S. Army Corps of Engineers provides a very detailed discussion of night work lighting systems for construction equipment (*6*). Although quite old, recommendations from this study are evident in the positioning of lights on current equipment. It should be noted that as with SAE recommendations, this study is without any substantive information with regard to required or desired illumination levels. It is, however, very thorough and takes into consideration subjective opinions of experienced equipment operators while forming a consensus standard for the mounting of equipment lights. This process is not all that different from the one used in developing the current illuminance recommendations.

Among other constraints when considering equipment-mounted lighting is alternator capacity for the particular piece of equipment. A review of manufacturers' data shows standard equipped alternators ranging from 20 to 75 amps. Assuming that approximately 10 amps are required for battery charging and that there is no other significant electrical load, the available ampacity for task lighting could range from 10 to 65 amps. Using the relationship Watts = Volts $\times$ Amperes, there is a potential to run lights rated from 240 to 1,560 W on a 24-V system or 120 to 780 W on a 12-V system.

Many contractors mount portable generators on the construction equipment to operate 120-V lighting systems. A survey of available generators found a 350-W unit with a footprint of 632 sq cm (98 sq in.) on the low end of the power spectrum and a 2,500-W unit with a footprint of 2,129 sq cm (330 sq in.) on the high end. Portable generators are available up to about 6,500 W; however, they tend to be bulky, for instance 7,884 sq cm (1,222 sq in.), and would not fit on most construction equipment.

One problem reported by Cashell was reduced lamp life when using the 120-V system. This was attributed to vibrations and was such a problem at the time that using AC generators was discarded as an option. This problem, although still present to a limited extent, is not as severe due to advances in lighting equipment technology. There are light manufacturers specializing in lights for what is characterized as rough or vibration service.

The following advantages were found when comparing equipment-mounted lights with area floodlighting:

1. High-intensity illumination on the work plane.
2. Elimination of shadows when lights are positioned between operator and task.
3. Operator's ability to adjust light to high-intensity illumination where needed.
4. Increased nighttime rate of work to a level approaching that of the daytime work.
5. Ability to operate equipment independently of general illumination.
6. Reduced possibility of general shutdown of work due to failure of lighting and power generating equipment.
7. Reduced need for equipment such as floodlight trailers and generators thus eliminating time and labor spent in transporting and erecting such equipment.

In reviewing literature provided by construction equipment manufacturers, there was a very noticeable similarity in the positioning of lights for equipment of the same type made by different manufacturers. These layouts are very similar to those suggested by Cashell and allow the development of equipment-mounted lighting schemes that are rather generalized with respect to equipment type.

Mounting Considerations

Luminaire mounting systems include all of the structural hardware used to hold the luminaire in place. Vertical supports or pole selection will depend on specific configurations and could be either metal or wood. Vertical supports should be capable of supporting the mounted-equipment weight including luminaires, brackets, and any crossarms. At the same time, they should withstand the effects of the maximum velocity winds to which they will be subjected. Using manufacturers' catalogue data, appropriate brackets and poles can be selected based on luminaire weight, effective projected area, desired mounting height, and maximum anticipated wind velocity for the geographic area. Wind velocity can often be found in the manufacturers' data or structural design manuals such as ANSI/ASCE 7-88, *Minimum Design Loads for Buildings and Other Structures*.

GLARE AVOIDANCE

IES/NEMA beam spreads have been established by locating the point away from the beam center where 10% of the maximum candlepower occurs (*7*). Floodlight patterns, which are described with reference to both horizontal and vertical axes, can be categorized as either symmetrical or asymmetrical. Effective projection distances are measured in a straight line from the base of the mounting pole to the area being illuminated. Vertical beam spread is potentially a source of glare, and as narrow a spread as possible should be selected for most highway construction applications.

Determination of proper mounting height is also crucial in controlling glare. Mounting luminaires at lower-than-optimum levels can cause severe problems. In general, mounting height is related to lumen rating of the light source as shown in Figure 2. High luminance sources require increased mounting heights.

Minimum glare-producing mounting height is based on the accepted principle that the angle created by the horizontal working surface and a line drawn through the floodlight and a point one-third the distance across the work zone should not be less than 30 degrees (*8*). By analyzing the geometry, it can be seen that if the light is set back any distance from the work zone, mounting height will increase dramatically. Typically, 6.1 m (20 ft) is accepted as the minimum mounting height for floodlights or area lights. Task-specific lighting is generally of much lower wattage or luminance and can be mounted at heights appropriate to the task.

Luminaire location or positioning in the horizontal plane can also generate disabling glare. Maximum glare occurs when the viewer must face directly into the luminaire. As the luminaire is viewed from angles away from the beam axis, glare appears to decrease. By moving luminaires away from normal lines of sight of motorists and workers, effects of glare can be diminished. Positioning of luminaires out of normal lines of sight or critical viewing angles of motorists and workers can be accomplished through the selection of pole location and the actual luminaire aiming. Three factors affect the angle between normal lines of sight and a particular luminaire: (1) distance between viewer and luminaire, (2) relative height of luminaire, and (3) aiming angle. If any one factor changes, the others will also change. As a rule of thumb, luminaires should be aimed in such a way that a line from the luminaire beam axis should cross normal lines of sight at angles between 45 and 135 degrees in the horizontal; angles less than 45 degrees and greater than 135 degrees should be avoided. While angles between 90 and 135 degrees are acceptable, they need to be evaluated in terms of traffic in the opposite direction.

Proper aiming of floodlights is another factor that should be considered. A general rule for aiming is that angles created by the nadir and the center of the luminaire beam spread should not exceed 60 degrees. Another very important consideration in the control of glare is intensity of light at angles greater than 72 degrees from vertical. An angle of 72 degrees was selected since it is generally recognized in the lighting industry that discomfort glare is minimized when light strikes an observers eye at an angle less than 72 degrees (*8*). If maximum candlepower in the upper beam as shown in Figure 3 can be limited to 20,000 candela, discomfort glare can be effectively controlled. SAE J579 provides standards

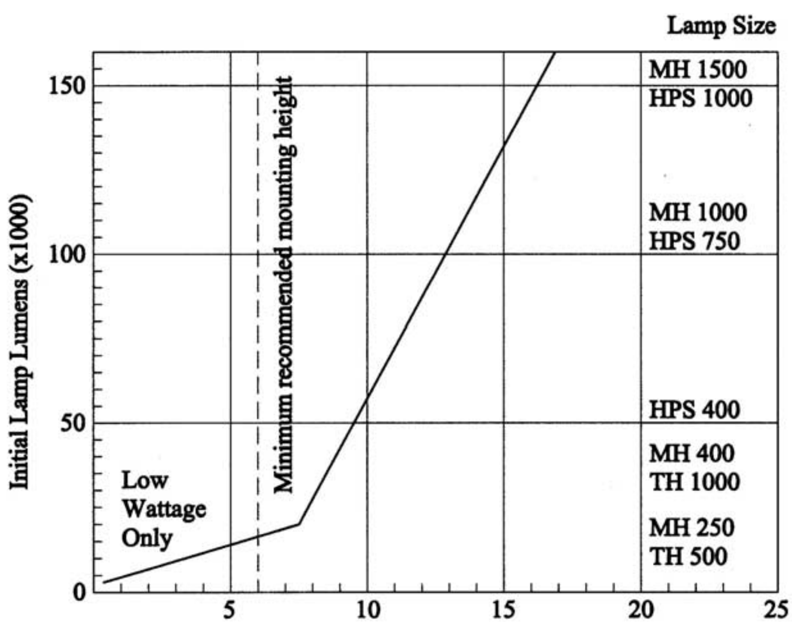


Figure 2. Recommended relationship between mounting height and source lumens.

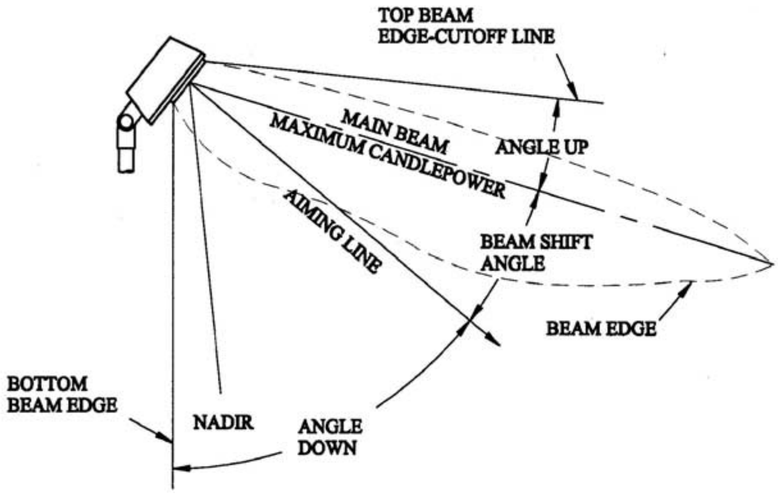


Figure 3. Vertical beam components.

for automotive headlamps. In this case, 20,0000 candela is the maximum permissible in a low-beam unit. As a contrast, maximum allowable for a high-beam unit is 75,000 candela (*5*).

At times, physical constraints of the work zone may limit the location of mounting poles to less than ideal sites. In these situations, positioning must be carefully evaluated in terms of vital lines of sight or critical viewing angles. Use of shields, visors, and louvers can help reduce glare in these circumstances. Disadvantages with this approach are that total projected wind load factor will increase, causing additional mounting concerns, and that useable light emitted from the luminaire is decreased.

Glare avoidance screens or barrier walls are often used as a method to protect workers and motorists. This approach should be considered in any case in which the work zone configuration cannot be arranged to avoid glare. The height of the screen is an important factor. By increasing height, surface area is also increased and the wind loading will need to be addressed if this option is chosen.

SUMMARY

Work zone lighting systems can be configured in different ways to best meet contract requirements. Options include temporary systems, portable systems, and equipment-mounted systems. Temporary systems have the potential for high-quality light; however, it is usually at higher cost. Equipment-mounted systems appear to provide adequate illumination at the lowest cost. An ideal solution might be any one or combination of the three options subject to the particular constraints of a given project. The selected configuration should be viewed from the perspectives of passing motorists as well as on site workers. If a glare hazard to either party is detected, consider use of glare avoidance hardware.

CHAPTER 5

DESIGNING THE LIGHTING SYSTEM

INTRODUCTION

This chapter is an easy-to-use manual of a lighting-system design process based on work zone geometry and light source characteristics. It begins with a discussion of design criteria that are input for the design of a lighting system and continues with an explanation of a simplified sequential design process. Procedures are then given for checking the adequacy of the design. Since computer design applications are becoming readily available, their use will also be addressed followed by a discussion of techniques incorporated into the design process to minimize potential problems due to glare.

DESIGN CRITERIA

Design criteria in all referenced standards have been based on horizontal illuminance. It is a well known and accepted practice that task luminance and glare criteria provide a better correlation with lighting quality. It is also recognized that illuminance criteria do not comprise a direct measure of task visibility. However, if a good design practice is followed, illuminance criteria can be effective. In practice, lighting designs are based on horizontal illuminance. In most cases, use of illuminance rather than luminance is more practical due to visual complexity of scene and simplicity of computational procedures.

Table 3 provides recommended illumination levels for various highway construction tasks. These illumination levels are average maintained lighting levels in the work area. Lighting designs should also address the glare avoidance features given in Table 4. Designers are additionally advised to consult applicable government regulations and construction contract specifications.

The American National Standard is incorporated into law by the CFR. OSHA Safety and Health Standards, 29CFR 1926/1910 (1990), provide minimum illumination intensities for construction areas as shown in Table 7.

Requirements for a contractor to comply with certain standards are most often conveyed through contract documents such as specifications. Another type of standard requiring compliance arises because of local ordinances. Problems of light trespass have been given increasing attention and a number of ordinances are in effect or proposed (*7*). The intent of ordinances is to reduce light spillage, restrict illuminance levels, and reduce glare. These constraints are sometimes in conflict with specifications and need to be considered in the lighting design.

ILLUMINATION DESIGN

In general, calculation of illumination involves two basic laws. The inverse square law states that illumination varies directly with luminous intensity (candlepower) and inversely with distance (D) squared. The cosine law states that illumination varies as the cosine of the angle between the light ray striking the surface and a line perpendicular to that surface (α). When combined, they give illumination at a point in accordance with the following equation:

$$\text{Illuminance} = \frac{\text{candlepower}}{D^2} \times \cos\alpha$$

Geometry of the multisource illumination problem is illustrated in Figure 4. Illumination at any point is the sum of values contributed by each source. Designs based on this point calculation are referred to as point-by-point or, more simply, point designs. Trigonometric and vector expressions for tilt, rotation, and point of aiming for each individual floodlight are essential parameters in the design process. When calculating a large number of points, the value of using a computer is readily evident. Since design by the point method requires extensive calculations, use of a less complicated procedure is proposed.

A modified lumen method that is often used for preliminary evaluation of floodlight luminaires and mounting locations is ideally suited for this application. The formula for calculating the average horizontal illumination on the work zone is as follows:

$$E = \frac{N \times \phi \times PCU \times MF}{A}$$

where

E = illuminance in lx or fc
N = number of luminaires
Φ = lamp lumens per luminaire
PCU = preliminary coefficient of utilization

TABLE 7 OSHA-required values (CFR 1926/1910, 1990)

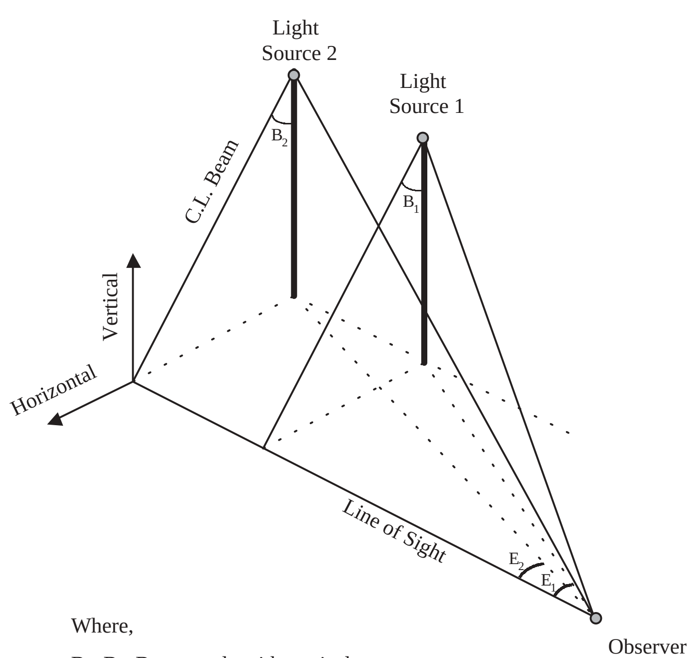
lx (fc)	Area of Operation
50 (5)	General construction area lighting.
30 (3)	General construction areas, concrete placement, excavation and waste areas, accessways, active storage areas, loading platforms, refueling, and field maintenance areas.
50 (5)	Indoors: warehouses, corridors, hallways, and exitways.
50 (5)	Tunnels, shafts, and general underground work areas: (Exception: minimum of 10 footcandles is required at tunnel and shaft heading during drilling, mucking, and scaling. Bureau of Mines approved cap lights shall be acceptable for use in the tunnel heading.)
100 (10)	General construction plant and shops (e.g., batch plants, screening plants, mechanical and electrical equipment rooms, carpenter shops, rigging lofts and active storerooms, barracks or living quarters, locker or dressing rooms, mess halls, and indoor toilets and workrooms).
300 (30)	First aid stations, infirmaries, and offices.

MF = maintenance factor
A = area in m^2 or ft^2

Figure 5 presents the data obtained from the modified lumen equation for three principal lamp types. The preliminary coefficient of utilization is the ratio of beam lumens falling within the area to be illuminated and is assumed to be 0.5 for a conservative design. The maintenance factor accounts for lamp depreciation and dirt on reflecting and transmitting surfaces of the equipment. Values of 0.65 to 0.85 were used to derive the lines in the figure. Using this figure, recommended watts/square meter (watts/m^2) can be estimated for a given level of illuminance and lamp type.

Overview of Design Procedure

Illumination based designs rely on the amount of light flux reaching working surfaces and light uniformity on that surface. The steps in the design process are as follows:



Where,

B_1, B_2: Beam angle with vertical

E_1, E_2 : Eccentricity of observer's position

Figure 4. Geometry of the multisource illumination problem.

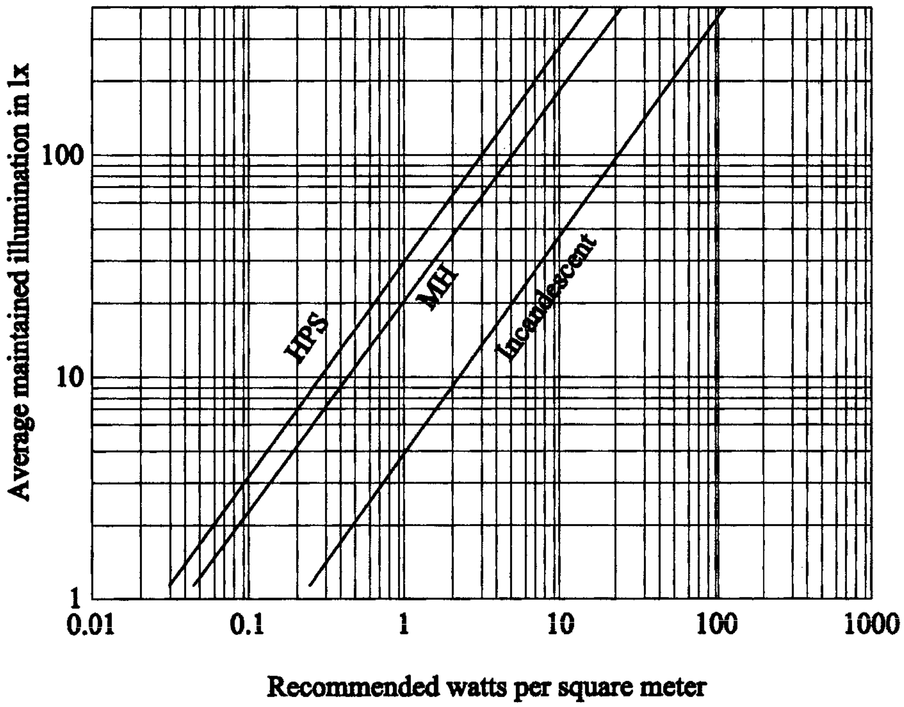


Figure 5. Recommended watts per square meter for different illumination levels and lamp types.

1. Determine the area to be illuminated.
2. Determine the work activities to be performed.
3. Select the type of light source.
4. Determine required lighting level and watts/m^2.
5. Select fixture locations.
6. Determine luminaire wattage.
7. Select luminaires and aiming points.
8. Check design for adequacy.

These steps are arranged in the order in which they normally occur in the design process and can be applied to a completely new design or a design based on specific equipment. The process is iterative and should be repeated until the required criteria are met. It is assumed the design will be accomplished by an individual with some engineering background, but with limited lighting experience.

Design Steps

Step 1. Determine the Area to Be Illuminated

Important considerations here are physical dimensions and work zone layout. By keeping the work zone rectangular in shape, total area can be computed easily. It may be necessary to define multiple work zones rather than one large area, for example, opposite ends of a paving machine. This step also provides initial opportunity to minimize glare. Normal lines of sight for motorists and workers should be defined and monitored throughout the process.

Step 2. Determine the Work Activities to Be Performed

The different types of activities that are to be performed in the work area should be inventoried. This step requires a good understanding and knowledge of the planned work process, whether it is construction or maintenance. Designers should verify planned work activity by checking with field supervisors.

Step 3. Select the Type of Light Source

The type of light source selected determines important factors such as lumen output; energy requirements; and lamp life, color, and optical controllability. The type of source selected in this step will affect the rest of the design process. Refer to Table 6 for recommended applications.

Step 4. Determine Required Lighting Level and Watts/m^2

Recommended lighting levels will normally be specified in terms of average maintained illumination and can be found in the project specifications or recommended practices discussed previously. Table 3 provides recommended minimum illuminance levels for nighttime highway construction and maintenance tasks. To determine watts/m^2, enter Figure 5 at the recommended illumination level on the left axis and project horizontally to the appropriate lamp line and then drop down to recommended watts/m^2 on the horizontal axis.

Step 5. Select Fixture Locations

Fixture locations in both vertical and horizontal planes can be selected based on knowledge of site-imposed constraints. This would include considerations such as equipment dimensions, nearby lighting, motorist and worker lines of sight, nearby buildings, and local restrictions. In order to maintain adequate uniformity, an accepted rule of thumb is that separation between luminaires should not exceed two to four times the mounting height. A more conservative approach is to limit spacing on unidirectional nominally interlaced systems to twice the mounting height. For multidirectional well interlaced systems, spacing should not exceed three mounting heights. As pole spacing increases, so does uniformity ratio. This step provides the number of poles or locations to be used in later calculations.

Step 6. Determine Luminaire Wattage

Total lamp watts needed for an area can be calculated from the formula

$$\text{Total Watts} = \text{Area} \times \text{Watts/m}^2$$

Luminaire wattage at each mounting location can then be calculated from the formula

$$\text{Luminaire Wattage} = \frac{\text{Total Watts}}{\text{Number of Luminaires}}$$

Step 7. Select Luminaires and Aiming Points

Knowing required wattage and beam spread, a specific luminaire can then be selected using manufacturers' data and beam spread information. Luminaires should be selected based on desired light distribution characteristics such as beam shape and cutoff. It may be necessary or helpful to use more than one luminaire at each location, particularly when low mounting heights restrict source lumens as shown in Figure 2.

Table 8 can be used to determine maximum aiming line separation when luminaires are mounted adjacent to each other. Care should be taken to aim lights away from any oncoming traffic to reduce glare problems. For normal area lighting, aiming points should be ¾ the distance across the area or twice the mounting height, whichever is lowest. Use of higher aiming angles will not improve utilization or uniformity. As a rule of thumb, highest horizontal illumination from a floodlight occurs when it is aimed at an angle of 53 degrees. This is the angle formed by a 3, 4, 5 triangle as shown in Figure 4. This relationship can also be used to determine mounting height as a function of preferred aiming point.

Step 8. Check Design for Adequacy

As a final step in the design process, check for adequacy should be made using the five-point method or computer analysis. The importance of this step cannot be overemphasized. Use of the design process does not guarantee satisfactory results in all cases. Certain combinations of beam shape, mounting height, tilt and lamp rating provide unpredictable responses. The contribution from every luminaire within eight mounting heights needs to be calculated for the points of interest. This will serve to verify the quantity of illumination in critical areas; if a representative cross section of the work zone is selected, average illumination and uniformity can also be evaluated. If either criteria is not satisfied, repeat the design process with the appropriate modification to location, spacing, luminaire, aiming point, or mounting height.

Design Precision

Accuracy of an illumination design is a function of the detail used in the design process. Average illuminance designs based on wattage and luminaire type are considered accurate to within ±25%. Further accuracy up to ±5% can be gained

TABLE 8 Relationship between beam spread and aiming line (*9*)

NEMA Type	Horizontal Beam Spread	Suggested Maximum Aiming Line Separation
2	18°–29°	12°
3	29°–46°	24°
4	46°–70°	40°
5	70°–100°	60°
6	100°–130°	90°
7	130° +	120°

by using more complex and expensive procedures. The upper limit is established by uncertainty in measurement. For purposes of assessing illuminance as it relates to vision and visibility-related lighting systems, the ±25% accuracy is considered sufficient by the IES (*10*). Recognizing that an illumination level that is 25% lower than specified levels might not be acceptable, the data of Figure 5 have been adjusted to provide a more conservative design by inducing error on the high side. It should also be noted that this design procedure is a very rough approximation and if all of the design parameters are optimized, there will be a tendency for the overall design to be sub-optimal. For this reason, it is also recommended that all calculated luminaire wattage be rounded up to the next available standard lamp rating.

Analysis of the adequacy check using the five-point method has shown it to be a reliable and fairly precise indicator of the desired system performance. Experiments were conducted using three different beam spreads and a 100-W metal halide luminaire. Tilt angle was rotated from 0 to 60 degrees with a fixed mounting height. At 10 degree increments, average illuminance was calculated using the five-point method and compared with statistical reports generated by AGI software. The average error computed over 21 samples was –8.2%. For tilt angles between 40 and 60 degrees, the error improved to –6%. By consistently erring on the low side, the technique serves its intended purpose as a conservative indicator.

COMPUTER DESIGN APPLICATIONS

As lighting design software becomes more affordable and available, it will become a most useful tool in the design of illumination for construction work zones. In theory, the design process will follow that described previously through Step 5. The major benefit of computers will be in Step 6, checking design adequacy. Here, designers can actually model work zones including obstructions, define boundaries, and accurately evaluate illumination for any point or area. Computer software also provides computations of average illumination and uniformity for specified areas. If the designer is not satisfied with results, it is a simple matter to modify quantity, location, type, and aiming point for any number of luminaires.

Glare Evaluation

The greatest challenge facing lighting designers is that associated with glare. Evaluation of glare has traditionally been very subjective, using scales such as borderline BCD. Various computational procedures have been proposed. In general, they closely parallel the point methods of calculating illuminance. In effect, they are calculating the vertical illuminance at a point as opposed to horizontal. Viewers' exposure to particularly high values of source luminance is the primary concern.

Rather than associate empirical value with different levels of glare, the goal of glare evaluation is to recognize causes of glare and treat them in the design process to the maximum extent possible. There are several basic techniques that have been incorporated within the design process that will help reduce glare. These techniques are presented in the glare avoidance checklist in Table 4 and include selecting aiming points away from common lines of sight, coordinating luminaire wattage with mounting heights, and minimizing the vertical angle of incidence with respect to nadir.

At the conclusion of the design process, the illumination system should be viewed in its entirety. If recommended procedures have been followed and there still appear to be potential problems with glare, use of glare avoidance devices such as lamp inserts, hoods, and barriers is recommended.

Field Input into the Design

Designers are encouraged to review work zone lighting design details with experienced field personnel including equipment operators. These field personnel may not be knowledgeable about lighting design; however, they do know their work tasks, and they generally can tell you where they "need to see."

PRACTICAL LIGHTING CONFIGURATION GUIDELINES

Discussions with contractor personnel and with SHA field personnel indicated the need for a more simplified approach to configuring basic work zone lighting. Figures 6 through 9 are intended to provide guidance for field personnel in configuring standard work zone lighting situations. However, in all cases, lighting configurations should be tested for compliance with illumination requirements and glare avoidance prior to commencing the work activity.

SUMMARY

The basic design procedure outlined in this chapter is simple enough to be accomplished by an individual with some engineering background, but with limited lighting experience. The procedure can be used with or without computers. It requires a basic knowledge of lamp characteristics and access to manufacturers' photometric data. Although a completely new design is assumed, it can also be used as a very quick method to evaluate existing systems. Checking the adequacy of the design is a necessary step and will ensure positive results. Should a higher degree of precision be required in the design process, the use of computer design software would be recommended. An example design is included as Appendix for Section Three: Lighting Design Example.

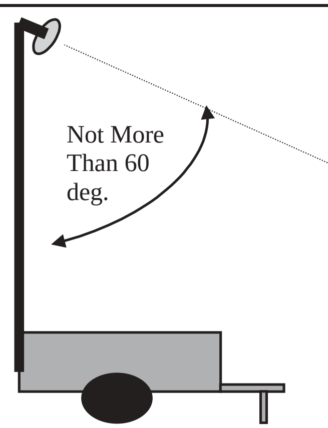
Fixed Work Areas	
Drainage Excavation, Pipe Installation, Structures, Signalization, Maintenance Activities, Staging and Startup of Paving Operations	
Illumination Requirements	Minimum Area Illumination Level = 54 lx Category II Work – Minimum Illumination Level = 108 lx Category III Work - Minimum Illumination Level = 216 lx
Recommended Lighting Equipment	Portable Light Plants with extending towers, four luminaires (typically 1000w metal halide)
Configuration Guidelines	1) Extend Tower to Maximum Practical Height 2) Use Glare Control Shades on the Luminaires 3) Maintain Glare Control Aiming When possible aim lights away from oncoming traffic Angle between the vertical and the aiming direction of the lamps should not exceed 60 degrees 4) Space Light Plants to Provide Required Illumination Levels
Typical Configuration Sketch	

Figure 6. Field guidelines for fixed area lighting.

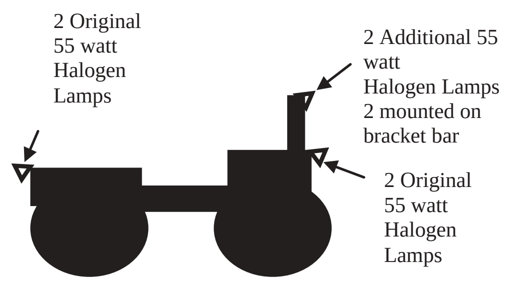
Pavement and Soil Rollers	
Asphalt pavement compaction, Base and Subgrade compaction	
Illumination Requirements	Category I Work – Minimum Illumination Level = 54 lx Illuminate 5 meters in direction of travel by width of the machine to 54 lx Minimum distance to 54 lx in direction of travel = 20 meters
Recommended Lighting Equipment	Four 55w halogen lamps mounted on front of machine Two 55w halogen lamps mounted on back of machine
Configuration Guidelines	Mount lamps as high as practical without effecting operator vision For work adjacent to curbs, roller drum must be seen by operator
Typical Configuration Sketch	

Figure 7. Field guidelines for roller compactor lighting configuration.

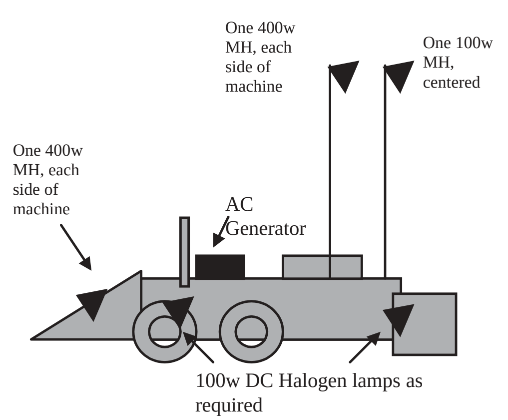
Asphalt Paving Machines	
Asphalt pavement placing	
Illumination Requirements	Category II Work – Minimum Illumination Level = 108 lx Illuminate 5 meters behind machine by width of the machine to 108 lx Minimum distance to 10.8 lx in direction of travel = 5 meters
Recommended Lighting Equipment	Four 55w halogen lamps mounted on front of machine Two 55w halogen lamps mounted on back of machine
Configuration Guidelines	Mount tower lamps as high as practical. Side mounted lamps should be positioned so that workers can see the necessary machine components. Select AC generator with good sound control features. Avoid aiming lights to front of machine to avoid causing glare hazard for backing trucks.
Typical Configuration Sketch	

Figure 8. Field guidelines for asphalt paver lighting.

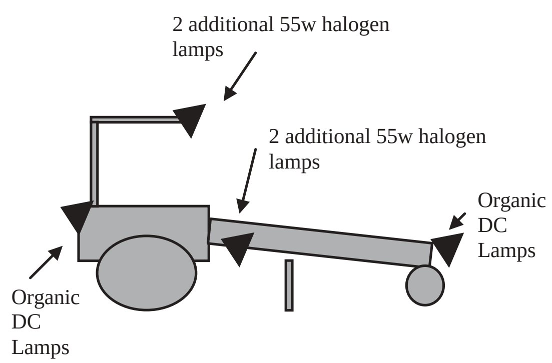
Motor Grader	
Grading and shaping base and subgrades	
Illumination Requirements	Category II Work – Minimum Illumination Level = 108 lx Illuminate 5 meters in direction of travel by width of the machine to 108 lx Minimum distance to 10.8 lx in direction of travel = 20 meters
Recommended Lighting Equipment	Organic DC lamps and four additional 55w Halogen lamps.
Configuration Guidelines	Position 2 additional 55w halogen lamps high on machine ROPS aimed to illuminate area to front of machine. Position 2 additional 55w lamps to illuminate the area adjacent to the mortar board.
Typical Configuration Sketch	

Figure 9. Field guidelines for motor grader lighting.

CHAPTER **6**

SYSTEM OPERATION AND MAINTENANCE

INTRODUCTION

Lighting system effectiveness clearly depends on the initial design development. An equally important and often overlooked aspect of continued effectiveness is proper operation and maintenance of the lighting system. To ensure intended lighting quantity and quality, whether for task performance or safety reasons, lighting systems must be properly operated and maintained. Another important consideration is expected system reliability. Project delays due to malfunctioning illumination systems could be very costly, especially when materials with specified placement times, such as concrete and asphalt, are involved. Important concerns of power source maintenance, hardware maintenance, and provision of backups are discussed in this chapter.

POWER SOURCE MAINTENANCE

Operation of any lighting system is dependent on the provision of power. In a construction work zone, power is available from three different sources: line, portable generators, and alternators installed on the construction equipment. Periodic monitoring of the power supply will ensure proper lighting system operation.

Power systems are typically characterized by voltage and could range from a low of 12 V to as high as 480 V or more. As a general rule, lamps should be operated at rated voltage. Over-voltage operation results in a drastically reduced lamp life; however, wattage, efficacy, and light output are improved. Operating under-voltage will increase lamp life with corresponding reductions in wattage, efficacy, and light output. Characteristic curves for an incandescent lamp indicate a voltage as little as 5% below normal results in a loss of light amounting to more than 16%. Similar relationships hold for other types of lamps. Maintenance of proper voltage is therefore an important factor in obtaining good lighting system performance.

When dealing with electricity, it is very important to be aware of the provisions of the National Electric Code (NEC). Article 305 pertains to temporary electrical power and lighting wiring methods that may be of a class less than would be required for a permanent installation, such as the construction work zone. Important provisions of this article include requirements for temporary wiring to be located where it will not be subject to physical damage and for all general illumination lamps to be protected from accidental contact or breakage by a suitable fixture or lampholder with a guard. There is also a provision requiring separate ungrounded conductors for lighting and receptacle loads so that the activation of a fuse or circuit breaker or a ground fault circuit interrupter due to a fault or overload of equipment will not de-energize the lighting circuit (*11*).

Grounding of temporary lighting systems is governed by Article 250 of the NEC, which also includes provisions for the grounding of portable and vehicle-mounted generators. Portable generator frames are not required to be grounded and can serve as the grounding electrode for a system supplied by the generator if certain conditions are met. First, the generator may only supply equipment mounted on the generator and/or cord and plug connected equipment mounted through receptacles mounted on the generator. Non-current-carrying metal parts of equipment and the equipment grounding conductor terminals are to be bonded to the generator frame. The frame of a vehicle is permitted to serve as the grounding electrode for a system supplied by a generator mounted on the vehicle if (1) the frame of the generator is bonded to the vehicle frame and the generator supplies only equipment located on the vehicle and/or cord and plug connected equipment through receptacles mounted on the vehicle or on the generator and (2) the non-current-carrying metal parts of the equipment and the equipment grounding conductor terminals of the receptacles are bonded to the generator frame (*11*).

LIGHTING HARDWARE MAINTENANCE

Lighting hardware maintenance is necessary to recover light losses due to the effects of time and usage such as lamp lumen depreciation, dirt accumulation on lamps and luminaires, lamp burnouts, and misdirected lights. Combined effects of equipment age and dirt depreciation can reduce illuminance by as much as 50%. Much of this potential light loss is taken into account in system design through inclusion of maintenance factors. This provides a higher luminance at the onset than that actually recommended in the design criteria.

Planned lighting maintenance has been shown to be the most effective method of consistently maintaining illuminance and lighting quantity at the lowest operating and maintenance cost. It entails group relamping, cleaning of lamps and luminaires, and replacement of broken or otherwise defective components on a scheduled basis. The system should also be monitored between scheduled maintenance activities to ensure proper and safe operation.

Group relamping has been shown to reduce the cost of operating a lighting system and also improve performance. It entails replacing all or some portion of the lamps in a system together at a fixed interval, which is usually determined to be between 70 and 80% of rated life. This method is directed at systems with large numbers of lamps, and savings result from a reduction of labor and delay costs associated with a lamp outage. It typically costs less per lamp to replace a large number at once than to replace one at a time as they fail. Lighting quality is maintained, and a better means for other maintenance and cleaning is provided.

A construction environment poses higher than normal exposure to the effects of dirt accumulation and its resulting decrease in light output. Periodically cleaning lamps and luminaires will maintain light output and distribution at intended values. Because of high concentrations of dust or dirt in the air, cleaning should be accomplished at more frequent intervals than group relamping.

Planned maintenance of lighting systems is more than changing lamps and cleaning. It also affords the opportunity to efficiently locate and repair defective or broken components that might cause system problems. Demand or emergency maintenance is directed at known problems. This could include situations such as lamp flickering, short lamp life, no or slow starting, low output, unusual color, and blown fuses. These problems warrant immediate attention. In many cases, the manufacturers' troubleshooting guide for a particular system will provide a simple solution. More complicated problems should be addressed by a qualified electrician.

Throughout the design process, significant attention was given to the importance of luminaire angles, both vertical (tilt) and horizontal (orientation). This importance carries on into the operational phase. In order to maximize system effectiveness, luminaire positions should be monitored and maintained as specified. From a practical viewpoint, aiming luminaires precisely is not a very realistic expectation. An understanding of system sensitivities to variations in parameters is necessary.

Three different 100-W luminaires were tested to determine the effects of height, tilt, and orientation on uniformity and average illuminance: wide 7 in. × 7 in., common 6 in. × 6 in. and narrow 3 in. × 4 in. luminaires were tested. A 1-m (3.3-ft) increase in height resulted in approximately 30% reduction in average illuminance for all luminaires. For wide beams, the average illumination remained constant throughout approximately 20 degrees of shift.

The third parameter that might vary is the luminaire tilt; narrow beams are more responsive to variation. Comparing uniformity and illuminance, an optimal range for wide beams could be described as 10 to 40 degrees of tilt. For narrow beams, optimum average illuminance does not coincide with optimum uniformity. Since the average is being distorted by high values, uniformity should prevail and an operating area of from 45 to 55 degrees should be selected. This is consistent with the previous discussion regarding maximum illuminance at about 53 degrees of tilt.

Backup Systems

Lighting system failure could be catastrophic and costly. From the viewpoint of safety, risk of accidents increases. From that of productivity, workers are idle and materials that need to be placed within a fixed period, for example, concrete and asphalt, are wasted. Many contract specifications currently have provisions requiring standby equipment. If not, the prudent contractor should assess potential risk and costs of a blackout, then provide backup equipment accordingly. For the purpose of discussion, backup equipment will be considered as distinct from spare maintenance parts, such as lamps and fuses, that should always be available.

There are many causes of system or component failure that relate to maintenance and operation. If scheduled maintenance is performed as described earlier, many potential problems can be resolved before they impact work. A common source of problems is in system operation. Users of portable electric equipment find lighting system generators a very convenient source of power. The danger here is in overloading the circuit. If the breaker trips and discharge lighting is being used, there is a potential blackout of up to 10 minutes for the re-ignition of the lamps. The solution is to have dedicated circuits for power tools and to not allow the lighting circuit to serve as a backup source, as prescribed by the NEC. The inclusion of incandescent lamps in the lighting system would also help to accommodate the long re-ignition times of HID sources.

The amount of backup equipment provided will depend on the specific job and the equipment employed. For example, a work zone powered from a single generator is much more susceptible than one that uses multiple generators. Another case would be the retrofitting of a paving machine with auxiliary lights and a portable generator. If this generator were to fail, operations would come to a standstill while another generator was mounted. It would certainly be worthwhile to have a second generator mounted on the platform and readily available.

SUMMARY

Proper operation and maintenance of lighting systems is as important as design. Installation should be in accordance with the appropriate NEC provisions. Performance of routine maintenance such as relamping, cleaning, necessary repairs, and monitoring of luminaire positioning will ensure that the system operates as intended. Although this type of program will minimize breakdowns in the field, it will not totally eliminate them; it is highly recommended that backup equipment be provided for critical functions.

CHAPTER 7

ECONOMIC CONSIDERATIONS

INTRODUCTION

When designing lighting systems, a primary concern should be the provision of sufficient amounts of quality light at a reasonable cost. Economic impacts of lighting requirements could very well be significant and certainly warrant consideration during bid preparation. Through application of accurate cost analysis, it is possible to evaluate alternative approaches, determine the impact of the lighting system on construction schedules, manage budget and cash flow, quantify benefits of various systems, and simplify the complexities of lighting systems into cost, a basic language that is easily understood.

Many techniques are available for analyzing the economics of a lighting system. A useful approach to analysis of somewhat dissimilar lighting systems is to evaluate quantity and quality factors in terms of dollars and cents. It is then possible to compare the cost or benefit of specific installations on the basis of equal levels of illumination of the same quality. This chapter highlights important factors and provides a general framework from which any economic analysis can proceed.

COST ELEMENTS

Total cost of light can be computed by assembling all elements of both fixed and variable charges, which are relevant to a particular configuration. This total can then serve as a comparison of the cost of light with other units of production or as a comparison of various lighting systems.

Fixed costs of any lighting system are most often associated with initial installation. This would include the cost of installation labor and hardware such as lamps, luminaires, ballasts, wiring, and mounting devices (e.g., poles and brackets). If any shielding systems are used, they would also be included as fixed costs. Costs of generators and portable light towers are also considered fixed although they might be incurred over time rather than initially.

Variable costs are those that are related to the operation and maintenance of the system. This normally includes energy costs, replacement lamps, and maintenance labor. These costs will vary with system utilization and longevity for specific lamp types. A summary of cost elements is provided as Table 9.

When determining total cost, care should be taken to include anticipated reuse of materials. For example, if the work zone is 9 km (5.6 mi) long and the design calls for a light source every 30 m (98.4 ft), it might not be necessary to illuminate all 9 km (5.6 mi) simultaneously. If the construction plan calls for work to be done in 1 km (0.62 mi) sections, it would only be necessary to procure 33 light sources—each being reused 9 times. Coordination of the lighting plan with the construction schedule development is a crucial step in the planning process.

Analysis on a total cost basis appears to be the most practical approach to this problem. Since the duration of most projects is less than 1 year, it can be reasonably argued that there is no need to be concerned with the time value of money and the application of discount factors. This lump sum approach provides meaningful information to the contractor for bidding purposes. Awareness of operation and maintenance costs will also be helpful in the management of budget and cash flow throughout the project duration.

For purpose of comparisons, approximate costs have been developed for each configuration described in Chapter 5. It is estimated that temporary system costs could run as much as $67,000 per km to install and operate while portable systems would be approximately $37,000 per km. Cost of equipment-mounted systems does not lend itself to a per mile analysis; for comparison, it has been estimated at less than $2,000 per piece of equipment. A normal suite of equipment for a project could include 15 to 20 pieces, resulting in a total cost of about $40,000. After converting costs of temporary and portable systems to a total cost basis for comparison, use of equipment-mounted systems appears highly desirable assuming illuminance and uniformity criteria are equivalent.

BENEFITS

Benefit-cost ratio analysis is a technique that has found considerable application in government projects. Simply stated, if benefits exceed cost, there is definite value to the alternative under consideration. The difficulty in using this approach is in quantification of benefits. While benefits are widely understood to mean cost savings, in many cases, there is no direct income; other benefits, both tangible and intangible, must be considered very carefully.

From the public viewpoint, benefits would include traffic safety and minimal delays. From that of the contractor,

TABLE 9 Cost elements

Basic Data	Number of Lamps Lamp Life (hours) Energy Rate ($/KWH) Generator Fuel (Gal/Hr x $/Gal)
Initial Cost	Luminaires Lamps Wiring Mounting Hardware Labor Equipment Rental (towers) Generators
Operating Cost	Power (electricity or fuel) Replacement Lamps Maintenance Parts Maintenance Labor

benefits would include improvements in safety, quality, and productivity. Although previous research has suggested such a correlation exists, it remains to be quantified. When these data become available for nighttime construction activities, it is anticipated that benefit-cost ratio analysis will find widespread acceptance and usage since it provides an easily understood figure of merit.

SUMMARY

This chapter delineated those elements contributing to the cost of illuminating a construction work zone. Calculation of total cost provides important information to management that can be used for bidding, scheduling, and project financial control. Although not quantified at this time, there are also clear economic benefits associated with quantity and quality of illumination provided. An overall awareness of economic costs and benefits is essential to the further development of nighttime construction operations.

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APPENDIX FOR SECTION THREE

LIGHTING DESIGN EXAMPLE

EXAMPLE WORK ZONE LIGHTING DESIGN

Requirement

Construction contractor needs to determine the proper lighting configuration for a 3.3-m-wide pavement roller which will be used on a nighttime highway repaving project.

Design Step One: Determine the Area to Be Lighted and the Required Illumination Levels

Using Table 3, the lighted areas and illumination level are set. This information is summarized as follows:

Area to Be Illuminated: 20 m × 3.3 m = 66 m^2

Recommended Average Maintained Illumination: 54 lx

Design Step Two: Select the Type of Light Source to Be Used

This application involves low mounting heights and moderate areas of coverage. Low wattage Quartz Halogen sources are selected. They provide good control, which is important for task lighting. Also, these lamps are easily adapted to construction equipment.

Design Step Three: Determine the Indicated Watts/m^2

Using the illumination levels established in Step One and Figure 5, the indicated watts/m^2 are summarized as follows:

Indicated Watts/m^2: 2.5

Design Step Four: Determine the Total Required Lamp Wattage

Calculate the total required watts. Calculations are summarized as follows:

Total Area: 66 m^2

Watts/m^2: 2.5

Total required watts: $66 \times 2.5 = 165$

Design Step Five: Select and Configure Luminaires

A 55-W Quartz Halogen 12-V luminaire is selected. Luminaires and mounting configurations are given as follows:

Choose 3 ea. 55-W Luminaires (front and back)

Mount Luminaires as high as practical. Point of aim is to be not more than 60 degrees from vertical.

Design Step Six: Field Check Design for Conformance to Required Illumination Level and Glare Control Check List

Review mounting configuration with field personnel. Verify illumination levels achieved by field measurement. Verify that the luminaire beam angle is less than 60 degrees. Verify that all criteria have been satisfied.

SECTION FOUR

GUIDELINES FOR THE USE OF TEMPORARY ROADWAY LIGHTING

CHAPTER **1**

INTRODUCTION

PURPOSE OF GUIDELINES

These guidelines have been prepared to assist SHAs and other public agencies in using temporary roadway lighting for illumination during nighttime highway-related maintenance and construction operations. These guidelines are largely based on the findings of a study by the University of Florida (*1*).

These guidelines are intended for use as a guide in planning, design, operation, and maintenance of temporary roadway lighting systems during nighttime construction and maintenance operations. Average maintained illuminance levels are recommended for a variety of nighttime work on highways. Guidelines also assist in selecting the appropriate lighting hardware and equipment, determining the configuration of the lighting system, and designing the lighting system. The guidelines address the issues related to economic considerations and the operation and maintenance of the lighting system. The format of the guidelines is designed to ensure practicality for both the construction and the public agency administrating the construction project. The material in this document is presented in such a way that it may be used by lighting designers, engineers, contractors, and other public officials as a reference document for temporary roadway lighting design. Readers are encouraged to review "Guidelines for Work Zone Illumination Design" (Section Three of this report).

Although this document is intended to provide basic tools to the lighting designer to develop a functional and acceptable lighting system, it does not set any regulatory requirements or national policies. The recommendations are intended to satisfy safety requirements and to be interpreted as an informational guide for efficient visual performance for working crews, equipment operators and inspectors, and to reduce discomfort glare to passing motorists.

NIGHTTIME HIGHWAY CONSTRUCTION

The scope of nighttime maintenance and construction operations includes a wide variety of tasks. Table 1 presents a list of the most common work tasks. The use of temporary roadway lighting in construction applications is a relatively new concept. Although the research team contacted every state, only one project could be found where temporary roadway lighting was used as part of the construction operations. Nevertheless, the concept does offer substantial benefits with regard to work zone safety.

Nighttime highway work activities are accomplished with the use of temporary area lighting setup by the workforce and with the aid of lighting mounted on moving equipment. Occasionally, existing street lighting or roadway lighting may be present and can serve to supplement the temporary lighting; in most cases, it will not provide adequate illumination levels for the work activities. The primary purposes of roadway lighting are as follows:

1. Reduction in night accidents,
2. Aid in police protection and general security,
3. Facilitation of traffic flow, and
4. Promotion of business and the use of public facilities during night hours (*2*).

Roadway lighting in highway construction work areas provides three important benefits:

1. It assists the motorist in identifying objects at a greater distance ahead of the vehicle than possible with only vehicle lights.
2. It reduces the possibility of glare hazards to the motorist caused by the temporary construction lights.
3. It facilitates movement between temporarily lighted work areas.

ORGANIZATION OF GUIDELINES

These guidelines have been prepared to assist roadway lighting designers in using temporary roadway lighting for illumination during nighttime highway-related maintenance and construction operations. These guidelines are not intended to replace existing standards of practice for the design of roadway lighting. The focus of these guidelines is on the specific characteristics of temporary roadway lighting that are different from normal roadway lighting applications. The guidelines are organized into the following subjects:

- Visibility Requirements, and
- Lighting Design Considerations.

TABLE 1 Most common work tasks performed at night

Construction Tasks	Maintenance Tasks
Resurfacing	Sweeping and cleanup
Barrier walls, traffic separators	Repair of concrete pavement
Milling and removal	Bridge deck rehab. and maint.
Painting stripes and markers	Resurfacing
Bridge deck construction	Milling and removal
Concrete pavement construction	Highway lighting system repair
Base courses—day, cement, asphalt	Traffic signal maintenance
Excavation—regular, ditch, channel	Painting stripes and markers
Embankment, filling and compaction	Surface treatment
Highway signing	Barrier walls

CHAPTER **2**

VISIBILITY REQUIREMENTS

INTRODUCTION

Vision depends on light and the primary goal of any lighting design is to provide an environment in which people, through their sense of vision, can function effectively, efficiently and comfortably. In the case of the highway construction work zone, visual performance considerations should not be limited to the construction workers but should also include quality assurance personnel and passing motorists. Unless adequate care is taken, a suitable lighting situation might exist for one group yet pose serious hazards for another. Ideal lighting systems strike a balance between all groups involved or affected by the construction process.

VISUAL COMPONENTS OF THE DRIVING TASK

The motorist approaching or passing through a construction work zone must manage all normal driving tasks with the possible added burden of negotiating various lane shifts, as well as the visual distractions of the construction activities and lighting. Normal driving tasks include the following (*2*):

1. A pavement that is clear of defects and obstacles for a reasonable distance;
2. Locations of the lane or roadway edges within which the vehicle maintains a lateral position;
3. Location and meaning of the traffic control devices and signs that affect the "rules of the road";
4. Present location and future course of moving objects on or near the roadway; and
5. Present position of the driver's own vehicle relative to his/her immediate destination, other objects, and intended turning locations.

Research has indicated that appropriate roadway lighting can reduce the instances of highway accidents. Furthermore, nighttime accidents are more severe than daytime accidents. Common sense suggests that roadway lighting can be especially beneficial in situations where traffic must pass through or adjacent to a highway work zone. It is especially important to maintain roadway lighting during nighttime construction operations in situations where the roadway lighting was in place prior to construction. This is especially important for two reasons:

1. Justification for the roadway lighting still exists and may be greater with construction activity and
2. Motorists are likely to have become accustomed to the roadway lighting.

VISIBILITY REQUIREMENTS OF THE WORK TASKS

With respect to visual performance during night work, three basic areas are discussed in this chapter: visual task, lighting conditions, and human factors. These areas are traditionally considered primary factors in visual acuity. Table 2 lists variables affecting each of these components. Although the variables are very often discussed individually, a large number of interrelationships exist.

Visual Task

In analyzing the visual task, the most important influencing variables are luminance of the object, luminance of the background, contrast, size, and duration. These variables are all quantifiable and have found application in analytic models.

Luminance is often referred to as photometric brightness and is by definition the luminous flux (light) being emitted, transmitted, or reflected from a surface. It depends on both the intensity of the light striking an object and the proportion of that light reflected in the direction of the eye.

Visual perception tends to improve with apparent size of the visual task, its contrast to background, and the average luminance level of the visual field. In practice, the only factor that can be controlled is luminance.

Studies show that as background luminance increased, performance as measured by speed and accuracy increased at a decreasing rate until a point was reached where large changes in the background luminance resulted in only small changes in performance (*3, 4*).

The duration variable is related to the time it takes for the human eye to register a meaningful visual image. Given enough time, fine detail can be distinguished in poor light. The principle of diminishing returns is also evident with this variable.

Tasks showing high contrast between the task target or critical detail and its background results in good visibility

TABLE 2 Primary factors in visual acuity

Visual Task	Lighting Conditions	Human Factors
Size	Illumination	Condition of the eyes
Luminance	Glare	Adaptation level
Contrast	Uniformity	Fatigue level
Exposure time		Subjective impressions
Type of object		
Degree of accuracy required		
Task motion		
Peripheral patterns		

with relatively lower illumination levels. The opposite is also true—low contrast results in low visibility and higher levels of required illuminance.

Lighting Conditions

Sometimes referred to as quantity and quality of lighting, the influencing variables for lighting conditions are illuminance, veiling luminance (disability glare), discomfort glare, luminance ratios, brightness patterns, and chromaticity.

Quantity of lighting refers to illuminance, the illuminous flux density measured in lumens per square meter (lx) or square foot (foot-candles). Usually illuminance is given in the horizontal plane; however, it can also be measured in the vertical plane.

Quality of lighting relates to the relative ability of available light to provide the contrast differences so that people can make quick, accurate, and comfortable recognition of cues required for the seeing task. Variables most often associated with quality are glare, uniformity, and chromaticity. It should be recognized that, in many instances, changes intended to optimize one variable will adversely affect another and that the resultant total quality of the configuration may be degraded. A good lighting layout is the result of compromise among variables.

By definition, glare is the sensation of discomfort and interference with vision produced by visual field luminance sufficiently greater than that to which eyes are adapted. It arises because of an unsuitable luminance distribution or extreme luminance contrasts in space or time. Two types of glare are discussed in the literature, disability glare and discomfort glare.

Uniformity is a measure of relationships of illuminance over an area, for example, brightness ratios and patterns of luminance. Poor uniformity may distort the visual perception of the work zone. For industrial lighting, uniformity is typically expressed as the ratio of the average illuminance to the minimum illuminance over the relevant area. Acceptable values range from 10 : 1 to 2 : 1, with 5 : 1 generally considered suitable for construction activities. Uniformity depends on luminous intensity distribution, spacing/mounting height ratio, and direction of the luminaires' beams.

Since brightness attracts the eye's attention, all individual sources in the field of view produce an overall impression. If there is a lack of harmony or order among sources, the overall impression can be annoying to observers. Visual clutter, which is referred to as "noise," results in losses in productivity due to fatigue. Positioning of light sources is therefore very important.

Human Factors

Issues of the illumination problems introduced by human factors, both physical and psychological, are most complex. On the physical side, the primary variables are the condition of the eyes, adaptation level, and fatigue level, all of which are extremely difficult to quantify.

Adaptation refers to the ability of the visual system to change its sensitivity to light. Transient adaptation is the phenomenon of reduced visibility after viewing a higher or lower luminance than that of the task. In a construction work zone, this could be related to an equipment operator whose scan might move from well-illuminated nearby tasks to more distant tasks that have little or no lighting. It also suggests that the existing illumination in areas adjacent to the work zone needs to be considered when optimizing the lighting environment. A recent study concluded that as motorists passed from dark areas to an illuminated area, their visual performance can be measurably impaired by work zone lights (*5*).

There is growing evidence that perceived quality of lighting systems relates to more than task visibility. Subjective impressions or psychological reactions have been evaluated with respect to illuminance, spatial distribution, and color.

A general trend replicated in numerous studies is for increased satisfaction with higher illuminance, followed by a decrease in satisfaction at the highest illuminance.

Recommended Illumination Level Categories

To facilitate highway construction lighting design, three illuminance categories are recommended for various tasks covering the majority of the highway- and bridge-related maintenance and construction operations. The three categories, as provided in Table 3, require average maintained illuminance levels of 54 lx (5 fc), 108 lx (10 fc), and 216 lx (20 fc), respectively. Although the recommended levels satisfy safety requirements, they are also intended to provide a guide for efficient visual performance. For this reason, they may not be interpreted as recommended requirements for regulatory

TABLE 3 Recommended minimum illumination levels and categories for nighttime highway construction and maintenance tasks

Description of Construction and Maintenance Task	Average Maintained Illumination	
	Category	Target Level lux (fc)
Excavation – Regular, Lateral Ditch, Channel	I	54 (5)
Embankment, Fill and Compaction	I	54 (5)
Barrier wall, Traffic Separators	II	108 (10)
Milling, Removal of Pavement	II	108 (10)
Asphalt Paving and Resurfacing	II	108 (10)
Concrete Pavement	II	108 (10)
Asphalt Pavement Rolling	I	54 (5)
Subgrade, Stabilization, and Construction	I	54 (5)
Base Course Grading and Shaping	II	108 (10)
Surface Treatment	II	108 (10)
Base Course Rolling	I	54 (5)
Waterproofing and Sealing	II	108 (10)
Sidewalk Construction	II	108 (10)
Sweeping and Cleaning	I	54 (5)
Guard Rails and Fencing	II	108 (10)
Striping and Pavement Marking	II	108 (10)
Landscaping, Sod and Seeding	I	54 (5)
Highway Signs	II	108 (10)
Traffic Signals	III	216 (20)
Highway Lighting Systems	III	216 (20)
Bridge Decks	II	108 (10)
Drainage Structures and Drainage Piping	II	108 (10)
Other Concrete Structures	II	108 (10)
Maintenance of Embankments	I	54 (5)
Reworking Shoulders	I	54 (5)
Repair of Concrete Pavement	II	108 (10)
Crack Filling	III	216 (210)
Pot Hole Filling	II	108 (10)
Repair of Guardrails and Fencing	II	108 (10)
Implement Glare Control Measures. (See Table 4 for Glare Control Check List.)		

Recommended Illumination Areas for Typical Highway Construction Equipment	
Provide target illumination over task working area. This is the effective working width of the machine by approximately 5 meters.	
Minimum distance from machine to	
Slow Moving Equipment: Paver Milling Machine	5 meters
Fast Moving Equipment: Backhoe Loader Wheel Loader Scraper Roller Motor Grader	20 meters
Other Equipment: Maximum uniformity ratio of 10:1 in the work area. Minimum of average maintained illumination of 54 lx (5 fc) for all work areas.	

minimum illuminance. Determination of the three categories and their illuminance values is based on several factors including IES recommendations, OSHA requirements, provisions in state specifications, and opinions and views of various experts. The number of categories is limited to three so that different illumination requirements in the same operation could be specified by a single category. The three recommended categories are found to be adequate to account for differences in visual display and variations in speed and accuracy for the majority of highway construction tasks.

Category I is recommended for general illumination in the work zone, primarily from the safety point of view, in the area where crew movement is expected or taking place. This category is also recommended for tasks requiring low accuracy, involving slow-moving equipment, and having large-sized objects to be seen.

Category II is recommended for illumination on and around construction equipment and the visual tasks associated with the equipment. The primary concerns in suggesting the minimum illuminance value for this category are equipment safety and medium accuracy desired for the task. For certain tasks such as resurfacing, not only is the safety around the paver and roller crucial, but the quality of the finished surface is also important.

Category III is suggested mainly because of the efficient visual performance required for certain tasks. Highway tasks that present higher visual difficulty and require increased attention from the observer include crack and pothole filling, joint sealing, critical connections, and tasks involving maintenance of electrical connections and moving mechanical parts. Table 3 includes other examples for each of the three categories.

TABLE 4 Glare control check list

Beam Spread	Select vertical and horizontal beam spreads to minimize light spillage. Consider using cutoff luminaires.
Mounting Height	Coordinate minimum mounting height with source lumens (see Figure 3).
Location	Luminaire beam axis crosses normal lines of sight between 45° and 90°.
Aiming	Angle between main beam axis and nadir less than 60° (see Figure 5). Intensity at angles greater than 72° from the vertical less than 20,000 candela.
Supplemental Hardware	Visors Louvers Shields Screens Barriers

Recommended Illumination Levels

Table 3 provides the recommended illuminance levels and categories for some of the most commonly performed nighttime construction and maintenance operations. The work activities are identified as a result of a survey of SHAs (*1*). These activities are compared with visually similar nonhighway activities and the recommended illuminance levels are adopted. The illuminance levels provided in the Table 3 are recommended average levels that should be maintained over the specific visual task for desired visual performance. As a safety requirement, it is recommended to maintain a minimum of 54 lx (5 fc) in the immediate areas of work. A uniformity ratio of 10 : 1 should be maintained in accordance with the target illuminance levels for specific tasks.

To recommend guidelines for equipment lighting, a set of construction equipment most commonly used for highway work is selected. Based on the equipment's characteristics, its application and relevant SAE current practices, a minimum area to be illuminated in front and back of the equipment is recommended. The suggested minimum area to be illuminated for each piece of equipment is also provided in Table 3. For simplification, most of the equipment is classified in two broad categories: (1) slow-moving equipment and (2) fast-moving equipment. The illumination level at the maximum range provided in Table 3 should not be less than 10.8 lx (1 fc). However, the task illumination levels around the equipment should conform to the illuminance categories and target levels recommended for various tasks. Also, the glare control measures suggested in Table 4 should be considered.

SUMMARY

Visibility requirements for temporary roadway lighting used during night work operations include the visibility needs of the motorist and of the construction workers. Designers must be aware of both sets of requirements. Work area lighting guidelines and design procedures are provided in Sections Two and Three of this report. Work area illumination minimum levels depend on the visibility requirements of the work activity and are divided into three categories:

- Category I 54 lx
- Category II 108 lx
- Category III 216 lx

Visibility requirements for motorists depend on the driving conditions encountered. In general, the illumination levels required for work tasks exceed those required for normal roadway lighting. Designers are referred to the *American Standard Practice for Roadway Lighting RP-8-00* for a comprehensive discussion of the visibility requirements for the motorist (*2*).

CHAPTER **3**

TEMPORARY ROADWAY LIGHTING DESIGN CONSIDERATIONS

INTRODUCTION

Although the ambient illumination provided by existing roadway lighting is certainly helpful to the performance of nighttime work tasks, the typical illumination levels provided by roadway lighting fall significantly below the minimum levels required for work tasks. For example, the minimum illumination level recommended for work activity is 54 lx. Roadway lighting illumination levels may be in the range of 6 to 10 lx. Therefore, it does not appear practical to use roadway lighting as a substitute for the temporary lighting normally provided for the performance of nighttime work activities. Rather, the purpose of the temporary roadway lighting should be to assist the motorist and, if appropriate, the pedestrian in their travel through the nighttime work area.

Accordingly, the design criteria for temporary roadway lighting is essentially the same as those used for permanent roadway lighting except that the locations and mounting details may depend on the specifics of the construction project. In most cases, the same visibility criteria used for permanent roadway lighting designs should be used for temporary roadway lighting design. Several authoritative standards of practice for the design of roadway lighting currently exist. The *American Standard Practice for Roadway Lighting RP-8-00* is the foremost (*2*). Rather than including a partial duplication of available design standards, this report will focus on those unique features of temporary roadway lighting that are of importance to the designer.

RESULTS OF FIELD VISITS

During the research conducted in this study only one state was identified as using temporary roadway lighting in connection with highway construction. The project was the I-30 in Dallas, Texas. On this project, temporary roadway lighting was mounted on aluminum poles using rigid concrete barrier wall sections as a base. The lighting hardware was supplied by the Texas DOT and installed by the contractor. Specially fabricated pole bases were used to connect the poles to the barrier wall sections. The temporary roadway lighting that was installed to aid the motorist in travel through the work zone did not illuminate the area of construction; Texas DOT personnel reported that the justification for temporary roadway lighting was as follows:

- The roadway section had been previously lighted with roadway lighting and
- The roadway section was “very dark” without lighting.

Texas has developed a standard specification for Temporary Lighting Systems that includes both aluminum and timber pole installations. The essential features of the specification are as follows:

1. Contractor is required to comply with National Electrical Safety Code and the NEC.
2. Contractor is required to pay for all utility connections.
3. Texas DOT will pay for electrical power.
4. Measurement and payment are by lump sum price for installation and removal.

NEED FOR COORDINATION WITH MAINTENANCE OF TRAFFIC PLANS

The design of temporary roadway lighting must include a review of the proposed maintenance of traffic (MOT) plans for the project. Highway construction projects routinely include complex MOT planning to facilitate traffic flow during construction. The construction phasing often requires lane shifts and closures. Locations for temporary lighting must be coordinated with the MOT strategy for the project. In many cases, median barrier walls will be kept in place throughout the project and can be effectively used for lighting bases.

MOUNTING SUPPORTS AND OTHER DETAILS

Utility Connections

Special attention should be given to the design detail for the utility connection to the lighting system. The connection design must accommodate both the planned construction operations and the passage of traffic through the work zone. The Texas specification allows for either overhead or buried connections, but if an overhead connection is used, a vertical clearance of 22 ft must be maintained over the roadway. Designers are also cautioned to check right-of-way clear zone requirements when determining pole locations.

Barrier Walls as Bases

Rigid concrete barrier walls have been used successfully as the bases for temporary roadway lighting. The poles require specially fabricated mounting hardware for attachment to the concrete barrier wall. These special fabrications should be appropriately structurally designed, and the structural stability of the light and barrier wall section should be checked. Mounting height may be limited by the stability of the barrier wall section to lateral loading. Another design consideration is the need for flexible conduit. Generally, the conduit connection between barrier wall sections requires flexible conduit.

MAINTENANCE AND OPERATIONAL CONSIDERATIONS

Maintenance responsibility should be addressed in the construction contract provisions. One approach may be to assign maintenance responsibility to the contractor in the same way as for temporary traffic control devices. Alternatively, the SHA may elect to assume maintenance responsibility. In either case, routine nightly inspections of the system should be conducted and documented. Maintenance, including changing lamps, will normally be performed with the use of a bucket truck. In some situations, such as with a median barrier mounting, a temporary lane closure will be required. Any maintenance-related lane closures or other traffic shifts should be addressed in the MOT for the project.

COST CONSIDERATIONS

Cost considerations for temporary roadway lighting are similar to those associated with permanent roadway lighting. The cost elements are presented in Table 5. Cost estimates should consider reuse of components if applicable. When determining total cost, care should be taken to include anticipated reuse of materials. For example, if the work zone is 9 km (5.6 mi) long and the design calls for a light source every 30 m (98.4 ft), it might not be necessary to illuminate all 9 km (5.6 mi) simultaneously. If the construction plan calls for work to be done in 1-km (0.62-mi) sections, it would only be necessary to procure 33 light sources with each being reused 9 times. Coordination of the lighting plan with the construction schedule development is a crucial step in the planning process.

TABLE 5 Cost element summary for temporary roadway lighting

Basic Data	Number of Luminaires Number of Lamps Lamp Life (hours) Energy Rate ($/KWH) Conductors (LF) Service Connections
Initial Cost	Luminaires Lamps Wiring Mounting Hardware, Support Bases Labor Service Connections
Operating Cost	Power (electricity or fuel) Replacement Lamps Maintenance Parts Maintenance Labor

Analysis on a total cost basis appears to be the most practical approach to this problem. Since the duration of most projects is less than 1 year, it can be reasonably argued that there is no need to be concerned with the time value of money or the application of discount factors. This lump sum approach provides meaningful information to the contractor for bidding purposes. Awareness of operation and maintenance costs will also be helpful in the management of budget and cash flow throughout the project duration. For purpose of comparisons, approximate costs for each configuration are discussed.

It is estimated that temporary system costs could run as much as $67,000 per km to install and operate while portable systems would be approximately $37,000 per km. Cost of equipment-mounted systems does not lend itself to a per mile analysis. For comparison, the cost has been estimated at less than $2,000 per piece of equipment. A normal suite of equipment for a project could include 15 to 20 pieces resulting in a total cost of about $40,000. After converting costs of temporary and portable systems to a total cost basis for comparison, use of equipment-mounted systems appears highly desirable assuming illuminance and uniformity criteria are equivalent. However, it should be noted that temporary roadway lighting is not a substitute for the temporary task and area lighting required to perform the night work. Therefore, in most situations, both temporary roadway lighting and temporary construction lighting will be required.

Benefit-cost ratio analysis is a technique that has found considerable application in government projects. Simply stated, if benefits exceed cost, there is definite value to the alternative under consideration. The difficulty in using this approach is in quantification of benefits. While benefits are widely understood to mean cost savings, in many cases, there is no direct income and other benefits both tangible and intangible must be considered very carefully.

From the public viewpoint, benefits would include traffic safety and minimal delays. From that of the contractor, benefits would include improvements in safety, quality, and productivity. Although previous research has suggested such a correlation exists, it remains to be quantified. When these data become available for nighttime construction activities, it is anticipated that benefit-cost ratio analysis will find widespread acceptance and usage since it provides an easily understood figure of merit.

SUMMARY AND CONCLUSIONS

The use of temporary roadway lighting in connection with highway construction promises to offer many benefits for the motorist. As with all design applications, cost and benefits will depend on the project specifics. In general, roadway situations that merit the application of roadway lighting should receive temporary roadway lighting during construction. In other situations where the extent of construction activity, construction lighting, and maintenance of traffic plans may present significant hazards for the motorist, the use of temporary roadway lighting is justified.

The basic design approach for temporary roadway lighting is the same as that for permanent roadway lighting. The *American Standard Practice for Roadway Lighting RP-8-00* (*2*) is recommended as a design reference. The temporary nature of the temporary roadway lighting system and the need to be compatible with the construction work process must be considered when developing a design.

REFERENCES

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation