

CONLIGHT: Lighting Design Model for Nighttime Highway Construction

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Abstract: The utilization of nighttime work in highway construction and rehabilitation projects has been increasing in recent years throughout the United States. In this type of projects, construction planners are required to develop and submit a lighting plan that provides: (1) adequate illuminance levels for all planned nighttime construction tasks; (2) reasonable uniformity of light distribution in the work area, and (3) acceptable glare levels to both road users and construction workers. In order to support construction planners in this vital and challenging task, this paper presents a lighting design model, named *CONLIGHT*, which is capable of considering the specific requirements of nighttime highway construction operations. The model is developed to enable construction planners to evaluate the performance of various lighting plans and select a practical design that complies with all lighting requirements for the nighttime work being planned. An application example is analyzed to illustrate the use of the model and demonstrate its accuracy and capabilities in generating practical lighting plans for nighttime construction and rehabilitation projects.

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Introduction

Highway construction and rehabilitation projects often cause partial closure of existing roads during construction operations, resulting in traffic congestions and delays to the traveling public. In order to alleviate these adverse effects of daytime construction operations, an increasing number of highway construction projects throughout the United States are being performed during off-peak nighttime hours (Cottrell 1999; Hancher and Taylor 2001; El-Rayes and Hyari 2002; O'Malley 2002; Park et al. 2002; Al-Kaisy and Nassar 2003). This recent increase in the utilization of nighttime construction can be attributed to two main reasons: (1) the growing need for significant highway rehabilitation and maintenance projects due to the deterioration of the existing road network; and (2) the negative impact of this type of projects on traffic congestions, especially in urban roads that are currently operating near capacity during daytime hours (Bryden and Mace 2002; Al-Kaisy and Nassar 2003). In a recent survey, Departments of Transportation (DOTs) in 22 states reported that they have expanded their utilization of nighttime construction in recent years, and indicated that an average of 17% of their projects in fiscal year 2001 involved nighttime operations (El-Rayes and Hyari 2003).

Despite this recent increase in the utilization of nighttime construction in various states, this practice still faces serious challenges especially in the area of providing adequate lighting conditions during nighttime operations. Lighting was reported to be one of the most important factors affecting safety, quality, cost, and productivity in nighttime construction projects (Kumar 1994; Ellis and Amos 1996; Bryden and Mace 2002). As such, lighting in these projects should be properly designed and implemented in order to: (1) ensure safety and quality of construction operations and (2) satisfy the relevant specifications of state DOTs. These specifications often require the development and submission of a lighting plan that clearly shows all relevant lighting design parameters, including the number and type of lighting equipment as well as their location, mounting height, rotation, and spacing for review and approval prior to the start of night work. The plan should also verify that the proposed lighting design satisfies all nighttime construction requirements, including the provision of: (1) adequate illuminance levels for all planned nighttime construction tasks; (2) reasonable uniformity of light distribution in the work area, and (3) acceptable glare levels to both road users and construction workers (New York State Department of Transportation 1995, and North Carolina Department of Transportation 1995).

In addition to satisfying the above requirements of state DOTs, the development of practical lighting plans can significantly improve safety, quality, cost, and productivity in nighttime construction projects. This, however, requires scientific and detailed computations to evaluate various lighting plans and verify that the selected one satisfies the specific lighting design requirements for the nighttime construction work being planned. In order to support this vital and challenging task in nighttime projects, there is a pressing need for a practical lighting design model that is capable of considering the specific requirements of nighttime highway construction operations.

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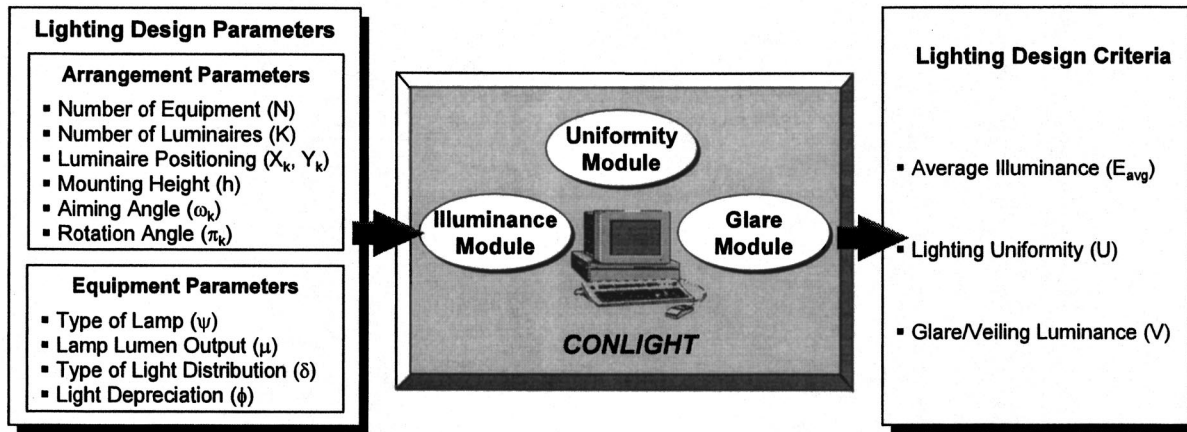


Fig. 1. Construction lighting design model (CONLIGHT)

Objective

The objective of this paper is to present a practical lighting design model for nighttime highway construction and rehabilitation projects. The model is designed to provide the necessary support for highway contractors and resident engineers in the design and implementation of practical lighting plans for nighttime construction operations. The present model is named *CONLIGHT* and is developed in two main stages: design and implementation.

Model Design

CONLIGHT is designed to support the development of a practical lighting plan for nighttime highway construction operations. As stated earlier, this developed plan needs to: (1) provide a practical lighting design that specifies all relevant design parameters in this lighting problem and (2) verify that the selected plan complies with all lighting design requirements. In order to support construction planners in this vital task, *CONLIGHT* is designed to evaluate the impact of all relevant lighting design parameters on the specified design criteria in nighttime work zones, as shown in Fig. 1.

Lighting Design Parameters

The present model is designed to consider all lighting design parameters that need to be specified in the required lighting plan for nighttime construction projects. As shown in Figs. 1 and 2, these design parameters are divided into two major categories: lighting arrangement and lighting equipment parameters. First, lighting arrangement parameters represent various positioning and configuration of the utilized lighting equipment on site, including: (1) number of lighting equipment (N), which represents the total number of utilized equipment (e.g., trailer mounted light towers and equipment mounted luminaires); (2) number of luminaires (K), which represents the total number of utilized luminaires in all the lighting equipment on site; (3) luminaire positioning (X_k, Y_k), which depicts the horizontal location of luminaire k in the work zone in terms of its coordinates (see Fig. 2); (4) mounting height of luminaire (h), which represents the vertical distance between the center of the luminaire and the pavement surface as shown in Fig. 2; (5) aiming angle of luminaire (ω_k), that denotes

the vertical angle between the center of the beam spread of luminaire k and the nadir as shown in Fig. 2; and (6) rotation angle of luminaire (π_k), which represents the rotation of luminaire k around a vertical axis (see Fig. 2).

Second, lighting equipment parameters are used in this model to represent the availability of various types of nighttime lighting equipment, including: (1) type of lamps (ψ), that can be used in lighting equipment such as metal halide lamps and halogen lamps; (2) lamp lumen output (μ), which specifies the light and energy emitted from the utilized lamps (IESNA 1998); (3) type of luminaire light distribution (δ), which depicts the distribution of light in different directions; and (4) light depreciation (ϕ), which represents the reduction in the produced light from luminaires over time depending on the age of lamps and the accumulation of dirt on them, and it often varies from 1 for new luminaires to 0.7 or 0.85 for used ones depending on the type of luminaire (Homburger and Kell 1988). The present model is designed to consider the impact of these two categories of design parameters on lighting performance on site in order to develop a practical lighting plan that satisfies all lighting design requirements for nighttime construction sites.

Lighting Design Criteria

In order to comply with state DOTs specifications and to ensure safety and quality in nighttime construction projects, the present model is designed to verify that the selected lighting plan is capable of satisfying three major lighting design criteria, namely: (1) average illuminance (E_{avg}); (2) lighting uniformity (U); and (3) glare (V), as shown in Fig. 1. First, a minimum level of average illuminance needs to be provided on site to ensure the availability of adequate lighting conditions for all planned nighttime construction tasks. Illuminance represents the intensity of light incident on a surface area in lux (lumen/meter²), and it can be measured on site using simple light meters (Kaufman and Haynes 1981). Second, a maximum ratio of lighting uniformity (U) should not be exceeded in the work area to ensure that light is uniformly distributed and reaches all parts of the construction site. Lighting uniformity can be quantified using a ratio of average illuminance on site to the minimum level of illuminance in the work area (IESNA 2000). Third, a maximum level of glare (V) should not be exceeded in and around the work area to minimize its negative impact on road users and construction workers.

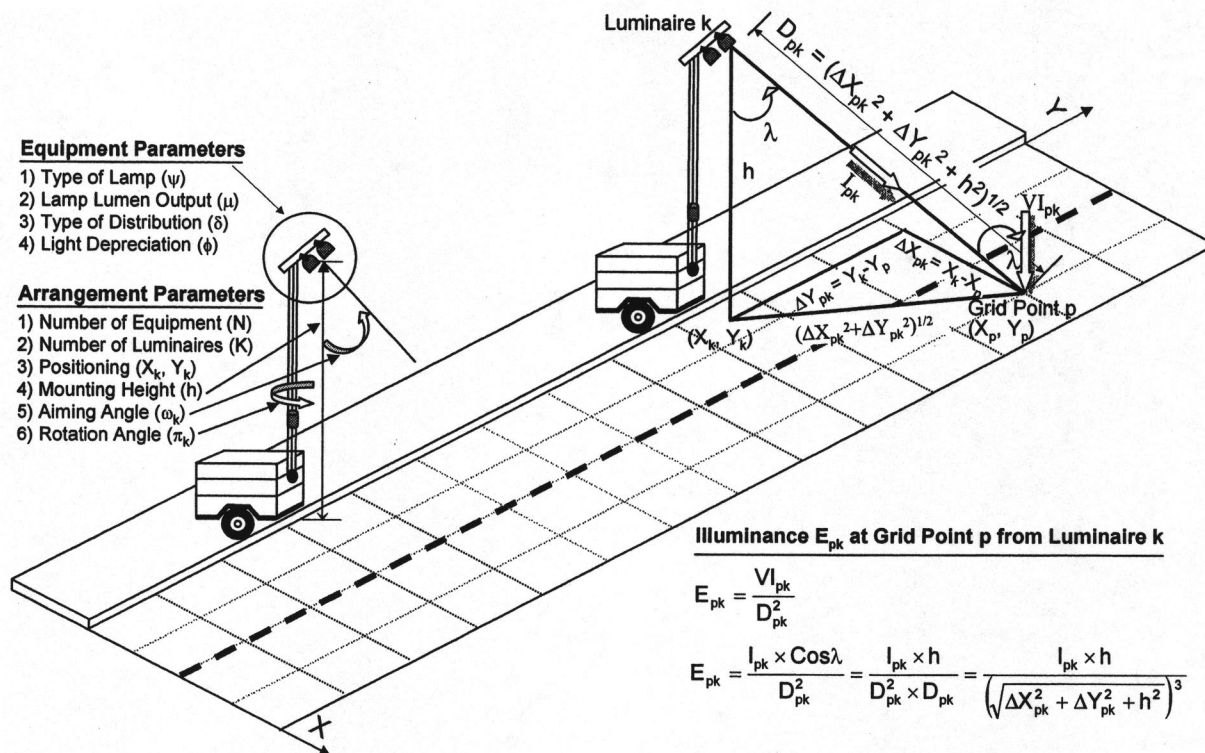


Fig. 2. Design parameters and their impact on illuminance calculations

Glare can be defined as the sensation of annoyance, discomfort, or loss of visual performance and visibility due to experiencing luminance in the visual field significantly greater than that to which the eyes of the observer are adapted (Pritchard 1999), and it can be quantified using the veiling luminance ratio (IESNA 2000). In order to enable the evaluation of various lighting plans and study their impact on these lighting design criteria, the present model is designed to incorporate three major modules: illuminance, uniformity, and glare, as shown in Fig. 1.

Model Implementation

The main purpose of this stage is to implement the illuminance, uniformity, and glare modules in the present lighting design model, as shown in Fig. 1. These three modules were implemented using C++ programming language in order to provide a practical Windows application that runs on Microsoft Windows XP and supports user-friendly interface. The following sections provide a brief description of the design and computation procedures used in each of these three modules.

Illuminance Module

In this module, the average illuminance level in the work zone is calculated using the design procedure shown in Fig. 3. The procedure is capable of considering and quantifying the impact of: (1) lighting arrangement parameters; (2) lighting equipment parameters; and (3) layout and configuration of the nighttime work zone, as shown in Fig. 3. This module utilizes the point-by-point method to calculate the average horizontal illuminance in the work area, using the following five main steps:

1. Design a grid system for the nighttime work zone by dividing the area that needs to be illuminated into identical grid cells in order to obtain a set of uniformly distributed points (P), as shown in Fig. 2. The x and y coordinates for each point p (x_p, y_p) in this grid is then calculated to facilitate the computations of horizontal illuminance in all grid points. The accuracy of the lighting model can be improved by increasing the number of grid points for the same area; however this increase leads to higher computational requirements. It should also be noted that the accuracy of *CONLIGHT* improves when it is used to analyze rectangular shapes which represents the majority of work areas in highway construction (FHWA 2000). Other irregular shapes can also be analyzed by the model after dividing them into a set of rectangular shapes.
2. Determine the light intensity I_{pk} that reaches each grid point p from each luminaire k , as shown in Fig. 2. In this module, the value of light intensity I_{pk} is calculated considering the impact of the earlier described lighting arrangement parameters and lighting equipment parameters. First, lighting arrangement parameters (i.e., luminaire positioning, mounting height, aiming angle, and rotation angle) affect the vertical angle (λ) between the nadir and the line connecting luminaire k and point p (see Fig. 1), and therefore they have a direct impact on the intensity of light I_{pk} that reaches point p from luminaire k . Second, lighting equipment parameters (i.e., type of lamp, lumen output, type of light distribution, and light depreciation) affect the light intensity produced by luminaire k in all directions, which is typically represented by the photometric data file for that specific luminaire. In order to consider the impact of these two groups of design parameters (arrangement and equipment parameters), the

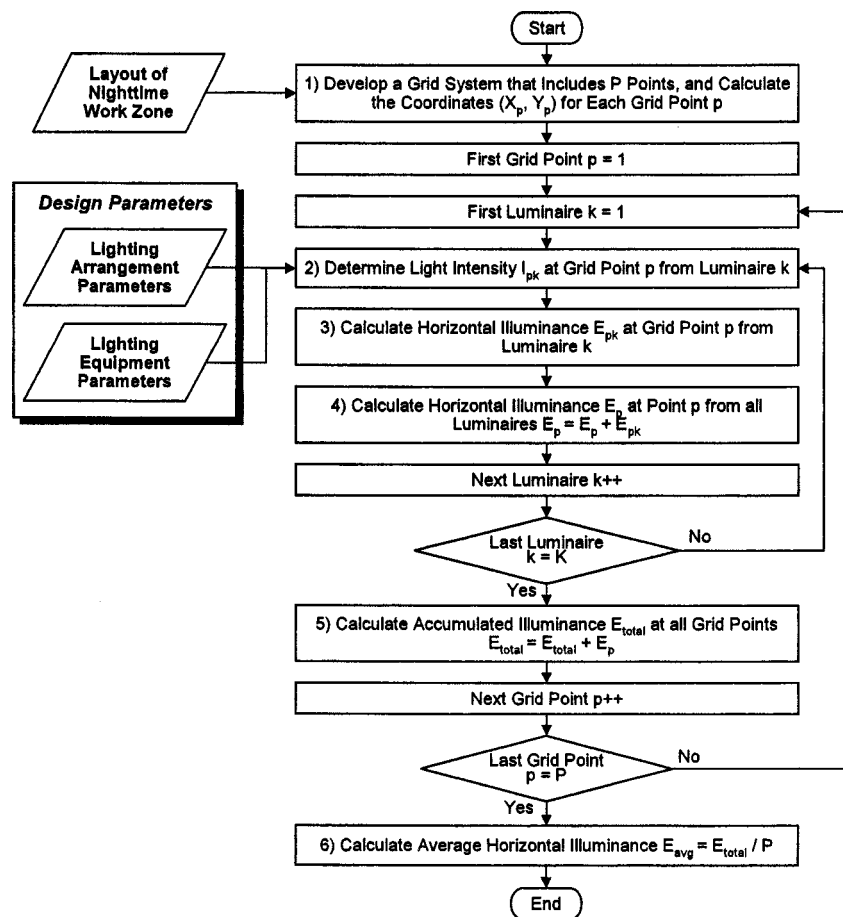


Fig. 3. Illuminance module

computations in this step performs a two-dimensional polynomial interpolation between the available light intensity values in the photometric data file to obtain the required values of light intensity (I_{pk}) that reaches each grid point p from luminaire k . It should be noted that light intensity values are affected by the condition of the lighting equipment on site, and therefore they should be properly maintained and kept in good shape to ensure an acceptable level of lighting quality in the work area.

- Calculate horizontal illuminance (E_{pk}) at each grid point p from each contributing luminaire k , using the light intensity values (I_{pk}) calculated in the previous step and the inverse square law (Pritchard 1999). This law states that the horizontal illuminance (E_{pk}) at grid point p from a light source k is directly proportional to the vertical component of light intensity (VI_{pk}) reaching point p from light source k , and inversely proportional to the square of the distance (D_{pk}) between that light source and the considered point [see Eq. (1)]. As shown in Fig. 2, the first equation is used to derive the second equation in order to facilitate the computation of E_{pk} as a function of readily available data including: light intensity (I_{pk}) at grid point p from luminaire k , mounting height (h) of the luminaire, coordinates of luminaire position (x_k, y_k), and coordinates of grid point p (x_p, y_p) as shown in Fig. 2 and the second equation

$$E_{pk} = \frac{VI_{pk}}{D_{pk}^2} \quad (1)$$

$$E_{pk} = \frac{I_{pk} \times \cos \lambda}{D_{pk}^2} = \frac{I_{pk} \times h}{D_{pk}^2 \times D_{pk}} = \frac{I_{pk} \times h}{(\sqrt{\Delta X_{pk}^2 + \Delta Y_{pk}^2} + h)^3} \quad (2)$$

- where E_{pk} =horizontal illuminance at grid point p from luminaire k ; VI_{pk} =vertical light intensity at grid point p from luminaire k ; λ =vertical angle between the nadir and the line connecting luminaire k and grid point p (see Fig. 2); D_{pk} =distance between grid point p and luminaire k and as shown in Fig. 2; I_{pk} =light intensity directed from luminaire k towards grid point p ; h =mounting height of luminaire k above the road surface; ΔX_{pk} =horizontal distance in the x direction between point p and luminaire k ; and ΔY_{pk} =horizontal distance in the y direction between point p and luminaire k .
- Determine the horizontal illuminance (E_p) at each grid point ($p=1-P$) considering all contributing luminaires ($k=1-K$). As shown in the following equation, E_p is calculated by summing up all the horizontal illuminance values (E_{pk}) produced by all contributing luminaires

$$E_p = \sum_{k=1}^K E_{pk} \quad (3)$$

where E_p =horizontal illuminance at point p from all contributing luminaires; and K =total number of luminaires.

- Calculate the accumulated illuminance (E_{total}) in all grid points by summing up the calculated illuminance levels at all grid points ($p=1-P$), as shown in the following equation:

$$\text{total accumulated illuminance} = E_{\text{total}} = \sum_{p=1}^P E_p \quad (4)$$

where P = total number of grid points in the work area.

6. Compute the average horizontal illuminance for the entire work area (E_{avg}) by dividing the total accumulated illuminance (E_{total}) in all grid points over the number of points P , as shown in the following equation. It should be noted that shadows caused by construction equipment on site may slightly affect the actual average illuminance obtained in the work zone, however, this effect is often minimal since the mounting height of the luminaries is significantly higher than the height of all construction equipment on site

$$\text{average horizontal illuminance} = E_{\text{avg}} = \frac{E_{\text{total}}}{P} \quad (5)$$

Uniformity Module

This module is implemented to perform the necessary computations to identify the lighting uniformity ratio in the work zone. Lighting uniformity (U) in this module is represented by the ratio between the previously calculated average illuminance in the work area (E_{avg}) and the minimum illuminance computed at any grid point in the work zone, as shown in the following equation. It should be noted that lighting uniformity improves on site when the value of the uniformity ratio decreases, which indicates smaller difference between the darkest point and the average illuminance in the work area.

$$\text{uniformity ratio}(U) = \frac{E_{\text{avg}}}{E_{\text{min}}} \quad (6)$$

where E_{avg} = average illuminance in the work area, calculated using Eq. (5); and E_{min} = minimum illuminance level in all grid points, calculated using Eq. (3).

Glare Module

This module calculates the maximum veiling luminance ratio in order to control glare in the work zone. The module utilizes the same input data used in the first module in addition to the reflectance characteristics of the pavement surface in the work area. Road pavements are classified into four categories according to their reflectance properties (IESNA 2000), where the reflectance coefficient of each category is represented by a data file that considers the location of luminaire, observer, as well as the observer line of sight, as shown in Fig. 4. This input data is used in this module to perform the necessary glare computations in three major phases that are designed to calculate: (1) possible observer positions; (2) pavement luminance for each observer position; and (3) veiling luminance experienced by drivers at each observer position as shown in Figs. 4 and 5. A brief description of the computations involved in these three phases is provided in the following sections.

Phase 1: Observer Positions Identification

This phase is intended to identify various observer points that represent possible drivers' positions and lines of sight as they approach and drive by the work zone in both directions. As shown in Fig. 4, these observer points ($o=1-O$) are designed to cover all possible positions where drivers are exposed to glare from night-

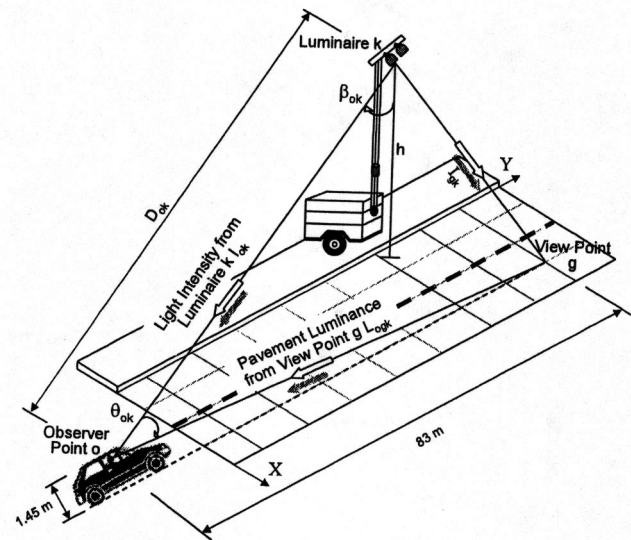


Fig. 4. Glare computations

time construction lighting in order to verify that the maximum computed glare value at all observer positions comply with the design criteria requirements.

Phase 2: Pavement Luminance Calculations

The purpose of this phase is to calculate the average pavement luminance viewed by potential drivers at each observer position because the sensation of glare by drivers is not only dependent on the amount of veiling luminance reaching their eyes as an absolute value, but also the lighting level at which the driver's eyes are adapted to when exposed to that amount of glare (veiling luminance). As such, computations in this module are performed to calculate average pavement luminance values (L_o) at various observer points ($o=1-O$), using the following seven main steps:

1. Develop a set of all possible view points ($g=1-G$) that exist in the field of view of the driver, and calculate the coordinates (x_g, y_g) of each point. These points are set to be equally spaced and cover a field of view that extends to a distance of 83 m ahead of the considered observer position o , as shown in Fig. 4. This distance is used in compliance with IESNA standards for roadway lighting that specifies the line of sight of driver to be inclined 1° downward and the average height of driver eye to be considered 1.45 m (IESNA 2000).
2. Determine the light intensity I_{gk} that reaches each view point ($g=1-G$) from each luminaire ($k=1-K$), as shown in Fig. 4, in a similar procedure to that earlier utilized and described in Step 2 of the illuminance module.
3. Identify the reflectance coefficient for the type of existing pavement in the work zone at each view point g using the earlier described input data file for pavement reflectance characteristics. These files provide the value of this coefficient r_{ogk} as a function of the observer location o , positions of luminaire k , and view point g .
4. Calculate pavement luminance L_{ogk} produced by the portion of light from luminaire k that is reflected at view point g towards observer point o , as shown in Fig. 4. This calculation is performed using a similar procedure to that recommended by IESNA for roadway lighting (IESNA 2000). This procedure calculates L_{ogk} as a function of the light intensity incident on view point g from luminaire k , reflectance coefficient

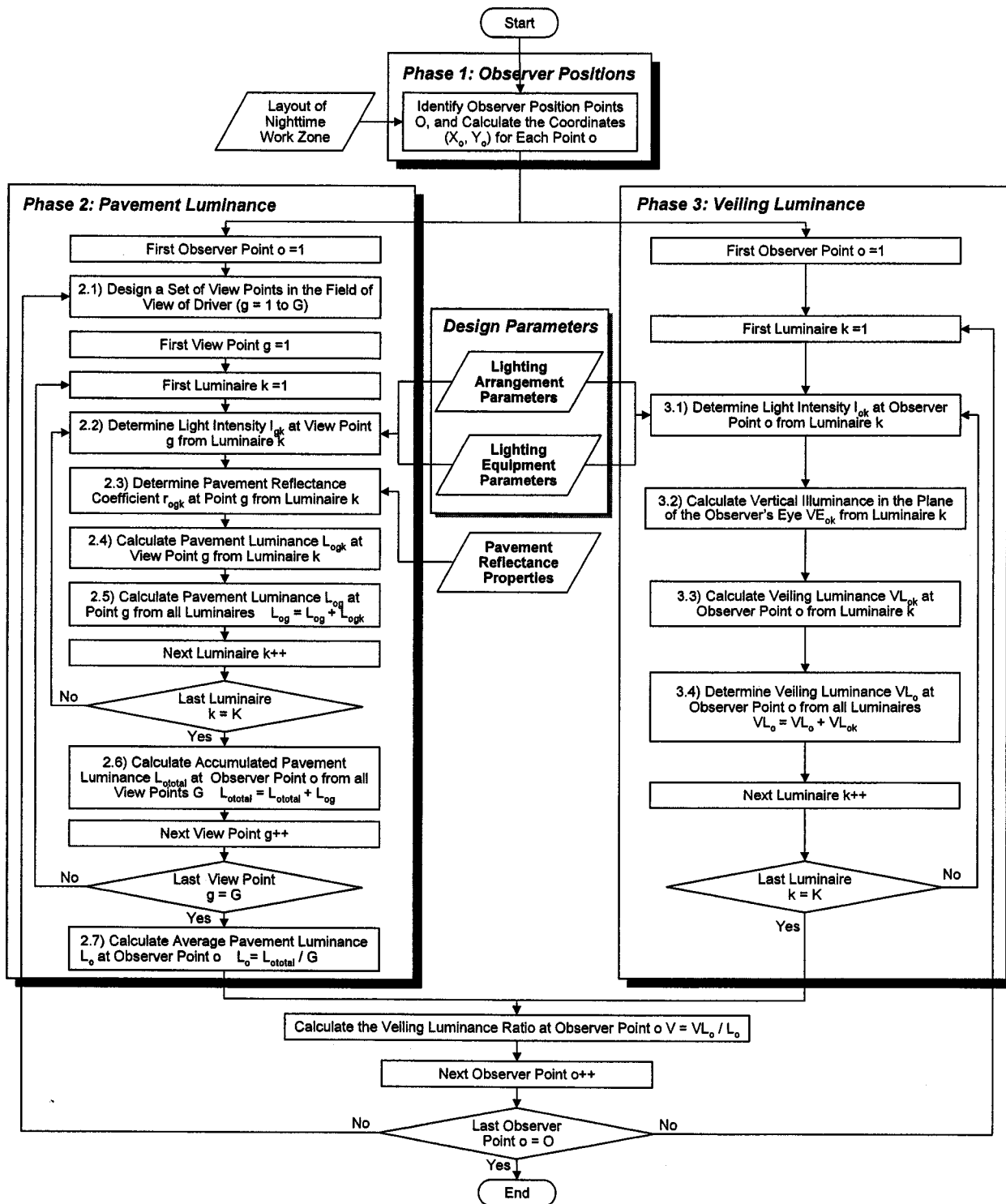


Fig. 5. Glare module

of the pavement r_{ogk} , and the mounting height of luminaire k , as shown in the following equation:

$$L_{ogk} = \frac{I_{gk} \times r_{ogk}}{h^2} \quad (7)$$

where L_{ogk} =pavement luminance produced by the portion of light from luminaire k that is reflected at view point g towards observer point o , as shown in Fig. 4; and r_{ogk} =reflectance coefficient for the light generated from luminaire k , and reflected at view point g towards observer point o .

5. Determine the pavement luminance L_{og} at view point g from all contributing luminaires ($k=1-K$), as shown in the following equation:

$$L_{og} = \sum_{k=1}^K L_{ogk} \quad (8)$$

where L_{og} =pavement luminance produced by the reflected light from all luminaires at view point g towards observer point o .

6. Calculate the accumulated pavement luminance L_{ototal} at observer position o , by summing up all calculated luminance values at all view points ($g=1-G$) as shown in the following equation:

$$L_{ototal} = \sum_{g=1}^G L_{og} \quad (9)$$

where L_{ototal} =accumulated pavement luminance for observer at point o .

7. Calculate the average pavement luminance at observer position o (L_o), by dividing the accumulated pavement luminance L_{ototal} over the number of view points G , as shown in the following equation. These seven steps are repeated for every observer position ($o=1-O$), as shown in Fig. 5:

$$L_o = \frac{L_{ototal}}{G} \quad (10)$$

where L_o =average pavement luminance viewed by the driver at observer point o .

Phase 3: Veiling Luminance Computations

This phase is intended to calculate the veiling luminance (disability glare) in the plane of the observer's eye at each observer position ($o=1-O$), considering all contributing luminaries ($k=1-K$) in the field of view of the observer. Computations in this module are performed to identify the veiling luminance ratio (V_o) at various observer points ($o=1-O$), using the following four main steps:

1. Determine the light intensity (I_{ok}) that reaches observer point o from luminaire k , as shown in Fig. 4, in a similar procedure to that earlier utilized and described in Step 2 of the illuminance module.
2. Calculate average vertical illuminance (VE_{ok}) in the plane of the driver's eye at observer point o from each contributing luminaire k , using the inverse square law in a similar procedure to that earlier described in the illuminance module. The only difference between the two is that glare evaluation in this procedure requires the computation of the horizontal component of light intensity (HI_{ok}) at observer point o from luminaire k rather than the vertical one (VI_{ok}) used in the illuminance module procedure, as shown in the first equation.

This equation is used to derive the next equation to calculate VE_{ok} as a function of light intensity (I_{ok}) at point o from luminaire k , mounting height (h) of luminaire k , coordinates of observer point (x_o, y_o), and coordinates of luminaire k positioning (x_k, y_k)

$$VE_{ok} = \frac{HI_{ok}}{D_{ok}^2} \quad (11)$$

$$\begin{aligned} VE_{ok} &= \frac{I_{ok} \times \sin \beta_{ok}}{D_{ok}^2} \\ &= \frac{I_{ok} \times \sin \beta_{ok}}{((h - 1.45)^2 + \Delta X_{ok}^2 + \Delta Y_{ok}^2)} \\ &= \frac{I_{ok} \times \sqrt{\Delta X_{ok}^2 + \Delta Y_{ok}^2}}{(\sqrt{(h - 1.45)^2 + \Delta X_{ok}^2 + \Delta Y_{ok}^2})^3} \end{aligned} \quad (12)$$

where VE_{ok} =vertical illuminance at the plane of the observer's eye at point o from luminaire k ; HI_{ok} =horizontal component of light intensity in the direction of the observer's eye at point o from luminaire k ; I_{ok} =light intensity in the direction of the observers' eye at point o from luminaire k ; D_{ok} =distance between luminaire k and observer's eye at point o as shown in Fig. 4; β_{ok} =vertical angle between the nadir and the line connecting luminaire k and observer's eye at point o (see Fig. 4); ΔX_{ok} =horizontal distance in the x direction between observer at point o and luminaire k ; and ΔY_{ok} =horizontal distance in the y direction between observer at point o and luminaire k .

3. Calculate the veiling luminance (disability glare) VL_{ok} experienced by the observer/driver at point o from luminaire k , by using the formula adopted in IESNA standards for roadway lighting (IESNA 2000). As shown in the following equations, VL_{ok} is computed as a function of the above computed vertical illuminance (VE_{ok}) in the plane of observer's eye at point o , and the angle (θ_{ok}) between the observer line of sight and the line connecting observer's eye at point o and luminaire k (see Fig. 4)

$$VL_{ok} = \left(\frac{T}{\theta^n} \right)_{ok} \quad (13)$$

$$T_{ok} = 10 \times VE_{ok} \quad (14)$$

$$n = 2.3 - 0.7 \times \log(\theta)_{ok} \quad \text{for } \theta_{ok} < 2^\circ \quad (15)$$

$$n = 2 \quad \text{for } \theta_{ok} \geq 2^\circ$$

where VL_{ok} =veiling luminance (glare) experienced by observer at point o from luminaire k ; T_{ok} =variable that can be calculated using Eq. (14); θ_{ok} =angle between the line of sight at observer's location o and the line connecting observer's eye and luminaire k (see Fig. 4); and n =variable which can be calculated using Eq. (15).

4. Calculate the veiling luminance (disability glare) VL_o experienced by observer eye at point o from all contributing luminaries, as shown in the following equation:

Table 1. Analyzed Lighting Plans

| Analyzed lighting plan | Lighting arrangement parameters ^a | | | | | | | | | | | |
|------------------------|--|----------|----------|----------------------------|-------------------------------|------------|------------|------------|---------------------------------|------------|------------|------------|
| | Luminaire positioning ^b | | | Mounting height h (m) | Aiming angle of luminaire k | | | | Rotation angle of luminaire k | | | |
| | (X_k, Y_k) | | | | ω_k | | | | π_k^c | | | |
| | $k=1-4$ | $k=5-8$ | $k=9-12$ | | $k=1,5,9$ | $k=2,6,10$ | $k=3,7,11$ | $k=4,8,12$ | $k=1,5,9$ | $k=2,6,10$ | $k=3,7,11$ | $k=4,8,12$ |
| 1 | (−2, 15) | (−2, 45) | (−2, 75) | 7.8 | 20 | 32 | 20 | 21 | 45 | 45 | −45 | −45 |
| 2 | (−2, 15) | (−2, 45) | (−2, 75) | 7.8 | 28 | 27 | 20 | 18 | 45 | 45 | −45 | −45 |
| 3 | (−2, 15) | (−2, 45) | (−2, 75) | 7.8 | 25 | 20 | 25 | 20 | −45 | −45 | 45 | 45 |
| 4 | (−2, 15) | (−2, 45) | (−2, 75) | 7.8 | 45 | 45 | 45 | 45 | −45 | −45 | 45 | 45 |
| 5 | (−2, 15) | (−2, 45) | (−2, 75) | 7.8 | 42 | 42 | 20 | 20 | 70 | 22 | −70 | −20 |

^aThe total number of lighting equipment (N) is 3, and the total number of luminaires (K) is 12.

^bPosition of luminaire k is represented by its coordinates in the work zone (X_k, Y_k) , as shown in Fig. 2.

^c π_k value represents rotation angle measured from a perpendicular direction to the road, where positive and negative values indicate clockwise and counterclockwise rotations, respectively.

$$VL_o = \sum_{k=1}^K VL_{ok} \quad (16)$$

where VL_o =veiling luminance (i.e., disability glare) value experience by observer at point o from all contributing luminaires.

After the completion of computations in Phases 1 and 2, the obtained values of pavement luminance L_o and veiling luminance VL_o are then used to evaluate the glare levels experienced by the drivers in various observation points ($o=1-O$). This is achieved by calculating the veiling luminance ratio at each observer point o (V_o), which represents the ratio between the veiling luminance (VL_o) and the pavement luminance (L_o) experienced by the driver at each observer point o , as shown in the following equation. This module searches for the maximum (i.e., most critical) veiling luminance ratio (V) in all possible observer points ($o=1-O$) in order to ensure that the highest glare level in the vicinity of the nighttime construction site is within the maximum allowable limits imposed by the relevant lighting design criteria

$$\text{veiling luminance ratio}(V_o) = \frac{VL_o}{L_o} \quad (17)$$

Application Example

An application example is analyzed to illustrate the use of the present model and demonstrate its capabilities. The analyzed example requires the development of a practical lighting plan for a typical nighttime work zone that is 90 m long and 6 m wide. The lighting specifications for this work zone requires the provision of: (1) a minimum average illuminance level of 216 lx in the work area to ensure the availability of adequate lighting conditions for all nighttime construction tasks; (2) a maximum uniformity ratio of 6 to guarantee uniform distribution of lighting in the entire work zone; and (3) a maximum veiling luminance ratio of 0.4 in and around the construction site to minimize the negative impact of glare on road users and construction workers, alike.

The available lighting equipment for the construction planner in this example is three identical light towers. In order to ensure the best utilization of this available equipment, the construction planner needs to evaluate various lighting plans and select a practical one that satisfies all the above lighting requirements. In order

to support the construction planner in this vital task, the present lighting design model is used to examine a number of lighting designs that represents various combinations of the earlier described lighting equipment parameters and arrangement parameters (see Fig. 1). First, the examined lighting equipment parameters in this example are considered to have the following typical values for the three available light towers: (1) type of lamps used (ψ) is metal halide; (2) lamp lumen output (μ) is 100,000 lm; (3) type of luminaire light distribution (δ) is NEMA 7 (Excelline 2003); and (4) light depreciation (ϕ) is assumed to be 0.85. Second, the analyzed lighting arrangement parameters in this example are varied to enable the examination of several lighting designs, as shown in Table 1.

A total of five lighting plans were analyzed using the present model to enable the examination of various design parameters, as shown in Table 1. The impact of each lighting plan on the three lighting design criteria of illuminance, uniformity, and glare was evaluated using *CONLIGHT*, as shown in Table 2. The results of this evaluation indicate that all these developed plans are capable of satisfying all the lighting requirements in this example (see Table 2). The planner can evaluate the performance of these alternatives and select a lighting plan that provides the best tradeoff among the three lighting design criteria, depending on the priorities of the specific project being planned. For example, if minimizing glare is the most important criterion in the project, the planner can select lighting Plan 3 (see Table 2) that provides the least possible glare while satisfying all the requirements of the remaining lighting design criteria.

In order to measure the accuracy of *CONLIGHT*, a set of field experiments were conducted to enable a comparison between the results provided by the model and those measured in the field for the same set of five lighting plans developed in this example. In order to facilitate the measurement of actual illuminance levels and lighting uniformity ratios in the field tests, the experimental site was divided into a grid of equally spaced points that were marked on the pavement surface. This grid of points in the field was designed to match that used in the present model to ensure consistency between the results provided by both. Similarly, the experimental site was set up in a way that enabled driving through the work zone in both directions in order to measure and evaluate glare levels (i.e., veiling luminance ratio) in and around the construction site.

For each of the tested lighting plans, the measured performances in the three major lighting design criteria (i.e., average

Table 2. Accuracy of Model Computations

| Tested lighting arrangement | Average illuminance lx E_{avg} | | | Lighting uniformity ratio U | | | Glare (veiling luminance ratio) (V) | | |
|-----------------------------------|-------------------------------------|---------------------|------------------------------|----------------------------------|---------------------|------------------------------|--|---------------------|------------------------------|
| | Computed by model | Measured on site | Accuracy ^a (%) | Computed by model | Measured on site | Accuracy ^a (%) | Computed by model | Measured on site | Accuracy ^a (%) |
| 1 | 459 | 539 | 85 | 4.59 | 4.40 | 96 | 0.130 | 0.109 | 81 |
| 2 | 424 | 454 | 93 | 3.94 | 4.16 | 95 | 0.131 | 0.115 | 86 |
| 3 | 354 | 346 | 98 | 3.73 | 4.90 | 76 | 0.111 | 0.095 | 83 |
| 4 | 451 | 358 | 74 | 3.76 | 4.40 | 86 | 0.230 | 0.199 | 84 |
| 5 | 455 | 408 | 88 | 4.15 | 5.20 | 80 | 0.194 | 0.166 | 83 |
| Average accuracy | | | 88 | | | 86 | | | 84 |

^aAccuracy (%) = $100\% - [(| \text{measured value} - \text{computed value} |) / \text{measured value}] \times 100\%$.

illuminance, lighting uniformity, and glare) were compared to those obtained using *CONLIGHT*. The results of this analysis indicate that there is close agreement between the results provided by the model and those measured on site (see Table 2). For these five tested lighting plans, the average accuracy of *CONLIGHT* was found to be: (1) 88% for average illuminance levels; (2) 86% for lighting uniformity ratios; and (3) 84% for veiling luminance ratios/glare, as shown in Table 2. This level of accuracy combined with the practical capabilities of the present model provides much needed support for construction planners who are required to develop and evaluate practical lighting plans for nighttime highway construction projects.

Summary and Conclusion

A construction lighting design model, named *CONLIGHT*, was developed to support the required lighting design process in nighttime highway construction and rehabilitation projects. *CONLIGHT* was developed in two main stages: design and implementation. In the first stage, the model was designed to enable decision makers to evaluate the performance of practical lighting designs prior to the start of nighttime construction. In the second stage, *CONLIGHT* was implemented in three modules to quantify and measure the impact of various lighting plans on three major design criteria in order to ensure that: (1) illuminance levels on site are adequate for all planned nighttime construction tasks; (2) uniformity of light is evenly distributed in all parts of the work area; and (3) glare levels are controlled in and around the nighttime construction site to minimize their negative impact on both road users and construction workers. An application example was analyzed to illustrate the use of the model and demonstrate its accuracy and capabilities. The results of this analysis indicate that *CONLIGHT* is capable of providing reliable results, and therefore can be used as a practical and useful tool to: (1) generate practical lighting designs that specify all relevant design parameters in this lighting problem; and (2) verify that the selected design complies with all design requirements for nighttime construction. This provides much needed support for construction planners and is expected to enhance lighting conditions in nighttime construction projects, leading to improved levels of safety, quality, and productivity in these projects.

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Notation

The following symbols are used in this paper:

- D_{ok} = distance between observer point o and luminaire k ;
- D_{pk} = distance between grid point p and luminaire k ;
- E_{avg} = average illuminance in work area;
- E_{min} = minimum illuminance level in all grid points;
- E_p = horizontal illuminance at grid point p from all contributing luminaires;
- E_{pk} = horizontal illuminance at grid point p from luminaire k ;
- HI_{ok} = horizontal component of light intensity in direction of observer's eye at point o from luminaire k ;
- h = mounting height of luminaire k above road surface;
- I_{ok} = light intensity directed from luminaire k towards observer's point o ;
- I_{pk} = light intensity directed from luminaire k towards grid point p ;
- L_o = average pavement luminance viewed by driver at observer point o ;
- L_{og} = pavement luminance at view point g produced by reflected light from all luminaires towards observer point o ;
- L_{ogk} = pavement luminance produced by portion of light from luminaire k that is reflected at view point g towards observer point o ;
- L_{ototal} = accumulated pavement luminance for observer at point o ;
- r_{ogk} = reflectance coefficient for light generated from luminaire k , and reflected at view point g towards observer point o ;
- U = lighting uniformity ratio in work area;
- VE_{ok} = vertical illuminance at plane of observer's eye at point o from luminaire k ;
- VI_{pk} = vertical light intensity at grid point p from luminaire k ;
- VL_o = veiling luminance (i.e., disability glare) value experience by observer at point o from all contributing luminaires;
- VL_o = veiling luminance ratio at observer point o ;
- VL_{ok} = veiling luminance experienced by observer at point o from luminaire k ;
- β_{ok} = vertical angle between nadir and line connecting luminaire k and observer's eye at point o ;

ΔX_{ok} = horizontal distance in x direction between observer point o and luminaire k ;
 ΔX_{pk} = horizontal distance in x direction between grid point p and luminaire k ;
 ΔX_{yk} = horizontal distance in y direction between grid point p and luminaire k ;
 ΔY_{ok} = horizontal distance in y direction between point o and luminaire k ;
 θ_{ok} = angle between line of sight at observer's location o and line connecting observer's eye and luminaire k ;
 λ = vertical angle between nadir and line connecting luminaire k and point p ;
 π_k = rotation angle of luminaire k ; and
 ω_k = aiming angle of luminaire k .

Subscripts and Superscripts

g = view point (from $g=1$ to G);
 k = luminaire (from $k=1$ to K);
 o = observer point (from $o=1$ to O); and
 p = grid point (from $p=1$ to P).

References

- Al-Kaisy, A., and Nassar, K. (2003). "Nighttime construction issues revisited." *Proc., Transportation Research Board 82nd Annual Meeting*.
- Bryden, J., and Mace, D. (2002). "Guidelines for design and operation of nighttime traffic control for highway maintenance and construction." *NCHRP Rep. No. 476*, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C.
- Cottrell, B. H. (1999). "Improving night work zone traffic control." *Final Rep. Prepared for Virginia Transportation Research Council*, Virginia Department of Transportation and the University of Virginia, Charlottesville, Va.
- Ellis, R. D., Jr., and Amos, S. J. (1996). "Development of work zone lighting standards for nighttime highway work." *Transportation Research Record. 1529*, Transportation Research Board, Washington, D.C.
- El-Rayes, K., and Hyari, K. (2002). "Automated DSS for lighting design of nighttime operations in highway construction projects." *Proc., 19th Int. Symp. on Automation and Robotics in Construction, ISARC 2002*, National Institute of Standards and Technology, Gaithersburg, Md.
- El-Rayes, K., and Hyari, K. (2003). "Lighting design requirements for highway nighttime construction." *Proc., Construction Research Congress*, ASCE, Reston, Va.
- Excelsine (2003). "Floodlighting lighting design." http://www.excelsine.com/catalog_pdf/SINGLEPA/PAGES100/Page_179.pdf
- Federal Highway Administration (FHWA). (2000). *Manual on uniform traffic control devices*, United States Department of Transportation, Washington, D.C.
- Hancher, D., and Taylor, T. (2001). "Night-time construction issues." *Paper Presented at the Transportation Research Board 80th Annual Meeting*.
- Homberger, W. S., and Kell, J. H. (1988). *Fundamentals of traffic engineering*, 12th Ed., Institute of Transportation Studies, Univ. of California at Berkeley, Berkeley, Calif.
- Illumination Engineering Society of North America (IESNA). (1998). "IESNA guide for choosing light sources for general lighting." *Rep. No. DG-10-98*, New York.
- Illuminating Engineering Society of North America (IESNA). (2000). "IESNA practice for roadway lighting." *Rep. No. ANSI/IESNA RP-8-00*, American National Standard, New York.
- Kaufman, J. E., and Haynes, H., eds. (1981). *IES lighting handbook*, Reference Vol., Illuminating Engineering Society of North America, New York.
- Kumar, A. (1994). "Development of a model for determining work zone illumination requirements during nighttime highway construction." PhD dissertation, Univ. of Florida, Gainesville, Fla.
- New York State Department of Transportation (1995). "Lighting for nighttime operations—special specifications." *Engineering Instruction 95-005*, New York.
- North Carolina Department of Transportation (1995). "Portable construction lighting." www.doh.dot.state.nc.us/preconstruct/highway/dsn_srvc/specifications/english/s1412.htm
- O'Malley, P. (2002). "Construction work at night: The view from under the lights." *Grading and Excavation Contractor* (July/August) www.gradingandexcavation.com
- Park, S., Douglas, K., Griffith, P., and Haas, K. (2002). "Factors of importance for determining daytime versus nighttime operations in Oregon." *Paper Presented at the Transportation Research Board 81st Annual Meeting*.
- Pritchard, D. C. (1999). *Lighting*, 6th Ed., Addison Longman, Edinburgh Gate, Harlow, Essex, U.K.