Field Experiments to Evaluate and Control Light Tower Glare in Nighttime Work Zones

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Abstract: An increasing volume of highway repair and construction work is being performed during the off-peak nighttime hours to mitigate the impact of construction-related daytime traffic congestions and shorten the duration of construction operations. The utilization and placement of light towers to illuminate the work zone in this type of construction can cause harmful levels of glare for both drivers and construction workers. This paper presents the results of field experiments which were conducted to (1) study the levels of glare and lighting performance generated by light towers in and around nighttime work zones; (2) analyze the combined impact of the light tower set up parameters including its height as well as its aiming and rotation angles on glare and lighting performance; and (3) provide practical recommendations to reduce and control lighting glare in and around nighttime work zones. The results of these experiments confirm that the set up of light towers has a significant impact on glare and therefore it should be carefully designed and executed on nighttime highway construction projects to ensure the safety of the traveling public as well as construction workers.

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Introduction

Light towers are often used to provide lighting for stationary operations in nighttime work zones (TDOT 2006; Bryden and Mace 2002; DelDOT 2001; New York State Department of Transportation 1995). Improper utilization of this type of lighting equipment, however, causes harmful levels of glare to both the traveling public and construction workers (El-Rayes and Hyari 2005a,b; Hyari 2004; Ellis et al. 2003; El-Rayes et al. 2003; Bryden and Mace 2002; Ellis and Amos 1996; Amos 1994). Glare is a term used to describe the sensation of annoyance, discomfort, or loss of visual performance and visibility produced by experiencing luminance in the visual field significantly greater than that to which the eyes of the observer are adapted (Traister 1982). Glare from work zone lighting is reported to be one of the most serious challenges confronting nighttime construction operations as it leads to increased levels of hazards and work zone crashes (El-Rayes et al. 2003; Hancher and Taylor 2001; Shepard and Cottrel 1985).

The levels of glare generated by light towers in and around nighttime work zones depend on two main setup parameters: (1) the height of the light tower and (2) the aiming angle (AA) and rotation angle (RA) of the luminaries in the tower (El-Rayes and Hyari 2005a,b; El-Rayes et al. 2003). A number of research studies were conducted to control glare in and around nighttime highway construction projects (Hyari and El-Rayes 2006a,b; El-Rayes and Hyari 2005a,b; Hyari 2004; El-Rayes et al. 2003; Ellis et al. 2003; Bryden and Mace 2002; Greenquist 2001; Hancher and Taylor 2001; MUTCD 2000; Cottrell 1999; Ellis and Amos 1996; Ellis et al. 2003; Amos 1994; Shepard and Cottrel 1985). For example, Ellis and Amos (1996) developed a number of recommendations to control glare such as keeping the AA of luminaries to be less than 60°. Similarly, Bryden and Mace (2002) recommended that light towers should be fully extended to their maximum mounting height to control lighting glare. Despite the significant research efforts and contributions of these studies, they all focused on providing recommendations to control glare and did not measure and quantify the impact of the aforementioned equipment setup parameters on the levels of glare experienced by the traveling public. To control and mitigate the hazardous effects of this type of glare on nighttime drivers, there is a pressing need to measure and quantify the impact of the setup parameters of light towers on the generated levels of glare.

Objective

The objective of this paper is to present the results of field experiments that were conducted to study and evaluate the levels of glare and lighting performance caused by light towers in nighttime work zones. The objectives of these experiments are to (1) analyze and compare the lighting performance and levels of glare generated by typical setup arrangements for light towers in nighttime highway construction; (2) analyze the combined impact of light tower height, AA and RA on glare levels, and lighting performance in and around nighttime work zones; and (3) provide practical recommendations for light tower setup and arrangements to reduce lighting glare. To accomplish these objectives, the field experiments were conducted in four stages that focused on (1)

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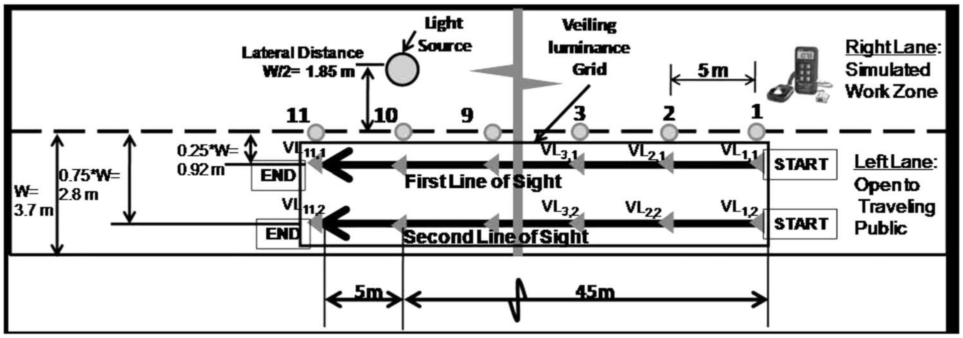

Fig. 1. Veiling luminance measurements

setting up the experiment site and measurement procedures; (2) measuring glare and lighting performance for a number of tested lighting arrangements; (3) analyzing the impact of lighting parameters on glare; and (4) developing practical recommendations to control the glare. The following sections describe these four main phases of the conducted field experiments and summarize their main findings.

Experiment Setup and Measurement Procedures

The field experiments were conducted at the Illinois Center for Transportation (ICT) at the University of Illinois at Urbana–Champaign, which is located in Rantoul, Illinois. The experiments were conducted over a period of 33 days from May 10, 2007 to June 12, 2007 at the ICT in Rantoul, Ill. During this period, the experiments were interrupted several nights due to adverse weather conditions of thunderstorms and rain. The daily experiments typically started 1 h before sunset to enable the research team to prepare the construction site for the experiment. Every night, the research team proceeded with lighting measurements as soon as it was completely dark after sunset and continued until sunrise.

The location of the experiments was selected in a segment of street not equipped with any type of a street lighting. A length of 405 m of the two-lane street was closed to traffic from both directions to allow the research team to safely simulate typical lighting conditions in nighttime work zones and facilitate the measurement of lighting glare. As shown in Figs. 1 and 2, the two lanes were used to simulate (1) a nighttime work zone in the right lane to enable the positioning and testing of various types of lighting arrangements and (2) an open traffic lane for the traveling public in the left lane to measure glare that would be experienced by drive-by motorists. Each work zone layout was divided into a grid of equally spaced points of 5 m. The grid was marked by construction cones on the pavement surface to enable a uniform pattern of measurements to facilitate the calculation of the veiling luminance and lighting uniformity ratios. A typical light tower was used in this experiment that was equipped with four 1,000-W metal halide luminaries. AA and RA of all luminaries are adjustable in all directions and their mounting height can be extended up to 8.5 m.

Veiling Luminance Ratio (Glare) Measurements Procedure

To control and minimize the harmful effects of glare on nighttime drivers, Illuminating Engineering Society of North America (IESNA) recommends a maximum veiling luminance ratio of 0.4 in roadway lighting design (IESNA 2004). The veiling luminance ratio can be calculated using the formula recommended by IESNA standards for roadway lighting (IESNA 2004) as follows:

$$\mathrm{VL} = \frac{10\mathrm{VE}}{\theta^n} \tag{1}$$

$$n = 2.3 - 0.7\log_{10}(\theta) \quad \text{for } \theta < 2° \tag{2}$$

$$n = 2 \quad \text{for } \theta > 2° \tag{3}$$

where VL = veiling luminance from the light source; VE = vertical illuminance measured using an illuminance meter at the plane of the observer's eye; and θ = angle between the line of sight at the observer's location and the line connecting the observer's eye and the luminaire.

In the field experiments, the measurement and calculation of the veiling luminance ratio (glare) were designed to comply with the recommendations of the IESNA (2004) for isolated traffic conflict areas (partial or noncontinuous intersection lighting) due to the similarity between the lighting conditions in these areas and those encountered in nighttime work zones. The IESNA recommends that test points for the veiling luminance be along two quarter lane lines in all lanes in the chosen direction. Moreover, the area for glare measurements should extend from one mount-

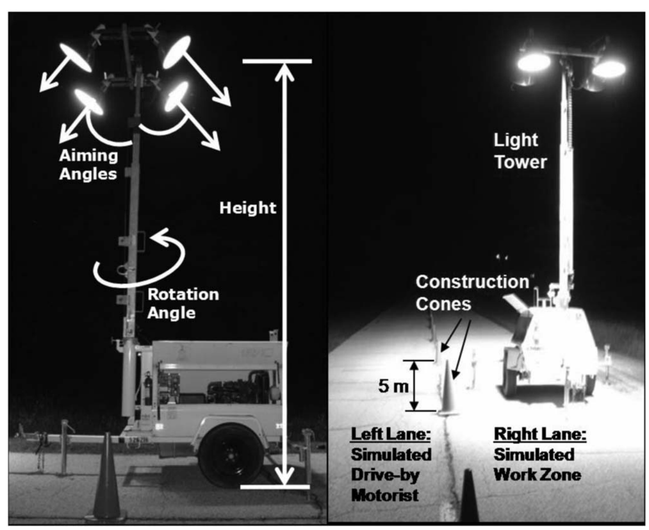

Fig. 2. Tested lighting parameters and site layout

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Fig. 3. VE measurements

ing height of the light tower in front of the light to 45 m before that point using a grid spacing of 5 m, as shown in Fig. 1.

The measurement and calculation of the veiling luminance ratio (glare) were performed using three main steps: (1) veiling luminance measurement and calculation; (2) pavement luminance measurement and calculation; and (3) veiling luminance ratio calculation.

Step 1: Veiling Luminance Measurement and Calculation

The locations for measuring and calculating the veiling luminance were selected in compliance with the IESNA/ANSI RP-8-00 recommendations, as shown in Fig. 1. Accordingly, the vertical illuminance (VE) was measured using an illuminance meter at each location on the grid for both lines of sight. These measurements were taken from inside the car to simulate the VE experienced by nighttime drivers passing by the construction zone, as shown in Fig. 3. The first measurement for the first line of sight was taken at Point 1 (see Fig. 1) and then the car was moved 5 m along the first line of sight and the next reading was taken until the end of the grid. Upon the completion of measurements along the first line of sight, the car was repositioned on the second line of sight, which is 1.88 m separated from the first line of sight and the process was repeated for the rest of the grid points. For each point on the grid, the veiling luminance was calculated using Eq. (1).

Step 2: Pavement Luminance Measurement and Calculation

The pavement luminance was measured using a luminance meter for each grid point shown in Fig. 4. Based on IESNA recommendations, the observer was located at a distance of 83.07 m from each grid point on a line parallel to the centerline of the roadway (IESNA 2004). The height of the observer's eyes was also set at 1.45 m in compliance with the IESNA recommendations, which results in a downward direction of view of one degree. The pavement luminance was measured using a luminance meter inside the car to simulate the conditions experienced by motorists driving by the construction zone. The first pavement luminance measurement at Point 1 on the first line of sight ($PL_{1,1}$) was taken by positioning the car and observer at Point A at a distance of 83.07 m from Point 1, as shown in Fig. 4. The car was then moved 5 m along the first line of sight and the next reading was taken until reaching the last pavement luminance reading ($PL_{27,1}$). Upon the completion of measurements for the first line of sight, the car was repositioned at Point B on the second line of sight, which is 1.88 m separated from the first line of sight and a similar measurement procedure was repeated for the rest of the grid points. The second line of sight measurements were conducted in compliance with IESNA standards that require measurements in both lines of sight to control glare for drivers in all types of vehicles. The average pavement luminance was then calculated by averaging the pavement luminance measurements for all the points in the grid shown in Fig. 4 in compliance with IESNA recommendations (IESNA 2004).

Step 3: Veiling Luminance Ratio (Glare) Calculation

In this step, the veiling luminance ratio (glare) is calculated as the ratio between the veiling luminance, which was measured in Step 1 at each point in the shown grid in Fig. 1, to the average pavement luminance calculated in Step 2.

Horizontal Illuminance and Uniformity Ratio Measurements Procedure

To ensure the availability of adequate lighting conditions for nighttime construction tasks, existing nighttime construction

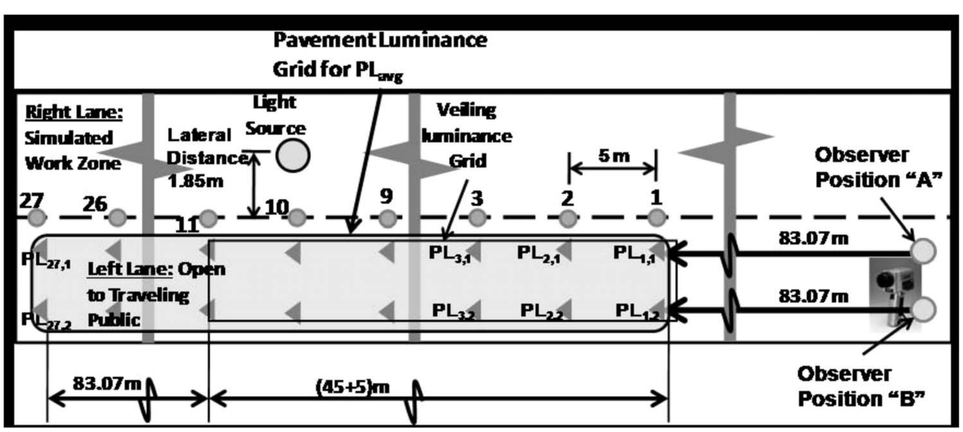

Fig. 4. Pavement luminance measurements

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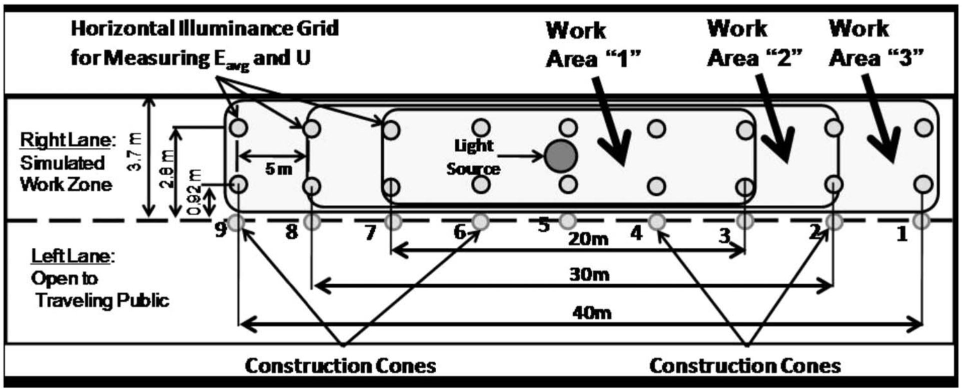

Fig. 5. HI measurements

specifications require a minimum level of average horizontal illuminance (HI). Illuminance represents the density of luminous flux (i.e., time rate of flow of light measured in lumens) incident on a surface area in lux (lm/m^2) and it can be measured on-site using simple illuminance meters. The minimum illuminance level required by existing nighttime lighting specifications depends on the type of construction task and it ranges from 54 to 216 lx (Bryden and Mace 2003; Ellis et al. 2003; Oregon DOT 2003; California DOT 2001; Michigan DOT 1999; Hutchings 1998; New York State DOT 1995; North Carolina DOT 1995; CIE Technical Committee TC-4.5 1986; Australian Government Publishing Service 1979; American National Standard Institute 1973). Similarly, existing nighttime lighting standards specify a maximum allowable ratio of lighting uniformity in the work area to ensure that light is uniformly distributed. Lighting uniformity can be quantified using a ratio of average illuminance on site to the minimum level of illuminance measured in the work area (IESNA 2004). The maximum levels of uniformity ratio specified in existing nighttime lighting standards range from 5:1 to 10:1 (Ellis et al. 2003; El-Rayes et al. 2003; Oregon DOT 2003; New York State DOT 1995).

To evaluate the lighting performance of the tested lighting tower in satisfying the aforementioned lighting specifications, the HI and the lighting uniformity ratio were measured in the field experiments. The HI was measured using an illuminance meter at each measurement point on the grid shown in Fig. 5. The measurement points in this grid were located along the two quarter lane lines in the simulated work zone and extended 20 m on both sides of the light tower with spacing of 5 m in compliance with IESNA (2004). These HI measurements were then averaged to calculate the average HI (E_{avg}) in the specified work area. For each tested lighting arrangement, the average HI was calculated for three possible scenarios of work areas with a length of 20, 30, or 40 m, as shown in Fig. 5. These lengths were selected to represent the typical work areas on both sides of the light tower and/or the spacing between equally spaced light towers along the length of the work zone that were observed during a number of site visits to nighttime work zones.

The lighting uniformity ratio (U) is represented by the ratio between the previously calculated average illuminance in the work area (E_{avg}) and the minimum illuminance measured at any grid point in the work zone, as shown in Eq. (4). It should be noted that lighting uniformity improves on construction zones when the value of the uniformity ratio decreases, which indicates smaller differences between the darkest point and the average illuminance in the work area

$$U = \frac{E_{\mathrm{avg}}}{E_{\mathrm{min}}} \tag{4}$$

where E_{avg} = average HI in the work area (in lux) and E_{min} = minimum measured value of the HI in the grid in the work zone (in lux).

Glare and Lighting Performance Measurements

Field experiments were conducted to study the lighting performance and glare for 14 different lighting arrangements for the tested light tower, as shown in Table 1. These 14 tested cases were selected to represent typical lighting arrangements in nighttime highway construction based on the findings of several site visits that were previously conducted by the research team (El-Rayes et al. 2007). During the site visits, the research team observed the utilization of light towers to illuminate the work area for a number of nighttime highway construction activities, such as bridge girders repairs, pavement patching and repairs, and work zone flagger stations. One of the main findings of the site visits was that the most critical location of the light tower was encountered when it was positioned in the middle of the closed lane in the work zone at a distance of 1.85 m (see Fig. 1) from drive-by

Table 1. Tested Lighting Arrangements

Tested lighting arrangement	Tested parameters		
	Height (H)	RA	AA of four luminaries
1	5.0 m		0°
2			20°
3		0°	45°
4			2 at 20° and 2 at 0°
5		20°	2 at 45° and 2 at 0°
6			2 at 20° and 2 at 0°
7		45°	2 at 45° and 2 at 0°
8	8.5 m		0°
9			20°
10		0°	45°
11			2 at 20° and 2 at 0°
12		20°	2 at 45° and 2 at 0°
13			2 at 20° and 2 at 0°
14		45°	2 at 45° and 2 at 0°

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Table 2. Veiling Luminance Ratios at First Line of Sight

Distance from light tower (m)	Tested lighting arrangements													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−5	0.01	0.03	0.04	0.13	0.07	0.03	0.05	0.01	0.02	0.01	0.03	0.02	0.02	0.03
−10	0.11[b]	0.18[b]	0.36	0.18[b]	1.02[a,b]	0.35[b]	0.35	0.01	0.01	0.02	0.02	0.05	0.02	0.02
−15	0.08	0.13	0.77[a,b]	0.14	0.69[a]	0.19	0.39[b]	0.02	0.02	0.05	0.03	0.06	0.02	0.04
−20	0.06	0.10	0.64[a]	0.11	0.55[a]	0.13	0.29	0.03[b]	0.05[b]	0.19	0.14[b]	0.08	0.07[b]	0.08
−25	0.05	0.08	0.59[a]	0.09	0.48[a]	0.10	0.20	0.02	0.04	0.35[b]	0.14	0.27[b]	0.06	0.16[b]
−30	0.04	0.07	0.53[a]	0.09	0.43[a]	0.09	0.21	0.02	0.03	0.27	0.11	0.23	0.04	0.15
−35	0.03	0.07	0.49[a]	0.08	0.40	0.08	0.13	0.02	0.03	0.24	0.09	0.21	0.03	0.12
−40	0.03	0.06	0.47[a]	0.08	0.37	0.08	0.12	0.01	0.02	0.22	0.07	0.19	0.03	0.10
−45	0.03	0.06	0.43[a]	0.07	0.35	0.07	0.08	0.01	0.02	0.20	0.05	0.18	0.03	0.09

[a]Measured veiling luminance ratio exceeded the recommended 0.4 ratio by IESNA.

[b]Maximum veiling luminance ratio for the tested arrangements.

motorists in the adjacent open lane. Accordingly, the field experiments were designed to test the lighting performance of the light tower in this critical location to simulate the worst case scenario of glare that can be experienced by drive-by motorists.

The light tower was tested to examine the impact of three different parameters on the veiling luminance ratio and lighting performance. The tested parameters include (1) the height of the light tower (H) which represents the vertical distance between the center of the luminaries and the road surface; (2) the RA of the light tower which represents the rotation of the light tower pole around a vertical axis; and (3) the AAs of the four luminaries that denote the vertical angle between the center of the beam spread of the luminaire and the nadir, as shown in Fig. 2. Table 1 summarizes the 14 tested lighting arrangements that represent typical combinations of the tested lighting arrangements.

For each of the tested lighting arrangement, the veiling luminance ratio for drive-by motorists was measured and calculated as well as the average HI and lighting uniformity ratio in the work area. The measured veiling luminance ratios (V) for the two lines of sight for each test are summarized in Tables 2 and 3. Furthermore, the average illuminance and lighting uniformity ratio (U) values for the three work areas shown in Fig. 5 are shown in Table 4 for the 14 tested lighting arrangements. The main findings of the experiments for the 14 tested lighting arrangements can be summarized as follows:

1. The veiling luminance ratios (glare) exceeded the recommended 0.4 limit for roadway lighting design (IESNA 2004) in two of the tested lighting arrangements: Case 3 and Case 5 when the height of the light tower was 5 m, the AAs were 45° and when the RA was 0° and 20°, as shown in Tables 2 and 3.
2. The average illuminance in the work area for all the tested arrangements complied with existing lighting specification that requires a minimum of 216 lx, as shown in Table 4.
3. The lighting uniformity ratio in the work area exceeded the recommended 10:1 ratio in most of the tested cases, as shown in Table 4.
4. Veiling luminance ratio (glare) steadily increases for drive by motorists as they approach the light source and it reaches a peak at a distance that ranges between 10 and 15 m before the light tower for the 5-m light height while the peak glare value for the 8.5-m height was observed at a distance between 20 and 25 m before the light, as shown in Tables 2 and 3.

Table 3. Veiling Luminance Ratios at Second Line of Sight

Distance from light tower (m)	Tested lighting arrangements													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−5	0.01	0.01	0.01	0.09	0.04	0.02	0.04	0.01	0.01	0.00	0.02	0.01	0.01	0.02
−10	0.07[b]	0.08[b]	0.20	0.11[b]	0.67[a,b]	0.25[b]	0.30[b]	0.01	0.01	0.01	0.01	0.03	0.01	0.02
−15	0.05	0.08	0.44[a,b]	0.09	0.44[a]	0.13	0.26	0.01	0.01	0.01	0.03	0.07	0.02	0.04
−20	0.03	0.06	0.40	0.07	0.34	0.08	0.20	0.02[b]	0.04[b]	0.14	0.10	0.25[b]	0.06[b]	0.16[b]
−25	0.03	0.05	0.35	0.06	0.30	0.07	0.15	0.02	0.03	0.26[b]	0.11[b]	0.23	0.05	0.15
−30	0.02	0.04	0.33	0.06	0.28	0.06	0.12	0.02	0.03	0.21	0.08	0.19	0.03	0.13
−35	0.02	0.04	0.30	0.05	0.26	0.05	0.10	0.01	0.02	0.19	0.07	0.17	0.03	0.11
−40	0.02	0.04	0.29	0.05	0.24	0.05	0.09	0.01	0.02	0.18	0.06	0.16	0.02	0.09
−45	0.02	0.04	0.29	0.05	0.23	0.04	0.06	0.01	0.02	0.17	0.05	0.15	0.02	0.08

[a]Measured veiling luminance ratio exceeded the recommended 0.4 ratio by IESNA.

[b]Maximum veiling luminance ratio for the tested arrangement.

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Table 4. Average HI and Lighting Uniformity Ratios

	Work area length (m)	Tested lighting arrangement													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Average HI in lux (E_{avg})	20	1,311	680	826	1,011	979	945	696	750	6,201	557	687	620	593	528
	30	937	487	599	723	702	676	498	537	450	421	495	450	427	381
	40	729	379	468	563	547	526	388	418	352	333	386	352	333	298
Lighting uniformity ratio (U)	20	120	13	7	71	37	154	63	17	8	2	20	9	25	21
	30	440	76	22	160	116	735	125	95	19	6	38	23	59	38
	40	1,104	292	44	678	167	674	485	225	47	14	141	59	142	108

5. Veiling luminance ratios steadily decrease as the light height increases, as shown in Tables 2 and 3.
6. The RA and AA of the light tower luminaries have a direct impact on the veiling luminance ratios experienced at both lines of sight.

Impact of Lighting Parameters on Glare and Lighting Performance

This section summarizes the impact of the tested lighting parameters of (i.e., height, AA, and RA) on the veiling luminance ratio experienced by drive-by motorists as well as their impact on average HI and lighting uniformity ratio in the work area.

Height of Light

The results of the conducted experiments illustrate that the height of light tower has a significant impact on the veiling luminance ratio (glare) experienced by drive-by motorists. For the tested light tower, the results consistently indicate that veiling luminance ratios decrease as the light height increases. For example, the average veiling luminance ratio (V_{avg}) at the first line of sight when RA was 0° and AA was 45° was reduced by 64% when the height of the light source increased from 5 to 8.5 m, as shown in Fig. 6. Although increasing the height of light tower can significantly reduce the levels of glare for drive-by motorists and improve lighting uniformity, the only limitation of such a height increase is the associated reduction in the average HI (E_{avg}) in the work area, as shown in Table 4.

Aiming and Rotation Angles

The results of the conducted experiments illustrate that the aiming and RA of the light tower have an important impact on the veiling luminance ratio experienced by the traveling public. In the field experiments, 14 different combinations of AA and RA were tested, as shown in Table 1. The results of these experiments indicate that increasing the AA causes a steady increase in the veiling luminance ratios (glare) experienced by drive-by motor-

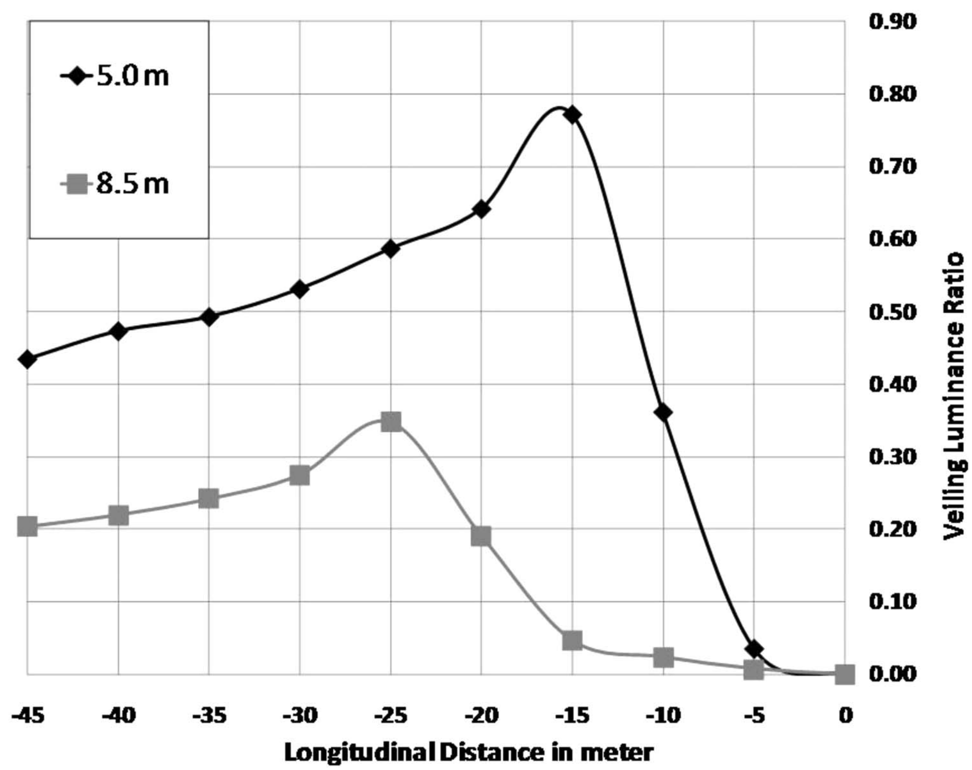

Fig. 6. Impact of height on veiling luminance ratio at first line of sight when RA is 0° and AA is 45°

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Table 5. Impact of Aiming Angle on Veiling Luminance Ratios

Tested lighting arrangement		1	2	3
Veiling luminance ratio (V_d) at distance (d) in meters	5	0.00	0.00	0.00
	0	0.00	0.00	0.00
	−5	0.01	0.03	0.04
	−10	0.11	0.18	0.36
	−15	0.08	0.13	0.77
	−20	0.06	0.10	0.64
	−25	0.05	0.08	0.59
	−30	0.04	0.07	0.53
	−35	0.03	0.07	0.49
	−40	0.03	0.06	0.47
	−45	0.03	0.06	0.43
Average veiling luminance ratio (V_{avg})		0.04	0.07	0.39
% change in V_{avg}		0	78	907
Maximum veiling luminance ratio (V_{max})		0.11	0.18	0.77
% change in V_{max}		0	62	615

ists. For example, when the height of the light tower was 5 m and the RA was 0°, the average veiling luminance ratio (V_{avg}) at the first line of sight increased from 0.04 to 0.07 (78%) and from 0.04 to 0.39 (907%) when the AAs of the luminaries were increased from 0° to 20° and 45°, respectively, as shown in Table 5. Moreover, an increase in the AAs from 0° to 20° and 45° decreases the average HI (E_{avg}) by 631 (48%) and 485 lx (37%) and decreases the lighting uniformity ratio (U) from 120 to 13 (89%) and 120 to 7 (94%) for the 20–m-long work area, respectively, as shown in Table 4.

The test results indicate that the impact of the RA on the veiling luminance ratio depends on the AA of the luminaries. For example, when the AA is 0°, varying the RA will have no impact on the veiling luminance ratio generated by the light tower. At an AA of 20° and a height of 5 m, the average veiling luminance

Table 6. Impact of RA on Veiling Luminance Ratios at 20° AA and 5-m Height

Tested lighting arrangement		2	4	6
Veiling luminance ratio (V_d) at distance (d) in meters	5	0.00	0.00	0.00
	0	0.00	0.00	0.00
	−5	0.03	0.13	0.03
	−10	0.18	0.18	0.35
	−15	0.13	0.14	0.19
	−20	0.10	0.11	0.13
	−25	0.08	0.09	0.10
	−30	0.07	0.09	0.09
	−35	0.07	0.08	0.08
	−40	0.06	0.08	0.08
	−45	0.06	0.07	0.07
Average veiling luminance ratio (V_{avg})		0.07	0.09	0.10
% change in V_{avg}		0	25	44
Maximum veiling luminance ratio (V_{max})		0.18	0.18	0.35
% change in V_{max}		0	1	98

Table 7. Impact of RA on Veiling Luminance Ratios at 45° AA and 5-m Height

Tested lighting arrangement		3	5	7
Veiling luminance ratio (V_d) at distance (d) in meters	5	0.00	0.00	0.00
	0	0.00	0.00	0.00
	−5	0.04	0.07	0.05
	−10	0.36	1.02	0.35
	−15	0.77	0.69	0.39
	−20	0.64	0.55	0.29
	−25	0.59	0.48	0.20
	−30	0.53	0.43	0.21
	−35	0.49	0.40	0.13
	−40	0.47	0.37	0.12
	−45	0.43	0.35	0.08
Average veiling luminance ratio (V_{avg})		0.39	0.40	0.17
% change in V_{avg}		0	1	−58
Maximum veiling luminance ratio (V_{max})		0.77	1.02	0.39
% change in V_{max}		0	32	−49

ratio (V_{avg}) at the first line of sight increased from 0.07 to 0.09 (25%) and from 0.07 to 0.10 (44%) when the RA increased from 0° to 20° and 45°, respectively, as shown in Table 6. Similarly when the AA was 20° and the height was 5 m, the maximum veiling luminance ratio (V_{max}) at the first line of sight increased from 0.0175 to 0.0176 (1%) and from 0.0175 to 0.35 (98%) when the RA increased from 0° to 20° and 45°, respectively, as shown in Table 6. At an AA of 45° on the other hand, the average veiling luminance ratio (V_{avg}) at the first line of sight first increased from 0.39 to 0.40 (1%) when the RA increased from 0° to 20° and then experienced a noticeable reduction from 0.39 to 0.17 (58%) when the RA increased from 0° to 45°, as shown in Table 7. Similarly when the AA was 45° and the height was 5 m, the maximum veiling luminance ratio (V_{max}) at the first line of sight increased from 0.77 to 1.02 (32%) when the RA increased from 0° to 20° and then experienced a reduction from 0.77 to 0.39 (49%) when the RA increased from 0° to 45°, as shown in Table 7.

These aforementioned results illustrate that the impact of the RA on the veiling luminance ratio depends on the AA and height, as shown in Fig. 7. When the AA is 20° and the height is 5 m, the center of the luminaires beam is aimed at a distance of 1.8 m from the base of the light tower, as shown in Arrangement A in Fig. 7. Rotating the light tower in this arrangement by 20° and 45° will lead to a steady increase in glare for drive-by motorists, which are represented by the shown two lines of sight in the figure. On the other hand, when the AA is 45° and the height is 5 m, the center of the luminaires beam is aimed at a distance of 5 m from the base of the light tower, as shown in Arrangement B in Fig. 7. Rotating the light tower in this arrangement by 20° will cause an increase in glare for drive-by motorists. However, a further increase in the RA to 45° will shift the center of the luminaires beam and its associated glare farther away from the drive-by motorists in the adjacent lane, as shown in Arrangement B in Fig. 7.

Practical Recommendations to Reduce and Control Glare

Based on the findings of the field experiments, the following practical recommendations can be made to reduce and control glare in and around nighttime highway construction zones:

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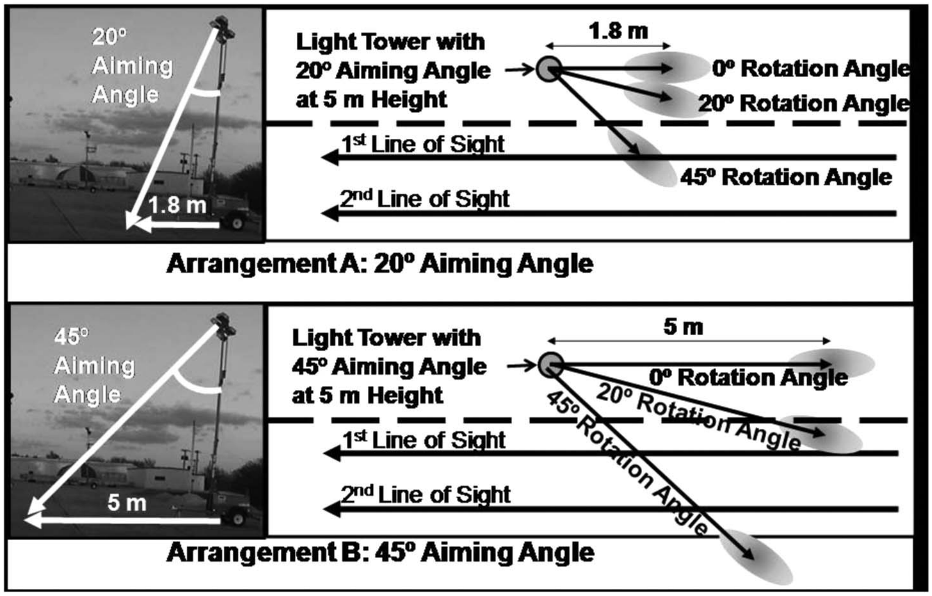

Fig. 7. Combined impact of AA and RA on drive-by motorists

1. The height of the light tower should be increased as practically feasible. As shown in Fig. 6, increasing the height of the light tower provides significant reductions in the average and maximum veiling luminance ratios. For example, increasing the height from 5 to 8.5 m reduced the average and maximum veiling luminance ratios in the conducted experiments by 64 and 55%, respectively.
2. The AA and RA for light towers should be kept as close as possible to 0°. The test results indicated that the veiling luminance ratios increase when the combined increase in the AA and RA leads to directing the center of the luminaires beam and its associated glare at the drive-by motorists in adjacent lanes, as shown in Fig. 7.
3. The location of the maximum veiling luminance ratios for the tested lighting arrangement in the experiments all were found at a range of 10–25 m before the light tower. For example, the maximum veiling luminance ratio at the first line of sight was encountered at a distance of 10 m from the light towers for tested arrangements 1, 2, 4, 5, and 6 when the height of the light tower was 5 m. Similarly, the maximum veiling luminance ratio was encountered at a distance of 15, 20, and 25 m for the other tested arrangements shown in Tables 2 and 3. Resident engineers can identify from these tables the critical locations (i.e., distances from the light tower) where the worst-case glare level is expected to occur for drive-by motorists based on the lighting setup on site and therefore can limit their evaluation of glare to only these few critical locations.

Summary and Conclusion

Field experiments were conducted to study and evaluate the levels of glare and lighting performance generated by typical light tower arrangements in and around nighttime work zones. A total of 14 different lighting arrangements were tested to examine the combined impact of the light tower height as well as its AA and RA on glare and lighting performance. The findings of the experiments confirm that (1) the veiling luminance ratio (glare) complied with the recommended 0.4 limit for roadway lighting design in 12 of the 14 tested lighting arrangements; (2) the average illuminance of all the tested lighting arrangements comply with existing state DOT lighting standards; (3) the lighting uniformity ratio in most of the tested cases exceeded the recommendation ratio by state DOT lighting standards; and (4) glare steadily increases for drive by motorists as they approach the light tower and it reaches a peak at a distance from the light tower that ranges between 10 and 25 m. Based on these findings, a number of practical recommendations were made to reduce and control glare in and around nighttime highway construction zones, including (1) increasing the height of the light tower as practically feasible and permissible by the equipment capabilities or the surrounding environment constraints such as the existence of adjacent bridges that may limit the light tower height and (2) adjusting the AA and RA of light towers to ensure that the direction of the center of the luminaires beam is not aimed at drive-by motorists in adjacent lanes by maintaining the angles as close as possible to 0°. These findings and recommendations should prove useful to resident engineers and contractors and are expected to enable them to control the harmful levels of glare in and around nighttime work zones to ensure the safety of the traveling public as well as construction workers.

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