New Approach to Compare Glare and Light Characteristics of Conventional and Balloon Lighting Systems

Marwa M. Hassan[1]; Ibrahim Odeh, S.M.ASCE[2]; and Khaled El-Rayes, M.ASCE[3]

Abstract: With the increasing needs to adopt nighttime construction strategies in order to avoid disruption of traffic flow, state agencies are currently experimenting with a new class of light towers known as balloon lights. Compared to regular lighting tower, balloon lights have been reported to reduce glare significantly and to provide more uniform lighting conditions at the site. The objective of this study was to measure light and glare characteristics of two balloon lighting systems in the field. Glare and lighting characteristics of this new class of light towers were compared to a conventional lighting system. For this purpose, field measurements were made of the pavement luminance and the horizontal and vertical illuminances on a predefined experimental grid. Results of this study indicated that while being comparable in terms of wattage and luminous flux, the tested balloon light systems differed in terms of light and glare characteristics. In addition, while conventional light tower provided greater illuminance at the light source than balloon lights, the disability glare was greater for conventional light tower than balloon lights when mounted at the same height. Results of this study revealed that optimum conditions should be sought in the work zone, through which adequate lighting conditions are provided for workers while disability glare is kept below a safe threshold for drive-by motorists. Plotting the maximum veiling luminance ratio (disability glare) against the workable distance provides a simple approach to consider the two factors concurrently in the design of work zone lighting.

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Introduction

The majority of the U.S. highway system was constructed during the 1950s and 1960s according to population, travel, and freight estimates relevant to those periods. Now, however, as traffic and freight loads have increased exponentially, and as aging, environmental action, use, and misuse have taken their toll, these older systems have begun to deteriorate rapidly, a situation that demands more effective pavement rehabilitation methodologies. Daytime repair and rehabilitation of deteriorated roads result in heavy congestion and delays for the traveling public and may affect the quality of the work performed under these conditions (Ellis et al. 2003).

As a result, many state agencies are increasingly favoring that repair and rehabilitation activities be performed at night. Nighttime construction offers many advantages to the public, to surrounding businesses, and to state agencies. These advantages have been widely recognized by researchers and practitioners in the field (Shepard and Cottrel 1985; McCall 1999; El-Rayes et al. 2008). Nighttime construction minimizes congestion and delay to the road users and reduces economic impacts of construction operations on the surrounding businesses. In addition, it minimizes pollution from idle vehicles in work zones and improves productivity at the construction site by allowing multiple activities to take place at the same time. It also allows for extended working hours at night and cooler temperatures in this environment are favorable for the equipment and the materials being installed.

In spite of these many advantages, lighting conditions may affect both the work quality and the safety of the workers and road users. Previous research has found that nighttime construction resulted in an 87% increase in accident rates (Sullivan 1989). Inadequate lighting conditions were also found to impact workers' morale and the success of traffic control measures at the work site (El-Rayes et al. 2008). In contrast, excessive lighting at the work site may cause glare for drivers and equipment operators. Glare is defined as the sensation produced by luminance in the visual field that is sufficiently greater than the luminance to which the eye has adapted to cause annoyance, discomfort, or loss of visual performance and visibility [Illuminating Engineering Society of North America (IESNA) 1993]. Controlling glare is a critical and an important issue in adequately lighting highway work zones as it is believed that up to 90% of the necessary information for operating a motor vehicle is visual (Lunenfeld and Alexander 1990).

With the increasing needs to adopt nighttime construction strategies to avoid disruption of traffic flow, state agencies are currently experimenting with a new class of light towers known as balloon lights. Compared to regular lighting tower, balloon

[1]Assistant Professor, Dept. of Construction Management and Industrial Engineering, Louisiana State Univ., 3128 Patrick F. Taylor, Baton Rouge, LA 70803-6419 (corresponding author).

[2]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana–Champaign, IL 61801. E-mail: iodeh2@illinois.edu

[3]Associate Professor, Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana–Champaign, IL 61801. E-mail: elrayes@uiuc.edu

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lights have been reported to reduce glare significantly and to provide more uniform lighting conditions at the site. Balloon lights are also characterized by high-powered lightings that can illuminate areas ranging from 550 to 1,395 m^2 and are mounted on shorter towers compared to regular lighting systems. In spite of these promising benefits, little research has been conducted to measure the lighting characteristics of balloon lighting systems as compared to traditional light towers. In addition, current balloon light technology has been adopted as a whole without the needed supportive research to measure the glare for this new class of light systems and to quantify its variation with lighting types and operational parameters such as height and setup at the work site. Therefore, the objective of this study was to measure light and glare characteristics of two balloon lighting systems in the field. Glare and lighting characteristics of this new class of light towers were compared to a conventional lighting system.

Background

Glare is defined as a hindrance to vision by excessive light (Vos 2003); it is divided into discomfort glare and disability glare. Discomfort glare is the glare that causes discomfort without necessarily impairing the vision of objects. Disability glare is the glare that results in reduced visual performance and visibility; it is often accompanied by discomfort glare (IESNA 2000). A third type of glare has also been mentioned in the literature and is referred to as dazzling glare, which refers to the discomfort associated with light overexposure originating from a bright field of view such as the sky or a sandy desert (Vos 2003). Since it is critical to control the loss of visual performance associated with nighttime construction activities, the focus of this study is given to disability glare.

Disability glare is quantified using the veiling luminance ratio, which is the ratio of the veiling luminance to the average pavement luminance in and around the work zone (IESNA 2000). Compared to the absolute veiling luminance, the veiling luminance ratio considers that the sensation of glare is not only dependent on the amount of veiling luminance reaching the driver's eyes as an absolute value, but also on the lighting level at which the driver's eyes are adapted to before being exposed to that amount of glare. Different models have been developed for the calculation of the veiling luminance. In broad terms, the veiling luminance was defined by Holladay as follows (Holladay 1926):

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

where VL = Veiling luminance (lx); VE = Illuminance upon the eye by the glare source (lx); k and n = constants that vary in the literature and with driver's age; and θ = glare angle, between the directions of the glare source and the direction of viewing. Pavement luminance is defined as a quantitative measure of the surface brightness measured in candelas per square meter (King 1976). Luminance controls the magnitude of the sensation, which the brain receives off the pavement surface. It depends on several factors including: (1) the amount of light incident on the pavement; (2) the reflection characteristics of the pavement surface; (3) relative angle from which the light strikes the surface; and (4) location of the observer.

Most of the work conducted in the area of glare measurements and quantification as related to transportation applications has been in the areas of headlamps and roadway lighting (Gibbons and Edwards 2007). However, limited research has been conducted to date on the measurements of glare in nighttime construction zones. Pioneer work in this area has been conducted by El-Rayes and coworkers (El-Rayes et al. 2003; El-Rayes et al. 2008). Through a comprehensive experimental program and an analysis of field sites, practical measures were recommended to control the levels of glare experienced by drive-by motorists in lanes adjacent to nighttime work zones (Odeh et al. 2009).

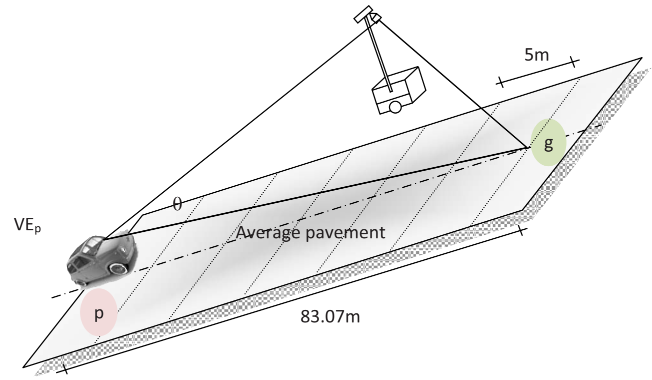

Fig. 1. Schematic representation for veiling luminance ratio calculations

Experimental Program

The objective of the experimental program was to measure and compare the glare and lighting characteristics of two types of balloon lighting systems and a conventional light tower. For this purpose, a field experimental setup was developed at the Louisiana State University (LSU) Petroleum Engineering Research and Technology Transfer Laboratory. A vehicle is operated at night in a lane adjacent to a simulated construction site and measurements are made of the pavement luminance and the horizontal and vertical illuminances on a predefined experimental grid. The pavement surface was a highly oxidized and bright asphalt material that may be classified as R1 according to the IESNA design guidelines (IESNA 2000). According to the IESNA guidelines and to quantify the levels of pavement reflectance, pavement surfaces are classified into four major categories depending on the mode of reflectance (R1, R2, R3, and R4). Additional details about the effects of pavement reflectance characteristics on glare calculation have been presented elsewhere (Hassan et al. 2008).

While pavement luminance was measured using a Minolta LS-110 handheld photometer, horizontal and vertical illuminances were measured using an EXTECH 401036 light meter. Measurements (illuminance and pavement luminance) were conducted along two lines of sight, the first located at 0.95 m from the edge of the lane and the second located at 2.8 m from the edge of the lane. These measurements were used to calculate the veiling luminance ratio (disability glare) experienced for different operational and lighting conditions.

To explain the calculation of the veiling luminance ratio, consider the arrangement shown in Fig. 1. This experimental arrangement was developed at University of Illinois by El-Rayes and coworkers (El-Rayes et al. 2008). As recommended by IESNA, a driver is assumed located on a line parallel to the centerline of the roadway. An average height of the driver eye was measured at 1.25 m with a line of sight inclined 1° downward. Given these two geometric parameters, the observer (driver) would be located

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Fig. 2. Illustration of the three types of lighting systems

at a distance of 83.07 m from the point of sight (the spot on the road that the driver looks at). An experimental grid was set up so that an observer point (p) is defined at a 5-m interval. The vertical illuminance from all contributing luminaires is measured in the plane of the driver's eye at each observer point p using a light meter ($p=1$ to P).

The veiling luminance experienced by the observer at point p (VL_p) from luminaire k is calculated as follows (El-Rayes et al. 2008):

$$VL_p - 10VE_p \frac{1}{(\theta_{pk})^n} \tag{2}$$

where VE_p=vertical illuminance measured at point p; θ_{pk}=glare angle, between the directions of the glare source and the direction of viewing at observer's point p and luminaire k; and n =variable calculated as follows (El-Rayes et al. 2008):

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

$$n = 2 \quad \text{for} \quad \theta_{pk} > 2°$$

To calculate the veiling luminance ratio, the veiling luminance calculated using Eq. (2) is divided by the average pavement luminance (L_p). To estimate the average pavement luminance, luminance is measured at each point in the grid shown in Fig. 2 and is then averaged over the number of viewpoints G

$$L_p = \frac{L_{p\text{total}}}{G} \tag{3}$$

where $L_{p\text{total}}$=total pavement luminance measured at all viewpoints and G=total number of points considered in the grid. The veiling luminance ratio is then calculated as follows:

$$VL_{\text{ratio}} = \frac{VL_p}{L_p} \tag{4}$$

Lighting Systems

Two types of balloon lighting systems manufactured and distributed by two companies were evaluated in this study, Fig. 2. The first balloon lighting system, referred to as B1, provided wattage of 1,000 W and a total luminous flux of 115,000 lm. The second balloon lighting system, referred to as B2, provided wattage of 1,000 W and a total luminous flux of 112,000 lm. The advantage of balloon lights over regular lighting towers is that they eliminate hot spots by providing the same light intensity in all directions (Airstar Space Lighting 2007). Balloon lighting systems use a diffusion mechanism, and therefore, are less prone to causing glare. Compared to regular lighting systems, balloon lights are extended light sources and are mounted on shorter towers than regular lights (up to 5.4 m). The tested conventional light tower was equipped with four floodlights, each with a wattage capacity of 1,000 W and a luminous flux of 110,000 lm. It provided a maximum mounting height of 9 m.

Table 1. Description of the Experimental Cases

Case ID	Light type	Height (m)	Aiming angle (deg)	Distance from lane edge (m)	Number of floodlights
1	B1[a]	2.6	NA	1.8	NA
2	B1	3.5	NA	1.8	NA
3	B1	4.0	NA	1.8	NA
4	B1	5.4	NA	1.8	NA
5	B1	4.0	NA	1.0	NA
6	B2[a]	2.6	NA	1.8	NA
7	B1 and B2	2.6	NA	1.8	NA
8	Ltower	4.0	45	1.8	2
9	Ltower	5.0	45	1.8	2
10	Ltower	7.0	45	1.8	2
11	Ltower	8.5	45	1.8	2
12	Ltower	8.5	35	1.8	2
13	Ltower	8.5	25	1.8	2
14	Ltower	8.5	45	1.8	4
15	No light	NA	NA	NA	NA

[a]B1 refers to the first type of balloon lighting system and B2 refers to the second type of balloon lighting system.

Experimental Cases

Operational parameters and lighting types were varied according to an experimental test matrix. Considered cases aimed at quantifying the experienced glare for different lighting conditions that may be encountered in construction work zones. Table 1 presents the simulated cases in this study; in total, 15 experimental cases were evaluated. As shown in this table, height of the light source was varied as well as the aiming angle of the conventional light system. To account for the interference that may be caused by external lights as well as moonlight, Case 15 was conducted without any sources of light at the site. Illuminance measurements for this case were subtracted from the illuminance measured for each of the experimental cases. For the conventional light system, number of floodlights that were turned on, were either two or four. To illuminate the work area before and after the light tower, floodlights were set in opposite directions.

Results and Analysis

Horizontal Illuminance

Figs. 3(a and b) compare the measured horizontal illuminance originating from a balloon light at a 4 m height to a light tower mounted at the same height (i.e., Cases 3 and 8). Horizontal illuminance was measured on two parallel lines laterally distributed across the closed lane to measure the adequacy of lighting for construction operations. As shown in these figures, conventional light tower provides greater illuminance at the light source when mounted at the same height. However, light uniformity should also be considered in judging the quality of a given light. Light

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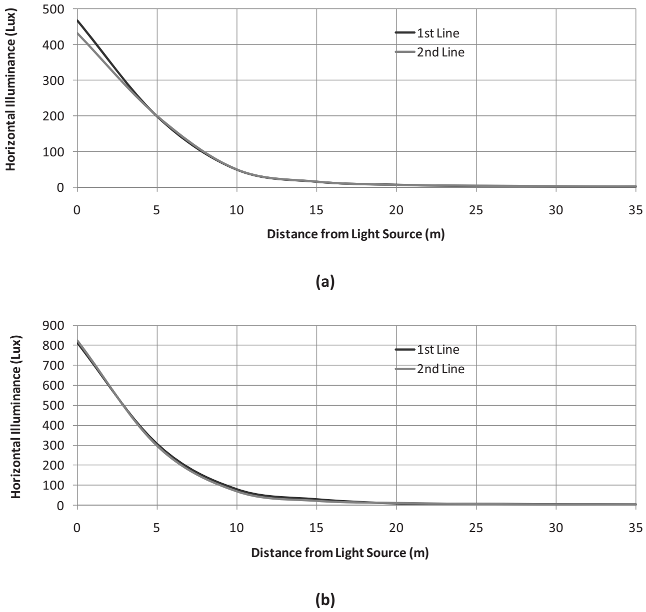

Fig. 3. Distribution of the horizontal illuminance for (a) a balloon light; (b) conventional light tower

uniformity was calculated as the ratio of average illuminance on the work area to the minimum level of illuminance.

Table 2 presents the maximum measured illuminance at the light source as well as the light uniformity calculated for each case. A lower value for the light uniformity is indicative of better work conditions in the construction area. The work area was defined considering a minimum illuminance of 54 lx as specified in Louisiana for Level I activities (e.g., excavation, sweeping, and cleanup). This illuminance threshold allowed defining the coverage distance for each experimental case. The coverage distance sets the maximum distance away from the light source where construction activities can take place with an illuminance of 54 lx or greater. The coverage distance for each case is also presented in Table 2. Assuming that the light source is placed in the middle of the work zone, the workable distance will correspond to twice the coverage distance presented in Table 2.

Table 2. Light Characteristics for the Evaluated Experimental Cases

Case ID	Maximum illuminance (lx)	Light uniformity	Coverage distance (m)
1	640	5.5	9.3
2	540	4.8	9.0
3	467	4.3	8.7
4	215	2.4	8.4
5	450	4.3	8.2
6	425	3.8	8.7
7	920	7.3	10.3
8	825	5.8	11.5
9	735	5.4	12.1
10	385	3.5	13.6
11	305	3.1	13.1
12	215	2.6	13.8
13	212	2.3	13.2
14	600	4.8	16.3

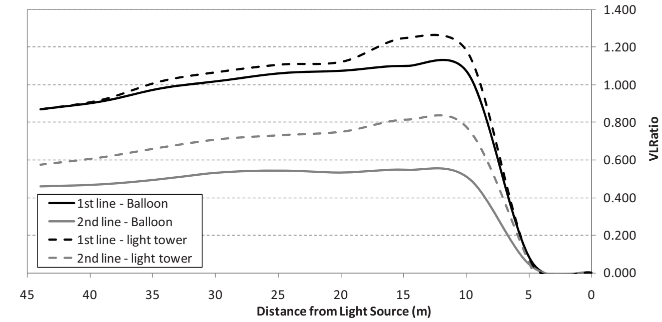

Fig. 4. Distribution of the veiling luminance ratio for two balloon lights and a conventional light tower (Cases 7 and 8)

Based on the results presented in Table 2, one may note that the two types of balloon lights differ in terms of maximum illuminance, light uniformity, and coverage distance (i.e., Cases 1 and 6). As previously mentioned, both balloon lights had the same wattage and comparable luminous flux. However, differences between the two balloon lights may be due to a number of factors. First, the geometry and the type of bulb light for the balloon light source were different. The balloon diameters for B1 and B2 were 110 and 120 cm, respectively. The light lamps for B1 and B2 were hydrargyrum medium-arc iodide and metal halide lamps, respectively. In addition, the age characteristics of the two balloon light sources may have been different and could have an influence.

As expected, light uniformity of balloon lights improved with the increase in the mounting height while the coverage distance gradually decreased (Cases 1–4). Comparing the balloon light at a 4 m height to a light tower mounted at the same height (i.e., Cases 3 and 8), one may note that the light tower provides significantly greater light intensity and coverage distance than a single balloon light. From a practical perspective, it appears that if a 20 m work zone is required, two balloon lights may be needed to provide sufficient illuminance intensity while two floodlights in a single light tower may be adequate. This means that Cases 7 and 8 are practically comparable. As for the effect of the mounting height on the light characteristics of conventional light tower (i.e., Cases 8–11), lighting uniformity improved with the increase in the mounting height under constant aiming angle; however, it appears that the coverage distance gradually increased until it reached a peak and then started to decrease. This means that an optimum height may exist at which the coverage distance is maximum while lighting uniformity is acceptable.

Disability Glare

Fig. 4 compares the veiling luminance ratio (disability glare) originating from two balloon lights mounted at a height of 2.6 m to a light tower mounted at a height of 4.0 m (i.e., Cases 7 and 8). It was shown in the previous section that these lighting arrangements provide comparable workable coverage distances in the field. Measurements (illuminance and pavement luminance) were conducted along two parallel lines of sight, the first located at 0.95 m from the edge of the lane and the second located at 2.8 m from the edge of the lane. Trends shown in Fig. 4 agree with the measurements reported by other investigators (El-Rayes et al. 2008). As shown in these figures, the glare experienced by a drive-by motorist gradually increases as we approach the light source, reaches a peak, and then diminishes to become negligible at the light source. The glare experienced at the first line of sight,

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Table 3. Glare Characteristics for the Evaluated Experimental Cases

Case ID	Maximum veiling luminance (VL)	Average pavement luminance	Maximum VL ratio	Average maximum VL ratio[a]
1	2.145	2.139	1.003	0.769
2	1.456	1.860	0.782	0.616
3	1.082	1.665	0.650	0.512
4	0.553	1.597	0.346	0.287
5	1.398	1.715	0.815	0.655
6	2.068	1.699	1.217	0.922
7	3.696	3.360	1.100	0.825
8	2.321	1.860	1.248	1.030
9	1.760	1.510	1.166	0.949
10	0.941	0.998	0.943	0.826
11	0.759	0.711	1.067	1.007
12	0.679	0.703	0.966	1.041
13	0.607	0.698	0.870	0.938
14	1.449	0.875	1.657	1.772

[a]Average of the maximum veiling luminance ratios on the two lines of sights.

located at 0.95 m from the edge of the lane, was always greater than in the second line of sight located at 2.8 m from the edge of the lane. One may note that the maximum glare experienced due the first lighting arrangement (two balloon lights) was less than what was experienced due the second light arrangement (conventional light tower—1.100 versus 1.248).

Table 3 presents the maximum veiling luminance, the average pavement luminance, the maximum veiling luminance ratio, and the average maximum veiling luminance ratio on the two lines of sight for each of the evaluated experimental cases. These measurements indicate that balloon lights reduce the experienced glare in the work zone. However, the two types of balloon lights provided different levels of glare (i.e., Cases 1 and 6). Therefore, assuming that all types of balloon lights would perform similarly in the field may be misleading. These differences may be related to the aforementioned factors (i.e., light geometry and type). As expected, increasing the mounting height of balloon and conventional light systems caused a reduction in the experienced disability glare by drive-by motorists. In addition, reducing the aiming angle for conventional light towers also results in a decrease in the disability glare. However, increasing the mounting height and reducing the aiming angle will decrease the coverage distance and may result in inadequate lighting conditions in the work zone. Therefore, optimum conditions should be sought, through which adequate lighting conditions may be provided while disability glare would be kept below a safe threshold for drive-by motorists.

To illustrate how both factors may be considered in the design of work zone lighting, Fig. 5 plots the maximum veiling luminance ratio (disability glare) against the workable distance in meter (the work area can be calculated by multiplying the workable distance by the lane width). The workable distance was obtained by multiplying the coverage distance by two assuming that the light source was placed in the middle of the work area. It is noted from the arrangement of points in this figure that a tradeoff between disability glare and workable distance may be needed. However, by appropriately designing the work area, an appropriate workable distance may be achieved without excessively increasing the glare at the site for drive-by motorists. Assume for instance that a workable distance of 15 m is needed while the disability glare is to be maintained below 1.1. Under these conditions, the highlighted cases in the upper rectangle are acceptable since they provide acceptable lighting conditions while maintaining the glare below the required threshold. Similar design strategies may be implemented depending on the maximum allowable glare and the minimum workable distance at the site.

Findings and Conclusions

The objective of this study was to measure light and glare characteristics of two balloon lighting systems in the field. Glare and lighting characteristics of this new class of light towers were compared to a conventional lighting system. Based on the analysis conducted in this study, the following findings and conclusions may be drawn:

- While being comparable in terms of wattage and luminous flux, the tested balloon light systems differed in terms of light and glare characteristics.
- The conventional light tower provided greater illuminance intensity at the light source than balloon lights when mounted at the same height. However, disability glare was greater for conventional light tower than balloon lights when mounted at the same height.
- Increasing the mounting height and reducing the aiming angle of light systems caused a decrease in the experienced glare in the work zone but decreased the coverage distance, in which construction activities can take place.

Results of this study revealed that optimum conditions should be sought in the work zone, through which adequate lighting conditions are provided while disability glare is kept below a safe

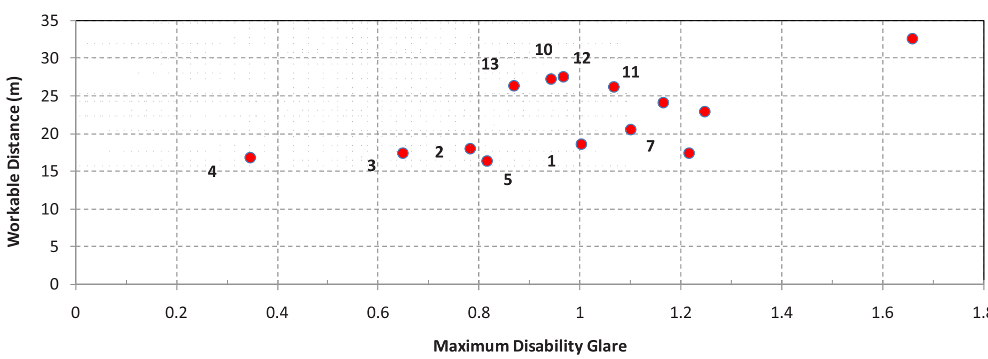

Fig. 5. Illustration of the use of dual concepts in the design of work zone lighting

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threshold for drive-by motorists. Plotting the maximum veiling luminance ratio (disability glare) against the workable distance provides a simple approach to consider the two factors concurrently in the design of work zone lighting. However, it is noted that results from this study do not provide the guidance about what the "safe threshold" actually is for disability glare. Therefore, further research is recommended to determine the safe threshold for disability glare in order to ensure the safety of the workers and drive-by motorists.

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