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Work Zone Lighting's Effect on Driver Visibility

Effects of Mounting Height, Offset Distance, and Number of Light Towers

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EXECUTIVE SUMMARY

Portable light towers are a significant source of glare to motorists entering a work zone. Although existing research has evaluated the effect of light tower orientation on visibility and glare, the effects of factors like mounting height, offset distance from the roadway, and number of light towers in the work zone on visual performance and discomfort glare are not known. Understanding these relationships can help to develop illumination guidelines for work zones that can reduce glare for drivers. The goal of this project was to understand the effect of mounting height, offset distance to the roadway, and number of light towers in the work zone on drivers' visual performance and discomfort glare. Participants drove through a realistic work zone and evaluated portable light towers with varying mounting heights, offset distances, and number of light towers. Results showed that the mounting height and offset distances play a critical role in affecting the driver's visual performance and discomfort glare rating. Portable light towers, irrespective of wattage and lumen output, at lower than a mounting height of 20 feet and closer to the roadway (in travel lanes than in the shoulder) result in decreasing drivers' visual performance and increasing their discomfort glare. Portable light towers should be mounted at a height of at least 20 feet, and balloon light towers with higher wattage (4,000 watts and greater) and lumen output (400,000 lumens and greater) should be located at an offset distance of at least 10 feet from the roadway.

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LIST OF ABBREVIATIONS AND SYMBOLS

CAN	Controller Area Network
DAS	data acquisition system
DGPS	Differential Global Positioning System
LED	light-emitting diode
LMM	linear mixed models
M	mean
MH	metal halide
SD	standard deviation
TRLMMS	Trailer-Mounted Roadway Lighting Mobile Measurement
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

Portable light towers are commonly used in nighttime work zones to provide illumination to workers. However, they are a significant source of glare to motorists entering the work zone. Glare in the eyes of the drivers entering the work zone could reduce visibility and potentially increase the risk of a crash. Great care should be taken when prescribing lighting for work zones so that workers have adequate light levels to effectively and safely complete their tasks without introducing glare for drivers entering the work zone.

Prior research in this area examined the effect of several commercially available portable light towers and their orientation on drivers' visual performance and their perceptions of visibility and glare (Bhagavathula & Gibbons, 2017). In that study, three commercially available portable light towers (4000-watt metal halide, light-emitting diode [LED], and balloon type) in three orientations (angle to the drivers' line of sight of 45, 90, and 135 degrees) were used. Visual performance and perception of visibility and glare were evaluated in a realistic work zone designed to simulate a work zone on a limited-access highway for the portable light tower types in all three orientations.

The results of this research showed that portable light towers aimed away from or perpendicular to the drivers' line of sight (90 degrees or greater) resulted in increasing the drivers' visual performance (longer detection distances) and lowering their perception of glare (lower glare ratings). However, the effect of mounting height and the location of the portable light towers with respect to the roadway on visual performance was not reported. Further, newer portable light sources like balloon light towers are being increasingly used in work zones. These newer light sources cannot be aimed and therefore care has to be taken to determine an ideal location for these light towers so that they do not decrease visibility for drivers entering the work zone.

Previous studies (Bhagavathula & Gibbons, 2017; Finley, Ullman, Miles, & Pratt, 2012) have shown that improper aiming could limit the visibility of objects in the work zones. Thus, it is important to understand the effect of mounting height and location of the light towers with respect to the roadway (or offset distance) on the visual performance and discomfort glare of drivers. Understanding this relationship can help in recommending appropriate illumination guidelines for nighttime work zones, which can result in increased safety for motorists and workers.

Other recent research (Bhagavathula, Gibbons, Medina, & Terry, 2017) conducted in the area of work zone lighting also showed that the mean vertical illuminance measured at driver eye level inside the vehicle in the distance range of 260 to 65 feet (also termed the *critical range*) to the light tower could be used as an objective measure of glare (see Figure 1). This research also specified that a mean vertical illuminance limit of less than 17 lux in the critical range to the light tower will result in lower discomfort glare ratings and recommended light tower orientations that ensure that the vertical illuminance is lower than the specified limit (Figure 1). In order for the vertical illuminance limit to be accepted, it is important to validate this vertical illuminance limit in the orientations specified.

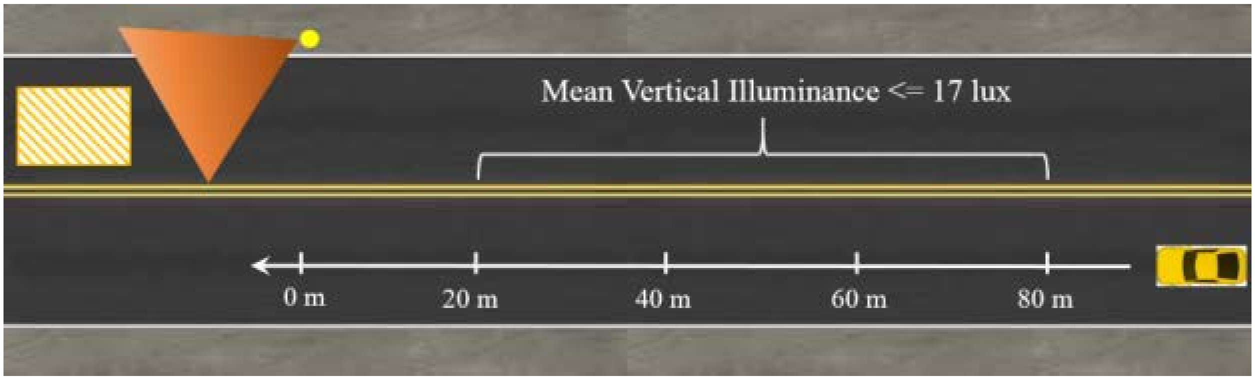

Figure 1. Diagram. Distances at which the vertical illuminance should be calculated to determine the mean vertical illuminance level in the critical range (65–260 ft. = 20–80 m).

This project had three goals. The first was to objectively evaluate the effects of mounting heights, offset distances, and the number of light towers on driver visual performance, especially on limited-access highways. The second was to understand the effects of these variables on the discomfort glare of drivers. The third was to validate if the specified orientations for portable light towers (for metal halide light towers: 60 degree angle to the vertical and aimed perpendicular to the driver's line of sight) will result in a lower mean vertical illuminance (less than 17 lux) in the critical range. Results from this study will add to the body of knowledge on work zone lighting and glare. These results could also help in developing lighting specifications for work zones.

CHAPTER 2. METHODS

PARTICIPANTS

Twenty-four participants were recruited to participate as drivers in this study. The participant sample was divided into two distinct age groups. The first group consisted of younger drivers whose ages ranged from 18 to 35 years (M = 25.4 years, SD = 3.8 years). The second group consisted of older drivers who were 60 years and older (M = 63.5 years, SD = 2.7 years). Both age groups comprised a participant sample with diverse visual capabilities and driving experiences. All the participants had a valid driver's license and a minimum visual acuity of 20/40 (corrected).

EXPERIMENTAL DESIGN

A repeated measures experimental design was used to evaluate the effects of mounting height, offset distance, and number of light towers on visual performance and discomfort glare. Visual performance was assessed by measuring detection and recognition distances of a worker as the participants drove through a simulated work zone on the Virginia Smart Road. Discomfort glare was assessed by means of a rating scale. The simulated work zone was set up in such a way that the lane closure was in the right lane when the participants were traveling in one direction and in the left lane when the participants were traveling in the opposite direction. Having the participants travel in both directions saved time and required fewer runs to collect the required data.

The independent variables and their levels are summarized in Table 1. In each experimental session, participants encountered all conditions. The presentation of the mounting heights, offset distances, and the number of light towers was counterbalanced to minimize order effects. Presentation of the simulated worker was also randomized with blanks (no worker presentation) to actively discourage participants from guessing.

Table 1. Independent variables and their categorical values.

Independent Variables	Levels
Age	Older (60+ years) Younger (18–35 years)
Light tower type	4000-watt metal halide 4000-watt balloon 800-watt balloon LED
Mounting height (only 4000-watt metal halide and 4000-watt balloon)	15 ft. 20 ft. 30 ft.
Offset distance (only 4000-watt balloon)	0 ft. (in the lane) 10 ft. (in the shoulder) 20 ft. (off the shoulder)
Number of luminaires (only 800-watt balloon LED)	1 2

INDEPENDENT VARIABLES

Types of Portable Light Towers

Three types of commercially available portable light towers were used (Figure 2). The first was a conventional metal halide portable light tower with four 1,000-watt (440,000 lumens) metal halide luminaires. The second was a balloon light tower (Manufacturer: 812 Illumination, model 4000-W HID) with four 1,000-watt metal halide luminaires (440,000 lumens) enclosed within a balloon, which diffused the light. The third was a smaller balloon light tower with an 800-watt LED luminaire (Manufacturer: 812 Illumination; 84,000 lumens). In order to account for the different wattages and lumen output of the portable light tower types, the vertical illuminance on the simulated worker was matched at 50 lux across all the light tower types, mounting height, and offset distances.

Figure 2. Photo. Portable light towers used in study.

Each portable light tower in the study was used only in certain orientations. The 4000-watt balloon light tower was evaluated in three mounting heights and three offset distances. The 4000-watt metal halide light tower was evaluated for only three mounting heights, as changing the offset distance changed the beam angle to the vertical of the luminaires. The beam angle to the vertical was maintained at 60 degrees and the angle between the beam axis and driver's line of sight was maintained at 90 degrees, as recommended by existing guidelines (Ellis, Amos, & Kumar, 2003). The 800-watt LED light towers were used at a fixed mounting height of 15 feet, as this was the highest setting provided by the manufacturer. These light towers are often mounted on paving or milling machines, either one or two towers at a time (Bhagavathula et al., 2017). Thus, the 800-watt LED light tower was used in two configurations, one light tower at a time and two light towers at time, to simulate their use in real work zones.

In order to facilitate the comparison across different light tower conditions, several characteristics, such as light tower type, their respective mounting heights, offset distances, and number of light towers, were merged to form 15 discrete categorical levels of a single variable called "light tower orientation" (see Table 2 column "*Light Tower Orientation*"). For example, the three mounting heights and three offset distances of the 4000-watt balloon light tower were merged to give nine levels. The three mounting heights of the 4000-watt metal halide contributed three levels. The two conditions of the number of luminaires for the 800-watt balloon LED light tower contributed two levels. Finally, a control condition with no light tower (only simulated worker under no lighting) was also used, which provided one level. Overall, the "light tower orientation" variable had 15 levels.

Table 2. Merging of light tower characteristics into a single categorical variable.

Light Tower Type	Offset Distance (ft.)	Mounting Height (ft.)	Angle to the Vertical (deg.)	Number of Luminaires	Light Tower Orientation
4000-watt balloon	0	15			Ball_0_15
	10				Ball_10_15
	20				Ball_20_15
	0	20			Ball_0_20
	10				Ball_10_20
	20				Ball_20_20
	0	25			Ball_0_25
	10				Ball_10_25
	20				Ball_20_25
4000-watt metal halide		15	60		MH_30_15
		20			MH_30_20
		25			MH_30_25
800-watt balloon LED	0	15		1	Ball_LED_1
				2	Ball_LED_2
Control condition					NoLight

Mounting Height

Three different mounting heights were used. They were 15, 20, and 25 feet from the surface of the roadway. Higher mounting heights could result in lower disability and discomfort glare for the drivers. Discomfort glare is the experience of uneasiness in the lighted environment without any reduction in visual performance. Disability glare occurs when the light from the glare source (portable light tower) is scattered in the eye and casts a veil of light across the observer's retina, reducing visual contrast and, in turn, visual performance. In this study, only discomfort glare was measured and reported.

Offset Distance

Offset distance is the location of the portable light tower on the roadway. This distance was calculated from the center of the closed lane in which the simulated work zone was established. Three offset distances were used. They were 0 feet (light tower in the lane), 10 feet (light tower in the shoulder), and 20 feet (light tower off the shoulder).

DEPENDENT VARIABLES

Visual performance was assessed by detection and recognition distances. These two variables are defined in the following subsections.

Detection Distance

Detection distance was defined as the distance at which the participant was able to detect the presence of the simulated worker in the work zone. Detection distance has been used as a measure of visual performance in previous nighttime roadway visibility research (Bhagavathula & Gibbons, 2013, 2017; Edwards & Gibbons, 2008; Shinar, 1985; Zwahlen & Schnell, 1999).

Recognition Distance

The simulated worker oriented in the work zone always stood facing right or left. Recognition distance is the distance at which the participant was able to recognize the direction the simulated worker was facing. Similar to detection distance, recognition distances have been previously used in nighttime roadway visibility studies as measures of visual performance (Gibbons et al., 2015; Terry & Gibbons, 2011).

Detection distance and orientation recognition distance can be used to evaluate how well a lighting source can help the driver identify hazards in a work zone.

Discomfort Glare

Discomfort glare was measured using a rating scale as shown in Table 3. This scale has been reported to produce reliable data, with smaller numbers meaning lower discomfort glare and higher numbers meaning higher discomfort glare (Fisher, 1991; Tyukhova, 2015). The scale also has a “zero” anchor for no discomfort glare. An established discomfort glare rating scale, such as the deBoer rating scale, was not used, as research has shown that they are not good predictors of driving performance (Theeuwes, Alferdinck, & Perel, 2002). Moreover, pilot tests showed that the 9-point deBoer rating scale was difficult for the participants to refer to or memorize while indicating their glare ratings, given the speed (55 mi/h) that was used in the current study. Participants had no issues with the selected discomfort glare rating scale for this study.

Table 3. Scale used to measure discomfort glare rating.

Description	Rating
No discomfort glare	0
Glare between non-existent and noticeable	1
Glare noticeable	2
Glare between noticeable and disagreeable	3
Glare disagreeable	4
Glare between disagreeable and intolerable	5
Glare intolerable	6

PROCEDURE

Two participants were scheduled for each experimental session. Upon arrival, participants reviewed and signed the informed consent form. Participants' driver's licenses were checked for validity by the experimenters. Participants then performed a basic Snellen visual acuity test. Participants were required to have at least 20/40 vision (with or without corrective lenses) to participate in the study. Participants who did not have 20/40 vision were not used for data collection.

Once participants had completed the paperwork, the experimenter read a brief overview of the driving portion of the study and answered participants' questions. Participants were then escorted to the test vehicle and orientated to the experimental vehicle. The experimental vehicles for this study were 1999 and 2000 model year Ford Explorers instrumented with a data acquisition system (DAS). The DAS collected kinematic data from the vehicle's Controller Area Network (CAN), including vehicle speed, differential Global Positioning System (DGPS) coordinates, four video images (driver's face, forward roadway, left side of roadway, and right side of roadway), audio from the driver, manual button presses, and other input from the in-vehicle experimenter. Low-beam headlamps were used during the study. The headlamps were Hella 90-millimeter Bi-Xenon projector lamps with a single 1-farad capacitor-stabilized headlamp input voltage on each vehicle. These headlamps were retrofitted along with a voltage stabilizer so that the headlamps' intensities were not affected by the speed of vehicles. These retrofitted headlamps also allowed the headlamps to be at the same height from the ground across both the experimental vehicles. Before every experimental session, vehicle headlamps were aimed and the windshields were wiped clean.

Participants drove for six laps in both uphill and downhill directions on the Virginia Smart Road. Each lap involved driving through two simulated work zones at the assigned speed limit for the study (55 mi/h). Participants drove in the left lane when going downhill and in the right lane when going uphill. Portable light towers were located at two stations on the Smart Road. The 800-watt LED and the 4000-watt metal halide light towers were located at the first station. The 4000-watt balloon light tower was located at the second station. When travelling downhill, participants first encountered the light tower at the first station and then the light tower at the second station. When traveling uphill, participants encountered the stations in the reverse order. All light towers were encountered in both directions. As the participants drove through the test area, they were asked to actively scan for a simulated worker located in the work area, who was dressed in retroreflective clothing along with a hard hat (see Figure 2) as recommended by the

Virginia Work Area Protection Manual (Virginia Department of Transportation, 2011). The vertical illuminance on the simulated worker was matched across all the light tower types, heights, offset distances, and number of light towers and was set at 50 lux. In order to match the vertical illuminance (light incident on a vertical plane) across each light tower and orientation, the worker's location within the work area was changed but it was always within the simulated work area.

Participants indicated when they could first see the simulated worker by saying "worker" aloud. The in-vehicle experimenter then flagged the data stream with a button press. Once participants recognized the direction the simulated worker was facing, they indicated the worker's orientation by saying "right" or "left" aloud. The in-vehicle experimenter then flagged the data stream with another button press. The GPS coordinates of the worker's locations were predetermined. The GPS coordinates at detection and recognition were cleaned up at a later point. The detections were adjusted to the point in time at which the participants said "worker" and stated the orientation, thereby eliminating the time delay due to experimenter input. A high-precision DGPS unit was used in the experimental vehicle and was also used to collect the GPS locations of the worker. The DGPS system had an accuracy of about 0.1 meters (0.33 ft.).

Once the first participant vehicle was clear of the test area, the in-vehicle experimenter notified the second participant vehicle via radio that they were clear to proceed and asked the participant to provide a discomfort glare rating for the condition they had just observed. A copy of the scale was provided to the participant for reference. After encountering the two simulated work zones in the downhill direction, the first vehicle was then parked in a turnaround and waited for the second vehicle. Once the second vehicle arrived at the turnaround, the process was repeated driving in the uphill direction. The two vehicles continued in this fashion until all light tower conditions had been observed.

ANALYSES

Three separate linear mixed model (LMM) analyses were used to assess the effect of light tower orientation on detection distance, orientation recognition distance, and discomfort glare rating. Age was included as a blocking factor. The level of significance was $p < 0.05$ for all statistical tests. Where relevant, post hoc analyses (pairwise comparisons) were performed using Tukey's honest significant difference for main effects and simple effects testing for interaction effects.

VERTICAL ILLUMINANCE CHARACTERIZATION

Vertical illuminance at the driver's eye level was measured inside the experimental vehicle. The Trailer-Mounted Roadway Lighting Mobile Measurement System (TRLMMS) was used to measure the illuminance levels for the three light towers, each in three orientations. The TRLMMS, which consisted of a specially designed "spider" apparatus containing four waterproof Minolta illuminance detector heads, was mounted onto the bed of a trailer (Figure 3c). Additionally, a vertically mounted illuminance meter was positioned in the vehicle windshield as a method to measure the vertical illuminance from the portable light towers in the work zone (Figure 3b). The waterproof detector heads and windshield-mounted Minolta head were connected to separate Minolta T-10 bodies that sent data to the data collection computer positioned inside the vehicle. A NovaTel GPS was positioned at the center of the "spider" apparatus (Figure 3c). The GPS was connected to the data collection box, and the vehicle's latitude and longitude position data were incorporated into the overall data file. A specialized software program created in LabVIEW™ controlled each component of the TRLMMS. The software synchronized the entire hardware suite, and data collection rates were set at 20 Hz. The final output file used during the analysis contained GPS information (latitude, longitude, etc.), input box button presses, vehicle speed, vehicle distance, and the illuminance meter data from each of the five Minolta T-10s. For collecting the lighting data, the TRLMMS system was hitched to a vehicle and was driven through the simulated work zone on the Smart Road (Figure 3a and Figure 3d).

Figure 3. Photo. (a) TRLMMS hitched to vehicle. (b) Illuminance meter that measures the vertical illuminance mounted to the windshield. (c) "Spider" apparatus with GPS unit in the center. (d) TRLMMS from behind with the headlamp barrier that eliminates the influence of the following vehicle's headlamps.

The TRLMMS was used to measure the illuminance levels for all the light towers in all orientations. A cubic spline smoothing algorithm was performed to smooth the vertical illuminance data. The smoothing spline was a knotted piecewise polynomial that responded very quickly to changes in the underlying form of the data. Thus it resulted in a data set that eliminated noise while still retaining the original characteristics. Another advantage of the smoothing spline technique is that it does not require any distribution assumptions, unlike its parametric counterparts.

After the vertical illuminance data were smoothed, vertical illuminance was calculated at each of the distances (20, 40, 60, and 80 m) in the critical range. The mean vertical illuminance in the critical range was also calculated by averaging the vertical illuminance at each of the distances.

CHAPTER 3. RESULTS

DETECTION DISTANCE ANALYSIS

The main effect of light tower orientation was significant, $F(14, 342) = 16.06$, $p < 0.0001$. The effect of light tower orientation on detection distance is shown in Figure 4.

The longest detection distances were attained under the 4000-watt balloon light tower at an offset of 20 feet and a mounting height of 25 feet (M = 549.3 m, SD = 205.7 m). The shortest detection distances were attained under the two-800-watt balloon LED light tower orientation (M = 253.4 m, SD = 75.7 m). For the 4000-watt balloon light tower, the detection distances were significantly longer for the offset distances between 0 and 20 feet at mounting heights of 20 and 25 feet only. The detection distances between the 800-watt balloon LED light tower and the 4000-watt balloon light tower were significantly longer at every offset distance and mounting height except at the offset distance of 0 feet and a mounting height of 15 feet. The differences in the detection distance between the 4000-watt metal halide light tower and the 4000-watt balloon light tower were only significant at mounting heights of 20 and 25 feet for the offset distance of 0 feet and at all mounting heights at an offset distance of 20 feet. The detection distance in the control condition was significantly lower than all light tower conditions except those of the 800-watt balloon LED and the 4000-watt metal halide at a height of 15 feet.

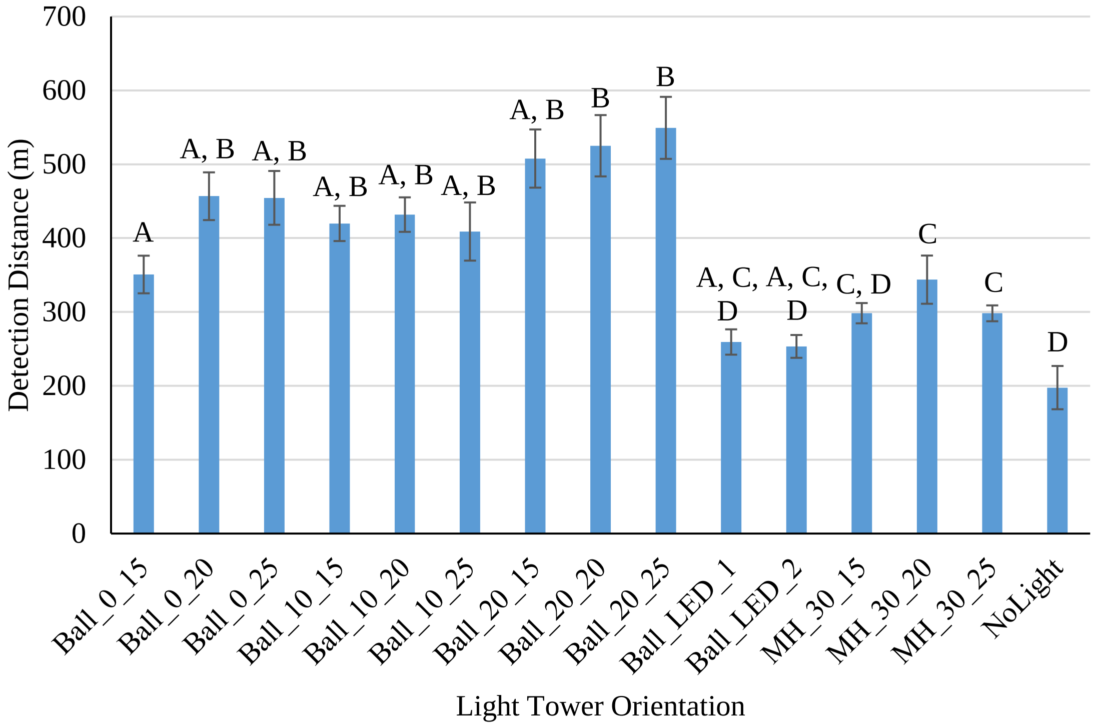

Figure 4. Chart. Effect of light tower orientation on detection distance. Values are means of detection distances and error bars reflect standard errors. Uppercase letters indicate significant (p < 0.05) post hoc groupings (from pairwise comparisons).

RECOGNITION DISTANCE ANALYSIS

The main effect of light tower orientation on orientation recognition distance was significant, $F(14, 333) = 3.45$, $p < 0.0001$. The effect of light tower orientation on recognition distance is shown in Figure 5. Post hoc pairwise comparisons indicated that none of the recognition distances between the light tower orientations was significant. Only the recognition distances for the control condition were significantly different from the 4000-watt balloon light tower at all mounting heights and offset distances except at the offset distance of 0 feet and a mounting height of 15 feet.

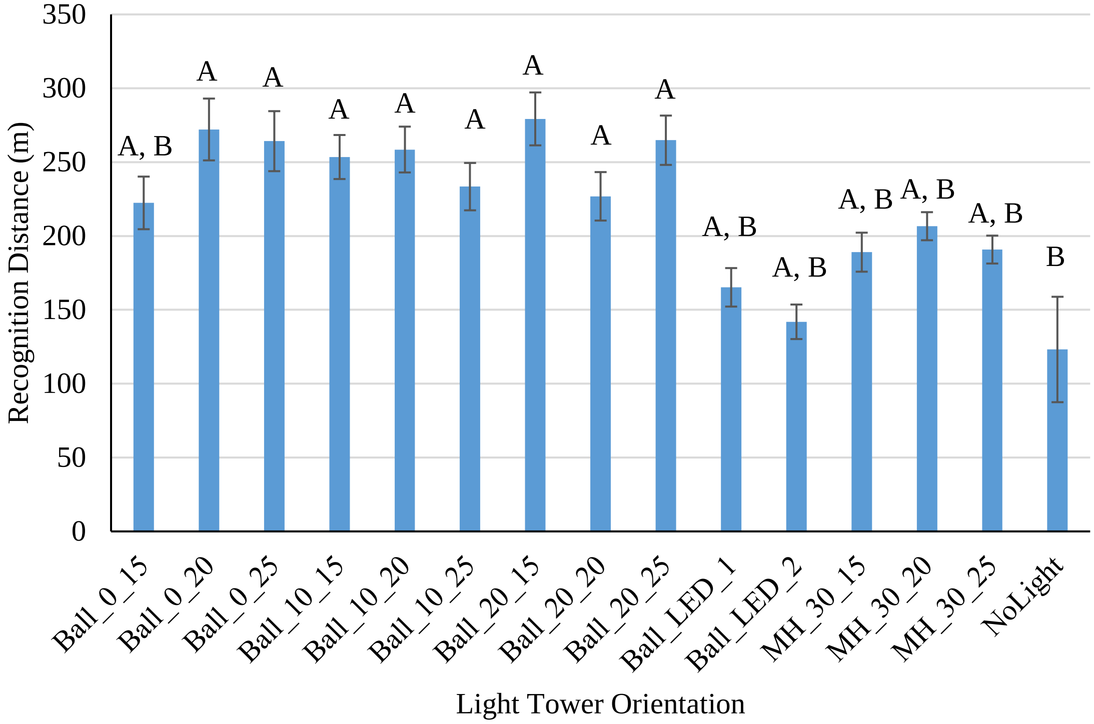

Figure 5. Chart. Effect of light tower orientation on recognition distance. Values are means of recognition distances and error bars reflect standard errors. Uppercase letters indicate significant ($p < 0.05$) post hoc groupings (from pairwise comparisons).

DISCOMFORT GLARE RATING ANALYSIS

The main effect of light tower orientation on discomfort glare rating was significant, $F(14, 342) = 25.83$, $p < 0.0001$. The two-way interaction between age and light tower orientation was also significant, $F(14, 342) = 4.16$, $p < 0.0001$. The effect of light tower orientation on discomfort glare rating is shown in Figure 6. The two-800-watt balloon light tower configuration had the highest discomfort glare rating ($M = 3.3$, $SD = 1.7$). This light tower orientation also had significantly higher glare ratings than the 4000-watt metal halide light tower at a mounting height of 20 and 25 feet. The control condition had the lowest glare rating, which was significantly lower than the glare ratings in all the light tower orientations for both age groups. The only significant age difference was for the 4000-watt metal halide light tower at a mounting height of 20 feet, where the older participants (*M* = 0.8, *SD* = 0.8) had a lower glare rating than younger participants (*M* = 3.2, *SD* = 1.6).

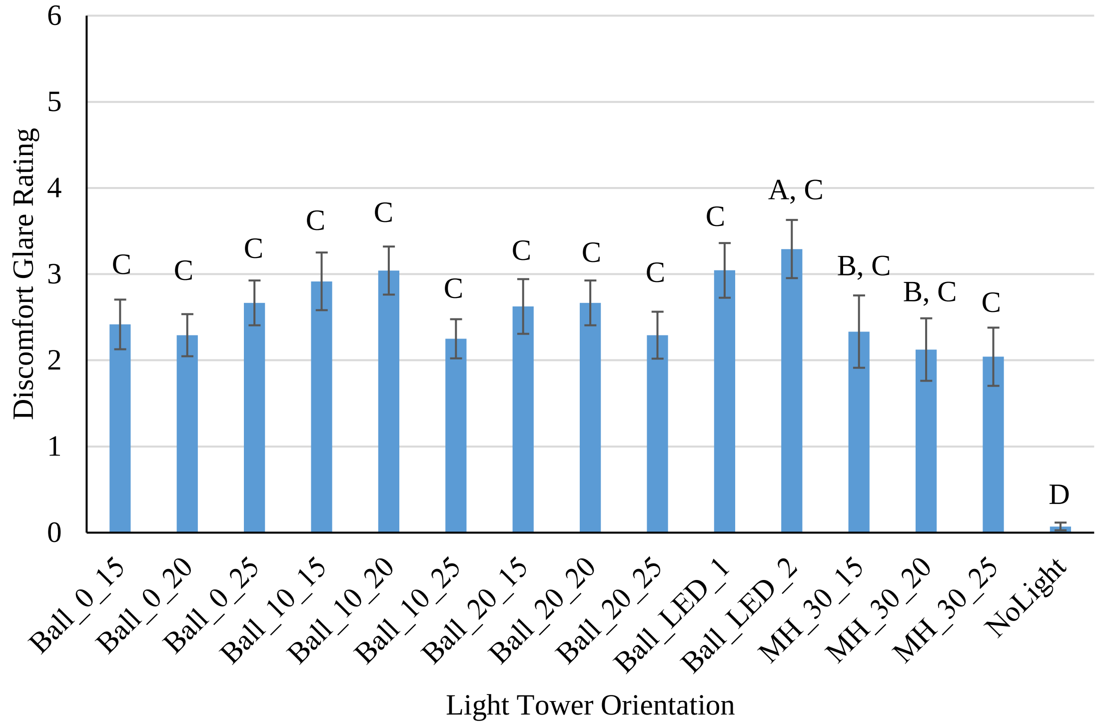

Figure 6. Chart. Effect of light tower orientation on discomfort glare rating. Values are means of discomfort glare ratings and error bars reflect standard errors. Uppercase letters indicate significant (*p* < 0.05) post hoc groupings (from pairwise comparisons).

VERTICAL ILLUMINANCE CHARACTERIZATION

The vertical illuminance for the 4000-watt balloon light tower in the critical range is shown in Figure 7. The vertical illuminance for the 800-watt balloon and the 4000-watt metal halide light towers is shown in Figure 8. Light levels increased as the vehicle got closer to the light tower as expected irrespective of the light tower type, mounting height, offset distance, and number of light towers.

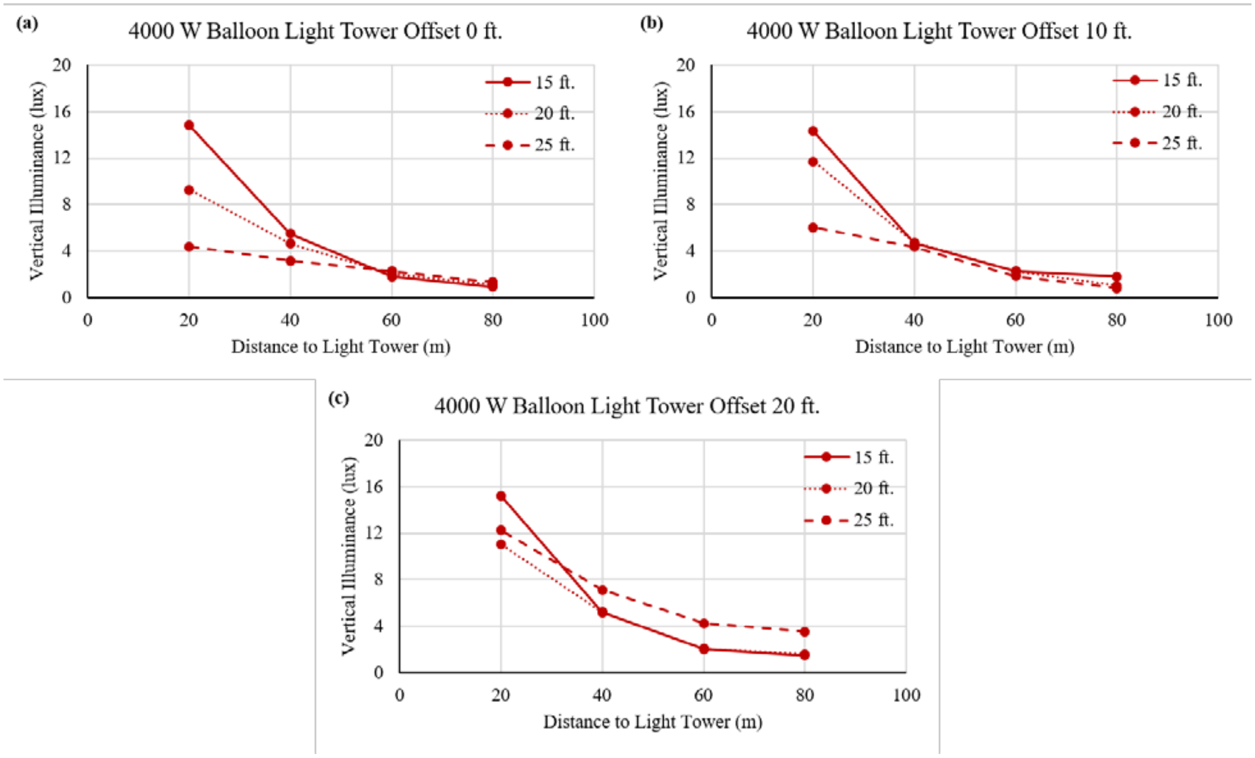

Figure 7. Chart. Change in the vertical illuminance with distance for different offset distances of the 4000-W balloon light tower: (a) 0 ft., (b) 10 ft., (c) 20 ft.

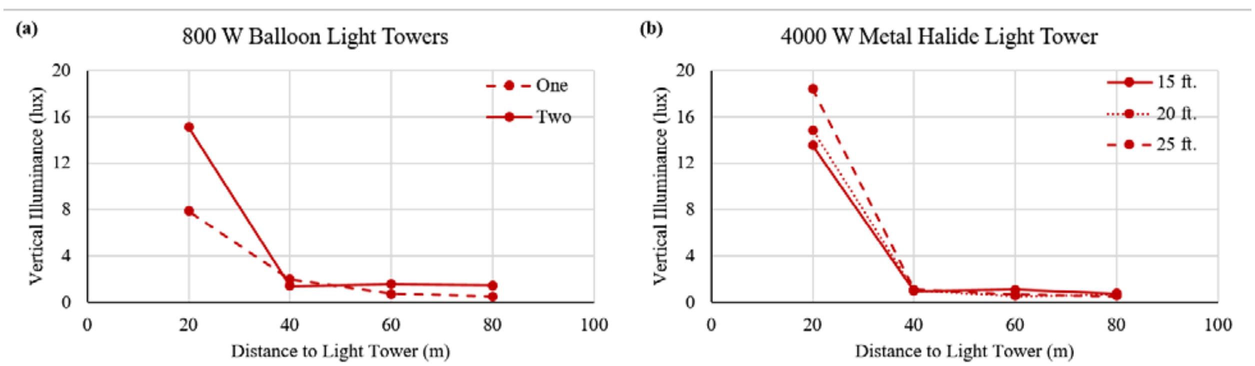

Figure 8. Chart. Change in the vertical illuminance with distance for different offset distances of (a) the 800-W balloon and (b) the 4000-W balloon light towers. Offset distance was not changed for these light towers.

The mean vertical illuminance in the critical range for each of the light towers in every measured orientation is shown in Table 4. For all the light towers in every orientation, the mean vertical illuminance was less than the specified upper limit of vertical illuminance of 17 lux. The list of light towers and orientations also includes the 4000-watt metal halide light towers, which were used in the perpendicular orientations as recommended by previous research (Bhagavathula et al., 2017; Bhagavathula & Gibbons, 2017).

Table 4. Mean vertical illuminance values in the critical range of the portable light towers used in this study.

Light Tower Type	Offset Distance (ft.)	Mounting Height (ft.)	Number of Light Towers	Mean Vertical Illuminance in Critical Range (lx)
4000-W Balloon	0	15		5.8
		20		4.3
		25		2.8
	10	15		5.8
		20		4.9
		25		3.3
	20	15		6.0
		20		5.0
		25		6.8
800-W Balloon			1	2.8
			2	4.9
4000-W Metal Halide		15		4.1
		20		4.3
		25		5.2

CHAPTER 4. DISCUSSION

The goals of this project were to evaluate the effects of mounting height, offset distance, and number of light towers of several commercially available portable light towers in a work zone on visual performance and discomfort glare ratings. Three major findings are evident. First, an increase in the offset distance and mounting height resulted in an increase in the detection distance. Second, an increase in offset distances and mounting heights resulted in lower discomfort glare ratings. Third, the mean vertical illuminance in the critical range for all light tower orientations was less than the specified upper limit of vertical illuminance.

Visual performance increased as mounting height and offset distance from the roadway increased, as evidenced by higher mean detection distances for the 4000-watt balloon light tower at mounting heights of 20 feet and 25 feet for an offset distance of 20 feet. An increase in the offset distance from the roadway and the mounting height could result in lowering the veiling luminance, thereby reducing disability glare (theoretically speaking), resulting in increased visual performance. The result of higher mounting height in increasing visual performance is also supported by current recommendations on nighttime construction safety (Ellis & Amos, 1996; Shane, Kandil, & Schexnayder, 2012). The results from this research also show that increasing the offset distance from the roadway or locating the portable light towers off the shoulder of the roadway could also increase visual performance (by increasing detection distances), especially for the higher wattage portable light towers like the 4000-watt balloon light tower, which cannot be aimed (i.e., the angle of the luminaire on the light tower cannot be altered).

For light towers that could be aimed like the 4000-watt metal halide light tower, an increase in the height of the light tower, while keeping the angle between the beam axis and vertical constant, could also result in increasing the visual performance (as longer but not statistically significant detection distances were observed with increase in the height of the light tower). Overall, detection distances for the 4000-watt balloon light tower at the highest offset and mounting height were significantly longer than those at the highest mounting height for the 4000-watt metal halide light tower. This result indicates that when located at the right distance from the roadway and mounting height, a balloon light tower with a similar wattage and lumen output to a metal halide light tower could result in higher visual performance. The results of this study also showed that light towers located closest to the roadway and at the lowest mounting height of 15 feet had the lowest visual performance (lower detection distances) irrespective of the wattage and lumen output of the luminaires, as evidenced by the lower mean detection distances of the 800-watt LED balloon light towers and both the 4000-watt balloon and metal halide light towers at a mounting height of 15 feet and an offset distance of 0 feet.

The discomfort glare rating analyses also showed that increasing the mounting height also resulted in lowering the discomfort glare ratings. This is evidenced by the significantly lower discomfort glare ratings of the 4000-watt metal halide light tower at mounting heights of 20 and 25 feet compared to the 800-watt LED balloon light tower mounted at a height of 15 feet. The result of decreasing glare rating along with increasing mounting height and increasing offset distance was also observed in the 4000-watt balloon light tower, but these ratings were not statistically significant. The results from the discomfort glare ratings analysis reinforced the results of the detection distance analysis for the portable light towers located closest to the roadway at the mounting height of 15 feet, as these orientations had the highest glare ratings and shortest detection distances.

The number of the light towers (800-W LED) did not affect the visual performance or the discomfort glare ratings as shown by the lack of significant post hoc pairwise comparisons between the one-light versus two-light tower configurations. Although, the discomfort glare ratings for the two-tower configuration were higher, the difference was not statistically significant. These results indicate that up to two 800-watt light towers could be mounted on work zone equipment without significantly affecting drivers' visual performance or discomfort glare ratings.

The mean vertical illuminance in the critical range for the 4000-watt metal halide light towers was less than the 17-lux specification from past research (Bhagavathula et al., 2017), indicating that these portable light tower orientations were not major sources of discomfort glare. These results are further supported by mean discomfort glare ratings for these portable light tower orientations, which are less than 3 (glare is noticeable). Thus, these results validate the specification that aiming the light towers perpendicular to the driver's line of sight and at 60 degrees to the vertical will result in lower discomfort glare ratings. In addition, based on this study, an upper limit of 17 lux on the mean vertical illuminance in the critical range to the portable light tower can be used to asses discomfort glare in work zones.

Interestingly, there were no differences in recognition distances across the several light tower orientations. This result could be because the recognition of the orientation of the worker in the currently study was dependent on the visual acuity of the driver. Recognizing the orientation is dependent on detection of finer details like the direction of face, hands, or shoes, which differs from detecting the presence of a worker. Since all the participants for the study had a visual acuity of at least 20/40, statistically significant differences between drivers could not be detected. However, more research is required to confirm this finding.

Driver age also did not significantly affect the drivers' visual performance, as evidenced by the lack of a significant main effect of driver age on detection or recognition distance. Drivers' age affected the discomfort glare ratings only for the 4000-watt metal halide light tower at a mounting height of 20 feet, where younger drivers had a lower glare rating than older drivers.

The visual performance analyses also showed that in all portable light tower conditions, detections and recognitions happened at distances beyond the range of the headlamps (greater than 100 m). However, the recognition distances in the control (no lighting) condition happened almost at the end of the range of the headlamps. The lack of lighting in the control condition could have resulted in the participants requiring the supplemental illumination provided by the headlamps.

The results of this study have several practical implications for nighttime work zones on limited-access highways. The differences in the visual performance and discomfort glare ratings show that light tower orientation plays an important role in affecting a driver's visibility in work zones. Light towers located closest to the roadway and at a mounting height of 15 feet had the lowest detection distances and highest discomfort glare ratings, irrespective of the wattage and lumen output. Thus, efforts should be made to locate the light towers away from the roadway and mount them higher than 15 feet. The results from the study also show that mounting heights of at least 20 feet can result in higher visual performance and lower discomfort glare. In addition to increasing the mounting height, increasing the offset distance of the portable light tower from the roadway, especially with the higher wattage (4000-W or greater) balloon light towers, can result in higher visual performance and lower discomfort glare ratings. The results from this study also reaffirmed that light towers aimed perpendicular to the driver's line of sight result in lower discomfort glare ratings. Finally, the results also show that balloon light towers could offer better visual performance than conventional metal halide light towers of similar wattage and light output, but only if they are mounted at a specified mounting height and offset distance from the roadway. It is important to remember that in all the orientations and mounting heights used in the study, the light levels required for the workers were either met or exceeded, indicating that using the recommended orientations and mounting heights for the portable light towers will not only increase the visibility of the driver but also ensure good visibility for the workers in the work zone.

This work has a few limitations. First, there was only one worker in the work zone and no other equipment with flashing beacons was present. Second, there was no other traffic in the test area other than the experimental vehicles. These simplifications were made in the experimental design to eliminate the confounding effects that could arise due to the presence of more workers, vehicles, and traffic. Adding more workers and vehicles could potentially reduce the detection and recognition distances as drivers have to scan the work zone to perform the detection task. These results represent drivers' visual performance and glare ratings under optimal conditions and performance decrements should be expected in real road conditions. Finally, these results are only applicable to work zones on limited-access highways where there are no other sources of roadway lighting other than the portable light towers. The presence of roadway lighting could further increase the detection and recognition distances and also reduce the perceptions of glare (as a result of an increase in the driver's adaptation level). To address the above-mentioned limitations, future work should evaluate the effects of work zone equipment, traffic density, presence of roadway lighting, and other more complex scenarios to better understand drivers' visual performance and their perceptions of glare in work zones.

CHAPTER 5. CONCLUSION

In conclusion, the orientation of portable light towers, more specifically, the mounting height and offset distance, play a critical role in affecting driver visual performance and discomfort glare. Portable light towers, irrespective of wattage and lumen output, at less than a 20-foot mounting height and closer to the roadway result in decreasing drivers' visual performance and increasing their discomfort glare. Based on the results of the study, portable light towers that cannot be aimed, like the balloon light towers, should be mounted higher than 20 feet and at distances greater than 10 feet from the roadway. In order to increase visual performance, portable light towers, like the conventional metal halide light towers that can be aimed, should be mounted at a height of at least 20 feet where the angle between the beam axis and driver's line of sight is greater than or equal to 90 degrees and the angle between the beam axis and vertical is less than or equal to 60 degrees. These recommended mounting heights and orientations for the portable light towers will not result in lowering the light levels for the workers in the work zone, thus ensuring optimal visibility for them.

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