University Transportation Research Center - Region 2

Final Report

Nighttime Highway Construction Illumination

Performing Organization: Rensselaer Polytechnic Institute

August 2014

Sponsors:
New York State Department of Transportation (NYSDOT)
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The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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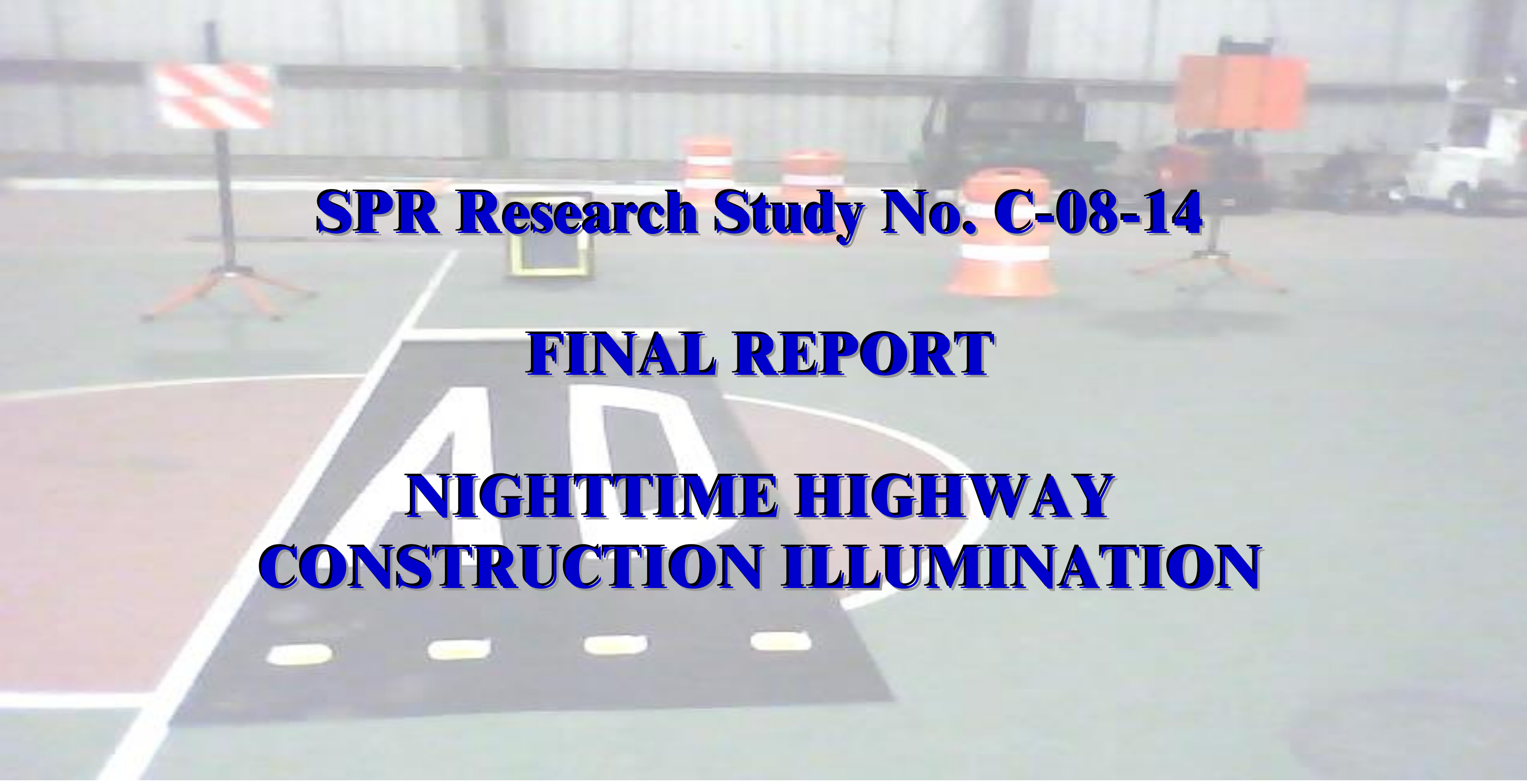

SPR Research Study No. C-08-14

FINAL REPORT

NIGHTTIME HIGHWAY CONSTRUCTION ILLUMINATION

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Conducted for the

NEW YORK STATE DEPARTMENT OF TRANSPORTATION

By the

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16. Abstract

The nighttime driving environment, consisting of roadway illumination, signs, vehicle lighting and markers, delineators and flashing lights, can be complex or even confusing for both pedestrians and drivers. The nighttime construction environment is even more complex and even chaotic because of the added presence of workers, construction equipment and bright lights (which are sometimes flashing). Work zones at night often involve changing conditions and new traffic patterns that are unfamiliar to drivers. Workers in highway construction areas and drivers navigating through these areas have distinct visual requirements that must be met both through lighting and other forms of visual information provided in the work zone. Conventional methods for illuminating work zones are prone to producing glare for workers and for drivers. At the same time, new technologies for lighting and traffic control, such as balloon lights, light emitting diodes (LEDs), highly reflective retroreflective sheeting and intelligent warning lights are being developed that could address many of the concerns associated with nighttime highway construction. As part of a multi-phase project, requirements for worker and driver visibility and visual information were identified through human factors research, and various technologies and new approaches to work zone lighting and traffic control were demonstrated and evaluated to provide preliminary guidance for when they might be of benefit. A checklist of planning and design issues, and a method for estimating visual performance under nighttime work zone lighting are provided to help transportation engineers and highway contractors identify promising solutions for work zone lighting.

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EXECUTIVE SUMMARY

The nighttime driving environment, consisting of roadway illumination, signs, vehicle lighting and markers, delineators and flashing lights, can be complex or even confusing for both pedestrians and drivers. The nighttime construction environment is even more complex and even chaotic because of the added presence of workers, construction equipment and bright lights (which are sometimes flashing).

Work zones at night often involve changing conditions and new traffic patterns that are unfamiliar to drivers. Workers in highway construction areas and drivers navigating through these areas have distinct visual requirements that must be met both through lighting and other forms of visual information provided in the work zone. Conventional methods for illuminating work zones are prone to producing glare for workers and for drivers. At the same time, new technologies for lighting and traffic control, such as balloon lights, light emitting diodes (LEDs), highly reflective retroreflective sheeting and intelligent warning lights are being developed that could address many of the concerns associated with nighttime highway construction.

As part of a multi-phase project, requirements for worker and driver visibility and visual information were identified through human factors research, and various technologies and new approaches to work zone lighting and traffic control were demonstrated and evaluated to provide preliminary guidance for when they might be of benefit. A checklist of planning and design issues, and a method for estimating visual performance under nighttime work zone lighting are provided to help transportation engineers and highway contractors identify promising solutions for work zone lighting.

1. INTRODUCTION

The nighttime driving environment, consisting of roadway illumination, signs, vehicle lighting and markers, delineators and flashing lights, can be complex or even confusing for both pedestrians and drivers. The nighttime construction environment is even more complex and even chaotic because of the added presence of workers, construction equipment and bright lights (which are sometimes flashing). Further, construction work zones at night often involve changing conditions and new traffic patterns that are unfamiliar to drivers. Workers in highway construction areas and drivers navigating through these areas have distinct visual requirements that must be met both through lighting and other forms of visual information provided in the work zone.

Lighting systems presently used in work zones must be bright enough to provide visibility for workers. Ironically, however, the same brightness also can reduce visibility by creating glare to drivers and to workers, which can contribute to visual chaos. Illumination from work zone lighting systems is also necessarily non-uniform, resulting in some portions of the work zone with high light levels adjacent to others in near-darkness. The use of delineation, pavement markings, channelization devices and warning lights helps identify the presence of lane changes, equipment, and other potential hazards, and signage provides additional instructions for safe navigation in and around work zones. Taming these diverse components of the work zone visibility system so that they work together and not in competition to provide unambiguous visual information can be a challenge.

To address these challenges, the New York State Department of Transportation (NYSDOT) initiated Project C-08-14, Nighttime Highway Construction Illumination. The present report summarizes activities conducted by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute to investigate approaches to work zone illumination, signage and delineation, and the use of signal lights in channelizing devices. This chapter summarizes published literature pertaining to work zone planning issues, luminance and color requirements for marking, delineation and signing, and characteristics of signal lights and other channelizing devices.

Subsequent chapters address each of these areas, first describing analytical and human factors research to address gaps in knowledge, and culminating with a mock-up demonstration to provide engineers with opportunities to view different configurations and provide feedback about their utility in work zones. Finally, a chapter containing a checklist including recommendations for NYSDOT to consider when planning and specifying lighting for work zone applications is given.

Literature Review

Planning Issues

Nighttime construction activities can have substantial impacts on roadway traffic and on the surrounding area around the construction site. One of the most important issues to consider in assessing these impacts is work zone lighting (Hancher and Taylor, 2001), according to transportation agencies and construction contractors. Factors such as light trespass can have substantial influence on the manner in which nighttime operations should be conducted (Bryden and Mace, 2002a). Of course, noise and other disruptions such as detouring traffic are also important, too (Bryden and Mace, 2002a).

It is important for nighttime construction operations to be planned well in advance so that these impacts can be anticipated, and mitigated (Bryden and Mace, 2002b). Through the National Cooperative Highway Research Program (NCHRP), Bryden and Mace (2002b) have developed sample plans for nighttime operation lighting and traffic control that can be used by transportation agencies and contractors to assist with this planning process. In addition, continual monitoring and inspections, including visual assessments by knowledgeable engineering staff (Bryden and Mace, 2002b), should be performed regularly.

Illumination Characteristics

Through various sources, albeit broadly scattered throughout the literature, there is a broad array of recommended illumination characteristics for the types of visual tasks performed at nighttime highway construction locations. Through the NCHRP, Ellis and Amos (1996) and Ellis et al. (2003) compiled recommendations from the Illuminating Engineering Society (IES) (Rea, 2000), the Occupational Safety and Health Administration, and the Mine Safety and Health Administration in the development of streamlined average illuminance recommendations for three categories of visual tasks:

- 5 fc: for work crew movement and large, simple tasks
- 10 fc: for areas on and around construction equipment
- 20 fc: for difficult visual tasks such as joint sealing, equipment maintenance and electrical work and inspection

These recommendations are also often accompanied by illuminance uniformity recommendations to ensure that excessive dark and bright patches of light are not produced by the lighting system (Ullman and Finley, 2007).

In practice, meeting these requirements is not always as common as it could be (Ullman and Finley, 2007), and contrary to the advice of Bryden and Mace (2002b), measurements of the light levels achieved by lighting systems were rarely performed.

El-Rayes and Hyari (2005a, 2005b) have developed mathematical models to predict light levels and uniformity and in essence to begin to optimize lighting systems for nighttime construction activities. El Rayes and Hyari (2005a) found that their model predicted light levels of optimized systems within 12% to the actual installations that were developed using their model.

While these recommendations are focused primarily on the visual performance requirements of the construction workers, it is also important that illumination be provided to make the workers themselves and their backgrounds visible to drivers in and around the work location (Takemoto et al., 2008).

Regarding specific lighting approaches for providing adequate visual performance, Freyssinier et al. (2008) conducted an evaluation of semi-permanent high mast illumination along a long-term highway reconstruction project. The system consisted of a large installation of pole-mounted floodlight-type roadway luminaires that provided high levels of very uniform illumination along the entire stretch of highway under construction. The high mounting locations and illuminance uniformity resulted in high visual performance of workers with few shadows, and low glare to workers and drivers (Freyssinier et al., 2008). Louis (2010) reported that workers' perceptions of their own safety improved when roadway lighting was present.

This lighting approach is expensive in terms of installation and operation (Bullough et al., 2008), about 15%-20% higher than conventional illumination using light towers, but substantially reduced setup and takedown time and shaved time from the project while using less fuel to generate power, and produced less noise than light tower generators. On a per-distance basis the high mast approach produced less light pollution as well (Bullough et al., 2008). Overall it was a sound approach for large-scale projects but would not be cost effective for shorter ones.

Another approach that has begun to be studied is the use of balloon lighting, whereby a light source is surrounded by a large, translucent covering that diffuses the light, producing softer and fewer shadows, and in principle, less glare (Hancher and Taylor, 2001). Balloon lighting systems have the ability to produce similar amounts of light for a given wattage (Hassan et al., 2011), although they tend to result in lower average illuminances in the work area. Hassan et al. (2011) confirmed that the balloon systems indeed produce less disability glare to comparable systems using conventional light towers and they also are less glaring than equipment mounted lights or vehicle headlamps (Huckaba, 2009). Opinions of construction workers to balloon systems are also favorable (Huckaba, 2009; Louis, 2010) and drivers also appear to appreciate these lights (Huckaba, 2009).

Luminance and Color Requirements

The luminance and color of signs, equipment markings, pavement markings, and worker clothing have been studied in several different contexts, mainly with the objective of providing sufficient information to drivers to safely navigate through a work zone and avoid hazards and workers. Some computational approaches have been explored such as one that is based on image processing (Barton et al., 2002), but these may be too complex to be used by highway construction contractors and rather could perhaps be used in the development of recommendations through subsequent research activities.

The ability to see and understand information from signage in work zones is rated by safety contractors and by truck drivers (who frequently must drive through many work zones) as one of the most important factors related to their satisfaction (Hirasawa et al., 2007). Being able to see workers is another very important factor. Not surprisingly, daytime visibility is judged by both contractors and truck drivers as more satisfactory than nighttime visibility (Hirasawa et al., 2007).

The type of information that is most desired by drivers as they approach and navigate through work zones is information about impending lane merges and closures, what speeds are appropriate when approaching work zones and what the starting and ending extents of the work zone is (Takemoto et al., 2008). Providing this information was often judged to be best when it was conveyed through short and simple text messages rather than a more complex combination of text and graphics (Takemoto et al., 2008). However, Wang et al. (2003) found that novel messages on signs such as “My Mommy/Daddy Works Here” in childlike fonts were effective as reducing speeds in work zones, at least in the short term.

Characterization of sign luminances is possible (Burns and Donahue, 2001) although it should be recognized that there are often substantial deviations between calculated and actual luminances in the field, probably because work zones by their nature are temporary, traffic control is set up and taken down multiple times over a given project, and mountings are often designed to be lighter weight and less permanent to allow flexibility.

A number of explorations of fluorescent-colored sign materials have been conducted. Schnell et al. (2001) reported that clear daytime visibility distances were slightly longer for fluorescent than non-fluorescent signs, and Zwahlen and Schnell (1997) found fluorescent signs more reliably detected in the visual periphery. Fontaine et al. (2000) found that fluorescent orange signs often were felt by work crews to be more visible than conventional orange signage. Hummer and Scheffler (1999) found that fluorescent orange signs were associated with slightly fewer traffic conflicts in work zones, with fewer vehicles in closed lanes and less variable (but higher) driving speeds. In contrast to Hummer and Scheffler (2004), Wang et al. (2003) found that fluorescent orange signs reduced driving speeds in work zones, although the effect was diminished over time. Gates et al. (2004) investigated the use of fluorescent red stop signs in conjunction with flashing red light emitting diodes (LEDs) and found these to be effective at encouraging traffic to stop when this was desired.

The use of non-fluorescent sign color has also been evaluated by several researchers. Brewer et al. (2006) reported that the use of orange borders around speed limit signs made them more conspicuous and visible, although they did not find any observed effects on driving speeds in work zones. Gates et al. (2004) studied the effect of a red reflectorized border around speed limit signs in work zones and reported that they had positive effects, increasing speed compliance. In a context somewhat different from work zone applications, Neale et al. (1999) found that several unconventional sign color combinations (yellow letters on purple, and black letters on light blue) resulted in reductions in late-braking maneuvers and were preferred by drivers, although such combinations are not presently permitted in the Manual on Uniform Traffic Control Devices (FHWA, 2009).

The colors of other visual elements have also been investigated. Orange colored portable rumble strips made from plastic or rubber were found to reduce driver speeds in work zones compared to uncolored asphalt rumble strips (Meyer, 2000) suggesting that the visual appearance was an important factor in speed reduction. Meyer (2000) reported that the portable rumble strips were ineffective at producing vibration or sound.

The effectiveness of worker clothing such as vests is also important for ensuring that drivers will not collide with workers. Turner et al. (1997) measured detection distances for workers wearing vests of different colors and found fluorescent orange-red vests were associated with the longest detection distances, during the daytime. Fontaine et al. (2000) found that fluorescent yellow-green vests tended to have the highest contrast ratios against their backgrounds; it is not known whether the locations studied by Fontaine et al. (2000) contained significant amounts of green vegetation. Arditi et al. (2003) measured luminances of several different colored vests and concluded that those producing the highest luminances were safest in terms of worker conspicuity.

Signal and Display Characteristics

Signal lights, often using flashing lights, and luminous displays of driving speed and other warnings are used in work zones along with the passive or reflective luminance systems described in the previous section of this report. As one example, stop sign paddles equipped with flashing red LEDs (as well as fluorescent sign faces) tended to increase traffic stopping behaviors in work zones (Gates et al., 2004).

Brewer et al. (2006) found that drivers tended to respond with greater probabilities to displays that provided information about their speeds, in terms of complying with work zone speed limits. Fontaine et al. (2000) reported that portable message signs could reduce traffic speeds by 1 to 2 mph in work zones, and that speed display trailers reduced speeds by 2 to 3 mph in one work zone, and by 7 to 9 mph in another work zone.

Mace et al. (1996) have developed recommendations for the appropriate luminous intensity of luminous displays such as speed signs, arrow panels or portable variable-message signs for daytime and nighttime conditions:

- Daytime: 300 to 500 cd (on-axis), 60 to 100 cd (off-axis)
- Nighttime: 90 to 150 cd (on-axis), 18 to 30 cd (off-axis)

To help control against glare from these types of displays, Mace et al. (1996) recommend that the maximum nighttime luminous intensity from the displays never exceed 380 cd.

The configuration of the display can also influence driver behavior and comprehension about appropriate driving maneuvers in work zones. The so-called “dancing diamond” display consisting of an alternating left-right position diamond was found to reduce approaching speeds of traffic entering work zones (Turley et al., 2003). A survey of drivers found that this diamond display was felt to encourage safe driving by the same authors (Turley et al., 2003).

The color of signal lights most frequently used in work zones is yellow (Ullman, 2000). There have been limited trials of combinations of signal light colors in work zones. For example, a combination of yellow and blue lights was found to reduce driving speeds in several real-world work zone locations (Ullman, 2000). The use of yellow, red and blue flashing lights together increased the likelihood of braking in work zones (Ullman, 2000), although this combination would not be permissible according to the Manual on Uniform Traffic Control Devices (FHWA, 2009).

The spatio-temporal pattern of lights is one that has not been widely implemented in work zones. Finley et al. (2001) evaluated the use of a sequential flashing system both in closed-track studies and in some real-world locations. Drivers were not confused by such systems (Finley et al., 2001) and in real-world locations, when used to delineate the appropriate traffic patterns for lane closures, Finley et al. (2001) found that there were fewer vehicles in the closed lane 1000 ft. ahead of the closure, than without the sequentially flashing system. However, such effects on driver behavior were substantially reduced after six months (Finley et al., 2001).

Discussion and Brief Annotated Bibliography

Nighttime work zones are visually complex locations and efforts to improve workers' and drivers' comprehension and visual performance are critical. The review of literature in this chapter reveals substantial efforts in terms of illumination systems for visual performance, signage and markings for hazard detection and avoidance, and the use of signaling and displays to provide additional visual guidance information. Recent advancements in lighting technologies, and in particular that of LEDs, might provide significant opportunities for providing visually effective, efficient and economical solutions to nighttime work zone lighting and traffic control.

Publications in this annotated bibliography are cited by author and date. Full bibliographic citations for these references are provided in the References section of this report.

Arditi et al., 2003:

- Safety vests for workers that produced the highest luminances under the prevailing lighting conditions in nighttime work zones were judged by the authors to be the most visible

Barton et al., 2002:

- A computational model based on image processing is proposed for analysis of work zone conspicuity

Brewer et al., 2006:

- Displays that provide drivers with feedback about their speeds in work zones appear to increase compliance with speed limits
- Orange borders around speed limit signs increase their conspicuity and visibility but did not influence compliance with speed limits

Bryden and Mace, 2002a:

- Factors that need to be considered in planning nighttime construction lighting are noise, traffic and light trespass impacts on the surrounding community

Bryden and Mace, 2002b:

- Glare is a critical concern in nighttime construction locations
- Visibility assessment by subjective evaluation is a valid method for ensuring good visibility in work zones
- Plans for lighting and traffic control devices for typical applications are provided

Bullough et al., 2008:

- High mast lighting used to illuminate a highway reconstruction project was 16% more costly than conventional trailer-mounted lighting
- On a per-linear-distance basis, the high mast system produced less light pollution and light trespass than a conventional system
- Sound levels in the work zone were lower with the high mast system than with conventional lighting, and the high mast lighting system reduced generator fuel, oil and maintenance costs to one-third that of conventional lighting
- The high mast approach is most suitable for long term projects along controlled access roads

Burns and Donahue, 2001:

- Laboratory measurements and field measurements of sign luminances under corresponding conditions were somewhat correlated but there was a substantial amount of scatter between corresponding measurements

El-Rayes and Hyari, 2005a:

- Predictions from a mathematical model for calculating light levels from temporary work lighting equipment used in work zones averaged less than 12% error in comparison with actual measurements of modeled installations

El-Rayes and Hyari, 2005b:

- A mathematical model for optimizing the light level from temporary work zone lighting systems, the glare from these systems, the uniformity of illumination, and the cost of the lighting system is demonstrated

Ellis and Amos, 1996:

- Based on a review of recommendations for lighting from the Illuminating Engineering Society, the Occupational Safety and Health Administration and the Mine Safety and Health Administration, 5 fc is recommended for locations where mainly crew movement tasks place or very large, simple tasks are performed; 10 fc is recommended on and around construction equipment, and 20 fc is recommended for difficult tasks such as joint sealing, equipment maintenance, and electrical work

Ellis et al., 2003:

- Recommendations of light levels of 5 fc, 10 fc and 20 fc are proposed for work crew movement, for levels on and near equipment, and for difficult visual tasks, respectively
- Guidelines for designing nighttime work illumination and temporary roadway lighting are proposed

Federal Highway Administration, 2009:

- Requirements and recommendations for signage and other traffic control devices in highway construction zones are provided

Finley et al., 2001:
- A sequential-flashing light system for lane closures was evaluated in controlled and real-world studies
- Drivers perceived the system positively and not as confusing
- In the real-world installation the number of vehicles 1000 ft ahead of the lane closure in the closed lane was reduced with the sequential flashing system shortly after installation
- These effects were reduced after 6 months of use

Fontaine et al., 2000:
- The use of fluorescent orange signs in work zones was liked by work crews, and fluorescent green-yellow vests resulted in high contrast ratios
- Portable message signs reduced traffic speeds by 1-2 mph
- Speed display trailers reduced traffic speeds by 2-3 mph in one location, and by 7-9 mph in another location

Freyssinier et al., 2008:
- A high-mast roadway lighting system along an interstate reconstruction project allowed a project to be completed sooner than with conventional trailer mounted lighting because of reductions in nightly setup and takedown times
- Visibility analyses confirmed that the lighting produced fewer shadows than conventional lighting and improved visual performance, on average
- Glare analyses confirmed that the high mast system produced lower glare than conventional lighting

Gates et al., 2004:
- Fluorescent red and flashing LED stop sign treatments resulted in greater numbers of drivers stopping on roadways
- A red reflectorized border around speed limit signs increased speed limit compliance+

Hancher and Taylor, 2001:
- Lighting-related issues are the second-highest problem associated with nighttime highway construction work based on surveys of transportation agencies, resident engineers and highway contractors
- Balloon lighting is suggested as a potential means for reducing glare at night

Hassan et al., 2011:
- Balloon lighting systems used similar wattages and produced similar amounts of light as conventional light towers
- Illuminances on work areas were lower from balloon lighting systems
- Disability glare was lower from balloon lighting systems

Hirasawa et al., 2007:
- A survey of traffic safety contractors and of truck drivers revealed slightly greater satisfaction with sign (conventional and electronic) visibility and with the visibility of workers during daytime than at night
- For traffic safety contractors, the understandability of signs, the color of workers' clothing and the nighttime visibility of crash cushions had the most influence on satisfaction
- For truck drivers, the understandability of signs and the daytime visibility of workers had the most influence on satisfaction

Huckaba, 2009:
- Veiling luminances from balloon lights were found to be much lower than from headlamps on equipment such as rollers, or from portable light towers
- Drivers and workers responded favorably to balloon lighting systems in work zones

Hummer and Scheffler, 1999:
- A real-world field evaluation of fluorescent orange work zone signs revealed an association between the fluorescent color and slightly fewer traffic conflicts
- Fewer vehicles were in the closed lane approaching the work zone with fluorescent signs
- Mean driving speeds increased but variance in speeds decreased with fluorescent signs

Louis, 2010:
- General roadway lighting in a nighttime work zone improved workers' perceptions of safety in the environment
- Balloon lights were regarded by workers as improving their productivity

Mace et al., 1996:
- Recommended luminous intensity values for arrow panels are 300-500 cd (on-axis) and 60-100 cd (off-axis) for daytime and 90-150 cd (on-axis) and 18-30 cd (off-axis) for nighttime conditions
- To control for glare it is recommended that the maximum nighttime luminous intensity never exceed 380 cd

Meyer, 2000:
- Orange-colored removable rumble strips were less effective at providing sound and vibration information than conventional asphalt rumble strips
- The orange strips were found to reduce driver speeds in work zones

Neale et al., 1999:
- Exploring different color combinations of signage for work zones and detours, the authors concluded that yellow letters on purple or black letters on light blue resulted in the fewest late-braking maneuvers when many tight curves were present
- Black letters on light blue resulted in the fewest turn errors of all color combinations, and were preferred by older drivers; younger drivers preferred yellow letters on purple

Rea, 2000:
- Recommended light levels for grading are 10 fc on the task plane
- Recommended light levels for simple inspection are 30 fc on the task plane
- Recommended light levels for performing equipment maintenance are 50 fc on the task plane
- Recommended light levels for emergency egress are 1 fc on the ground surface
- Recommended light levels for safety range from 0.5 fc with low activity and low hazard levels, to 5 fc with high activity and high hazard levels
- Recommended light levels for construction work are 5 fc on the task plane
- Recommended light levels for excavation work are 3 fc on the task plane
- Recommended light levels for lumber yards (i.e., materials storage) are 1 fc
- Advantages of projected lighting systems with a minimum of luminaires are fewer mounting sites, resulting in fewer obstructions and fewer concentrated electrical loads, with larger coverage areas
- Advantages of distributed lighting systems with smaller luminaires throughout a location are good utilization of light, less critical aiming of luminaires, lower mounting height facilitates maintenance, and potentially less light pollution

Schnell et al., 2001:
- Daytime legibility distances of signs using fluorescent colored materials were slightly longer in clear weather than those of signs using conventional colors

Takemoto et al., 2008:
- A survey of drivers about their needs regarding work zones revealed that a majority of them wanted information about lane reductions, when they should slow down, and where the work zone started and ended
- Signs with short and simple text were judged as easier to understand than ones with text and pictograms
- Ensuring that some work zone illumination is directed toward flaggers or other workers is important

Turley et al., 2003:
- A caution display consisting of a diamond alternating in left-right position was found to result in reduced speeds when approaching work zones relative to more conventional flashing displays
- A majority of survey respondents questioned about the diamond display reported that they felt it prompted safe driving

Turner et al., 1997:
- Detection distances of construction workers during daytime conditions were measured for several different clothing colors
- Fluorescent orange-red colored clothing resulted in the longest mean detection distances

Ullman, 2000:

- A combination of amber and blue warning lights were usually found to reduce speeds in several real-world highway locations
- A combination of amber, red and blue warning lights increased the frequency of braking in several locations

Ullman and Finley, 2007:

- Site inspections of nighttime work zones revealed that a substantial proportion (~40%) used three or four portable light towers, no matter what the work being performed was
- Providing uniform lighting for milling and repaving operations was very difficult to achieve
- Contractors rarely measure light levels actually achieved on the site of nighttime work zones

Wang et al., 2003:

- Fluorescent orange sign sheeting was reported to reduce speeds in highway work zones, with a diminished effect over time
- Innovative message signs such as "My mommy/daddy works here" in child-like fonts also reduced speeds in work zones with diminished effects over time

Zwahlen and Schnell, 1997:

- Fluorescent-colored targets and in particular, fluorescent yellow-green targets, were detected with greater probability than other colors

Survey of Regional Engineers and Contractors

A short survey questionnaire was developed, containing eight questions regarding the importance of lighting for nighttime highway construction work, the types of lighting and traffic control equipment presently used, and the types of technologies for lighting and for traffic control that should be used in the future for nighttime highway work.

The survey was implemented online through a web survey service (SurveyMonkey.com). Copies of the survey were distributed to the NYSDOT regions through the regional construction engineers, who either completed the survey or forwarded it to staff members, and to companies and contractors involved in highway construction. These were identified through the assistance of the New York chapter of the Associated General Contractors of America, the Empire State Highway Contractor Association, the American Traffic Safety Services Association's Temporary Traffic Control Committee, and lists of organizations who have provided highway construction services to NYSDOT listed on its website.

The survey was administered in February and March 2011. Survey respondents could email, fax or mail copies of the completed survey, or could perform the survey online. A total of 46 responses were received.

Importance of Lighting

To evaluate the importance of nighttime construction lighting and the tasks associated with nighttime road work, survey participants were asked how important they felt lighting was (Figure

1-1). About 91% of respondents believed that nighttime construction lighting was “very important,” and the remaining 9% responded “somewhat important.” There was a great deal of agreement among all respondents that lighting is a necessary and important component to nighttime construction.

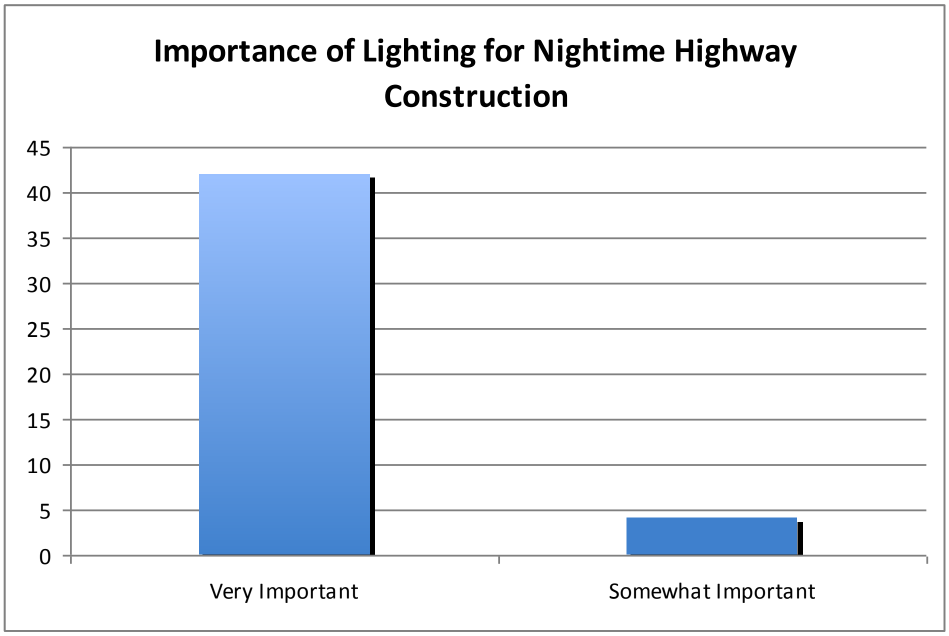


Figure 1-1. Number of respondents selecting each response regarding the importance of lighting in nighttime road work.

Primary Issues for Work Zone Illumination

When prompted to indicate which issues pertaining to nighttime construction lighting were most important, the majority ranked those factors associated with safety and visual task as highest (Figure 1-2). The biggest concern was the ability of drivers to see the workers, followed by traffic safety and by the ability of workers to see their tasks. Less important concerns included maintaining traffic flow, providing visual comfort, minimizing light trespass, and reducing equipment and fuel costs. Participants were more concerned with safety and with workers (and drivers) being able to see their tasks, than they were with costs and the temporary discomforts of nighttime lighting. One participant explicitly made this point by checking “Other,” noting “Worker Safety” as the main concern.

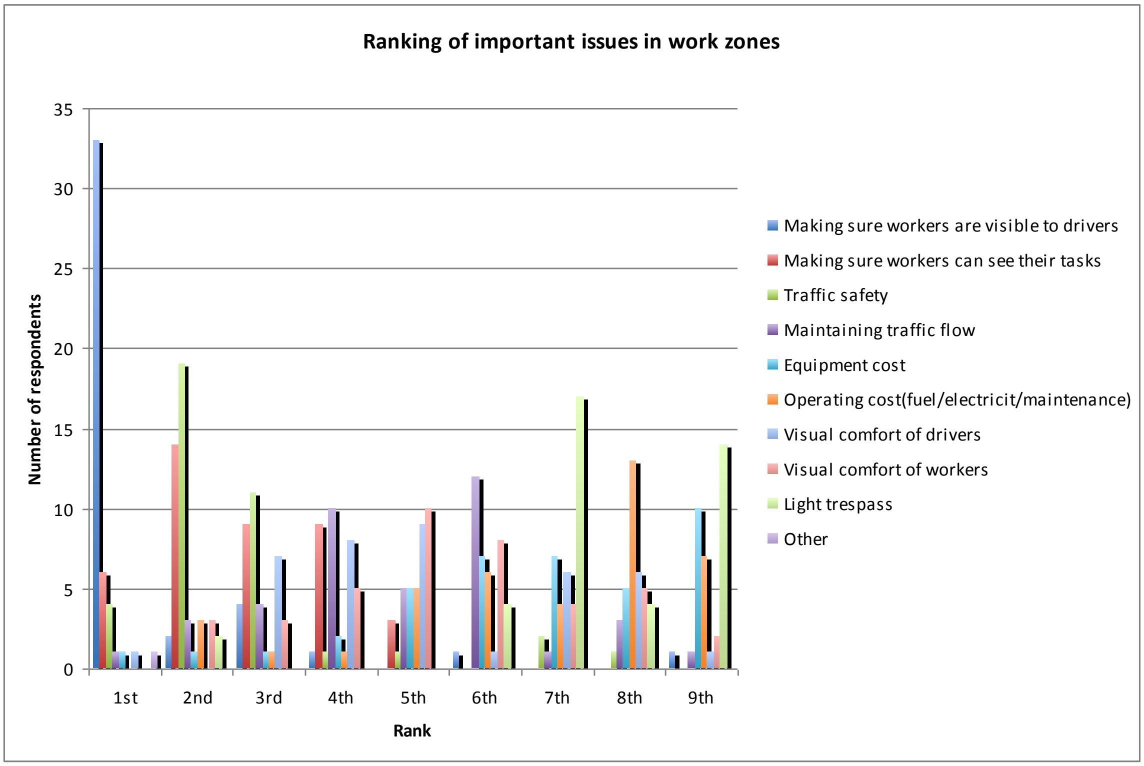


Figure 1-2. Ranking of important issues in work zones.

Primary Visual Tasks at Work Zones

The ranking of the importance of various visual tasks for nighttime work (Figure 1-3) reinforces the significance of being able to do work by ranking certain tasks associated with nighttime construction more highly than others. Tasks such as "general orientation," "driving and steering equipment," and "seeing the location of the equipment" were more important than dealing with seeing fine details, colors, and trip hazards. Notably, although traffic safety is a major concern of nighttime roadwork, trip hazards do not appear to be. Some participants stated that too much light may even be dangerous and less effective than less light in nighttime construction, noting however that each construction scenario is unique and where one scenario may utilize less light, another scenario may need more.

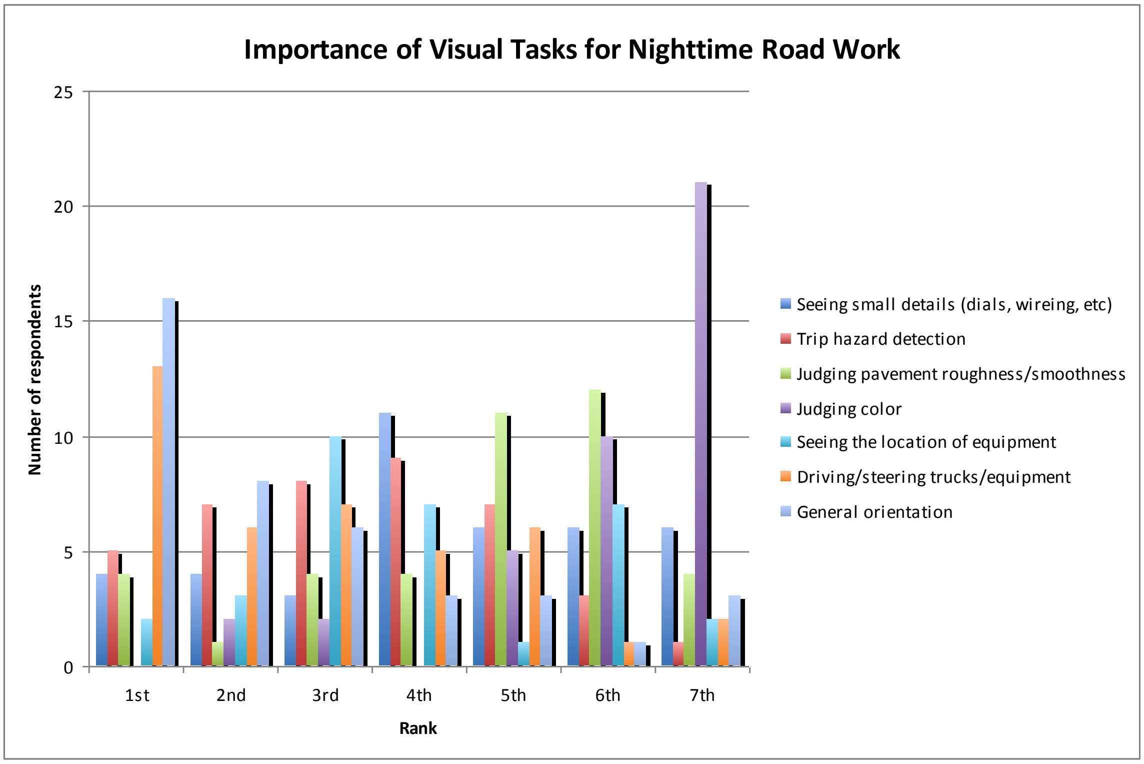


Figure 1-3. Ranking of the importance of different visual tasks in nighttime construction.

Lighting Technologies Currently Used for Illumination

Participants were also asked about the equipment they used for nighttime construction illumination (Figure 1-4). For such illumination, survey respondents have used the following technologies: trailer mounted light towers (91%), portable flashlights and clip-on lights (52%), vehicle headlights (46%), semi-permanent mast lighting (26%), balloon lighting (13%), and 21% reported using other sources including equipment-mounted lights, vehicle mounted lights, and existing street lighting.

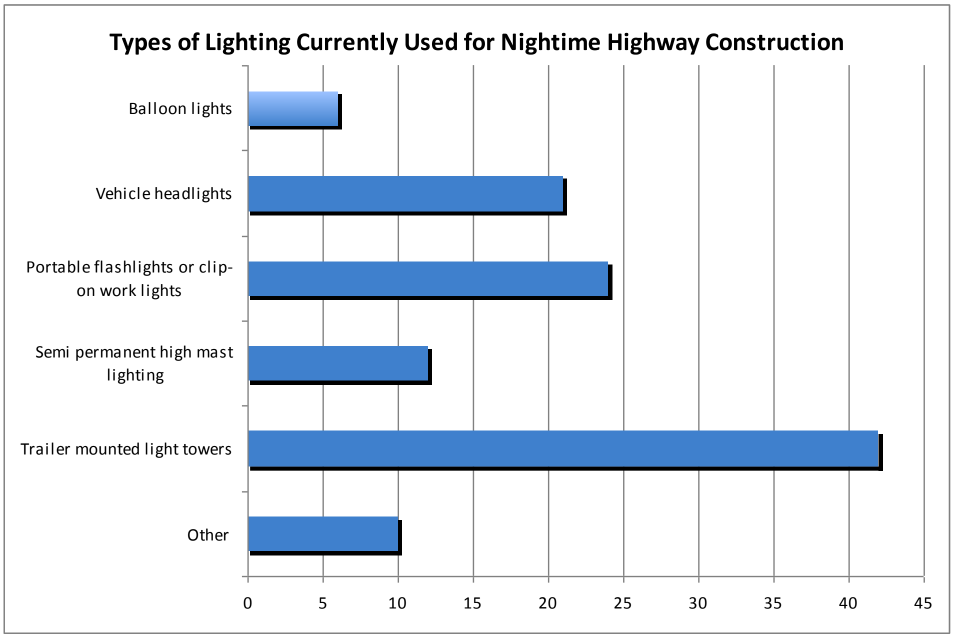


Figure 1-4. Types of lighting equipment currently used for nighttime construction.

Recommended Lighting Technologies

Future technologies that survey respondents indicated that they would like to employ for work zone illumination (Figure 1-5) include high mast lighting (52%), light emitting diodes (45%), portable flashlights or helmet worn lamps (39%), fluorescent or induction lamps (32%), balloon lighting systems (30%), and other sources including vehicle-mounted lights and light towers.

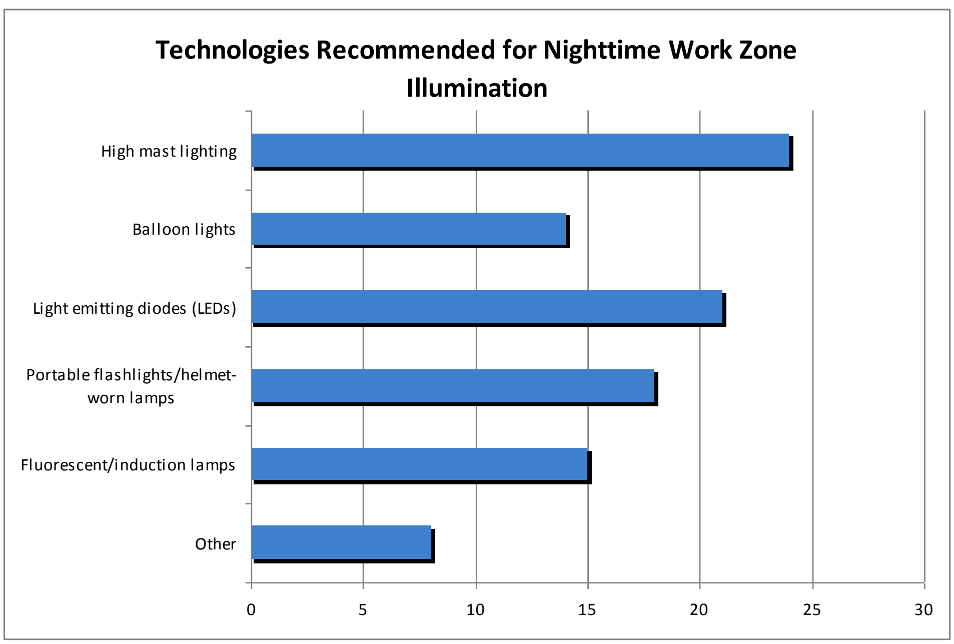


Figure 1-5. Lighting technologies recommended for use at work zones.

Technologies Currently Used for Traffic Control

Currently used traffic control equipment (Figure 1-6) was reported as follows: highly reflective sign sheeting (80%), barricade lights/flares (71%), temporary pavement marking tape (67%), speed display signs (63%), light emitting diode signal lights or beacons (56%), photoluminescent ("glow in the dark" materials (21%), automated flaggers (9%), and sequencing/chase lights (9%). One respondent used vehicle arresting nets and police cars. These statistics are well correlated with another survey question ranking nighttime work zone traffic equipment.

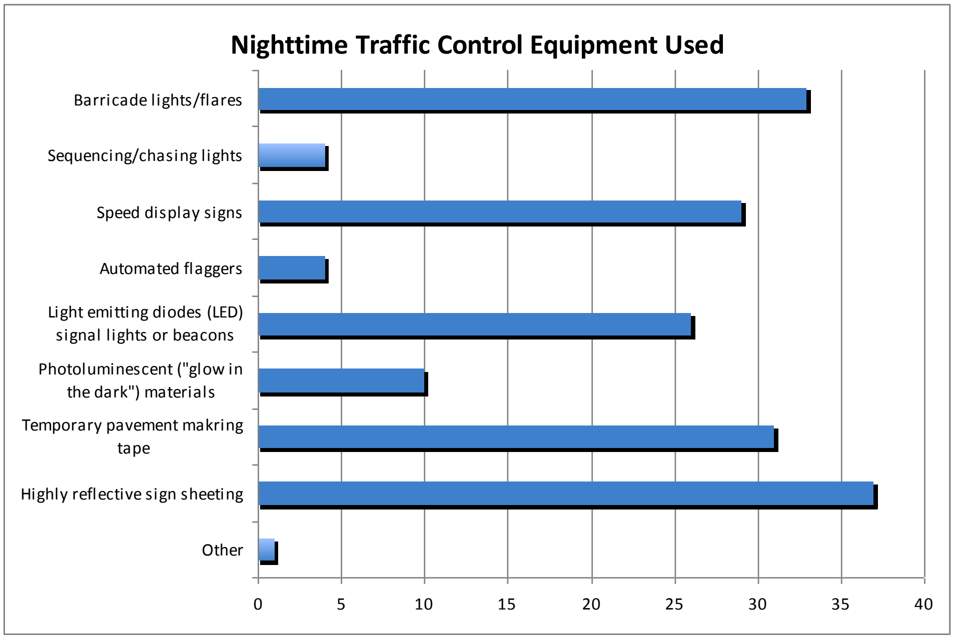


Figure 1-6. Reported traffic control equipment used.

These responses are consistent with rankings for various types of traffic control equipment (Figure 1-7). From highest to lowest, rankings were as follows: delineators (cones and drums), physical barriers (i.e., Jersey barriers), signs, flashing lights, temporary lane markings, flaggers, and steady burning lights. The highest-ranked traffic control equipment was associated with the most commonly used equipment (i.e., delineators may utilize highly reflective sign sheeting and barricade lights). The lowest-ranked traffic control equipment tended to be correlated with the least used traffic control (i.e., automated flaggers and sequencing or chasing lights).

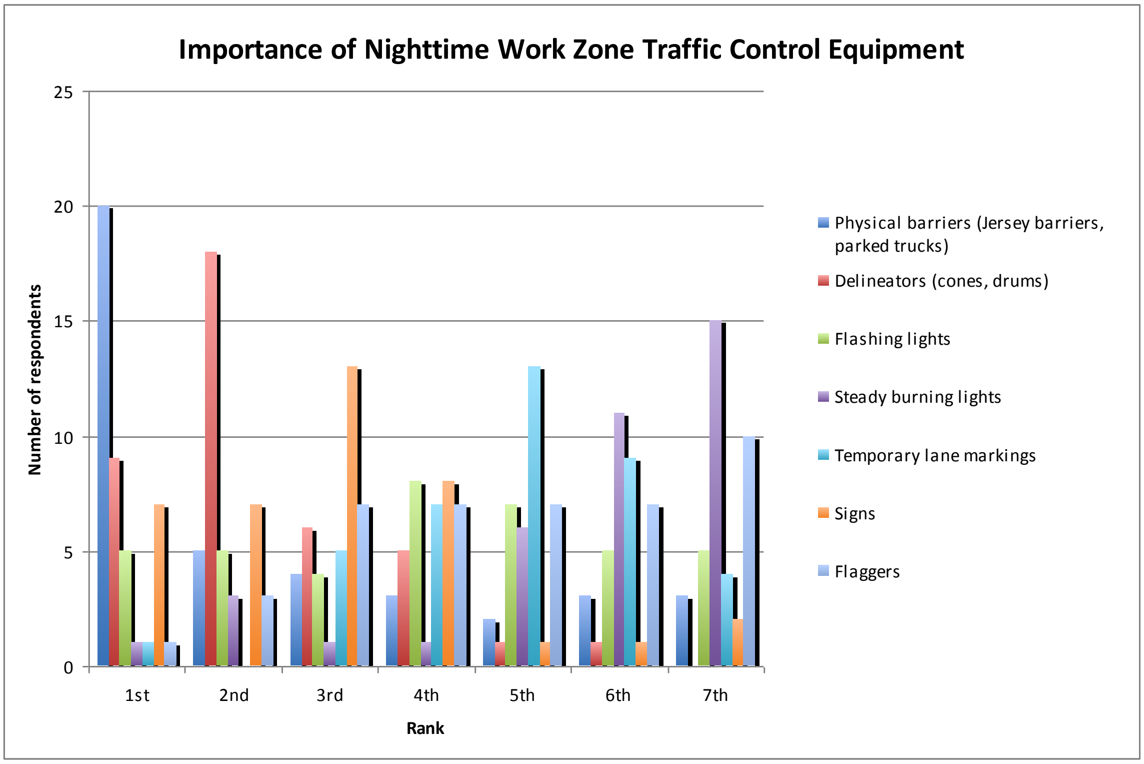


Figure 1-7. Rankings of different work zone traffic control equipment.

Recommended Traffic Control Technologies

Participants indicated what they believed were the most appropriate technologies for nighttime traffic zone lighting (Figure 1-8). These included: speed display signs (70%), highly reflective sign materials (65%), light emitting diodes (59%), steady burning lights (43%), strobe lights (37%), sequencing or chasing lights (24%), photoluminescent materials (24%), and other sources (8%). As with the responses regarding technologies that are presently being used, the highest-ranking responses to this question were also skewed towards highly-reflective, non-powered technologies which may be more durable and use less power. Interestingly, one participant did not agree with the use of speed display signs and asserted that although they are widely used, speed signs are also widely ignored by drivers.

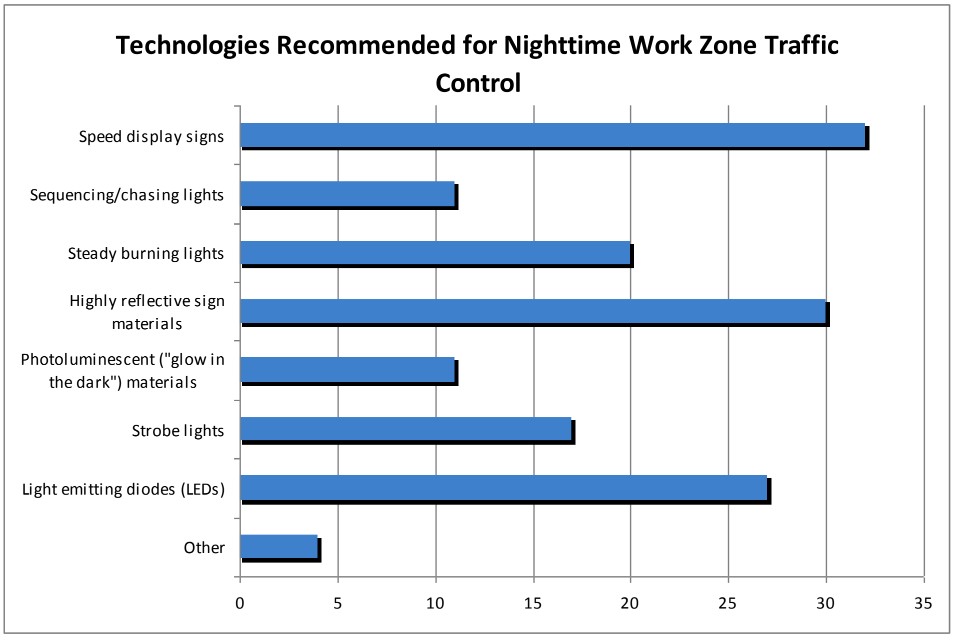


Figure 1-8. Traffic control technologies recommended for use in work zones.

Summary of Survey Results

The primary concerns of those involved in nighttime highway construction appear to be the safety and visibility of workers, especially from nearby vehicular traffic. Of interest, respondents tended to rank traffic control technologies highly that were passive and/or did not require electrical power (e.g., physical delineators and reflective materials).

The information from the present survey informs the recommendations developed and evaluated in subsequent chapters of the present project.

2. WORK ZONE ILLUMINATION SYSTEMS

The present chapter focuses on activities undertaken to investigate requirements for illumination in work zones for workers to see visual tasks, and for drivers navigating through work zones to identify potential hazards.

Visual Performance Assessments

Visual Task Scenarios

Several visual tasks were developed for subsequent visual performance analyses. These ranged from relatively small targets (e.g., a keyhole or small slot on a piece of equipment viewed from a distance of 3 ft), to medium-sized targets (e.g., a hand tool located 10 ft ahead on the ground while walking toward it that could become a tripping hazard), to large targets (e.g., a truck located 100 ft away that could be approaching a worker). The luminance contrast of the tasks used in the analyses was defined by the formula:

$$C = |L_t - L_b|/\text{maximum}(L_b,L_t) \qquad \text{(Eq. 2-1)}$$

Where L_t is the luminance (in cd/m²) of the target or object to be seen and L_b (in cd/m²) is the luminance of the target's or object's background. The luminance (L) of an object can be estimated by the illuminance (E) on an object and its reflectance (ρ: 0 is perfectly black, 1 is perfectly white) using the following formula:

$$L = E\rho/\pi \qquad \text{(Eq. 2-2)}$$

Where L is in cd/m² and E is in lx. The low contrast value used in the analyses was 0.2, and the high contrast value used was 0.8.

The range of light levels used in the analyses were from 3 lx, considered a minimum level for nighttime visibility in many traffic safety applications (Andre and Owens, 2001), to 300 lx, a level commonly experienced in many interior lighting applications (IES, 2000).

Visual Performance Assessment Method

The method used to assess visibility was the relative visual performance (RVP) model (Rea and Ouellette, 1991) which provides a determination of the speed and accuracy of visual processing (IES, 2000) as a function of:

- Background luminance
- Luminance contrast
- Target size
- Observer age

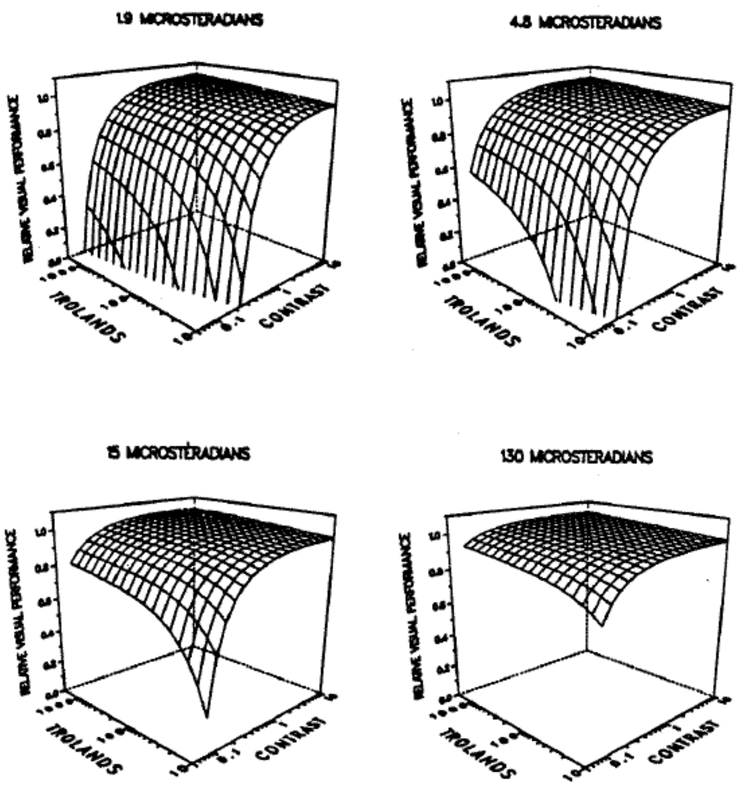


Figure 2-1. RVP surfaces for objects of four different sizes (Rea and Ouellette, 1991).

Figure 2-1 illustrates the value of RVP for a young (20 year old) observer, for four different object sizes, as a function of light level (specified as trolands in Figure 2-1; this quantity is approximately proportional to luminance) and contrast. RVP values typically range from zero near threshold to one, representing the near-maximum speed and accuracy of visual processing. When luminance and contrast are high enough, visual speed and accuracy reaches a "plateau" (a value near 1) illustrated by the flat portions of the figures. When one or more of these parameters is low, small changes in light level or contrast will have a large impact on visibility, corresponding to the steep "escarpment" of the surfaces in Figure 2-1. An objective of lighting is to put observers on the plateau without using excessive amounts of energy or power, which would be wasteful.

Object size is determined in terms of solid angle, in steradians (sr). The solid angular size (ω, in sr) of an object of a particular area (A) viewed from a particular distance (d) is given by the formula:

$$\omega = A/d^2 \qquad \text{(Eq. 2-3)}$$

Where A and d should be given in parallel units (e.g., m^2 and m, or ft^2 and ft). Appendix 1 contains the equations for calculating RVP values based on luminance, contrast, size and age. Age is important because the eye's lens decreases in transparency in a regular and nearly linear manner as a function of age. Pupil size also decreases systematically as a function of age. Both of these changes are gradual and nearly linear between 20 and 60 years of age. After 60 years, neural and other irregular and unpredictable pathologies also occur within the eye and visual performance decreases differently for different individuals.

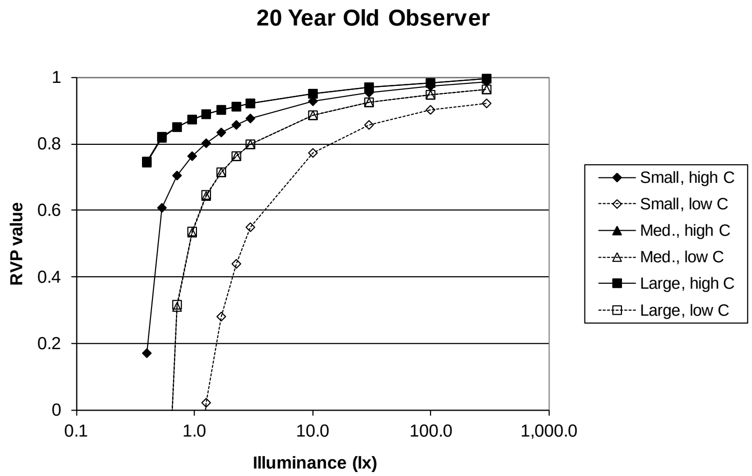


Figure 2-2. RVP values for a combination of task sizes and contrasts, for a 20-year-old worker.

Visual Performance Results

Figures 2-2, 2-3 and 2-4 illustrate the RVP values obtained for visual tasks varying in size and contrast for observers of age 20, 40 and 60 years, respectively. These figures demonstrate the relative importance of worker age, light level, object size and contrast on visual performance. As suggested by the plateau/escarpment surfaces in Figure 2-1, the curves in these figures all exhibit a similar characteristic of having a flat portion where visibility is largely insensitive to changes in light level, and some of them show a steep portion where visibility drops quickly with reductions in light level.

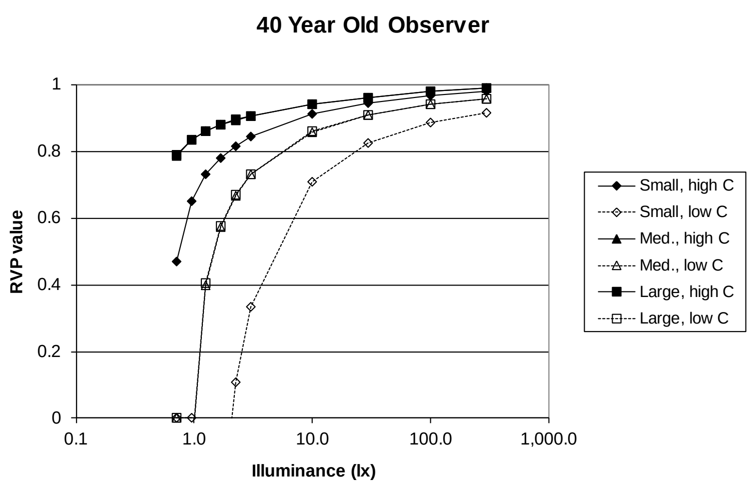


Figure 2-3. RVP values for a combination of task sizes and contrasts, for a 40-year-old worker.

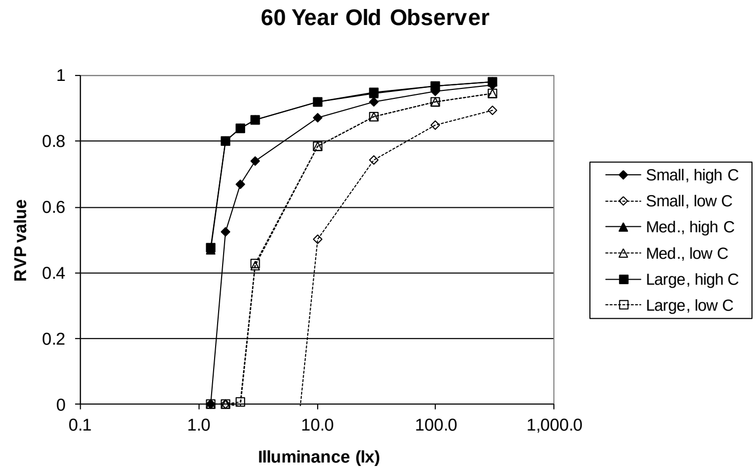


Figure 2-4. RVP values for a combination of task sizes and contrasts, for a 60-year-old worker.

For the smallest, low contrast tasks and for the oldest observers studied (60 year-olds), light levels lower than 10 lx can result in these tasks being essentially invisible. Illuminances approaching 100 lx are needed in order to make these targets highly visible (RVP value > 0.8) but even above 100 lx, further increases can yield rather substantial visibility improvements.

Accepting the relatively low, but still suprathreshold, visibility of the smallest, low-contrast objects by 60 year old workers (RVP value of about 0.5), the data in Figures 2-2 through 2-4 suggest that illumination of at least 10 lx would be sufficient to maintain a good level of visual performance for most visual tasks by most workers. Consideration of using higher illuminances when it is expected that very difficult visual tasks will be performed, and/or when a substantial number of workers are likely to be older, should also be made.

The analyses presented in this report are based on illumination alone, representing a range of conditions relevant to nighttime work zone lighting practice and able to be produced by conventional work zone lighting equipment (Ellis et al., 2003; Bryden and Mace, 2002). However, they do not consider glare, an important lighting factor (Bryden and Mace, 2002) that is addressed below.

Visual Performance Assessments and Glare

NYSDOT (1995) requirements for nighttime work zone lighting specify a maximum limit on the intensity from a luminaire of 20,000 cd at an angle corresponding to 70^o above the vertical. This corresponds approximately to an illuminance of 20 lx when viewed a distance of 100 ft away, from a location 20^o (90^o - 70^o) off axis. The impact of glare is to create a veiling luminance (L_g, in cd/m²) that is superimposed over the line of sight and acts to reduce the effective contrast of any objects to be seen. The veiling luminance (Fry, 1954) can be determined using the following formula:

$$L_g = 9.2E_g/[\theta(\theta + 1.5)] \qquad \text{(Eq. 2-4)}$$

Where E_g is the illuminance (in lx) from a glare source at an observer's eyes and θ is the angle (in degrees) between the glare source location and the line of sight. The veiling luminance L_g is added to the luminance of both the target or object to be seen and its background, and the resulting luminances are used to calculate RVP (Rea and Ouellette, 1991) as described above. Both the 20 lx value described above and a lower intermediate value of 2 lx were used in visual performance analyses to assess the influence of glare on visual performance.

Visual Task Scenarios

Several visual tasks were developed for subsequent visual performance analyses. For workers, these ranged from relatively small targets (e.g., a keyhole or small slot on a piece of equipment viewed from a distance of 3 ft), to medium-sized targets (e.g., a hand tool located 10 ft ahead on the ground while walking toward it that could become a tripping hazard), to large targets (e.g., a truck located 100 ft away that could be approaching a worker). These are the same visual tasks used in the Task 3 report for the present project, selected to permit comparisons with and without glare.

The luminance, contrast and size of the objects to be seen are defined as in the previous section of this chapter. Illuminances from work zone lighting range from 3 to 300 lx in approximately half-log-unit steps.

For drivers, the target of interest is assumed to be a small (8 inch square) target, viewed against the roadway pavement as a background such that it either has high (0.8) or low (0.2) contrast. This is the standard small target used by the Illuminating Engineering Society (2000) in its specification of visibility from roadway lighting. For the purpose of these analyses, a viewing distance of 100 ft is assumed, and a background luminance of 0.3 cd/m² (corresponding to 10 lx on pavement) is used to represent the illuminated roadway surface.

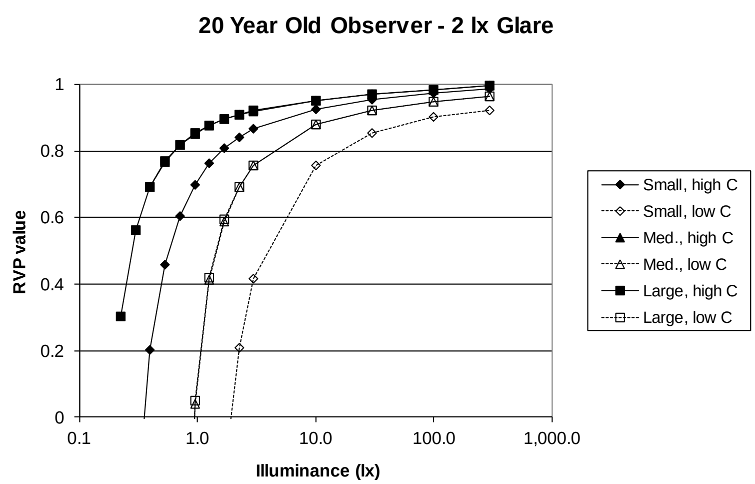


Figure 2-5. RVP values for a combination of task sizes and contrasts, for a 20-year-old worker, with glare of 2 lx present.

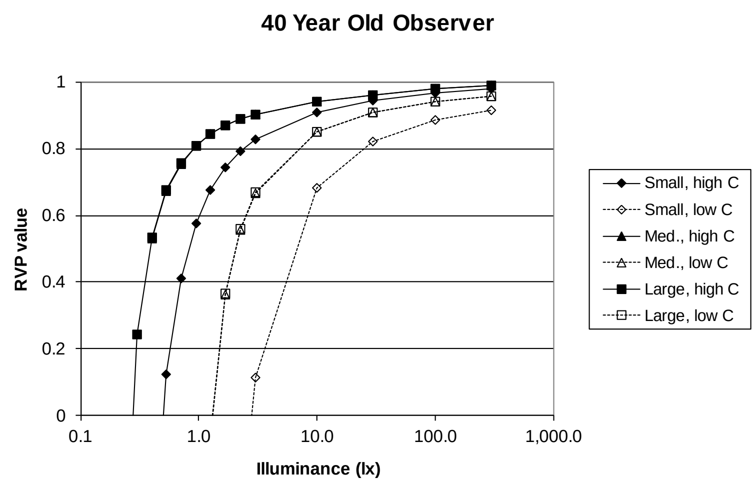


Figure 2-6. RVP values for a combination of task sizes and contrasts, for a 40-year-old worker, with glare of 2 lx present.

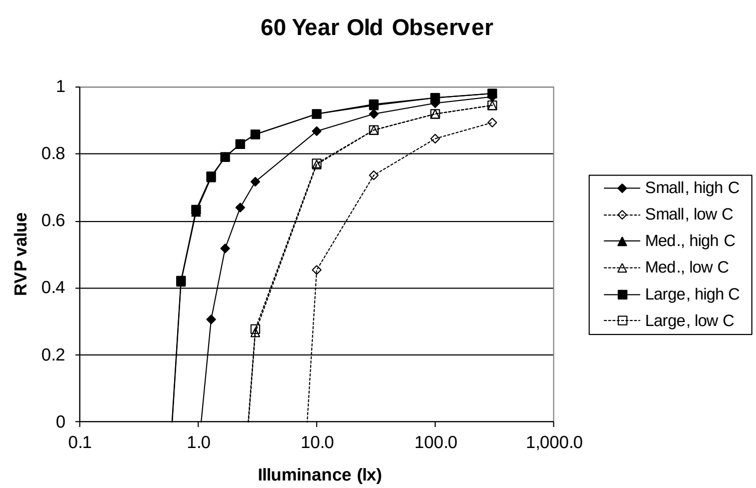


Figure 2-7. RVP values for a combination of task sizes and contrasts, for a 60-year-old worker, with glare of 2 lx present.

Results

Figures 2-5, 2-6 and 2-7 illustrate the visual performance results for each combination of visual target and contrast value, when a glare illuminance of 2 lx is present at a visual angle of 20º off axis, for 20-, 40- and 60-year-old workers. The reduction in visual performance from the no-glare case (see above) is greatest for the 60-year-old worker and the low-contrast object at the lowest illuminance, but for this condition, the object was already below the visual identification threshold. High-contrast objects are relatively resistant to glare of 2 lx, for all ages considered.

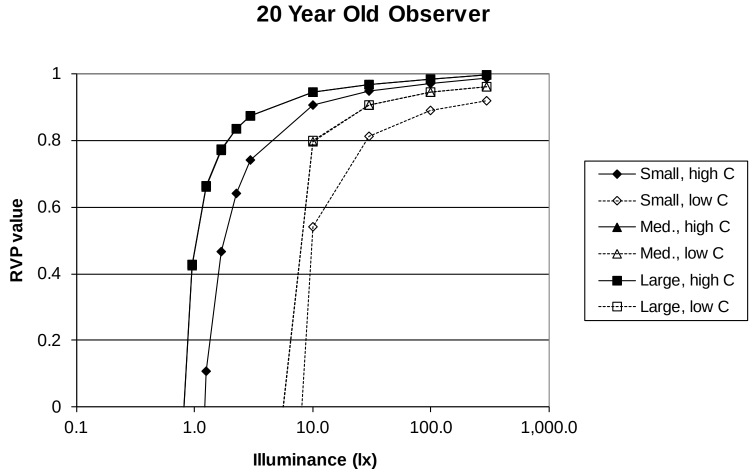


Figure 2-8. RVP values for a combination of task sizes and contrasts, for a 20-year-old worker, with glare of 20 lx present.

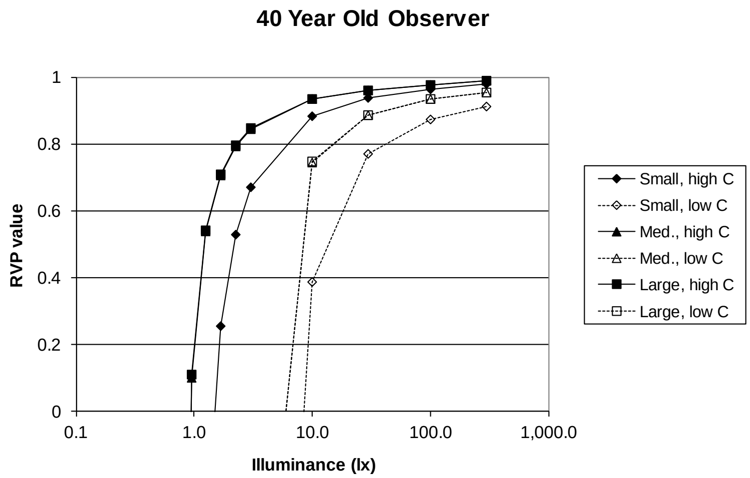


Figure 2-9. RVP values for a combination of task sizes and contrasts, for a 40-year-old worker, with glare of 20 lx present.

Figures 2-8, 2-9 and 2-10 contain parallel data as Figures 2-5 through 2-7, but for a glare illuminance of 20 lx. As might be expected, the influence of glare is greater, and can be seen even for 20-year-old observers, where the low contrast objects become invisible for the lowest work zone lighting illuminance (3 lx). The smallest, low contrast object falls below the visual threshold even when the illuminance is as low as 10 lx for the 60-year-old workers.

With the exception of this smallest, low contrast object, though, glare levels as high as 20 lx did not obliterate the visibility of objects as long as the pavement illuminance was at least 10 lx.

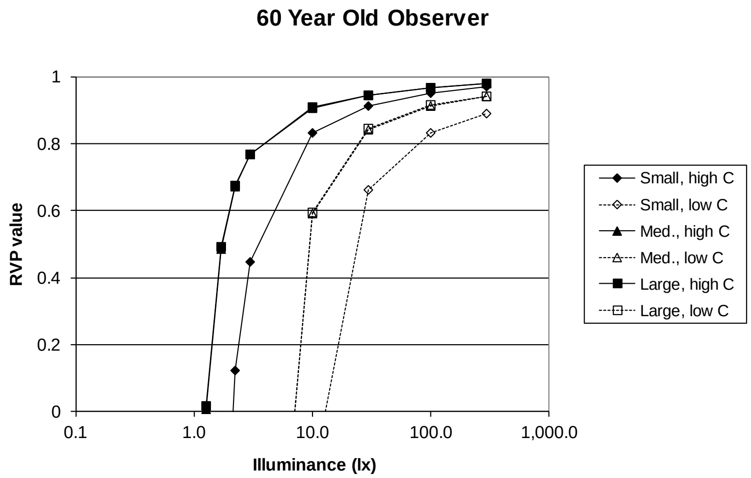


Figure 2-10. RVP values for a combination of task sizes and contrasts, for a 60-year-old worker, with glare of 20 lx present.

Figures 2-11, 2-12 and 2-13 illustrate the influence of differing glare levels on high- and low-contrast target detection by drivers aged 20, 40 and 60 years, respectively.

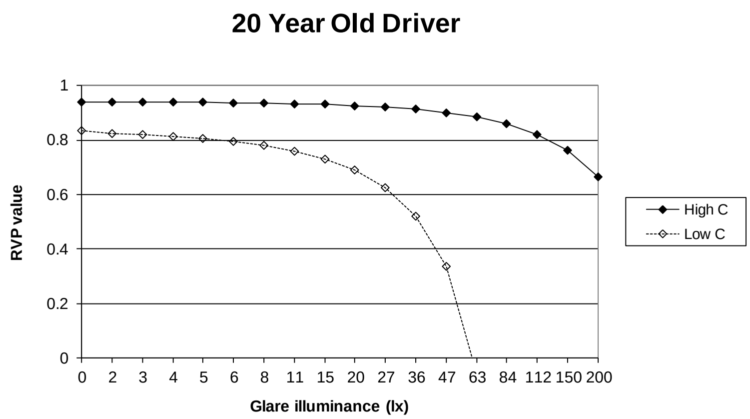


Figure 2-11. RVP values for high- and low-contrast targets viewed by 20-year-old drivers, as a function of the glare illuminance.

These three figures suggest that driver visibility of high contrast targets is relatively resistant to glare up to about 50 lx by all age groups. Even for low-contrast targets, visibility is largely maintained for glare illuminances up to about 5 lx, with reductions for all age groups at 20 lx from a glare source.

40 Year Old Driver

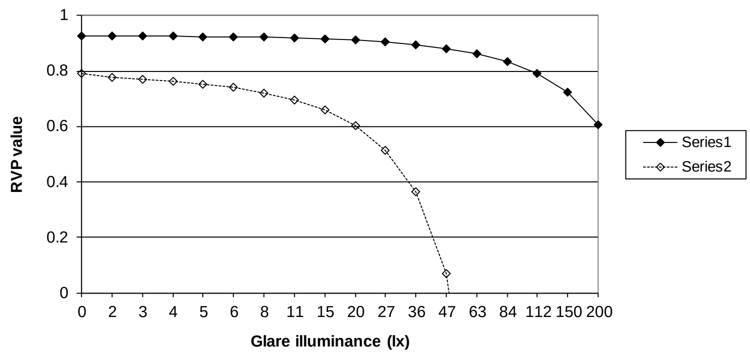


Figure 2-12. RVP values for high- and low-contrast targets viewed by 40-year-old drivers, as a function of the glare illuminance.

60 Year Old Driver

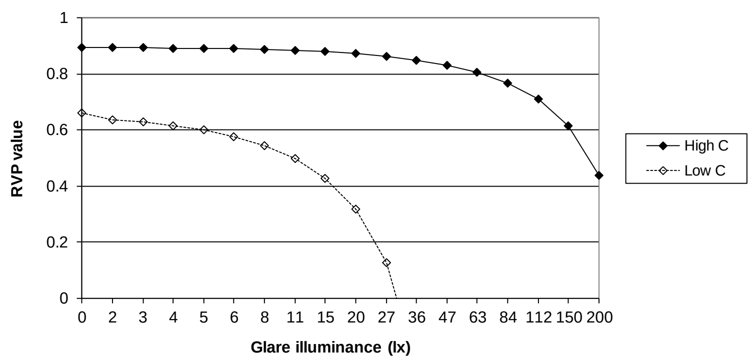


Figure 2-13. RVP values for high- and low-contrast targets viewed by 60-year-old drivers, as a function of the glare illuminance.

Discussion of Glare Analyses

The data in Figures 2-5 through 2-13, when compared to Figures 2-2 through 2-4 (without glare), provide empirical data upon which to assess the role of glare varying in illuminance on visual performance for workers and drivers. Assuming a minimum illuminance of 10 lx based on the visual performance analyses conducted without glare, a glare illuminance of 2 lx would not render any of the objects used in the analyses invisible, nor would such levels affect driver visibility in a substantial manner.

Naturally, the specific geometries of lighting equipment and the changing locations of tasks and potential hazards during nighttime construction will result in illuminances for both workers and drivers sometimes exceeding 2 lx. It may be more practical to specify a maximum *average* glare illuminance of 2 lx along the points in a grid for both workers and drivers. This would permit single instances of glare greater than 2 lx. However, since recovery of visual function after glare is dependent not upon a *peak* illuminance that the eyes are exposed to, but rather by the time-averaged *dosage* of light (Skinner and Bullough, 2009), a specification based on average illuminance could assist in mitigating the effects on driver vision during the recovery period.

Color Identification

In addition to visual performance (the relative speed and accuracy with which workers can respond to potential hazards and perform their tasks), the identification of colors is an important consideration in work zone lighting. The RVP model (Rea and Ouellette, 1991) is specified in terms of luminance photometric quantities and is essentially an achromatic system of specifying the visual stimulus. However, certain items such as caution panels, electrical wires and other items are often color-coded, and it is important that workers can identify colors accurately.

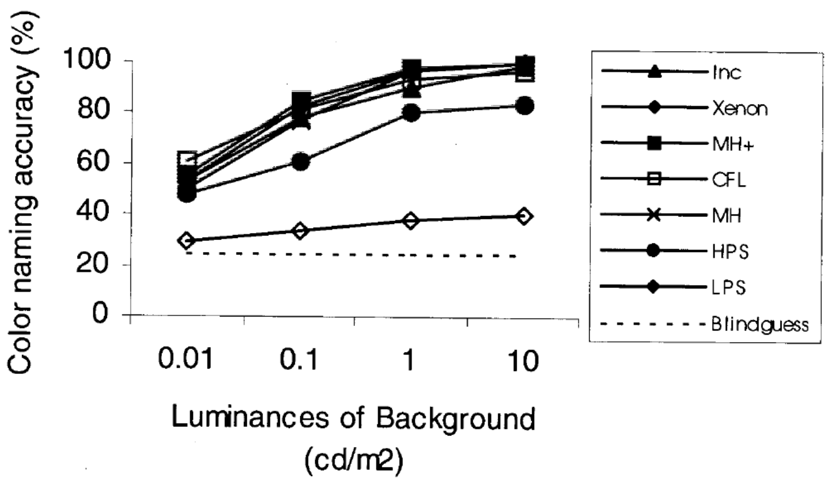


Figure 2-14. Color identification under different light sources and levels (Deng et al., 2005).

Color identification is, as might be expected, related to the overall light level. At very low light levels, color vision is impaired (IES, 2000). At light levels typical of nighttime applications, color identification is not as accurate as under daytime light levels. However, different light sources can also influence color perception. For example, light from low pressure sodium (LPS) lamps is monochromatic (589 nm, producing yellow light). All objects, regardless of their color, look either varying levels of the same shade of yellow, or else appear to be black. Most light sources permit much better color identification than LPS lamps.

Figure 2-14 illustrates the color naming accuracy by subjects in a study by Deng et al. (2005) who had to judge the presence of red, green, yellow or blue objects under different light sources (Inc=incandescent, Xenon=xenon arc lamp, MH=metal halide, MH+=enhanced metal halide for improved color, CFL=compact fluorescent, HPS=high pressure sodium, LPS=low pressure sodium) and levels (0.01 to 10 cd/m^2). The blind guess level was 25%, since there were four colors used in their study.

As expected, identification improved for all light sources as the light level was increased, but LPS provided little better than chance levels of identification. HPS, a yellowish lamp type common in roadway lighting applications, was somewhat poorer than the other lamps, all "white" light sources. Of interest, performance under HPS at 1 cd/m² was about equal to that under the "white" lamps at 0.1 cd/m².

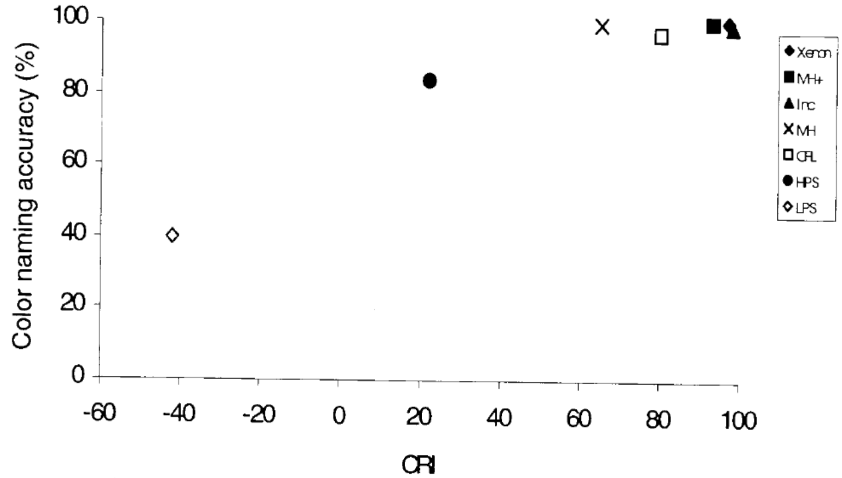


Figure 2-15. Color identification as a function of CRI value (Deng et al., 2005).

A common metric used to assess the ability of different light sources to properly reveal colors is called the color rendering index (CRI) which has a maximum value of 100, representing what is supposed to be ideal color rendering (IES, 2000). Although there are currently proposals to replace or refine CRI in the lighting and color communities (Rea and Freyssinier, 2008), CRI appears to have some relationship with color identification, as illustrated in Figure 2-15. However, once the CRI value was above a value of about 60, color identification did not improve, but was near a maximal value.

The data in Figures 2-14 and 2-5 suggest that excluding LPS, color identification can be moderately high under any light source, but for maximal identification, a CRI of 60 or higher is generally needed, especially below luminances of 0.1 cd/m².

Demonstration of Work Zone Illumination

The present section of this report summarizes a mock-up demonstration of various illumination systems including light emitting diode (LED) tower lights, balloon lights using various sources, and novel configurations of portable bollard lights, work lights and floodlights. The demonstration was attended by individuals from NYSDOT, from the Federal Highway Administration (FHWA), from roadway construction contractors and from equipment rental companies.

Location and Lighting Equipment Demonstrated

The demonstration was held on the night of April 18, 2012 during clear weather with calm winds. Seventeen individuals from NYSDOT, FHWA, roadway construction contractors and equipment rental companies participated. Ages ranged from 22 to 70 years old, with an average age of 48 years old. The location for the demonstration was along Temple Lane in the Town of

East Greenbush, a two-lane town roadway that was closed by NYSDOT's Rensselaer County residency the day of the set up. The Rensselaer County residency also placed orange barrels along the center of the road at 40-ft intervals. In addition to a conventional trailer-mounted light tower using four 1000 W metal halide (MH) floodlights, a number of vendors and manufacturers were invited to demonstrate various work zone lighting systems including solar- and generator-powered light-emitting diode (LED) systems, and balloon lights consisting of light sources within fabric balloons. Also demonstrated were several light sources not conventionally used for work zone lighting applications, including:

- An LED streetlight mounted onto a trailer and powered by a generator
- A pair of fluorescent floodlights mounted vertically as portable "bollard" fixtures providing mainly vertical illumination
- A floodlight using a low-wattage MH lamp with internal glare shielding
- An inflatable cylinder constructed from fabric in which a halogen light source was located
- An LED overhead fixture using a remote phosphor configuration to reduce source brightness

The lighting systems were divided into three zones, with Zone 1 consisting of the commonly used MH light tower, Zone 2 consisting of the LED and balloon lighting systems presently commercially available for work zone lighting applications, and Zone 3 consisting of the experimental and prototype concepts listed above. All lighting systems were spaced to minimize "crosstalk" so that each system independently illuminated a specific area along the road. Locations were also selected to avoid proximity with overhead power lines along part of the roadside. Figure 2-16 shows the layout and a brief description of each of the lighting systems used in the demonstration. Figure 2-17 through Figure 2-33 show photographs of each of the lighting systems used in the demonstration.

Evaluation Procedure

Participants in the demonstration were asked to arrive by sunset (7:45 p.m.) on the night of the demonstration. Each participant was given a clipboard containing a map of the demonstration equipment with brief descriptions of each lighting system, a questionnaire for assessing the light levels, quality, glare and usability of each system, and an informed consent form approved by Rensselaer's Institutional Review Board that was signed by each participant.

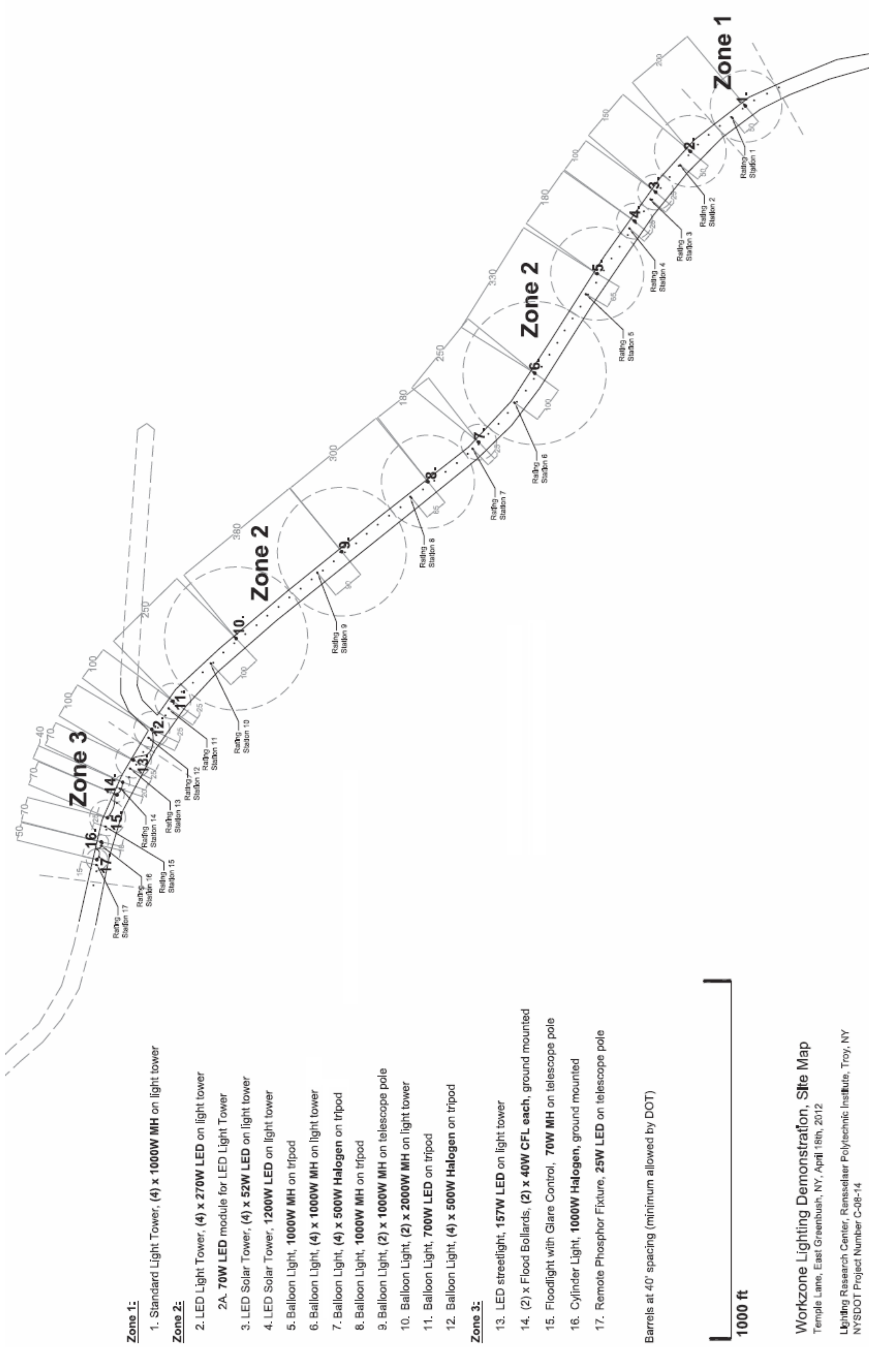


Figure 2-16. Layout of the work zone illumination system demonstration.

Figure 2-17. Conventional light tower with four 1000 W MH floodlights.

Figure 2-18. Light tower with four 270 W LED lights.

Figure 2-19. Solar-powered light tower with four 52 W LED lights.

Figure 2-20. Solar-powered light tower with 1200 W LED lights.


Figure 2-21. Balloon light (inflatable) with 1000 W MH source.


Figure 2-22. Balloon light (inflatable) with four 500 W halogen sources.

Figure 2-23. Balloon light (internal structure) with four 1000 W MH sources.

Figure 2-24. Balloon light (umbrella structure) with 1000 W MH source.

Figure 2-25. Balloon light (umbrella structure) with two 1000 W MH sources.

Figure 2-26. Balloon light (umbrella structure) with two 2000 W MH sources.

Figure 2-27. Balloon light (umbrella structure) with 700 W LED source.

Figure 2-28. Balloon light (umbrella structure) with four 500 W halogen sources.

Figure 2-29. Streetlight with 157 W LED source.

Figure 2-30. Bollard floodlights with 80 W fluorescent source.

Figure 2-31. Floodlight with internal glare shielding with 70 W MH source.

Figure 2-32. Ground mounted cylinder light with 1000 W halogen source.

Figure 2-33. Pedestrian light with 25 W remote phosphor LED source.

Figure 2-34. Visual rating station.

At 8:15 p.m. (corresponding to the end of civil twilight, 30 minutes after sunset), subjects were asked to visit each of the lighting systems and to assess several characteristics at the location of a pre-prepared visual evaluating station (Figure 2-34). The stations were located near the middle of the coverage area illuminated by each lighting system. The rating criteria included:

- The quality of illumination (e.g., distraction from shadows, uniformity and distribution of the light, ability to see three-dimensional details clearly)
- The light level for safety (e.g., would drivers and equipment operators be able to see workers)
- The light level for task visibility, based on the visual task corresponding to the printed information at each rating station
- The usability of the system (e.g., sturdiness, portability, durability, wind resistance)

- Discomfort glare from the lighting system (when looking in the direction of the light at eye height)

The rating scale for the quality, light level and usability judgments was as follows:

- 1: bad
- 3: inadequate
- 5: fair
- 7: good
- 9: excellent

The rating scale for the discomfort glare judgments was:

- 1: unbearable
- 3: disturbing
- 5: just permissible
- 7: satisfactory
- 9: unnoticeable glare

For both scales, higher numerical ratings correspond to higher quality. After participants judged all of the lighting systems, they returned the clipboard and received a list of the product information for each lighting system they viewed. Most participants took between 60 and 90 minutes to judge all of the lighting systems. Photometric measurements under each lighting system were also made at the location of the rating stations:

- Horizontal illuminance (lx: 1 lx ≈ 0.1 footcandle) on the roadway surface; illuminance corresponds to the amount of light falling onto a surface
- Vertical illuminance (lx) on the poster board chart at each rating station (see Figure 2-34)
- Vertical illuminance (lx) at eye height (5 ft from the ground) in the direction of the lighting system
- Luminance (kcd/m^2: 1 kcd/m^2 = 1000 cd/m^2) of the brightest portion of the lighting system visible to observers; luminance corresponds to the brightness of an illuminated or self-luminous surface in the direction of the observer

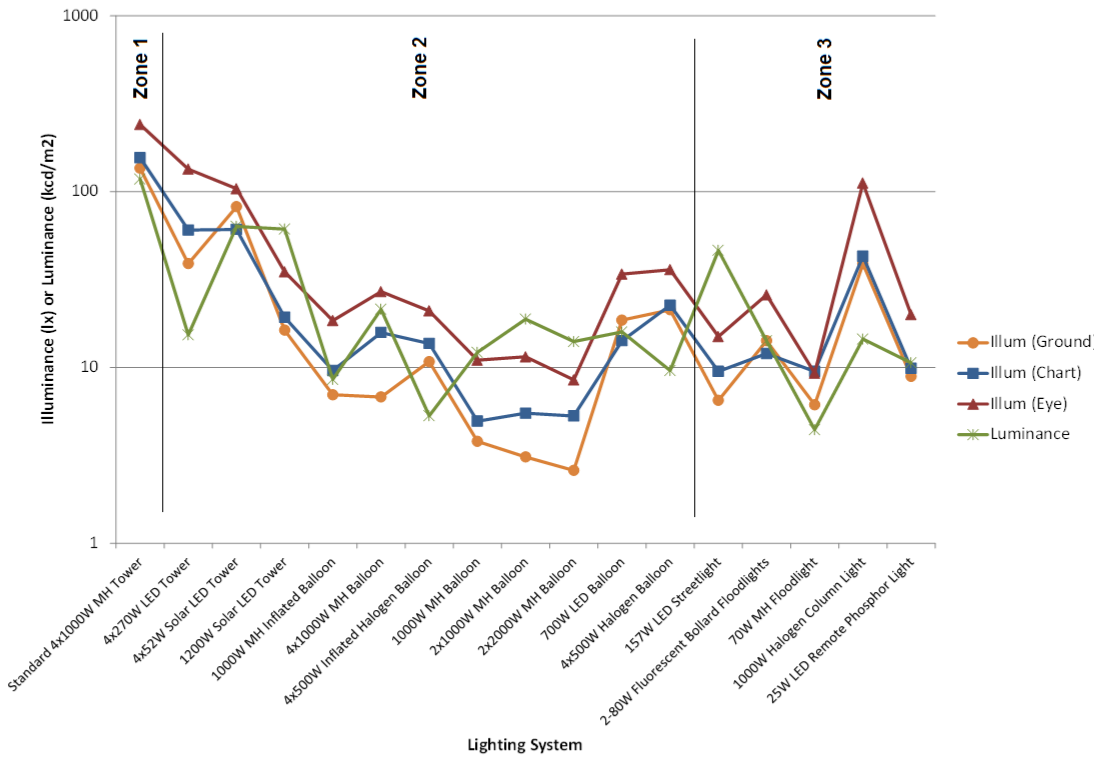


Figure 2-35. Measured light levels (in lx for illuminance, in kcd/m^2 for luminance) for each system. Also shown are the zones for each lighting system.

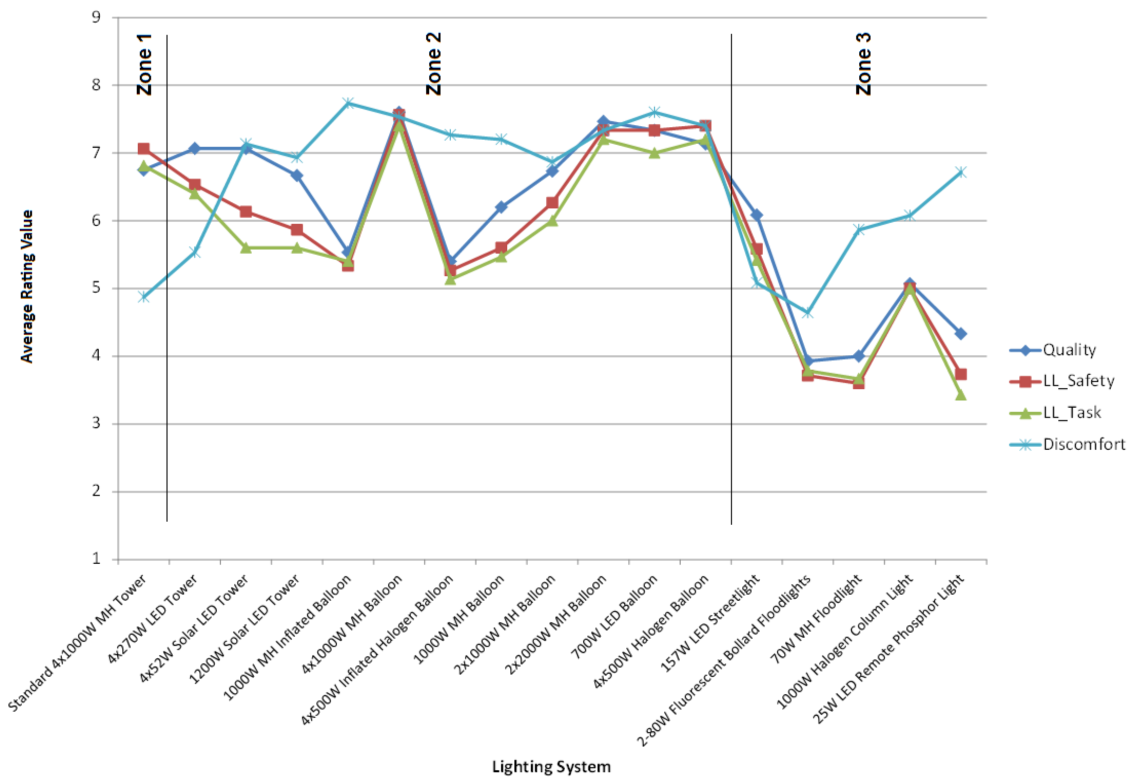


Figure 2-36. Average quality, light level (safety and task), usability and discomfort ratings for each lighting system. Also shown are the zones for each lighting system.

Evaluation Results

Shown in Figure 2-35 are the measured light levels (in lx for illuminance measurements, and in kcd/m^2 for luminance measurements) made for each lighting system. These measurements show that the conventional light tower was among the systems that provided the highest horizontal light levels on the ground and the highest vertical light levels on the visual task chart.

Figure 2-36 shows the average rating values for quality, light level (for safety and task visibility), usability and discomfort glare under each of the lighting systems that were demonstrated.

The conventional trailer-mounted light tower had the highest illuminance, just over 100 lx on the pavement, and the quality, light level and usability ratings for this system were all near a value of 7. The discomfort glare rating value of 5 was lower. In comparison, some of the LED systems and all of the balloon lighting systems had discomfort ratings close to a value of 7. The light level ratings for safety and task visibility were highly correlated (r^2 = 0.98) and this is not surprising given the strong correlation (r^2 = 0.95) between the measured illuminances on the ground and on the visual rating chart.

Of interest, quality and light level ratings were also high for several of the alternative lighting systems in Zone 2, particularly for several of the balloon lighting systems, despite the fact that the illuminances from these systems were substantially lower than 100 lx. Two of these systems produced just over 20 lx on the ground, while one produced 7 lx and another only 3 lx. The luminances of the balloon lighting systems were substantially lower than the conventional light tower too, and this lower luminance may have contributed to the reduced glare relative to the conventional light tower. However, some of the balloon lighting systems that resulted in similar illuminances and luminances were not rated as highly. An LED light tower that produced over 80 lx on the ground was also rated fairly positively for quality (average rating value around 7), light level (average rating values around 6), and discomfort glare (average rating value around 7).

In general the prototype and experimental systems in Zone 3 were not rated as highly as the conventional light tower. A substantial difference between these systems was the overall light output, which resulted in relatively low light levels compared to the systems in Zones 1 and 2.

To better understand the relationships between the photometric properties of the lighting systems that were evaluated and the subjective quality, light level and discomfort ratings, multiple regression models were developed using the mean responses on each question as the response, and the photometric quantities as possible predictors in the model. The models providing the best relationship between the predictors (E_{ground}: illuminance on the ground, E_{chart}: illuminance on the chart in lx, E_{eye}: illuminance at the eye in lx, L_{source}: luminance of the source in kcd/m^2) and the responses were as follows:

- Quality (Q): $Q = 5.95 + 0.0103E_{chart} - 0.0019E_{eye}$
- Light Level for Safety (LL_{safety}): $LL_{safety} = 5.60 + 0.00959E_{ground}$
- Light Level for Task Visibility (LL_{task}): $LL_{task} = 5.45 + 0.0142E_{chart} - 0.0034E_{eye}$
- Discomfort Glare (G): $G = 7.14 + 0.0280E_{ground} - 0.0175E_{eye} - 0.000014L_{source}$

For quality, higher illuminances on the chart and lower illuminances at the eye were predictive of higher quality. For light levels pertaining to worker safety, higher illuminances on the ground were predictive of higher ratings. For light levels pertaining to task visibility, higher illuminances on the chart and lower illuminances at the eye predicted higher ratings. And for discomfort glare, higher illuminances on the ground, lower illuminances at the eye, and lower source luminances were predictive of reduced discomfort glare.

Discussion of Evaluation Results

In general, the results shown in Figure 2-36, and the multiple regression models described above were consistent with the notion that higher light levels directed onto the ground areas where workers walk, and onto the locations where they perform their visual tasks, will maximize quality, provided that the light levels directed toward workers' eyes and the luminances of the light sources themselves are minimized. The visual performance analyses described earlier in this chapter are also consistent with these trends. Whereas recommended light levels for nighttime work zone lighting range from 50 to 200 lx on the ground, depending upon the type of work being performed, the typical light source used to provide illumination is the conventional light tower. Ratings from the observers in the present demonstration suggested, consistent with the previous visual performance analyses, that 10 to 20 lx on the ground could be sufficient for most visual tasks provided glare is controlled.

The demonstration's empirical findings suggest that balloon lighting systems are one way to accomplish this. The use of LED systems that have superior optical control to conventional MH floodlights used on conventional towers also appear to have promise for providing controlled illumination that reduces exposure directly into workers' eyes.

3. SIGNAGE, MARKING AND DELINEATION IN WORK ZONES

The present chapter summarizes human factors studies designed to evaluate the luminance requirements for sign legibility, visual guidance for delineation, and hazard marking, and a mock-up demonstration of various signage, marking and delineation materials for work zones.

Sign Legibility Requirements

Signs within work zones must provide adequate guidance to drivers navigating through the work zone. Ambient levels in and around work zones can range from very dark to very bright depending upon whether the location is urban or rural. A human factors laboratory experiment was conducted to identify the minimum luminance of a sign element in order to be legible. Eight subjects (5 male/3 female, mean age 42 years, range 22-60) participated in the experiment.

Stimuli were presented on a laptop computer screen adjusted to have a background luminance of 0.05 cd/m², representing the luminance typical of rural, unlighted locations. Landolt rings (Figure 3-1) were presented in randomized orientations, with luminances of 0.1, 0.15, 0.25 or 1 cd/m², also presented in random order. The gap in the Landolt rings was a 2.5 mm square with an area of 6.25 mm² and was viewed from a distance of approximately 450 mm. After adapting to the light level in the laboratory for 5 minutes, subjects in the study were presented with each Landolt ring and requested to identify the orientation of the gap in the ring (either up, down, left or right) by pressing the corresponding arrow key on the computer keyboard. If they did not indicate the direction within 5 seconds, the trial was aborted and the next Landolt ring was presented (the trial would be recorded as a "miss").

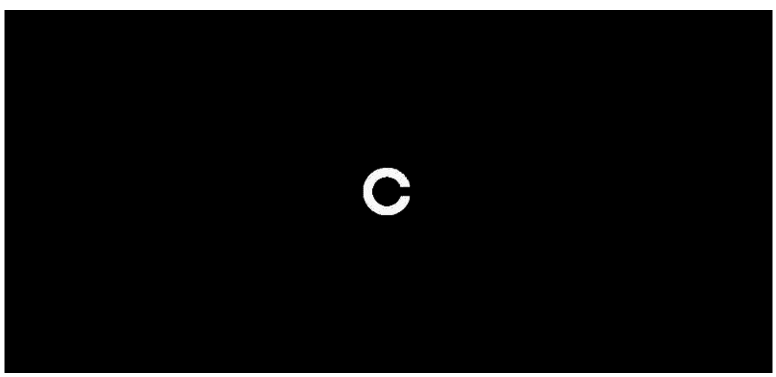


Figure 3-1. Example Landolt ring used in the sign legibility experiment.

Figure 3-2 shows the mean response times to each luminance condition. An analysis of variance (ANOVA) indicated that there was a statistically reliable ($p<0.01$) effect of luminance of the Landolt rings. The data show that once the luminance was at least 0.15 cd/m², there was relatively little benefit in terms of shorter identification times for higher luminances.

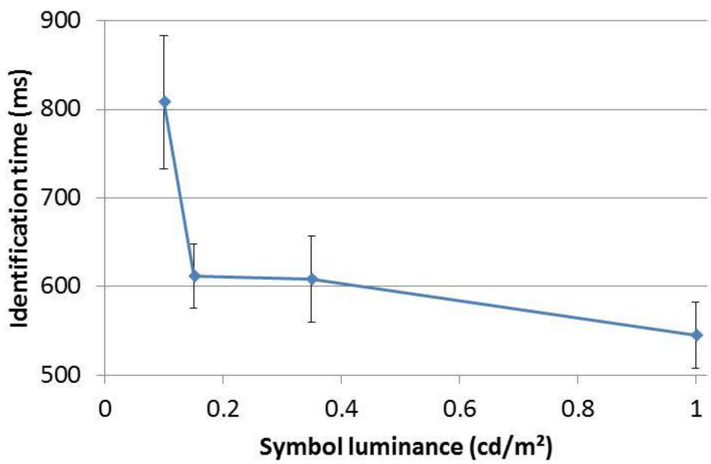


Figure 3-2. Mean (+/- s.e.m.) identification times to the symbols at each luminance.

Among all of the trials, only one resulted in an incorrect identification of orientation. The data suggest that maintaining the luminance of sign elements at least three times higher than the background luminance will ensure a high level of performance (in terms of short identification times); higher luminances would not substantially improve performance. For example, within an illuminated portion of a work zone where the illuminance is 5 footcandles, the luminance of asphalt pavement would be approximately 1.6 cd/m^2. Under such conditions, the luminance of a sign element should be at least three times this value, or about 5 cd/m^2 to ensure adequate legibility.

Visual Guidance from Delineators

Work zones are often delineated by barrels, drums, cones, temporary reflective tape, or post mounted delineators in order to identify important conflict points to drivers, such as lane closures and changes, and the locations of exit ramps that may be temporarily displaced. To assess the luminance requirements for delineation systems, a laboratory experiment was conducted. Eight subjects (5 male/3 female, mean age 42 years, range 22-60) participated in the delineator luminance experiment.

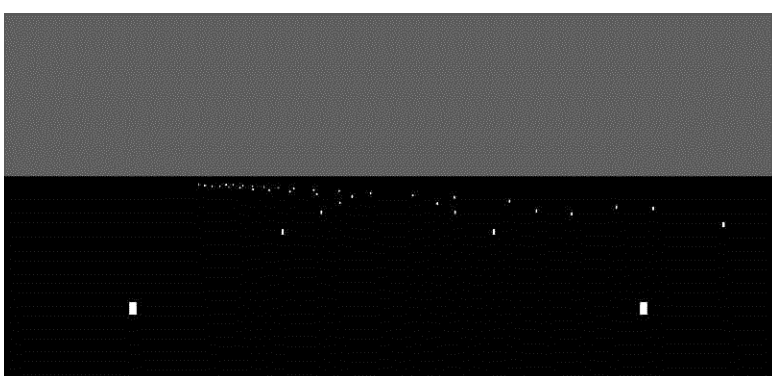


Figure 3-3. Example scene presented as a stimulus in the visual delineation experiment. The oblique angle in the intersection ahead is on the left side of this image.

Experimental stimuli in this experiment consisted of images presented on the screen of a laptop computer against a dark background of 0.05 cd/m². Figure 3-3 shows an example of one of the stimuli that was presented. It is a scene of a skew "tee-shaped" roadway intersection, delineated by rectangular elements. After adapting to the dark conditions in the test laboratory, subjects were presented scenes in which the orientation of the intersection (with the oblique intersection angle to the left as shown in Figure 3-3, or to the right) and the delineator luminance, ranging from 0.1, 0.15, 0.25 or 1 cd/m², were presented in randomized order. Subjects were requested to press either the left or right arrow key on the laptop keyboard as quickly as they could identify the orientation of the intersection. If they were unable to identify the orientation within 10 seconds, the trial was aborted, recorded as a "miss," and the next trial was presented. The size of the rectangular elements near the bottom of the screen (i.e., the closest) was 1.7 mm wide and 3.4 mm tall. The viewing distance averaged about 450 mm.

The mean identification times for each delineator luminance are shown in Figure 3-4. The accuracy percentages for each luminance are shown in Figure 3-5. The identification time data show a trend similar to that in Figure 3-2, with the longest times for the lowest luminance (0.1 cd/m²) and times rapidly becoming shorter for the higher luminances ($\geq$ 0.15 cd/m²). There weren't large differences in identification times for luminances higher than 0.15 cd/m². An ANOVA revealed a statistically significant ($p<0.001$) effect of luminance on the measured identification times. The accuracy percentages in Figure 3-5 also exhibit similar trends as the identification time data in Figure 3-4. Performance for the delineator luminance of 0.1 cd/m² was close to chance level of 50%, suggesting that subjects were near their visual threshold at this luminance. Above this luminance the accuracy remained high (~90% or higher).

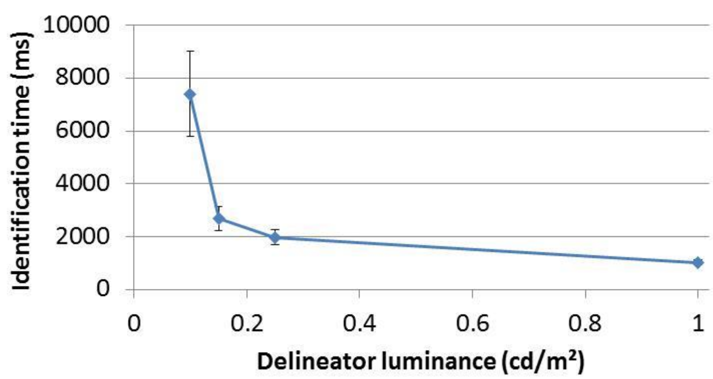


Figure 3-4. Mean (+/- s.e.m.) identification times for each delineator luminance.

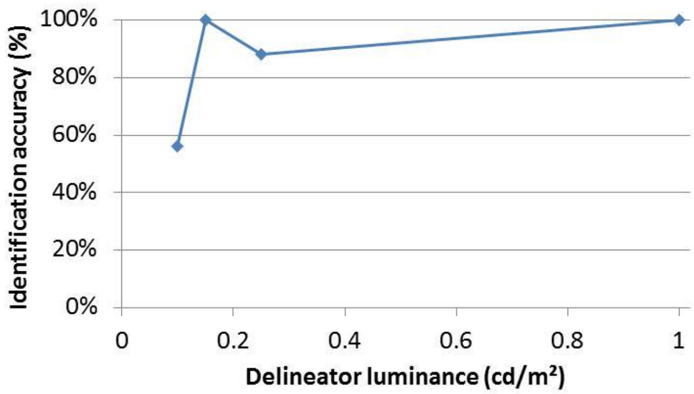


Figure 3-5. Overall accuracy percentages for each delineator luminance tested.

The results of this experiment indicate that a delineator luminance of 0.15 cd/m², when presented against a dark background of 0.05 cd/m², will ensure a high level of performance in terms of accurate and rapid identification of roadway configurations outlined by delineators; higher luminances did not substantially improve performance. This corresponds to a luminance that is three times the background luminance. If a horizontal illuminance of 5 footcandles were deployed in a work zone, the luminance of asphalt pavement would be 1.6 cd/m², which suggests a delineator luminance of 5 cd/m² would be sufficient to ensure the ability of drivers to identify delineator patterns.

Hazard Marking Requirements

It is important for both drivers navigating through a work zone and for workers in the work zone to be able to rapidly identify the presence of potential hazards located within the zone. In particular, the locations of hazards are generally inherently unknown and unexpected. Identifying the necessary requirements for marking potential hazards such as equipment, machinery, tools or even workers in nighttime construction environments is an important visual task. To address this concern, a laboratory study was conducted to investigate the role of luminance of hazard markings on the ability to identify and locate the potential hazard.

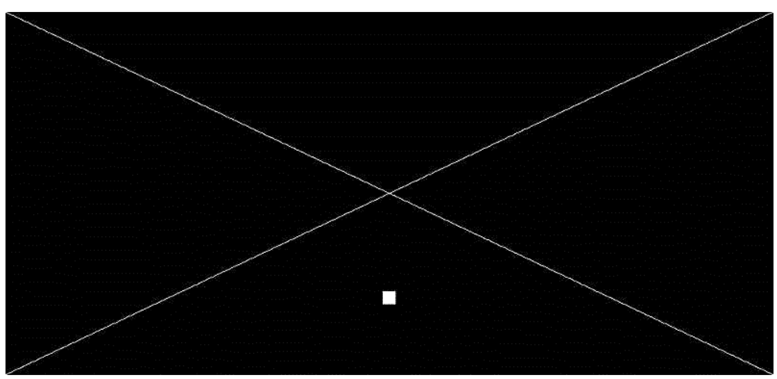


Figure 3-6. Example presentation scene in the hazard detection laboratory experiment, with the stimulus presented in the lower quadrant.

Eight subjects (5 male/3 female, mean age 42 years, range 22-60) participated in the delineator luminance experiment. Figure 3-6 shows an example of the experimental stimuli, which were presented on a laptop computer screen with a background luminance of 0.05 cd/m². The average viewing distance was approximately 450 mm. The screen area was divided by diagonal lines into four quadrants (top, bottom, left, and right). For each trial presentation, the stimulus (which varied in luminance of 0.1, 0.15, 0.25 or 1 cd/m²) was presented in a randomly ordered quadrant. After adapting to the light level in the laboratory, subjects were requested to identify the location of the hazard object (a square 3.4 mm by 3.4 mm in size) by pressing the appropriate arrow key (up for the top quadrant, down for the bottom quadrant, left for the left quadrant, and right for the right quadrant) as quickly as possible.

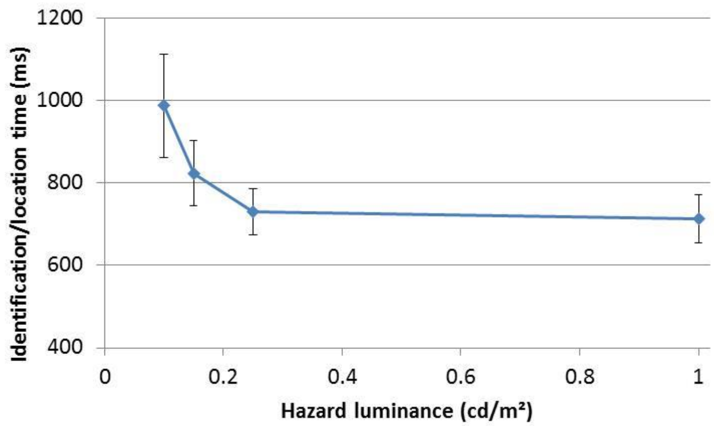


Figure 3-7. Mean (+/- s.e.m.) identification times for the hazard detection experiment.

Figure 3-7 shows the mean response times for each luminance. An ANOVA indicated that there was a statistically reliable ($p<0.05$) effect of luminance on response times. The data show reductions in response time as luminance increases, up to 0.25 cd/m². At this and the higher luminance investigated (1 cd/m²) there was little reduction in response times. Accuracy of location was 100% for all conditions.

The results of this experiment indicate that a hazard marking luminance of 0.25 cd/m², when presented against a dark background of 0.05 cd/m², would ensure high levels of performance in terms of the ability to accurately identify the location of the potential hazard; higher luminances did not exhibit substantially improved performance. The luminance of 0.25 cd/m² corresponds to a luminance that is at least five times the background luminance. If a horizontal illuminance of 5 footcandles were deployed in a work zone, the luminance of asphalt pavement would be 1.6 cd/m², which suggests that a hazard marking luminance of 8 cd/m² would be sufficient to ensure the ability of workers and drivers to rapidly and reliably identify and locate potential hazardous objects in the work zone.

Implications of Laboratory Study Findings

The results of the laboratory studies described above suggest that it is possible to develop minimum luminance requirements for reliable identification and location of features such as signs, delineators and hazard markings in work zones, by drivers and workers. In particular:

- Sign elements and delineator elements should be at least three times the luminance of the background.
- Hazard markings should be at least five times the luminance of the background.

The results of the experiments are consistent with the notion that when an object's location in the visual field is not known or expected ahead of time (as with a possible hazard) the luminance requirements for reliable detection and location are higher than for objects such as signs or delineators, whose locations are planned and more likely to be expected by both drivers and workers.

Photoluminescent Material Characterization

Like retroreflective materials, photoluminescent materials (e.g., so-called "glow in the dark" materials) require no active power supply in order to provide visual information for potential signage, marking or delineation. In recent years there has been active interest in the possibility of using such materials in transportation applications (Steyn, 2008). In order to provide a basis for comparing photoluminescent materials to other alternatives for signage, marking and delineation applications in work zones, laboratory measurements of several materials (provided by Performance Indicator, Inc.) were performed.

Materials evaluated included paint samples having a safety yellow appearance under outdoor or interior room illumination, and producing a slightly greenish yellow color appearance when viewed in the dark after exposure to illumination. Eight-inch square sheet metal samples were primed and painted according to the instructions provided by the pain manufacturer. In addition, a tape having a light green appearance (and producing light green emission in the dark), and adhesive strips with safety yellow, pale orange and red color appearance (appearing yellow, yellow and red in darkness, respectively) were evaluated. Figure 3-8 shows the samples that were measured.

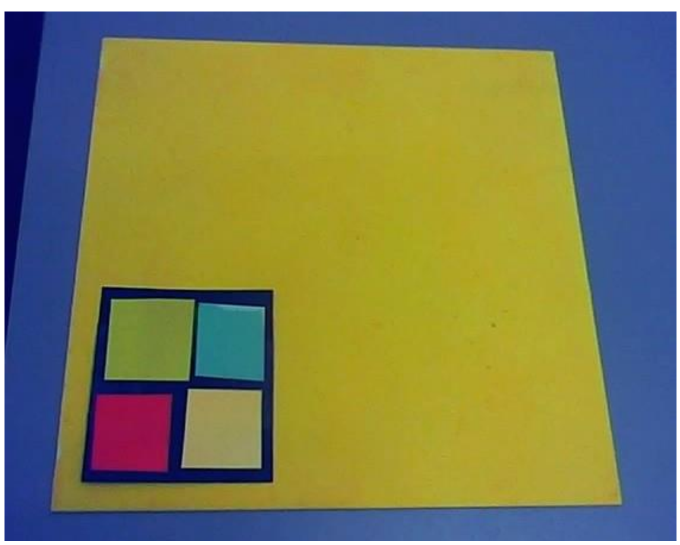


Figure 3-8. Photoluminescent material samples tested. The larger yellow sample is the photoluminescent paint sample, and the smaller squares are the tape and adhesive strip samples.

In a windowless, black-painted laboratory at the Lighting Research Center, each of the samples was illuminated continuously for 45 minutes under a minimum of 50,000 lx by a luminaire containing a metal halide (MH) light source. At a fixed time, the luminaire was extinguished and periodic luminance measurements were made using a portable hand-held luminance meter (Minolta, LS-100). The first measurement was made approximately 15 seconds after extinguishing the light source. At the beginning of each set of measurements, luminance readings were made every minute, with the duration between measurements gradually increasing over time. The maximum luminance of the sample was recorded for each time interval. When the luminance reached or dropped below 0.01 cd/m², measurements ceased. This luminance corresponds to a point at which rod photoreceptors in the eye dominate visual performance (CIE, 2010) and at which the central visual system does not support high acuity or color vision (Rea et al., 2004).

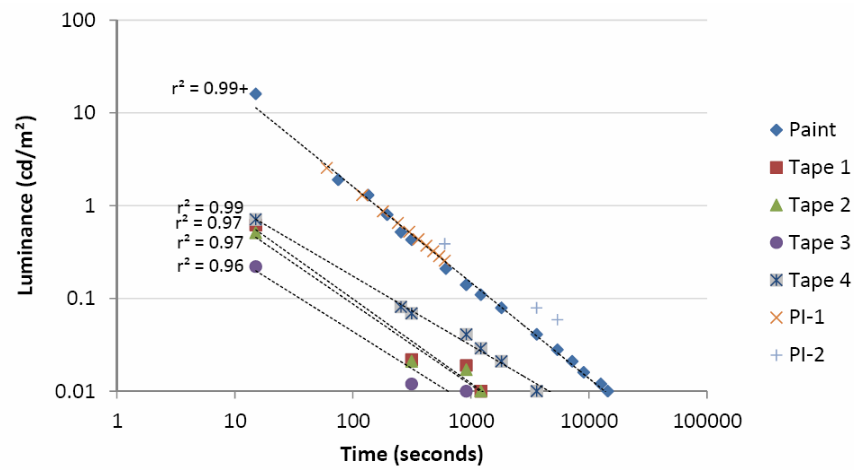


Figure 3-9. Measured luminances of the photoluminescent material samples evaluated as a function of time after exposure to light.

Figure 3-9 shows the measured luminances for each of the materials. The symbols labeled "Paint" represent the painted sample, and those labeled "Tape 1," "Tape 2," "Tape 3" and "Tape 4" represent the safety yellow, light green, red and pale orange tape/adhesive samples, respectively. It should be noted that both the abscissa and ordinate of Figure 3-9 are formatted to logarithmic scales. The data for each material follow best-fitting power functions (all with goodness-of-fit r^2 values of 0.96 or greater, shown in Figure 3-9 as dotted lines) having exponents between approximately –0.75 and –1. As indicated in Figure 3-9, the amount of time for the tape/adhesive materials tested to reach a luminance of 0.01 cd/m² ranged from about 10 minutes to an hour after exposure to light, depending upon the color. The paint sample maintained a luminance of at least 0.01 cd/m² for 4 hours after exposure to light.

Also shown in Figure 3-9 are data for materials from the same manufacturer that were published online (Meiselman, 2009). The data labeled "PI-1" represent a door sign measured every minute for 10 minutes, and the data labeled "PI-2" represent a different material measured at 10, 60 and 90 minutes. The "PI-1" data very closely match those of the paint sample; the "PI-2" data have a similar slope and slightly higher luminances than the pain sample measured in the present study.

The "PI-2" data in particular suggest that different photoluminescent materials could have even longer persistence times than the paint sample measured in the present project.

Demonstration of Signage, Marking and Delineation Materials

As part of its assessment of materials for signage, marking and delineation, the project team conducted a mock-up demonstration and evaluation of reflective and luminescent pavement marking, sign sheeting, delineation and hazard marking materials. The demonstration occurred in the Watervliet Dome, owned by the City of Watervliet. The facility is an enclosed, windowless structure that formerly housed a skating rink and is presently used by the city's recreation department to house indoor sporting and hobby events and to store some equipment. When the lights are switched off in the Dome, the large space is very dark, providing a suitable surrogate for a nighttime environment.

Participants

The demonstration was held on November 22, 2013. Participants from NYSDOT, the New York State Thruway, FHWA, several manufacturers, and several local construction firms and vendors were invited to participate. Individuals from the NYSDOT Technical Working Group for the present project, and individuals from manufacturers of materials under evaluation, attended and participated in the demonstration. Individuals from manufacturers participated only to provide technical information and to answer questions about specific materials at the request of the other participants, and did not perform visibility judgments.

Materials and Layout

Figure 3-10 shows the approximate layout of the demonstration, which included temporary pavement marking tape stripes, temporary pavement marking tape letters, raised pavement markers, orange sign sheeting materials, traffic drum wrap, reflective hazard marking tape, reflective barricade sheeting, and photoluminescent tapes and paint samples (the same materials evaluated as described earlier in this chapter). Also present was a set of high intensity discharge passenger car headlamps that could be adjusted to provide either high or low beams. Figures 3-11 through 3-14 show the materials used in the demonstration.

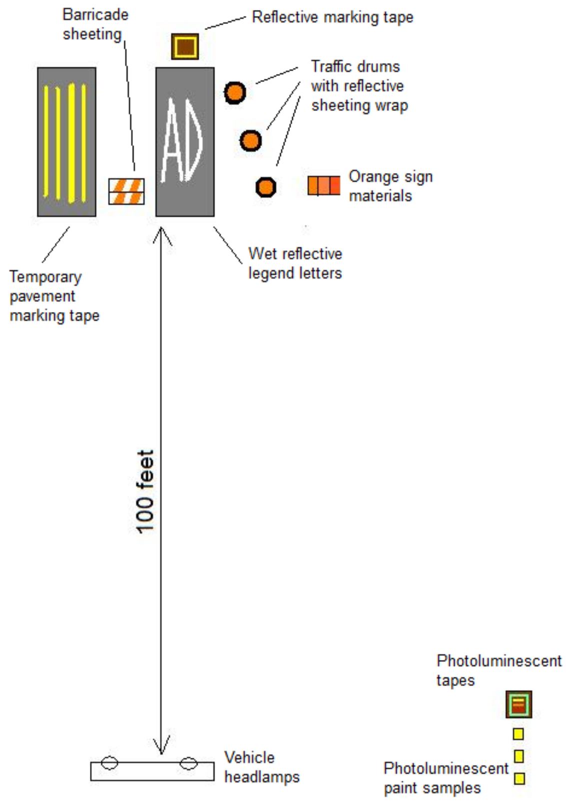


Figure 3-10. Approximate layout of signage, delineation and marking materials.

Figure 3-11. Traffic drums and orange reflective work zone sign panel containing three different sheeting materials.

Figure 3-12. Barricade sheeting, reflective marker tape, wet reflective pavement letter symbols, raised pavement reflectors and traffic drums.


Figure 3-13. Wet reflective temporary lane marking tape (left three segments) and economical grade temporary marking tape (right segment).

Figure 3-14. Photoluminescent tape materials (left) in various colors, and painted metal samples (right) of yellow color.

Because the floor of the Watervliet Dome facility is presently covered in a gymnasium flooring surface, 15 ft x 4 ft rolls of rubber flooring (see Figures 3-12 and 3-13) were used to serve as a surrogate asphalt pavement surface. Half of each pavement marking line and each reflective letter symbol was covered in water using a mop and half was left dry. This procedure differs from the American Society for Testing and Materials (ASTM, 2012) standard procedure for evaluating wet reflective materials, but was used for qualitative comparisons between wet and dry material samples. Sign sheeting was applied to sign panels and mounted using tripods, and reflective and photoluminescent tapes were mounted to black foam core sheets.

The photoluminescent materials (Figure 3-14) were located about 50 feet to the right of the headlamps so that they would not be illuminated by the headlamps. During the night before the demonstration, they were continuously exposed to light-emitting diode luminaires to an illuminance of at least 10,000 lux, and were removed from the light exposure at 11:00 a.m. on the day of the demonstration.

The high beam headlamps produce a vertical illuminance in the location of the forward test materials of 50 lux at a distance 100 feet ahead. The low beam headlamps produced a vertical illuminance of 20 lux. All other lights in the facility were switched off during the evaluation. Selected luminance measurements (under high beam illumination) of materials are summarized in Table 3-1.

Material	Luminance
High intensity orange sheeting (Type III)	132 cd/m²
High intensity prismatic orange sign sheeting (Type III/IV)	256 cd/m²
Full cube prismatic fluorescent orange sign sheeting (Type XI)	265 cd/m²
Engineering grade barricade tape (white portion) (Type I)	150 cd/m²
Full cube prismatic barricade tape (white portion) (Type XI)	630 cd/m²
Engineering grade white barrel wrap (Type I)	390 cd/m²
Full cube prismatic white barrel wrap (Mfr. A) (Type IV)	560 cd/m²
Full cube prismatic white barrel wrap (Mfr. B) (Type IV)	1100 cd/m²
Yellow photoluminescent paint sample (at time 11:36)	0.2 cd/m²
Green photoluminescent tape (at time 11:36)	0.1 cd/m²

Table 3-1. Luminance measurements of selected materials as measured in the Watervliet Dome. High beam headlamps were switched on during the measurements.

With the low beams of the headlamps switched on, the luminances of the reflective sign sheeting and marking materials were substantially lower, especially for those materials mounted higher from the ground. This was because the low beam had a relatively sharp cutoff line, above which relatively little light was produced. Nonetheless, all of the reflective materials produced luminances well in excess of 10 cd/m² under low beam illumination, which is higher than the values needed to ensure rapid visual acquisition (see previous sections of this chapter) under ambient illumination of 5 footcandles (50 lx) on asphalt pavement.

Evaluation Results

Demonstration participants were asked to view the materials under both high- and low-beam headlamp illumination and provide their overall ratings of the visibility of each visual element on a four-point rating scale with the following values:

1: very difficult to see
2: somewhat difficult to see
3: somewhat easy to see
4: very easy to see

For the photoluminescent materials, participants were also asked to indicate the time at which they made their judgments, since these materials gradually decay in luminance following exposure to light.

Table 3-2 lists the overall average rating values (using the four-point scale listed above) for each of the materials judged during the demonstration by the participants.

Although there was a relatively limited number of observers, statistical analyses (one-tailed, paired Student's t-tests) indicated that there were a number of statistically reliable ($p<0.05$) effects when the average rating values were compared across certain conditions, listed below.

- Ratings for wet pavement marking materials were lower than the same materials when dry, for three of the four configurations tested.

- Ratings for the wet reflective pavement marking tapes were higher than for the economical grade reflective tape, under both dry and wet conditions.
- Prismatic orange sign sheeting materials were rated as more visible than engineering grade material.
- Orange and yellow photoluminescent adhesive materials were rated as more visible than the red adhesive material.

Several observers offered written comments about their observations. Two observers indicated that the barrel wrap for one of the barrels containing prismatic barrel wrap was too bright, despite its high rated visibility. One observer noted that the visibility of the photoluminescent material samples improved when the headlamps were switched to low beams from high beams (even though the headlamps were not oriented to provide illumination in the direction of the photoluminescent materials).

Discussion of Evaluation Results

The photometric measurements and limited evaluation results from the demonstration summarized here lead to several tentative conclusions:

- Wet reflective temporary pavement marking tapes, while not maintaining 100% of their visibility when wet compared to dry conditions, offer substantial benefits over conventional, non-wet temporary pavement marking tapes.
- Prismatic sign sheeting, barricade tapes and traffic drum wraps provide higher luminances than engineering grade materials. Some very high performing materials may be judged as too bright, especially for items located within the central portion of a vehicle's headlamp system.
- Conspicuity marking tape such as the yellow tape used in the demonstration may be a way to assist in detection and identification of hazards in the work zone environment by operators of vehicles and moving equipment.
- The photoluminescent materials evaluated had relatively lower luminances than the reflective materials evaluated. Discussions among observers suggested that such materials might be useful in darker areas to indicate hazards, especially less active storage areas with little ambient light.

Material	**Mean Rating**
Economical grade yellow reflective tape, 4" width (dry)	2.2
Economical grade yellow reflective tape, 4" width (wet)	1.2*
Yellow wet reflective tape, 4" width (dry)	3.2[+]
Yellow wet reflective tape, 4" width (wet)	2.6*[+]
Yellow wet reflective tape, 6" width (dry)	3.2[+]
Yellow wet reflective tape, 6" width (wet)	2.8[+]
Yellow wet reflective tape, 4" width plus raised pavement markers (dry)	3.6[+]
Yellow wet reflective tape, 4" width plus raised pavement markers (wet)	2.8*[+]
White wet reflective pavement letter symbols (dry)	3.2
Temporary yellow raised pavement markers	3.2
High intensity orange sheeting (Type III)	2.6
High intensity prismatic orange sign sheeting (Type III/IV)	3.2^
Full cube prismatic fluorescent orange sign sheeting (Type XI)	3.2^
Engineering grade orange/white barricade tape, 8" width (Type I)	1.8
Full cube prismatic orange/white barricade tape, 8" width (Type XI)	3.0
Engineering grade white/orange barrel wrap, 4" width (Type I)	3.4
Full cube prismatic white/orange barrel wrap, 4" width (Mfr. A) (Type IV)	3.4
Full cube prismatic white/orange barrel wrap, 4" width (Mfr. B) (Type IV)	3.6
Yellow reflective conspicuity tape, 2" width	3.2
Yellow photoluminescent paint, 8" square (ave. viewing time 11:40)	3.0
Green photoluminescent tape, 1" width (ave. viewing time 11:40)	2.6
Red photoluminescent tape, 2" width (ave. viewing time 11:40)	1.4
Orange photoluminescent tape, 2" width (ave. viewing time 11:40)	2.0[§]
Yellow photoluminescent tape, 2" width (ave. viewing time 11:40)	2.2[§]

*Statistically significant ($p<0.05$) difference from dry condition.
[+]Statistically significant ($p<0.05$) difference from economical grade tape.
^Statistically significant ($p<0.05$) difference from high intensity sheeting.
[§]Statistically significant ($p<0.05$) difference from red photoluminescent tape.

Table 3-2. Evaluation ratings of the visibility of each delineation, sign sheeting and marking element.

4. FLASHING LIGHTS AND CHANNELIZING DEVICES FOR WORK ZONES

The present chapter summarizes the project team's investigations of intensity, spatial and temporal modulation requirements for signal lights used for delineation and channelization.

Intensity Characteristics for Warning Lights

As part of a laboratory investigation (Bullough and Rea, 2014), an experiment with simulated viewing conditions was set up to investigate the intensity requirements for flashing signal lights viewed under roadway conditions. A roadway scene was projected onto a white-painted plywood wall located 3 m in front of the seating position of subjects in the experiment. The width of the simulated roadway scene was 1 m, subtending a horizontal angle of nearly 20 degrees. Under the simulated nighttime conditions the background luminance was 1 cd/m^2, and under the simulated daytime conditions the background luminance was 300 cd/m^2.

A yellow (peak wavelength ~590 nm) light emitting diode (LED) was mounted to the plywood wall and was operated at a flash frequency of 60 flashes/minute (1 Hz) with a 50% duty cycle, and the current through the LED was adjusted in different conditions so that the LED would produce the same illuminance at subjects' eyes as a signal light located 67 m ahead, and with an effective intensity of 55, 130 or 370 cd. High-intensity Type B barricade lights, for comparison, are required to have a minimum effective intensity of 35 cd (ITE, 2001).

Subjects were instructed to look at a visual fixation point within the roadway scene that was 5 degrees off-axis and to the right of the flashing signal light. The off-axis angle corresponds to the approximate angular separation between adjacent roadway lanes. Subjects were instructed to press a button provided on the table in front of them as soon as they were able to detect the flashing light appear in the scene. Each subject responded to four presentations of the signal light at each effective intensity value and at each background luminance. Figure 4-1 shows the reaction times to the onset of the flashing light for the nighttime conditions.

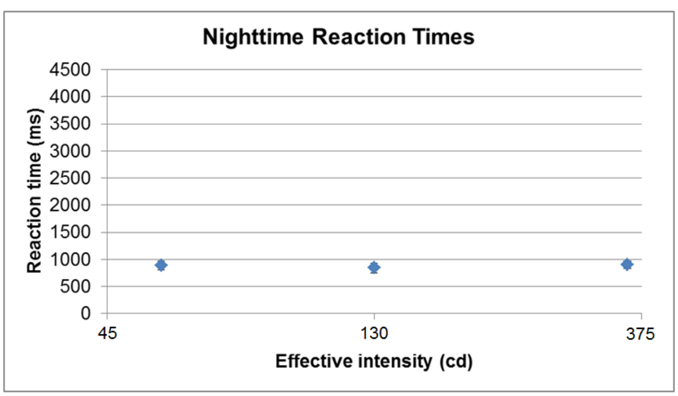


Figure 4-1. Average reaction times (+/- standard errors of the mean) for the off-axis signal light viewed under nighttime conditions, as a function of the effective intensity of the light.

Figure 4-2 shows the reaction times to the onset of the flashing light for the daytime viewing conditions.

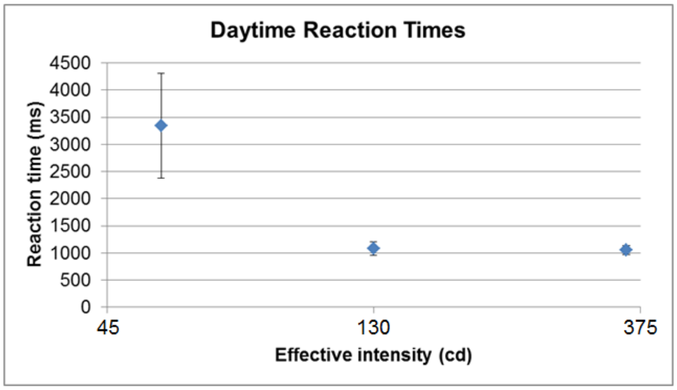


Figure 4-2. Average reaction times (+/- standard errors of the mean) for the off-axis signal light viewed under daytime conditions, as a function of the effective intensity of the light.

An analysis of variance (ANOVA) on the data in Figures 4-1 and 4-2 revealed statistically significant ($p<0.05$) main effects of both background light level (i.e., daytime or nighttime) and of effective intensity on the reaction times. There was also a statistically significant ($p<0.05$) interaction between background light level and effective intensity on the reaction times. The data revealed that for all effective intensities tested (between 55 and 370 cd), reaction times were unaffected by the effective intensity for nighttime conditions, but for daytime conditions, the lowest effective intensity tested (55 cd) resulted in substantially longer (and much more variable) reaction times than the higher intensities (130 and 370 cd).

These data suggest that an effective intensity of 55 cd would not be sufficient to achieve minimum reaction times during daytime viewing conditions; the minimum effective intensity could be as high as 130 cd. For comparison, Type B barricade lights are required to have a minimum effective intensity of 35 cd, and Type C barricade lights are required to have a minimum effective intensity of 2 cd. The data in Figures 4-1 and 4-2 suggest that even if Type C barricade lights are sufficient for detection during the nighttime, the daytime effective intensity should be higher than the minimum specified by Type B barricade lights, in order to ensure reliable detection when seen 5^o off axis.

Spatial Characteristics of Channelizing Signal Lights

As part of another laboratory study (Bullough and Skinner, 2014) to investigate the properties of edge delineation on visual acquisition, a laboratory experiment was conducted to compare different spacings of signal lights to a continuous delineation of the roadway edges. Perpendicular (with a 90^o angle between intersecting roads) and skew (with a 30^o angle between intersecting roads) intersections were modeled in a simulated roadway scene displayed on a computer screen. Subjects had to identify the shape of the intersection (e.g., four-way or tee) and whether the intersection was perpendicular or skew as quickly as possible and the identification times and accuracy of responses were recorded. Delineator spacings were 25, 50, 100 or 200 ft, or in a continuous line. Figure 4-3 shows several of the configurations shown to subjects.

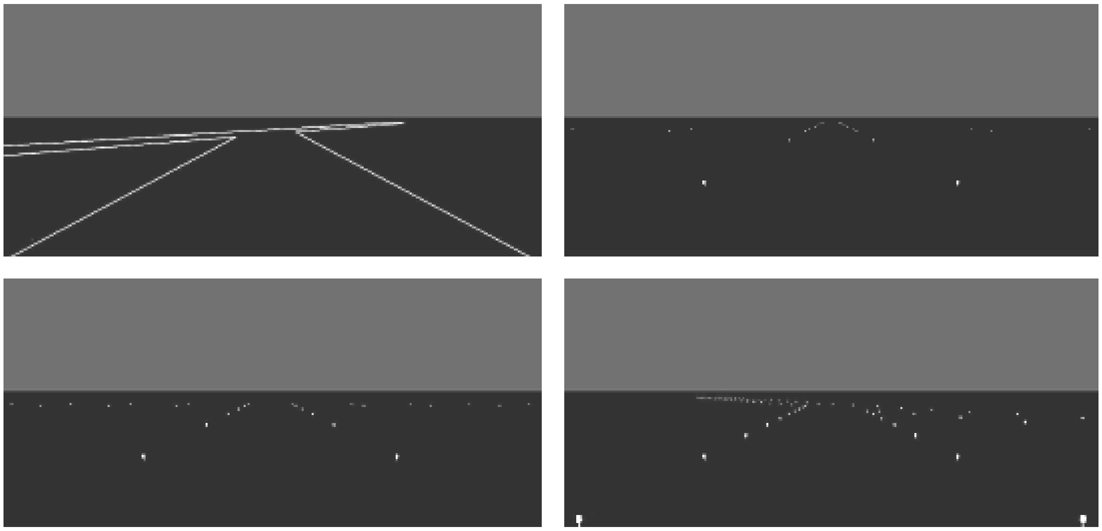


Figure 4-3. Examples of delineator spacing configurations shown to subjects.

Figure 4-4 shows the average identification times in the experiment, and Figure 4-5 shows the subjects' accuracy for each configuration.

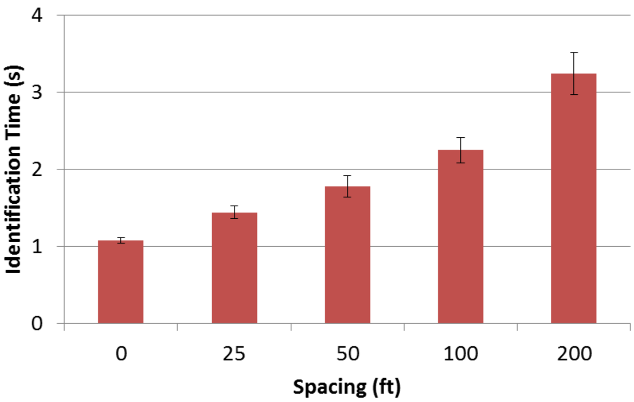


Figure 4-4. Mean identification times (+/- s.e.m.) to different delineator spacings.

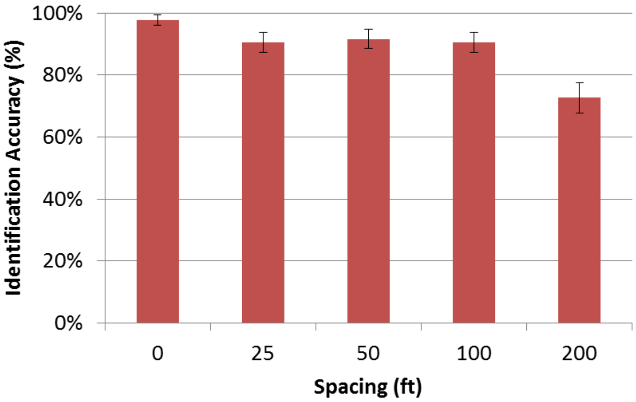


Figure 4-5. Accuracy of identification (+/- s.e.m.) for different delineator spacings.

There were statistically significant ($p<0.05$) effects of spacing on identification time and identification accuracy. Identification times increased as a function of increased spacing. Accuracy was highest for the continuous delineation, remained above 90% for spacings between 25 and 100 ft, and decreased substantially for the longest spacing (200 ft).

Temporal Characteristics for Channelizing Signal Lights

To better understand responses to lights used for channelization with different temporal characteristics, two sets of comparisons were made in a laboratory study setting. In the initial comparison, flashing but randomly unsynchronized (with frequencies between 0.9 and 1.1 Hz) lights, flashing and synchronized (1 Hz) lights, and sequentially flashing (1 Hz, staggered 0.03 seconds apart for each subsequent light) signal lights were compared. Lights were located along the left edge of the roadway in the scene as illustrated in Figure 4-6.

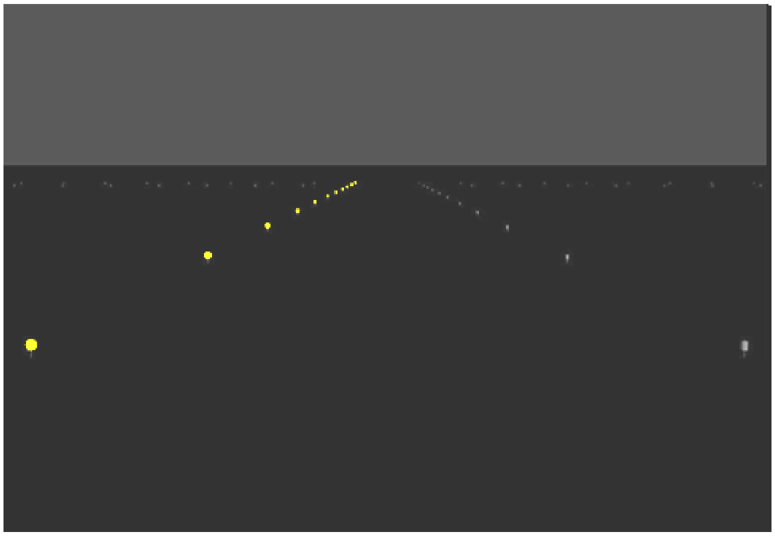


Figure 4-6. Roadway scene showing channelizing delineator lights along the left roadway edge.

Subjects viewed each configuration shown on a computer screen as if they were approaching the lights and provided ratings of informational clarity using the following scale:

- +2: very clear
- +1: somewhat clear
- 0: neither clear nor unclear
- -1: somewhat unclear
- -2: very unclear

Subjects also provided a rating of distraction from the lights using the following scale:

- 3: not at all distracting
- 2: slightly distracting
- 1: somewhat distracting
- 0: very distracting

Figure 4-7 shows the average clarity ratings and Figure 8 shows the average distraction ratings.

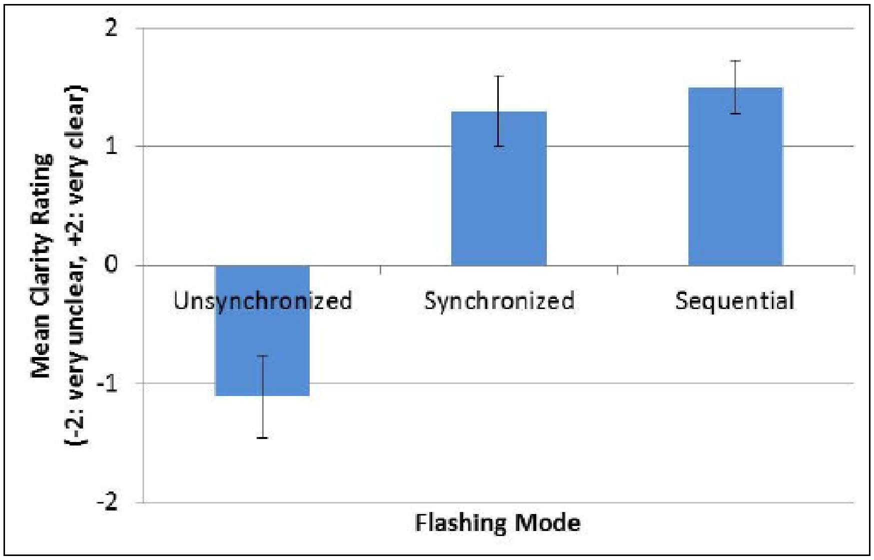


Figure 4-7. Mean clarity ratings (+/- standard error of the mean) for each of the three initial configurations evaluated.

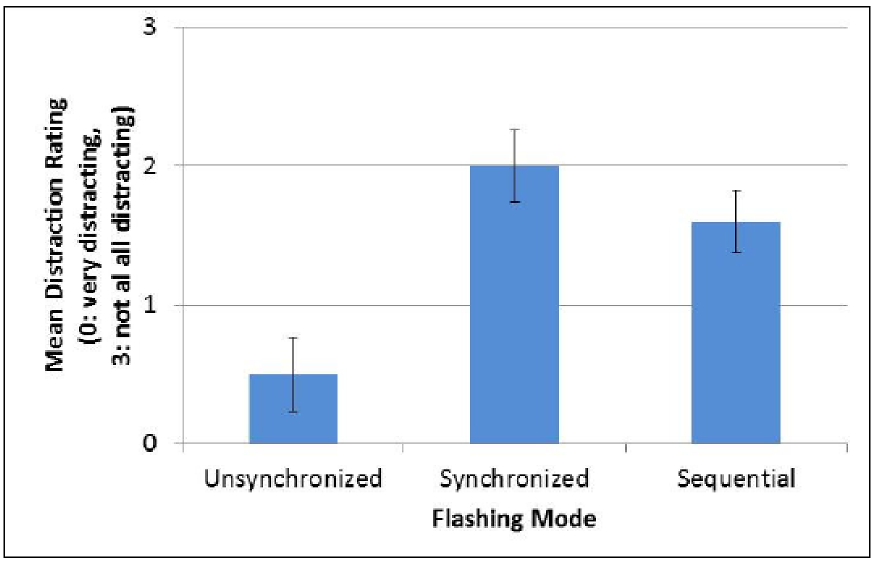


Figure 4-8. Mean distraction ratings (+/- standard error of the mean) for each of the three initial configurations evaluated.

In general, the unsynchronized flashing lights were judged as less clear and more distracting than the synchronized and sequentially flashing lights, with statistically significant ($p<0.05$) differences among the conditions based on one-way ANOVAs. In order to provide a comparison with steady-burning channelization lights, the second evaluation included five configurations: one with all steady-burning lights, one with a number of synchronized flashing lights followed by steady burning lights, one with sequentially-flashing lights as defined above, one with a number of sequentially-flashing lights followed by steady-burning lights, and one with randomly unsynchronized flashing lights as defined above.

Figure 4-9 shows the average clarity ratings for the second set of configurations, and Figure 4-10 shows the average distraction ratings.

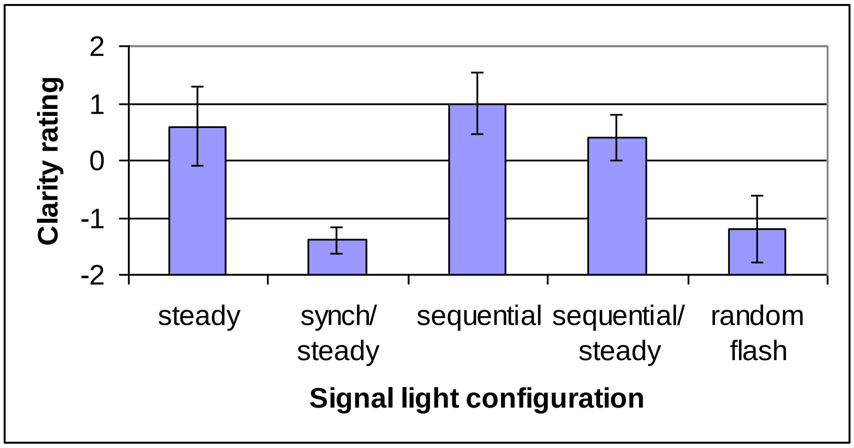


Figure 4-9. Mean clarity ratings (+/- standard error of the mean) for the configurations in the second evaluation set.

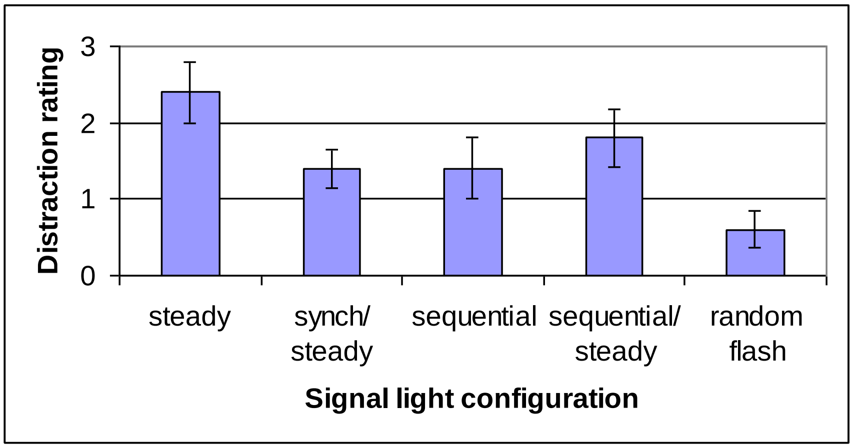


Figure 4-10. Mean distraction ratings (+/- standard error of the mean) for the configurations in the second evaluation set.

One-way ANOVAs confirmed that there were statistically significant ($p<0.05$) differences among the configurations in the second set of comparisons. Similar to the data from the first evaluation set, the randomly unsynchronized flashing lights were rated quite low in terms of clarity and were judged the most distracting. Both steady-burning lights, and several sequentially-flashing lights followed by steady-burning lights, resulted in positive ratings of clarity and relatively low ratings for distraction. These results suggest that using a large proportion of steady-burning lights could help drivers interpret and understand how they should respond to channelizing lights, and ensure that they will not cause unnecessary distraction.

Mock-Up Demonstration

In order to assess responses to barricade lights and channelizing devices with various flashing characteristics and luminous or effective intensity values, a mock-up demonstration was conducted at the Rensselaer Student Union inside Mother's Wine Emporium, a performance space without windows and in which the ambient room lighting could be switched off to present dark viewing conditions representative of a rural nighttime location.

Configurations and Method

The demonstration included the following devices:

- Steady-burning barricade lights (Type C) with a minimum luminous intensity of 2 cd
- Flashing (unsynchronized) barricade lights (Type A) with a minimum effective intensity of 4 cd
- Sequentially-flashing barricade lights (Type B) with a minimum effective intensity of 35 cd
- Sweeping barricade lights (Bullough et al., 2012) with a minimum effective intensity of 50 cd
- Expanding barricade lights (Bullough et al., 2012) with a minimum effective intensity of 50 cd
- Internally illuminated traffic drums

The sweeping and expanding barricade lights were tested as part of a previous study (Bullough et al., 2012) in which it was hypothesized that the side-to-side sweeping motion of the barricade light display face would encourage earlier lane change transitions when approaching lane closures, and the expanding configuration was hypothesized to result in greater deceleration in comparison to conventional flashing lights. The internally illuminated traffic drums were developed as part of a previous study (Lighting Research Center, 2013) as possible diffuse illuminants in inactive work zone locations where high (>50 lx) illuminances were not necessary for high levels of visual performance. The orange barrel material was translucent and appeared to have an orange glow that would be visible even when headlight illumination was not incident on the retroreflective barrel wrap surrounding the barrels (see previous chapter).

Five individuals from NYSDOT participated as observers in the demonstration, and were asked to evaluate each of the configurations in terms of their brightness and the informational clarity they provided. Brightness was rated on a four-point scale as follows:

- 1: not bright enough
- 2: bright enough for a dark area
- 3: bright enough for a lighted area
- 4: too bright

Informational clarity was rated on the following four-point scale:

- 1: very confusing
- 2: slightly confusing
- 3: somewhat clear
- 4: very clear

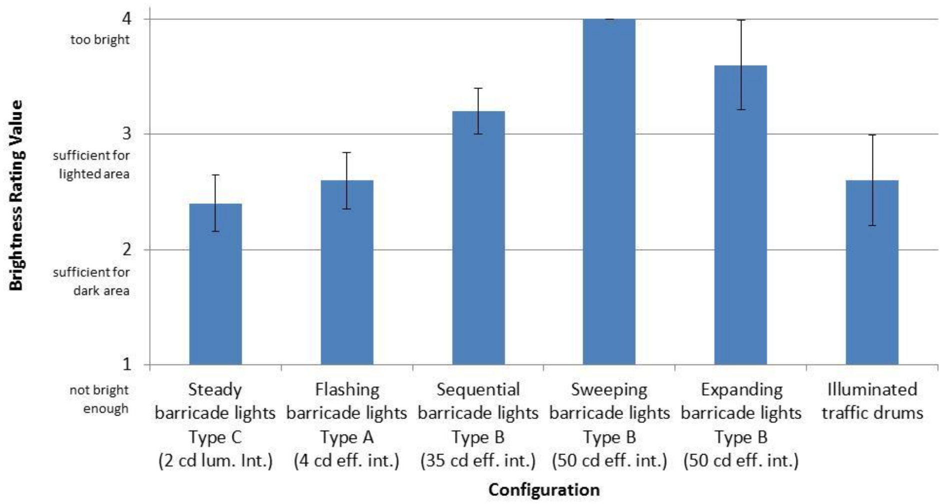


Figure 4-11. Mean brightness ratings (+/- s.e.m.) for each of the barricade lights/channelizing device configurations.

Demonstration Results

Figure 4-11 shows the mean brightness ratings for each of the configurations. None of them were judged as insufficiently bright under the viewing conditions in which they were seen. The Type A and Type C barricade lights, as well as the illuminated traffic drums, were judged as sufficient for dark areas (and possibly some lighted areas) whereas Type B barricade lights were judged as sufficient for lighted areas. The sweeping and expanding barricade lights, having luminous intensities higher than those required for Type B barricade lights, were judged overall as too bright or approaching excessive brightness.

A repeated measures ANOVA on the brightness ratings revealed that there was a statistically significant ($p<0.05$) effect of the configuration type on perceptions of brightness. Figure 4-12 sheds light on this effect, showing the mean brightness rating values plotted as a function of effective or luminous intensity for each of the barricade lights in the demonstration. The intensity values and mean ratings for each intensity value are strongly ($r^2=0.97$) correlated, suggesting that there is a meaningful relationship between the intensity of barricade lights and perceptions of whether they are bright enough or too bright.

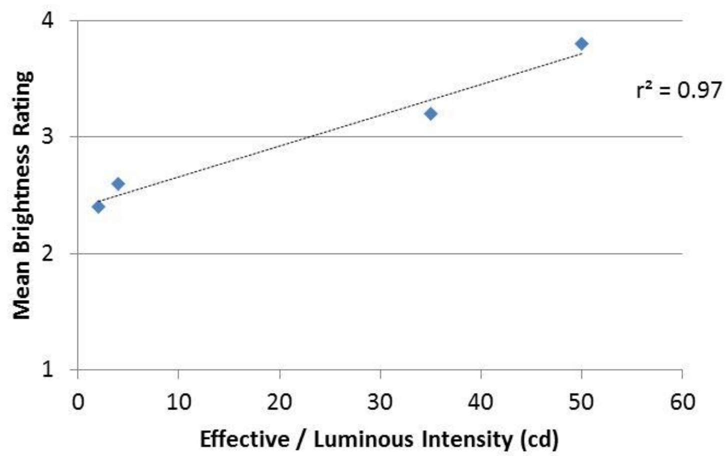


Figure 4-12. Relationship between barricade light intensity and perceived brightness.

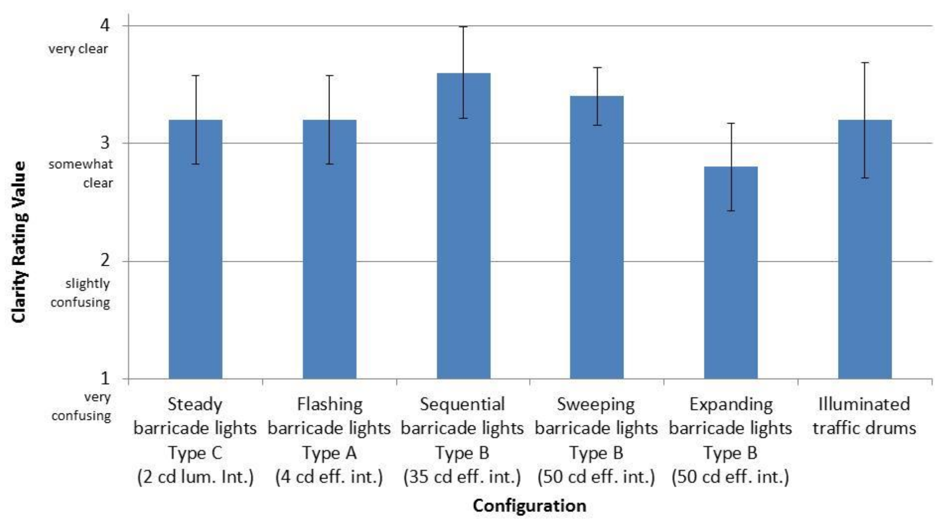


Figure 4-13. Informational clarity ratings (+/- s.e.m.) for each configuration.

Figure 4-13 shows the mean informational clarity ratings for each of the configurations in the demonstration. A repeated measures ANOVA revealed that there was no statistically significant effect of the configuration type on rated clarity ($p>0.05$). Most of the ratings were between somewhat and very clear, with the exception of the expanding barricade light, which was judged between somewhat clear and slightly confusing. The two configurations judged as clearest were the sequential and sweeping barricade lights. Also of interest, the use of steady-burning barricade lights (Type C) was not judged as clearer than the use of flashing barricade lights (Type A), which is somewhat of a contradiction to findings from the laboratory studies of the temporal flash characteristics of channelizing lights (Figures 4-7 and 4-9).

Discussion

Overall, the observations from the demonstration participants were consistent with the results of the laboratory studies described earlier in this chapter. They also suggest that for nighttime viewing conditions in dark locations such as rural areas, Type A (flashing) and Type C (steady-burning) barricade lights provide sufficient intensity, while Type B (flashing) lights are sufficient for lighted areas. Effective intensities higher than the 35 cd value that is required for Type B barricade lights may be too bright for nighttime conditions.

5. FINDINGS AND CONCLUSIONS

This chapter of the report for Project C-08-14, "Nighttime Highway Construction Illumination," includes a checklist for use during the planning stages of nighttime highway construction. Factors related to the duration of work, the type of work to be undertaken in a work zone or portion of a work zone, the characteristics of the roadway and surrounding location, the type and quantity of traffic in the adjacent location, and the nature of required traffic control can all impact decisions regarding the use of illumination, signage, marking and delineation materials, and warning lights and channelizing devices.

In planning nighttime highway construction work, the reader should work through the illustrated checklist and select options to each question. The technical notes adjacent to each response provide guidance and options for consideration in designing the work zone lighting and traffic control configuration.

This chapter also describes methods for estimating visual performance under work zone illumination, which can assist the planner in selecting light sources and wattages appropriate for the work to be undertaken in a work zone location.

Design Checklist: Work Zone Lighting, Delineation and Channelization Considerations

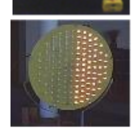
Project Duration		
☐ Temporary (1 night)	*Diffuse ground-level lighting can be moved easily and could be battery operated.*	
☐ Short term (<3 months)	*Balloon lights provide low, diffuse source luminance, reducing glare and minimizing shadows in the work area.*	
☐ Long term (>3 months)	*The use of high-mast semi-permanent lighting will minimize set up time at the start and end of each night.*	

Size and Contrast of Visual Task		
☐ Small/low contrast	*When large coverage areas are needed, conventional light towers using higher wattage MH lamps or LED sources may be needed but should be aimed very carefully to avoid glare.*	
☐ Large/high contrast	*Solar powered LED lights can provide sufficient illumination. Balloon lights will help minimize glare.*	 
☐ Basic orientation only	*Vehicle mounted or solar powered LED lights, lower wattage balloon lights, or diffuse ground-level lighting can provide sufficient illumination. If work vehicles with headlights are present, reflective conspicuity tape on stationary hazards can help in detection. Photoluminescent paint or tape can help in detecting hazards during initial hours of darkness. Illuminances of 1 footcandle may be sufficient in these areas.*	 

Complexity of Roadway Location		
☐ Simple/straight road	*Delineators and signs with engineering grade or high intensity retroreflective sheeting provide sufficient luminance.*	
☐ Complex with curves, intersections	*Consider using prismatic/full-cube sheeting/wrap on delineators such as barricades and traffic drums. Use of conspicuity tape on equipment could enhance detection.*	 

Separation/Barriers Between Work Zone and Traffic		
☐ Few physical barriers if any, close proximity to traffic	*Temporary pavement tape (wet-reflective if needed) and reflective markers can identify boundaries between work zone and adjacent traffic. Engineering grade or high intensity sign and delineator sheeting provide sufficient retroreflective luminance from headlights.*	
☐ Clear physical separation between work zone and traffic, such as concrete barriers	*High-mast semi-permanent lighting is best used far from active rights-of-way. Prismatic/full-cube sheeting can produce higher luminances for signs and delineators located off-axis from approaching vehicle headlight beams. Illuminated traffic drums can provide luminance.*	 

Amount/Speed of Adjacent Traffic		
☐ High volume, high speed	*Prismatic/full-cube sheeting for signs and delineators could provide greater viewing distances needed at higher driving speeds. Flashing barricade lights may produce lower speeds relative to steady-burning lights.*	 
☐ Low volume, low speed	*Engineering grade or high intensity sheeting should provide sufficient luminance from headlights.*	

Presence of Lane Closure		
☐ None - all traffic lanes may proceed	*Conventional delineator and channelizing devices provide sufficient guidance. Spacing should not exceed 100 feet.*	 
☐ One or more traffic lanes closed	*Consider sequential or sweeping barricade lights along lane closure tapers to encourage drivers to change lanes ahead of closure. Spacing should be less than 100 feet.*	 

Weather Conditions		
☐ Clear weather	*Economical grade temporary pavement marking is sufficient under dry conditions.*	
☐ Rain/wet road surface	*Wet reflective temporary pavement tape and pavement markers will maintain visibility under wet conditions.*	
☐ Snow possible	*Avoid pavement marking tape when activities such as snow plowing might become necessary. Reply on movable delineators and channelizing devices.*	

Estimating Visual Performance Under Different Lighting Conditions

Data sheets for some lighting systems provide templates illustrating the illuminances provided for different mounting heights. Others may provide information about the beam spread of the lighting system as well as the number of lumens produced by the system. As a rule of thumb, about half of the lumen output from a lighting system is produced within the angle defined by its beam spread (Rea and Bullough, 2000). Thus, a fixture that produces approximately 10,000 lumens in total can be estimated to produce about half of its lumen output, about 5000 lumens, within its nominal beam spread angle. If the same fixture is mounted at a height of 10 meters, and has a beam spread of 30^o (therefore having a beam half-angle of 15^o), it would provide illumination in a circular area with a radius of approximately 2.68 m, based on the following equation:

$$\begin{aligned} \text{Radius} &= 10 \text{ m} \times \tan 15^o \\ &= 10 \text{ m} \times (0.268) \\ &= 2.68 \text{ meters} \end{aligned}$$

The area of this circular region is 22.6 square meters (πr^2). Because illuminance is defined as luminous flux density (1 lux = 1 lumen/m^2; 1 footcandle = 1 lumen/ft^2) (Rea, 2000), distributing 5000 lumens in an area of 22.6 square meters is equivalent to approximately 5000 ÷ 22.6 or 221 lux (about 20 fc) within the beam spread, and lower levels outside this circular area.

Knowing the illuminance produced by a lighting system, it is possible to estimate the visual performance using the relative visual performance (RVP) model (Rea and Ouellette, 1991) described in an earlier chapter. This model provides a basis for calculating the speed and accuracy with which visual information can be processed given a number of input parameters:

- Size of a target or object to be seen
- Luminance of the area (usually the ground or pavement) surrounding the visual target
- Contrast between the target and its background
- Age of the observer

For reference, an RVP value of zero occurs at the threshold of being able to identify an object. An RVP value of one corresponds to a large, high-contrast visual task viewed under high light levels, such as reading laser-printed 12-point text under office lighting conditions. Once RVP values reach 0.8, visual speed and accuracy is nearly as high as it will be under any higher light level or with higher contrast. This section describes how RVP quantities can be estimated under work zone lighting, once the approximate illuminance is known.

The size of a target is expressed in terms of a solid angle, in steradians. To calculate the solid angle of an object of area A that is viewed at a distance d (and assuming A and d have the same dimensions; e.g., either meters or feet), the following equation is used:

$$\text{Solid angle} = A/d^2$$

The solid angle in steradians can be converted into microsteradians by multiplying by 1,000,000. To calculate the luminance (L) of an object (in cd/m²), on which is falling a specific illuminance (E, in lux), the following equation is used:

$$L = E\rho/\pi$$

Where ρ is the reflectance of the object. Reflectance is a unitless quantity between 0 (for purely black objects) and 1 (for purely white objects). The reflectance of asphalt pavement is approximately 0.1. Concrete has an approximate reflectance of 0.3.

The contrast of a target with a specific luminance (L_t, in cd/m²) against a background with a given luminance (L_b, in cd/m²) is expressed in terms of a unitless quantity between 0 and 1, where 0 represents an invisible object and 1 represents the maximum possible contrast (such as purely black surface viewed against a purely white one). The following equation is used to calculate the contrast (C):

$$C = |L_t - L_b|/\max(L_t, L_b)$$

When both luminance and luminance contrast are low, visual performance drops. Once both luminance and luminance contrast are high enough that visual performance is nearly maximal (with RVP values close to 1.0), further increases in either luminance or luminance contrast will not result in substantial increases in visual performance.

Appendix 1 contains the equations for calculating RVP with a particular illuminance, background surface reflectance, object size, and observer age, according to the model by Rea and Ouellette (1991). Lower values of RVP are associated with longer visual response times and reduced accuracy of visual processing.

6. STATEMENT ON IMPLEMENTATION

The findings summarized in this report can be used by NYSDOT engineers and its contractors charged with work zone lighting and traffic control to identify promising, underutilized systems and technologies to ensure visibility, reduce glare and reinforce work zone delineation. While some of the systems that have been demonstrated, such as the internally-illuminated traffic drum, are not readily available nor approved for use within work zones, others such as balloon lights and sequentially flashing barricade lights have been used successfully by agencies in the process of designing traffic control in work locations. In order to facilitate acceptance and approval for the eventual use of all of the systems that show promise for reinforcing visual information in work zones, NYSDOT is encouraged to test them in limited field trials and to evaluate their performance by gauging the responses of work zone personnel.

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APPENDIX 1: RELATIVE VISUAL PERFORMANCE CALCULATION

This appendix provides the calculation methods for assessing the relative visual performance (RVP; Rea and Ouellette, 1991) of a target with a particular background luminance (L_b, in cd/m²), luminance contrast and size (S, in steradians), for an observer of a particular age (A, in years):

Calculate the pupil radius P (in mm):

$$P = 2.39 - 1.22 \tanh(0.3 \log L_b)$$

Calculate the age-corrected retinal illuminance E_r [in trolands (Td)]:

$$E_r = \pi P^2 L_b[1 - 0.017(A - 20)]$$

Calculate five intermediate values x1, x2, x3, x4 and x5:

$$x_1 = \log[\tanh(20{,}000\ S)]$$
$$x_2 = \log[\log(10\ E_r/\pi)]$$
$$x_3 = 1 + [0.0025(A - 20)]$$
$$x_4 = \log[\tanh(5000\ S)]$$
$$x_5 = \log[\tanh(0.04\ E_r/\pi)]$$

Calculate the threshold luminance contrast C_t (a dimensionless quantity):

$$C_t = x_3\ 10^{(-1.36 - 0.18x_1 - 0.81x_2 + 0.23x_1^2 - 0.077x_2^2 + 0.17x_1x_2)}$$

Calculate the half-saturation constant K:

$$K = 10^{(-1.76 - 0.18x_4 - 0.031x_5 + 0.11x_4^2 + 0.17x_5^2 + 0.062x_4x_5)}$$

Calculate the maximum response R_{max}:

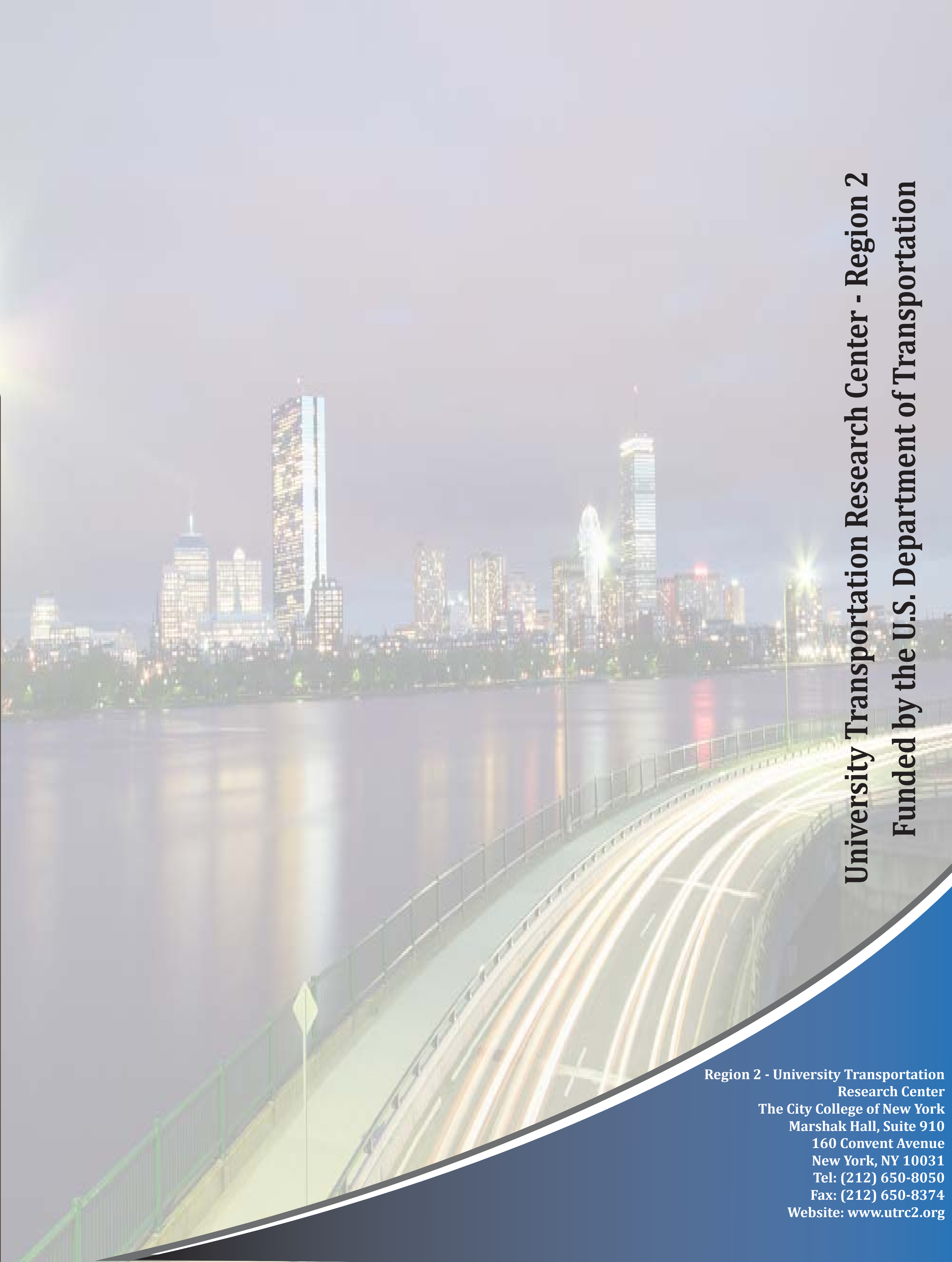
$$R_{max} = 0.0002 \log(E_r) + 0.0027$$

Calculate the visual response time V (in ms):

$$V = [(C - C_t)^{0.97} + K^{0.97}]/[(C - C_t)^{0.97}\ R_{max}]$$

Calculate the relative visual performance (RVP):

$$RVP = 1.42 - V/778.56$$



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