

## **Optimizing Work Zone Lighting**

FINAL REPORT

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Submitted by

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## **EXECUTIVE SUMMARY**

### **Background**

Work zones are inherently complex and confusing visual environments, where the usual patterns of traffic flow are perturbed, and where lights used by workers for task visibility can create glare not only to workers but to nearby drivers. The use of delineation and signage, in addition to warning lights that may be flashing, can all contribute to "visual chaos." The New Jersey Department of Transportation (NJDOT) commissioned the present study to address and begin to overcome these issues.

### **Objectives**

The objective of the present study was to identify the needs of workers and drivers in different work zone environments, and to review existing knowledge about ways in which lighting practices and technologies can be deployed to provide workers with sufficient illumination while minimizing glare and confusion to all individuals in and near the work zone.

### **Research Approach**

Following a literature review of recently published information on lighting and traffic control in work zones, and a questionnaire of safety engineers, technical analyses of illumination systems, signage and delineation materials, and warning lights were undertaken.

### **Analyses and Results**

The results of the technical analyses led to the development of several preliminary guidelines for illumination system selection/layout, application of sign and delineation devices and materials, and the use and control of warning lights to provide workers and nearby drivers with visual information in work zones.

### **Conclusions and Recommendations**

Implementation of the preliminary guidance in the present report can assist NJDOT in improving visual conditions in several different types of work zones through lighting that maintains visual performance while reducing glare and distraction from excessively bright lights.

## INTRODUCTION

The present report summarizes activities undertaken by a project team from the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute to investigate options and approaches for work zone lighting, including delineation, signage and warning lights. From the project statement developed for this study by the New Jersey Department of Transportation (NJDOT):

"At times it can be difficult to capture a driver's attention, since drivers do not always devote their full attention to the road. Both motion and visual intensity are needed to gain notice. Work zones can cause traffic congestion and pose a significant obstacle to both workers and motorists. Improving safety lighting at work zones is important because of extra visibility concerns. Concerns related to night time highway construction can be addressed by incorporating the developing technologies and resulting new methodologies for warning lights, such as light emitting diodes (LEDs), intelligent warning lights, balloon lights and highly reflective retroreflective sheeting. Warning light scheme innovations in work zones are needed to reduce the number of incidences. The characteristics of the warning light schemes needs to be evaluated to identify the best design for conveying the proper message to the traveling public. A best practice guide will be developed, to identify the optimum lighting schemes to be used on various work zone scenarios, and incorporated in the Warning Light Guide used by the Department. The quantitative benefits of this project include the decrease in work zone vehicle accidents, which costs an average of \$3,700 per incident."

In subsequent sections of this report, a review of recent published literature, responses to a brief questionnaire to NJDOT safety engineers, and technical analyses of illumination systems, signage and delineation materials, and warning light characteristics are described and synthesized, with recommended guidance for implementation of project findings into work zone lighting and traffic control practices.

## **BACKGROUND AND LITERATURE REVIEW**

Background information in this section of the present report is provided in the form of an annotated bibliography of recently published reports on work zone lighting and traffic control. Items in the annotated bibliography are divided into two sections: one on work zone illumination systems, and one on traffic control devices and systems.

### **Work Zone Illumination**

The information reviewed related to work zone illumination revealed several important findings. Glare from work zone lighting is a major problem and partly responsible for high light levels used in many work zones. Visibility under relatively low light levels is often sufficient for visibility when glare is effectively controlled, and relatively low light levels (<5 footcandles) are permitted in work zones by some jurisdictions. Balloon lights in particular appear to be a promising technology for work zone illumination and glare control.

#### ***American Traffic Safety Services Association, 2013<sup>(1)</sup>***

- Portable light towers in work zones should be aimed downward to prevent glare, unless the light fixtures have been specially designed to mitigate glare.
- Headlights on vehicles and equipment in work zones do not typically provide sufficient illumination for most work operations.
- Balloon lights provide an even, circular pattern of illuminance around the fixture.
- Missouri requires 5 footcandles of illumination in active areas within work zones, and 0.6 footcandles near flaggers and other locations.
- Nova Scotia requires a minimum light level of 3 footcandles within work zones.
- Illinois requires a minimum of 5 footcandles around moving work equipment within a distance of 25 ft ahead of and behind the equipment.

#### ***Anani, 2015<sup>(2)</sup>***

- Renderings from lighting calculation software packages can provide useful visualization of the lighting conditions in work zones.
- Review of design calculations by agency office staff should be performed before approving a work zone lighting design.
- Software packages for assessing the glare from work zones are available.

#### ***Bullough, 2015<sup>(3)</sup>***

- Glare from conventional light towers used to illuminate work zones is a primary cause for “ratcheting” of light levels to high values needed for workers.

- Observers ranging in age from their 20s to their 70s reported being able to see well under levels as low as 1 footcandle when glare was not present.
- Wet reflective temporary pavement tape maintained a high level of visibility when wetted.
- Photoluminescent materials maintained sufficient visibility for detection in dark locations after several hours at night.

***Bullough et al., 2013<sup>(4)</sup>***

- A demonstration of various work zone lighting technologies revealed that balloon lights can provide sufficient visibility for workers even when light levels are below 2 footcandles.
- A mathematical model to predict visibility, glare and acceptability was developed based on the illuminance from, and luminance of, work zone illumination systems.

***Finley et al., 2013<sup>(5)</sup>***

- Conventional headlights on vehicles and construction equipment in work zones should not be used to provide illumination when aimed toward oncoming traffic, in order to avoid glare.
- A light meter calibrated for illuminance should be used to verify light levels in the work zone lighting design plan.
- The Occupational Safety and Health Administration (OSHA) requires a minimum illuminance of 3 footcandles in general construction areas, active storage areas, and field maintenance areas.
- Commission Internationale de l'Eclairage (CIE) recommends 2 footcandles for very rough work.
- California requires a minimum of 3 footcandles in work zone areas; some locations require higher light levels depending upon the task.

***Finley et al., 2014<sup>(6)</sup>***

- Low contrast objects tended to be seen at distances insufficient for stopping by drivers under both light towers and under balloon lights, whether the light level was 5 footcandles or 0.2 footcandles.
- High contrast objects (i.e., workers in reflective vests) were visible with sufficient stopping distance under both light towers and balloon lights, whether the light level was 5 footcandles or 0.2 footcandles.
- Glare from light towers was very dependent upon the direction of travel relative to the aiming direction of the light towers.

***Hassan et al., 2011<sup>(7)</sup>***

- Balloon lights can be mounted on shorter towers than conventional work zone lights because they produce less glare.
- Balloon lights tend to produce lower veiling glare ratios than conventional work zone light towers.
- Balloon lights and conventional light towers are comparable in terms of power use and the amount of light produced.
- Increasing the mounting height of conventional light towers in work zones can reduce glare, but will also reduce the useful coverage area illuminated by the light tower.
- Conventional work zone light towers produce higher light levels than balloon lights in the area immediately adjacent to the work zone light.

***Miller et al., 2015<sup>(8)</sup>***

- Work zone lights using metal halide (MH) lamps have 2-3 times greater light output than work zone lights using light emitting diodes (LEDs) or plasma lamps.
- LED work zone lights have 1.6 times higher efficacy than MH work zone lights.
- Fuel costs for an LED work zone light powered by a fuel cell are 38% lower than for a MH work zone light powered by a diesel generator.

***Stoikes, 2015<sup>(9)</sup>***

- Eight out of ten drivers surveyed would prefer road construction and repair work to be performed during off peak hours (i.e., at night).
- Balloon lights are a promising option for equipment mounted lighting on vehicles in work zones, because they produce less glare than conventional work zone lights.
- Light emitting diode (LED) work zone lights use 40% of the energy to provide equivalent light levels as metal halide (MH) work zone lights, but cost significantly more than MH lights.

**Work Zone Traffic Control Devices and Systems**

The review of literature related to work zone traffic control identified several important features. Drivers are often confused and made uncomfortable by excessive use of strobing or flashing lights, although these are often important in capturing drivers' attention. Limiting the number of flashing lights and using sequential or synchronized flashing patterns can be effective methods for reducing the negative visual impacts of flashing warning lights. Dynamic speed display signs can be a useful tool for reducing speeds (when necessary) as well as variations in vehicle speeds in a work zone, with

effective placement. And the use of the flash rate as a piece of visual information to convey urgency (with higher flash rates) can be a useful intuitive cue for drivers.

***Bai et al., 2015<sup>(10)</sup>***

- The Manual on Uniform Traffic Control Devices (MUTCD) does not specify the use of portable changeable message signs (PCMSs) in work zones.
- A PCMS location 575 ft upstream of the “Road Work Ahead” sign signifying the beginning of a work zone resulted in the least variation in vehicle speeds between passenger cars and trucks entering the work zone.

***Bullough et al., 2014<sup>(11)</sup>***

- In a controlled field experiment, subjects responded to a dynamic speed display sign that requested different driving speeds by adjusting their speeds to the requested one, and reported that the dynamic messages on the sign were clearly understood.
- A dynamic speed display on a real-world roadway requesting a speed zone of 25 mph (when the usual speed limit was 30 mph) resulted in lower, and less variable, speeds than the baseline conditions without the dynamic speed display sign.
- Real-time speed messages may provide increased credibility over static signs in eliciting desired speeds in work zones.

***Bullough and Rea, 2015<sup>(12)</sup>***

- Study participants responded to the onset of a flashing yellow warning beacon presented in a projected roadway scene (daytime or nighttime) either on- or off-axis to their line of sight.
- Response times to the warning beacon onsets became asymptotic above 600 cd for daytime conditions and above 200 cd for nighttime conditions (and during daytime conditions when viewed on-axis).
- Reported visibility impacts on low-contrast objects in the scene were substantial only for nighttime viewing conditions and off-axis warning beacons above 600 cd.

***Li and Bai, 2009<sup>(13)</sup>***

- The use of flashing lights in work zones for traffic control applications was investigated using crash data.
- The presence of flashing lights was associated with a reduction in the severity of work zone related crashes.

***Minnesota Department of Transportation, 2013<sup>(14)</sup>***

- LED vehicle lighting and signaling equipment was stated to use less energy than conventional light sources, allowing lights to be used on vehicles with their engines turned off for longer periods, and reducing vehicle emissions.
- Including blue lights with yellow in vehicle mounted light bars did not reduce speeds of approaching traffic more than other types of lights, but did result in a larger proportion of traffic moving out of the lane adjacent to the service vehicle.

***Steele et al., 2013<sup>(15)</sup>***

- Focus groups of drivers about their responses to various warning light configurations revealed that drivers would prefer synchronized or sequentially flashing lights over randomly flashing lights.
- Drivers reported finding strobe lights to be excessive in number.
- In field tests, more drivers changed lanes ahead of a lane closure when strobes were not used than when they were.
- In many cases, dimming flashing lights to lower intensities had no negative impacts on visibility or detection, but reduced discomfort glare and anxiety.

***Turner et al., 2014<sup>(16)</sup>***

- A study in which observers viewed films showing various combinations of flashing lights and patterns was conducted.
- Higher flash rates (i.e., 4 Hz versus 1 Hz) for single pulse flashes resulted in larger “gaps” between the observer and the emergency vehicle at the last possible moment they would feel comfortable pulling out into the road containing the emergency vehicle.
- Higher flash rates were judged as more urgent than lower flash rates.

**Summary**

The review of literature on work zone lighting and traffic control presented above have identified important principles that should be incorporated into the design and specification of work zones:

- Requirements for illumination need to consider the glare produced by the lighting as well as the needs for visual information based on the type of work and visual tasks undertaken by workers.
- For work zone traffic control, the proper balance between capturing attention with bright, flashing lights needs to be balanced by providing clear, stable visual information about lane changes, desired speeds, and the presence of workers in the work zone.



Subsequent recommendations and guidelines will rely on these balancing principles to meet the visual needs of both workers and drivers in the nighttime work zone.

## QUESTIONNAIRE FOR SAFETY ENGINEERS

In order to better understand the challenges facing NJDOT in work zone lighting and traffic control related issues, a short questionnaire was developed and circulated to members of the Employee Safety office at NJDOT. This section of the present report summarizes the questions and responses, and based on those responses, identifies several work zone scenarios for subsequent analysis and development of guidelines.

### Questions and NJDOT Responses

In the list of questions and responses below, responses from NJDOT are italicized.

1. What types of work zone situations are the most hazardous for workers? For drivers?  
*Moving operations are the most hazardous by far, for workers and drivers.*

1a. Which workers are at the greatest risk in work zones, and why?  
*The workers that are performing a task are at the greatest risk. Their attention is on the work they are doing and not the traffic passing them by.*

2. Are formal records or reports of work zone related accidents available? (Yes/No)  
*Yes, the Employee Safety office investigates most work zone accidents.*

3. Can NJDOT list the most critical needs for improvement regarding work zone lighting and traffic control? Such as:

Warning lights?

*Controlling the intensity, and coordinate the flashes.*

Signage?

*Sometimes the background is too bright at night, and the message washes out.*

Illumination for workers?

*Glare problems need to be eliminated.*

Delineation?

*Arrowboards need to be coordinated into the overall scheme of the work zone lighting.*

Other(s)?

*Rural vs. urban work zones.*

4. How do ambient conditions (day vs. night, clear vs. rain vs. snow vs. fog, urban vs. rural) affect work zone lighting and traffic control?

*We have a need to prepare for each of these events. The same trucks are used in all scenarios.*

5. Has NJDOT experimented with new or novel technologies or approaches? (Yes/No)

*Yes, we have been working with vendors on LED technology.*

5a. What worked and what did not work?

*LED warning lights have worked to some extent.*

6. Is NJDOT willing to use new technologies and “intelligent” systems in work zone lighting and traffic control, even if they are not currently included in national standards for work zones? (Yes/No)

*Yes, the department is able to work on some pilot projects.*

7. Is there anything else we should know about NJDOT's work zone lighting and traffic control that will help make the project results more useful?

*The department is open to trying new products and technologies.*

## **Summary of Responses**

The survey of NJDOT safety office personnel on needs and requirements for work zone lighting and traffic control revealed several findings:

- The most significant issues related to work zone lighting and traffic control are glare, excessive sign brightness, and coordination of flashing lights.
- Workers pay attention to their tasks, but usually not to approaching traffic, creating safety issues.
- NJDOT has some initial experience with LED warning lights, with some success.
- NJDOT is open to trying new products and technologies.
- Moving operations are the most hazardous for workers and for drivers.
- There are very different needs in urban and rural areas, even though same trucks and equipment are used for operations in these locations.

## **Selection of Work Zone Scenarios**

Based on these responses, the project team proposed to develop guidelines in the following areas:

- Large, long term, stationary projects in urban and rural locations
- Slow-moving operations (painting lines, sweeping, plowing) in urban and rural locations
- Emergency incidents requiring immediate short-term activity (downed trees, accidents)

Project activities in subsequent tasks are based on these scenarios.

## TECHNICAL ANALYSIS OF ILLUMINATION SYSTEMS

This section of the present report summarizes activities undertaken to evaluate illumination technologies and systems for work zone illumination, which is primarily used by workers to provide visibility for their tasks.

### Visual Performance Analysis

Illumination systems serve the purpose of supporting worker visibility. Visual tasks can range in size (from seeing small details such as a keyhole or slot on a screw or fastener, to detecting a hand tool on the ground from several feet away) and contrast (from high contrast such as black print on white paper, to low contrast such as differentiating closely colored wires or finding cracks in new, dark asphalt). Lighting systems therefore should provide sufficient illuminance so that the combination of visual task size, contrast and luminance result in high levels of visual performance. To understand the relationships among these factors as they impact visual performance, several analyses of task visibility were conducted using the relative visual performance (RVP) model.<sup>(17)</sup> A 60-year-old observer was used in these analyses, to account for reductions in lens transmission and in pupil size as adults age, effects that influence visual performance compared to younger individuals.

The RVP model provides a relative estimate of the speed and accuracy of visual processing, where a value of zero corresponds to the threshold for visual identification of an object, and a value of one corresponds to very high levels of visibility such as laser-printed text under office lighting levels. Values even greater than one are possible, but RVP values are nearly asymptotic once they reach a value of 0.8 or higher. Bullough and Radetsky<sup>(18)</sup> summarized a broad array of studies conducted under nighttime driving conditions and found that the results of these studies, whether characterized by target detection times, target identification distances, legibility distances, vehicle stopping distances, or nighttime crash rates, were all predicted well by the RVP model.<sup>(17)</sup> Further, an RVP value of 0.8 serves as a practical criterion at which driver responses (e.g., braking, pressing a button, etc.) occur.

Figure 1 illustrates RVP values as a function of horizontal illumination (from approximately 0.1 to 50 footcandles [fc]) and task contrast (low: 0.2, medium: 0.5, or high: 0.8) for a small visual task observed by a 60-year-old adult (this is the highest age accounted for by the RVP model), corresponding to identifying a keyhole slot from a viewing distance of 3 feet. It can be seen that RVP increases as a function of both light level and contrast, and that differences in both light level and contrast are less important at the higher end of the range for each. An RVP value of 0.8 is reached when the

illuminance exceeds approximately 0.3, 1 and 3 fc, for high, medium and low contrast, respectively.

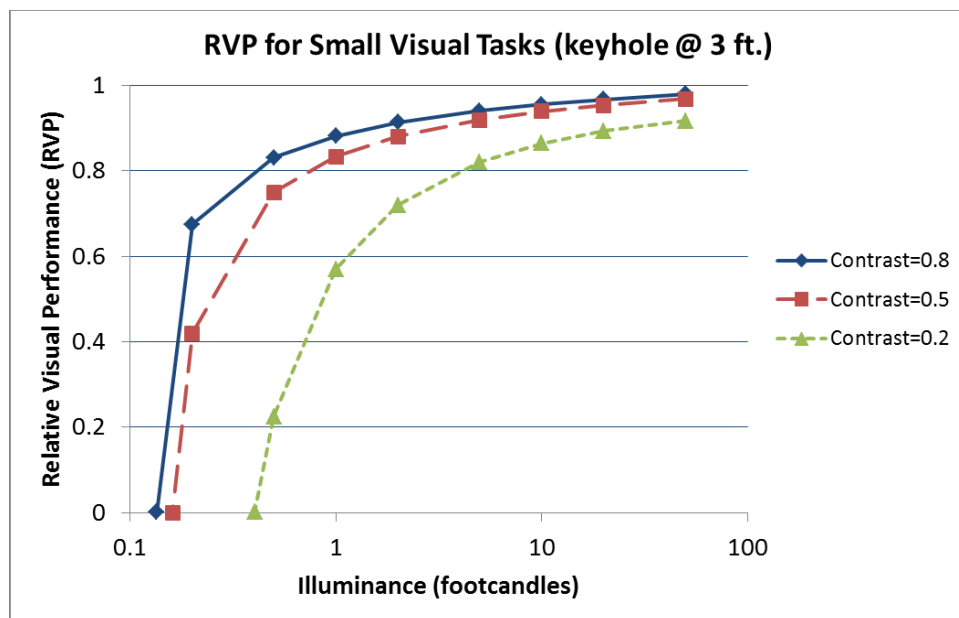


Figure 1. RVP values for a 60-year-old observer as a function of illuminance and contrast, for a small visual task.

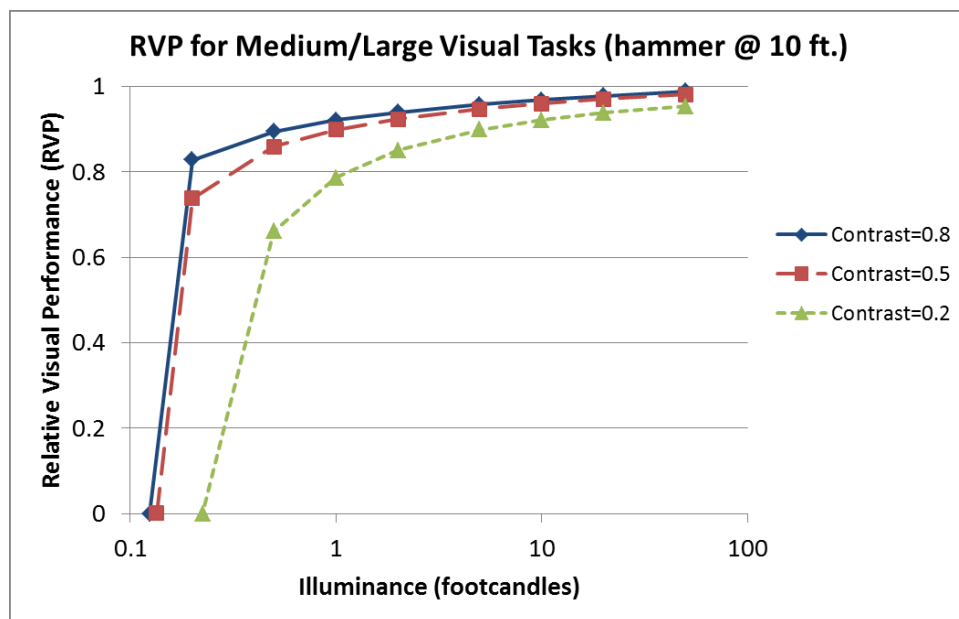


Figure 2. RVP values for a 60-year-old observer as a function of illuminance and contrast, for a medium or large visual task.

For medium- and large-sized visual tasks, such as seeing a hand tool like a hammer located on the ground from a distance of 10 feet away, Figure 2 shows the

corresponding RVP values for the same range of illuminances and contrasts as in Figure 1. Because RVP values are higher and less sensitive to changes in both light level and contrast when the visual task is larger, the differences among the visual task conditions in Figure 2 are even smaller than they are in Figure 1. (For even larger visual tasks such as detecting a moving vehicle, the differences in RVP from those illustrated in Figure 2 are negligible, so this figure also represents visual performance for large visual tasks.) An RVP value of 0.8 is reached when the illuminance exceeds approximately 0.2, 0.3 and 1 fc, for high, medium and low contrast, respectively.

Together, the analysis results in Figures 1 and 2 support previous literature indicating that for many visual tasks, illuminances of 1 fc are sufficient for ensuring high (RVP > 0.8) levels of visual performance. When small, low-contrast visual tasks need to be performed, illuminances of 3 fc will be necessary to maintain such levels of RVP.

### **Illumination System Comparison**

Work zone lighting systems can use a wide variety of light source technologies, each with different wattage ranges, luminous efficacies, operating lives, light output, lumen maintenance characteristics, color rendering capabilities, optical control characteristics, sizes, re-strike times, costs and requirements for auxiliary equipment. Table 1 summarizes the characteristics of each of these types of light sources with representative values.

At present, light emitting diode (LED) light sources are being used for a wide variety of lighting applications. These solid-state light sources are increasing rapidly in efficacy and in system life, which is heavily influenced by the thermal design of the LED system. In addition to this technological evolution, costs for LED systems are rapidly decreasing as the quantities of lighting products using this source increase in number and scale.

Table 1 – Comparison of light source characteristics for light sources that could be used for work zone lighting systems.

Lamp Type	Wattage*	Life (hours)*	Efficacy (lm/W)*	Typ. Lumens	Lumen Maint.	Color Rendering	Directional Control	Source Size	Relight Time	Auxiliary Equipment Needed	Representative Lamp Cost**	Representative Annual Operating Cost***	Representative Cost of Aux. Equipment**
Incandescent/Halogen	15 - 1,500 [150]	750 - 12,000 [1,000]	15-25 [15]	1500	2 - 5	5	4 - 5	Compact	Immediate	No	\$2	\$19	\$0
Linear Fluorescent	15 - 219 [57]	7,500 - 24,000 [20,000]	55-100 [80]	3100	2 - 5	3 - 5	2	Extended	Immediate	Yes	\$5	\$6	\$12
Compact Fluorescent	6 - 200 [35]	6,000 - 15,000 [10,000]	30-80 [60]	1800	2 - 5	3 - 5	2 - 3	Extended	Immediate	No	\$5	\$4	\$0
Induction Fluorescent	55 - 300 [128]	60,000 - 100,000 [60,000]	55-90 [75]	10,000	2 - 5	3 - 5	2	Extended	Immediate	Yes	\$200	\$20	\$200
Mercury Vapor	40 - 1,000 [200]	16,000 - 24,000 [20,000]	50-60 [50]	10,000	3	1 - 3	4	Compact	3 - 10 min.	Yes	\$25	\$23	\$50
Metal Halide	175 - 1,000 [418]	1500 - 15,000 [10,000]	80-100 [80]	32,000	3	4	4	Compact	10 - 20 min.	Yes	\$25	\$47	\$50
Metal Halide (with xenon fill)	25 - 35 [30]	1,000 - 2,000 [2,000]	60-80 [60]	1800	4	4	5	Compact	Immediate	Yes	\$50	\$53	\$100
High Pressure Sodium	70 - 1,000 [265]	24,000 [24,000]	75-140 [100]	26,000	5	2 - 4	4	Compact	< 1 min.	Yes	\$20	\$28	\$60
Low Pressure Sodium	60 - 180 [104]	18,000 [18,000]	100-180 [180]	18,000	5	1	2	Extended	Immediate	Yes	\$75	\$19	\$80
Xenon Arc Lamp	450 - 12,000 [1000]	2,000 [2,000]	30-50 [40]	40,000	4	5	5	Compact	Immediate	Yes	\$300	\$532	\$300
Plasma Lamp	100 - 5,000 [250]	10,000 - 50,000 [40,000]	80-100 [90]	22,000	3	4 - 5	4	Compact	Immediate	Yes	\$500	\$96	\$300
Light Emitting Diode****	0.5 - 20 [75]	10,000 - 100,000 [50,000]	20-200 [80]	240 [18,000]	3 - 5	3 - 5	4	Compact	Immediate	Yes	\$15	\$16	\$20
Electroluminescent Panel	0.54***** [0.54]	5,000 - 10,000 [10,000]	20 [20]	10	2 - 4	3 - 4	1	Compact	< 1 min.	Yes	\$40*****	\$8*****	\$50

Scale (Lumen Maintenance, Color Rendering, Directional Control): 1=Poor, 2=Fair, 3=Average, 4=Good, 5=Excellent

\*Representative values in brackets.

\*\*From searches on bulbs.com, amazon.com, shopping.google.com.

\*\*\*Based on 1000 hours/year, energy cost of \$0.10/kWh, and including lamp replacement at end of life.

\*\*\*\*High powered LEDs. Wattage range and typical lumen value is per LED; typical wattage and lumen value in brackets are for a 75-W array of LEDs.

\*\*\*\*\*Per square foot.



## **Floodlights**

Presently, trailer mounted floodlights (Figure 3) are among the most commonly used lighting systems for work zone illumination. Generally the trailers on which they are mounted contain large generators and for this reason these floodlights typically use relatively high wattages (1000 or 1500 W) metal halide light sources, although trailer-mounted floodlights using LED sources (typically with wattages from 50-300 W) are beginning to be used. Multiple floodlight units are usually used and angled in different directions to maximize the coverage of light in the work zone.



Figure 3. Trailer-mounted floodlight for work zone illumination.

When properly aimed they can illuminate large coverage areas to relatively high light levels, but these lights are challenging to keep in proper orientation and can create high levels of discomfort and disability glare to workers and drivers. Costs for these units are on the order of several thousand dollars. A typical fuel interval for the generators with these types of lights is 60 hours.

Set-up and take-down times for these lights can be substantial when there are multiple light towers used for a project. Table 2 summarizes cost and energy use information for a work zone lighting installation using trailer-mounted floodlights.

Several agencies have explored the use of semi-permanent high-mast floodlights for use in long-duration projects. Because these systems are installed on poles for the duration of a long-term roadway construction or reconstruction project, once they are installed there is no need to set-up or take them down. By using high mounting heights (typically 50 to 70 feet) these systems can provide uniform, high levels of illumination and tend to have reduced discomfort and disability glare because they remove the light source from the drivers' and workers' lines of sight.

Table 2 – Operational and energy costs associated with work zone lighting using trailer-mounted floodlights.

<b>Daily setup and removal cost</b>	
Number of crew members in charge of setup and removal	10
removal	
Estimated number of hours to set up and remove light towers, per night	3
Total worker hours per night	30
Estimated cost per hour (base rate + benefits + overhead and profit)	\$40
Total setup and removal cost per night	\$1,200
<b>Daily operational cost</b>	
Hourly operational cost per light tower (fuel, oil, regular maintenance, etc.)	\$3.60
Estimated daily cost per light tower (@ 6 h per night)	\$21.60
Daily rental cost (@ \$990 per month rent)	\$33
Total operational cost per night (assuming contractor owns 100 towers and rents 20)	\$3,252
Total cost per night (setup, removal, and operation)	\$4,452
Estimated duration of project in days	275
Total cost to provide lighting with 120 portable light towers	\$1,224,300

Despite the advantages of semi-permanent installations of lighting, such systems can be relatively expensive. A primary potential advantage is the impact that the drastically reduced set-up and take-down times can have on the duration of a project, compared to the use of trailer-mounted lights that need to be set up and taken down at the start and end of each nighttime work period. It is estimated that a project's duration could be reduced by more than 15% with this approach to work zone illumination. Table 3 summarizes the operational and energy costs associated with a semi-permanent high-mast work zone lighting installation for a project comparable in scope to the example used to create Table 2.

Table 3 – Operational and energy costs associated with work zone lighting using semi-permanent high-mast illumination.

Number of high-mast poles installed	108
Number of 250-kW generators installed	5
Installation costs	
Estimated installation cost per pole	\$2,844
Estimated installation cost per kW of generator capacity	\$24.50
Total estimated installation costs (poles and generators)	\$337,777
Lighting equipment rental	
Estimated rental cost per pole with four luminaires	\$5,500
Total lighting equipment rental (for the duration of the project)	\$594,000
Generation costs	
Estimated purchase cost per kW of generator capacity	\$200
Estimated total generator purchase cost	\$250,000
Operational cost	
Hourly operational cost per generator @ 55% load (fuel, oil, regular maintenance)	\$25.83
Total operational cost per night (@ 8 h per night)	\$1,033.20
Estimated duration of project in days	235
Estimated total operational cost over the length of the project	\$242,802
Total cost to provide lighting with 108 high-mast poles	\$1,424,579

Vehicle mounted floodlight units also exist. These are designed to illuminate from above, in contrast to vehicle headlights, which primarily illuminate in the horizontal direction and consequently can contribute to substantial levels of glare. A review of existing products showed that these can use halogen, metal halide or LED light sources, with wattages between 30 and 1500 W. Prices ranged from several hundred to nearly two thousand dollars.

### **Balloon Lights**

To counteract the glare from floodlights, especially from trailer-mounted floodlights, agencies performing nighttime roadway construction have been increasingly using balloon lights, in which a fabric covering surrounding a light source is used to diffuse the light and produce softer more uniform illumination in all directions around the light. The upper half of the balloons, which are usually mounted to foldable frames, often contains a reflective opaque coating that directs upward light emitted by the source inside downward, toward the road surface. See Figure 4.



Figure 4. Trailer-mounted balloon light.

Because of the more diffused light output, balloon lighting systems are used when illumination of an overall area is desired, rather than a specific controlled location. They tend to reduce the contrast of shadows in the illuminated area. While balloon lights have comparable light outputs to trailer-mounted lights, containing halogen, metal halide or LED light sources up to 2000 W in power, the resulting light levels that are produced are lower and tend to be distributed in a larger area. The direct luminance of balloon lights is substantially lower than that of floodlights, because of the fabric covering, which results in an extended visible source size. Measured luminances of balloon lights ranged from about 3000 cd/m<sup>2</sup> to 20,000 cd/m<sup>2</sup>, in comparison to luminances in excess of 100,000 cd/m<sup>2</sup> for a conventional trailer-mounted floodlight.

One potential advantage of balloon lights is that once set up, there is no further aiming that is necessary because the distributions is not sensitive to the rotation of the light. This contrasts with the directional distribution of floodlights, which are highly sensitive to different aiming angles. Balloon lighting systems typically cost several thousand dollars.

Technical information for eight different balloon lights from three manufacturers (MoonGlo, Airstar, and Powermoon) was collected regarding the illuminance (in

footcandles) on the ground at several distances (in feet) from each balloon light. The mounting heights for these data were specific for each product (between 8 and 33 feet); in addition, each product produced a different amount of light (between 6000 and 400,000 lumens). To compare the balloon lights, their distributions were scaled as if each light produced 100,000 lumens and was mounted at a height of 12 feet above the ground.

When the scaled illuminances were plotted as a function of the distance from the lamp, the light level data were quite consistent (Figure 5) among the balloon lights. The best-fitting empirical expression relating light level ( $E$ , in footcandles) to distance ( $D$ , in feet), for a balloon light scaled to produce a light output of 100,000 lumens and mounted 12 feet from the ground, was:

$$E = \frac{100}{\frac{D^2}{72} + 1} \quad (\text{Equation 1})$$

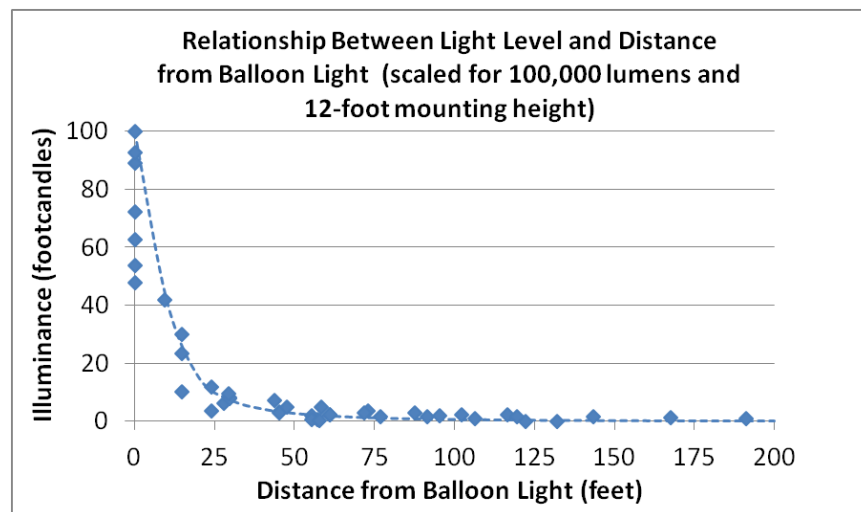


Figure 5. Relationship between light level (in footcandles) from balloon lights and distance (in feet), for balloon lights from several manufacturers, scaled to produce 100,000 lumens and mounted 12 feet above the ground.

Vehicle mounted balloon lights are also available for mounting on paving, milling and other work equipment and vehicles. These include high-wattage lights similar in design to those mounted to trailers, but also include lower-wattage lights (a representative halogen balloon light source uses about 200 W). Such systems are used when it is impractical to illuminate a large area being paved, for example. The equipment-mounted light ensures that there is sufficient illumination in front of such equipment.

## TECHNICAL ANALYSIS OF SIGNAGE, MARKING AND DELINEATION MATERIALS

Signage, marking and delineation elements in the work zone include retroreflective informational signs, typically with orange background and black letters, as well as delineating elements such as barricades and barrels. Barricade and barrel sheeting is also designed to be retroreflective to enhance visibility from a distance.

### Sign Materials

A review of commercially available sign sheeting materials used for work zone signage indicated that the most commonly use sheeting material for orange signs in work zones is American Society for Testing and Materials (ASTM) Type III sheeting, also known as high intensity sheeting. Other types that have been considered for work zone signing are ASTM Type IV (high intensity prismatic sheeting) and ASTM Type XI (full cube prismatic sheeting). Each of these sheeting types differ in the amount and distribution of reflected light. Performance specifications for these materials indicate the minimum retroreflectivity for several geometric conditions of incident light from vehicle headlamps and different reflection angles where drivers' eyes might be located.

In order to compare the impacts of using different sign sheeting materials, the minimum luminance of the sign sheeting was determined from the ASTM performance specifications, and in turn these luminances were used to calculate visual performance values for a 60-year-old driver viewing the sign (with 8-inch letters) from various distances. It was assumed for this comparison that the sign height was 5 feet and the sign was located along the right-hand edge of the driving lane, and that the illumination source was a pair of low-beam headlights. In addition it was assumed that the transmission of the vehicle windshield was 0.8, allowing 80% of light to pass through it.

Figure 6 shows the minimum luminance of Type III orange sheeting material under low-beam illumination. It should be noted that these analyses are based on the *minimum* performance specifications for each ASTM type and that the luminance of any particular material in practice could be substantially higher; this analyses considers the minimum floor for performance below which a material should not fall. Note that while the data in Figure 6 do not include values for viewing distances below 200 feet, a sign would still be expected to have some luminance at distances below 200 feet, but the ASTM performance specification simply does not specify the reflected light at larger angles associated with this particular viewing geometry.

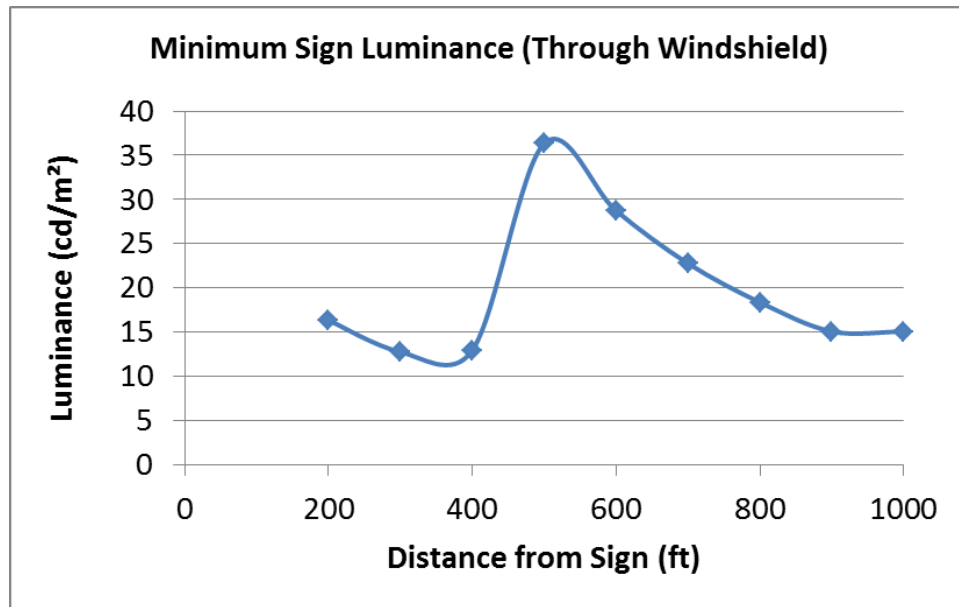


Figure 6. Minimum luminance of ASTM Type III orange sign sheeting under low beam illumination for viewing distances between 200 and 1000 feet from the sign.

Figure 7 shows the relative visual performance (RVP) for a 60-year old driver for the same ASTM Type III sign with the minimum luminances illustrated in Figure 6, with 8-inch letters having a luminance contrast of 0.8. It can be seen that RVP values change very little as a function of luminance at the intermediate distances between 200 and 600 feet, but RVP values drop off rapidly after a distance of 700 to 800 feet. Largely, this is caused by the relatively small size of the 8-inch letters viewed at these distances.

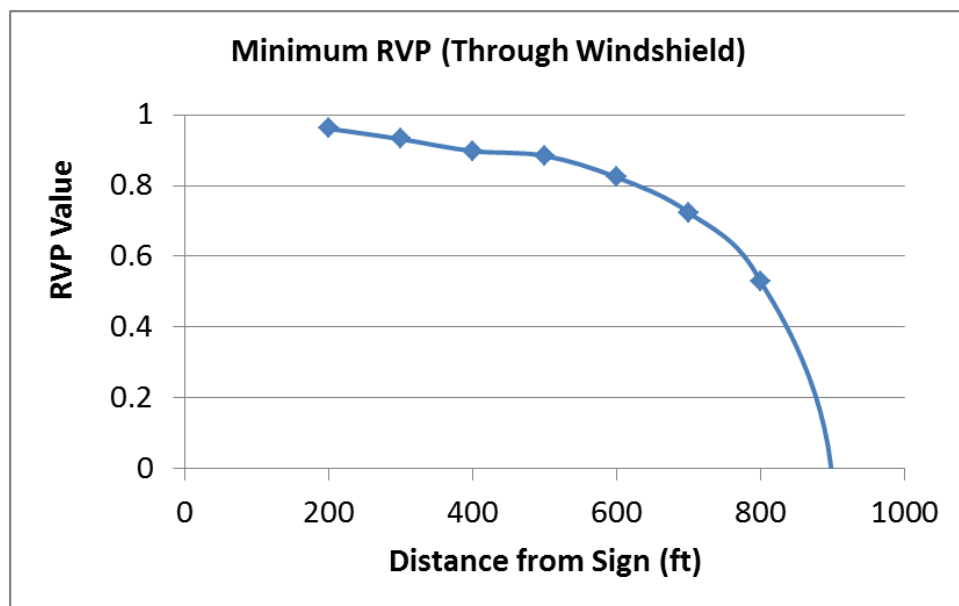


Figure 7. Minimum RVP values for ASTM Type III orange signs under low beam illumination for viewing distances between 200 and 1000 feet from the sign.

The ASTM specifications for retroreflective sign sheeting materials are for new, clean materials, but sheetings used in work zones may experience degradation caused by aging, dirt or damage. In order to assess the impacts of a 30% reduction in retroreflectivity, RVP calculations for the same scenario as above were performed with a corresponding 30% reduction in luminance of the sheeting material. Figure 8 shows the resulting RVP values. A comparison of Figures 7 and 8 indicates that the impact of a reduction in luminance is relatively small compared to the impacts of distance and size at the longer viewing distances (800 feet or greater).

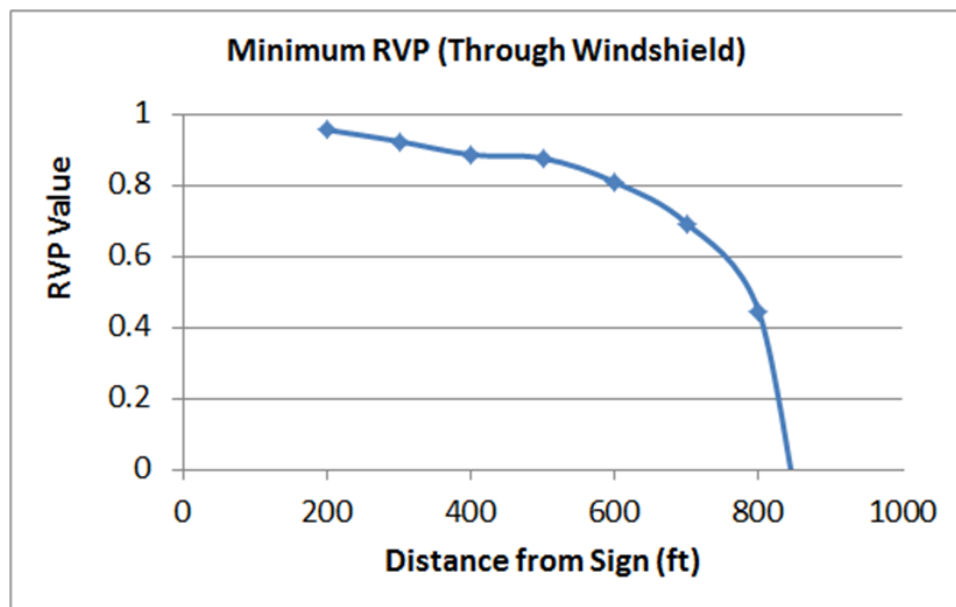


Figure 8. Minimum RVP values for ASTM Type III orange signs under low beam illumination for viewing distances between 200 and 1000 feet from the sign, assuming 30% degradation in sheeting retroreflectivity.

Figures 9 and 10 illustrate the minimum luminance and minimum RVP values for the same scenario but using ASTM Type IV sign sheeting material. Although the luminances for the higher ASTM type are higher, the RVP values differ by much less, maintaining RVP values of 0.8 at distances slightly longer than 600 feet from the sign. A 30% reduction in sheeting retroreflectivity (Figure 11) again had little impact on RVP values compared to distance and size.



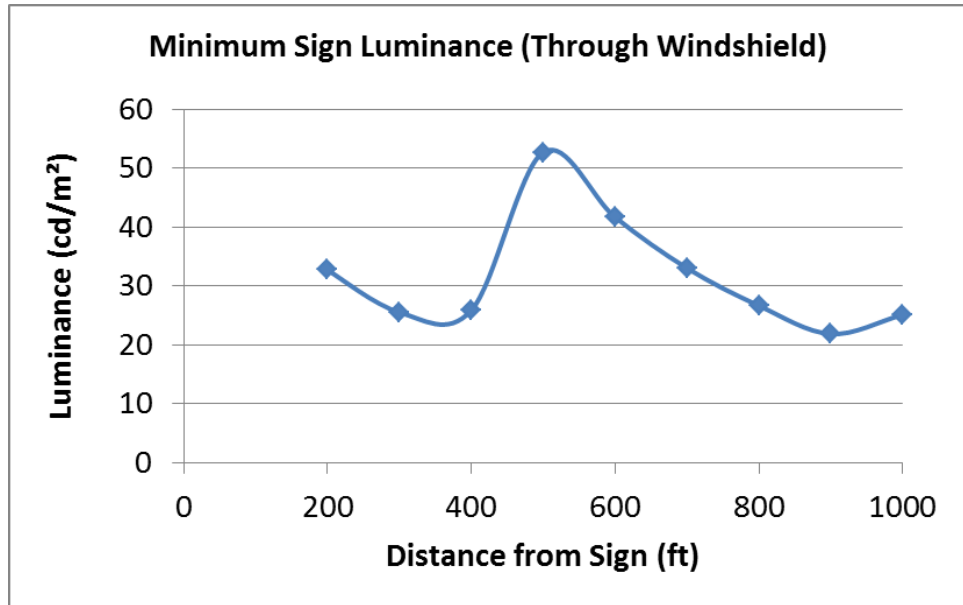


Figure 9. Minimum luminance of ASTM Type IV orange sign sheeting under low beam illumination for viewing distances between 200 and 1000 feet from the sign.

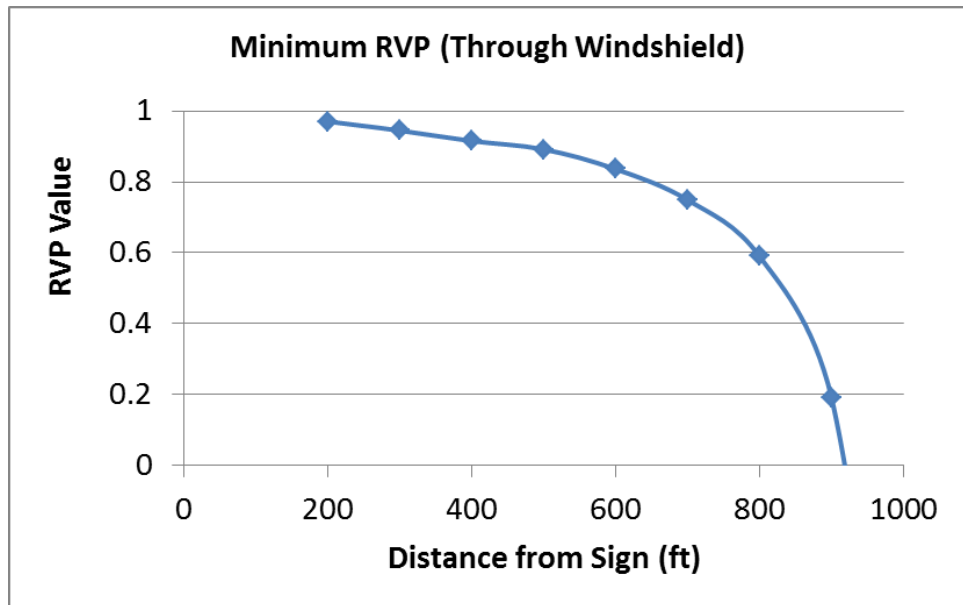


Figure 10. Minimum RVP values for ASTM Type IV orange signs under low beam illumination for viewing distances between 200 and 1000 feet from the sign.

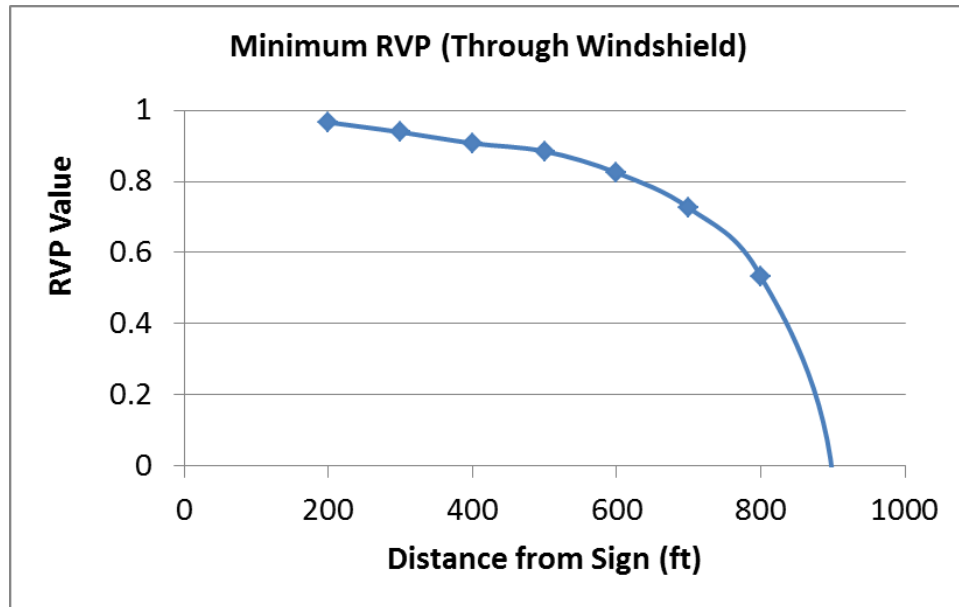


Figure 11. Minimum RVP values for ASTM Type IV orange signs under low beam illumination for viewing distances between 200 and 1000 feet from the sign, assuming 30% degradation in sheeting retroreflectivity.

Figures 12 and 13 illustrate the minimum luminance and minimum RVP values for this scenario with ASTM Type XI sign sheeting material. The minimum luminances for the ASTM Type XI material are even higher than for Type IV, but the RVP values still differ by relatively little, maintaining RVP values of 0.8 at distances slightly less than 600 feet from the sign. It can also be seen that a minimum luminance value (and thus, a minimum RVP value) can be calculated for this sheeting material at a distance of 100 feet from the vehicle; this is because the performance specification for ASTM Type XI material includes larger angles for retroreflection geometry than the other material types. Figure 14 shows the impact of a 30% reduction in retroreflectivity on RVP.

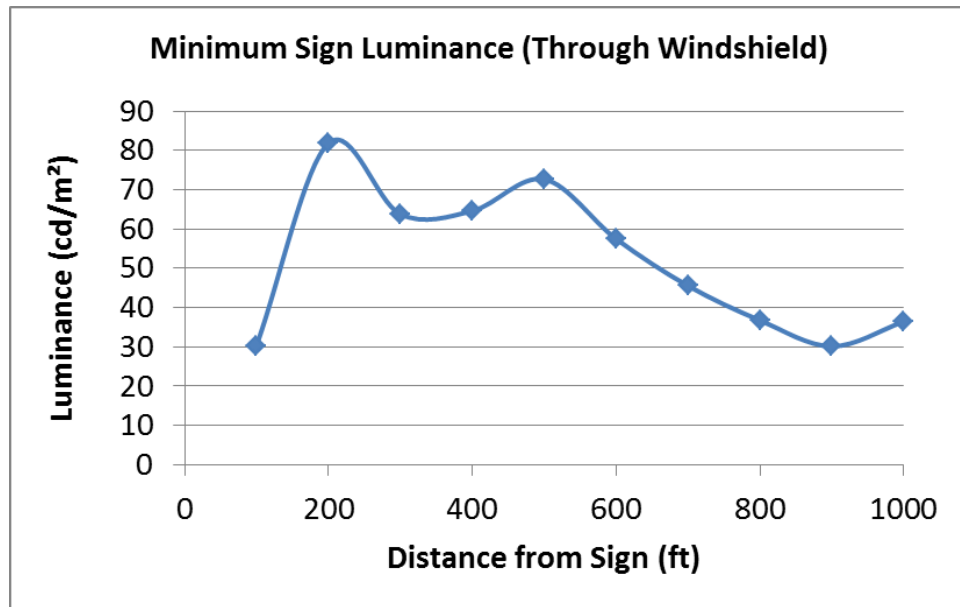


Figure 12. Minimum luminance of ASTM Type XI orange sign sheeting under low beam illumination for viewing distances between 100 and 1000 feet from the sign.

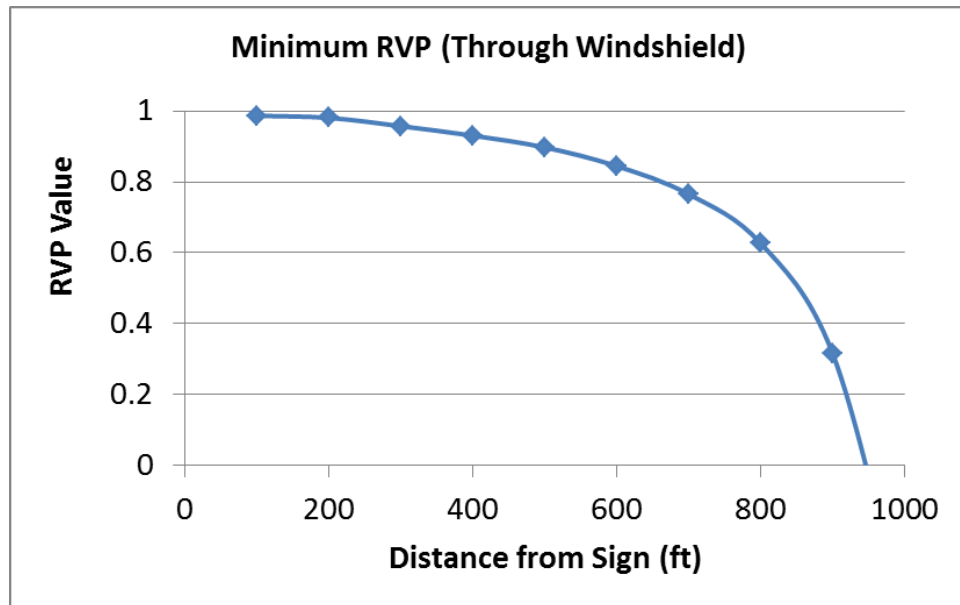


Figure 13. Minimum RVP values for ASTM Type XI orange signs under low beam illumination for viewing distances between 100 and 1000 feet from the sign.

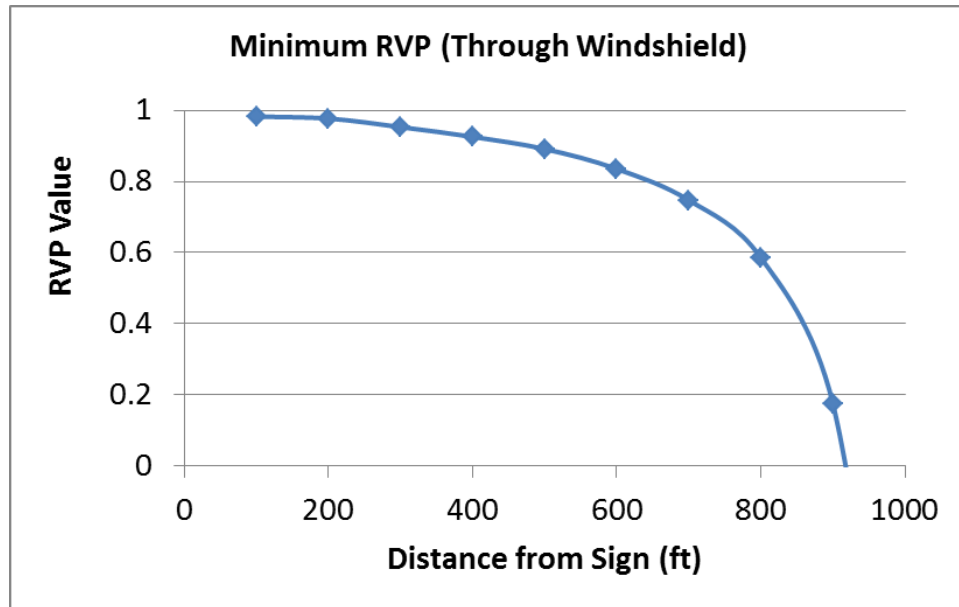


Figure 14. Minimum RVP values for ASTM Type XI orange signs under low beam illumination for viewing distances between 200 and 1000 feet from the sign, assuming 30% degradation in sheeting retroreflectivity.

Overall, these analyses emphasize that while different ASTM material types can result in very substantial differences in the luminance of the sign as viewed by an approaching driver, these luminance differences can have relatively little influence on visual performance (e.g., legibility of the information on the sign). This is generally because the luminance of high-contrast text such as that on a sign does not play a large role in influencing visual performance once the luminance is at least 10 cd/m<sup>2</sup>, as it is for all of the ASTM material types analyzed here (even when degradation of retroreflectivity is considered).

## Barricades

Barricades are used to indicate to drivers or pedestrians, locations that should be avoided. These devices used white and orange stripes slanted in the direction of the desired change in route, if necessary. Typically, retroreflective sheeting materials on barricades are ASTM Type I, but Type XI sheeting materials are also available for producing higher luminances.

Figure 15 shows the minimum luminance for the orange portion of a barricade panel located directly ahead of a vehicle and 3 feet above the ground, under low beam illumination as a vehicle approaches the barricade. Figure 16 shows the corresponding minimum RVP values under the same scenario, and Figure 17 shows RVP values when the sheeting retroreflectivity is reduced by 30%.

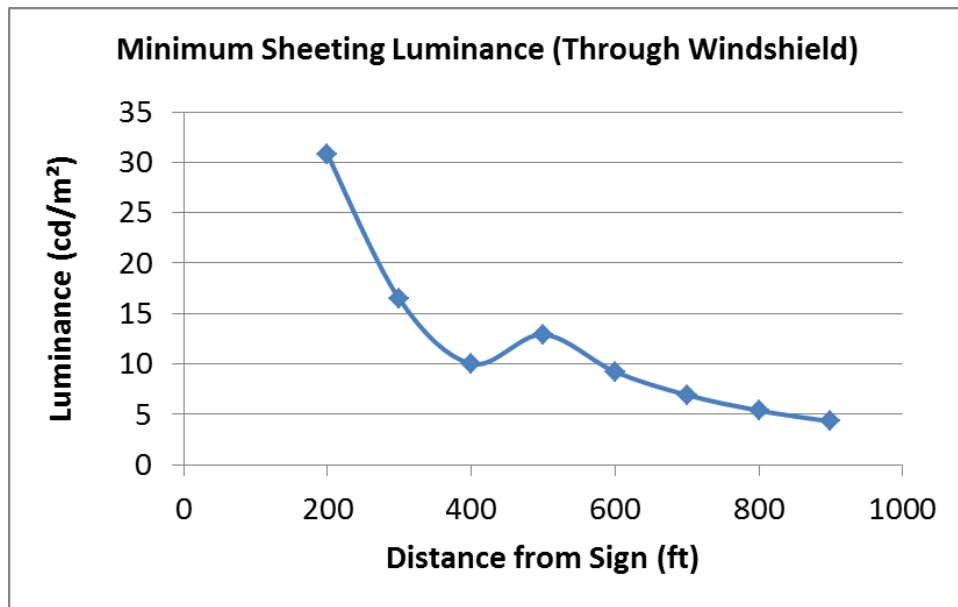


Figure 15. Minimum luminance of ASTM Type I orange barricade sheeting under low beam illumination for viewing distances between 200 and 1000 feet from the barricade.

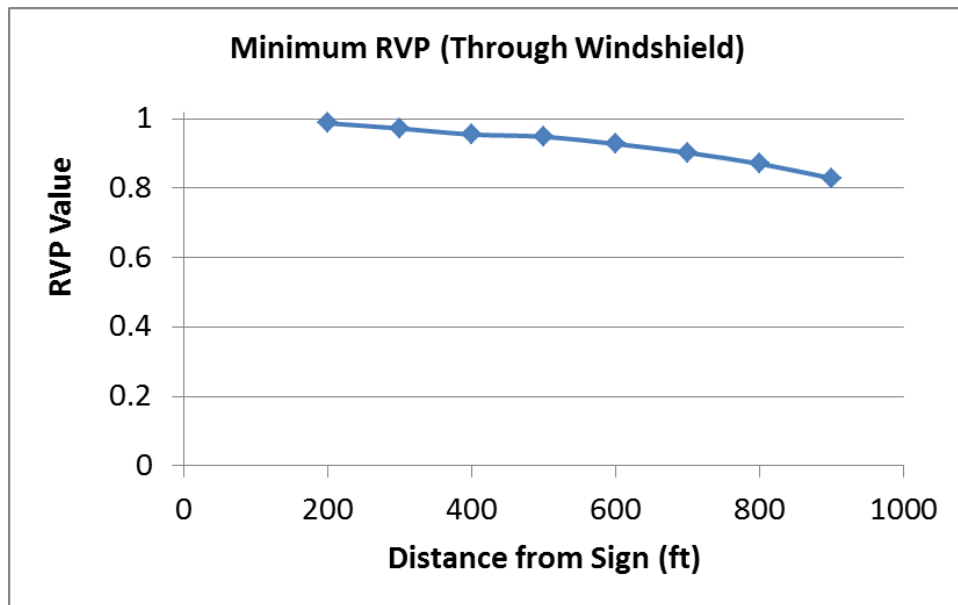


Figure 16. Minimum RVP values for ASTM Type I orange barricade sheeting under low beam illumination for viewing distances between 200 and 1000 feet from the barricade.

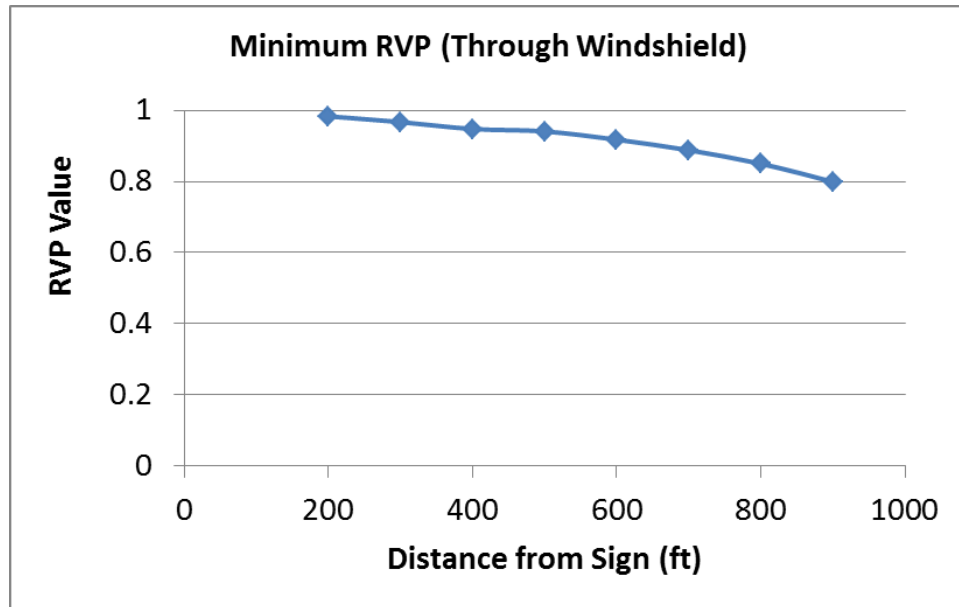


Figure 17. Minimum RVP values for ASTM Type I orange barricade sheeting under low beam illumination for viewing distances between 200 and 1000 feet from the barricade, assuming 30% degradation in sheeting retroreflectivity.

While the minimum luminance of the barricade sheeting material increases as the distance to the barricade decreases, the changes in relative visual performance are much smaller and the barricade maintains a minimum RVP value of at least 0.8 throughout the range above 200 feet away from the barricade.

Figures 18 and 19 illustrate the same information as Figures 15 and 16, but with ASTM Type XI orange sheeting material rather than ASTM Type I. The minimum luminances for the ASTM Type XI material are approximately an order of magnitude higher than for the ASTM Type I material. Again, however, the differences in visual performance are substantially smaller. Additionally, a 30% reduction in sheeting retroreflectivity (Figure 20) had relatively little impact on RVP.

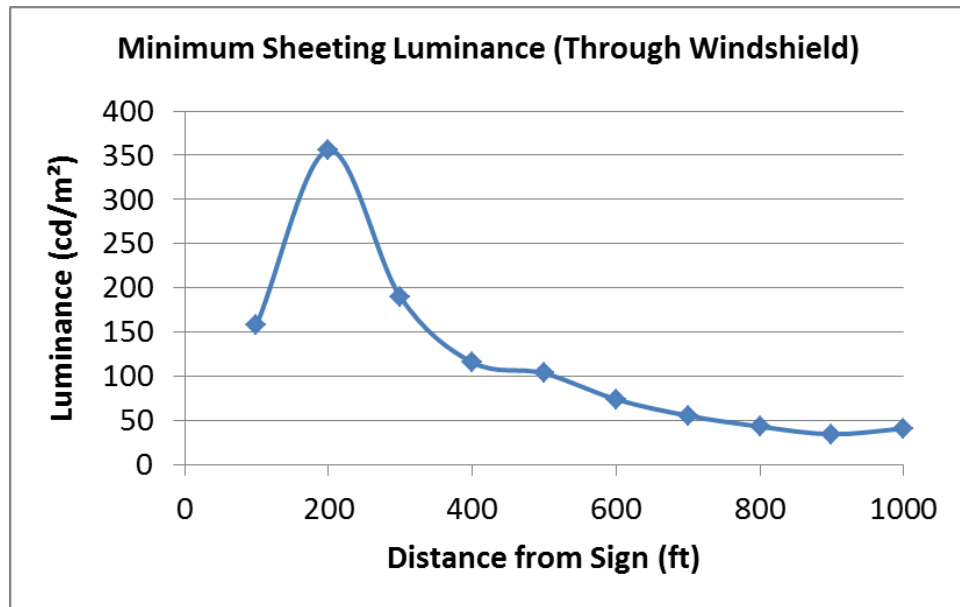


Figure 18. Minimum luminance of ASTM Type XI orange barricade sheeting under low beam illumination for viewing distances between 100 and 1000 feet from the barricade.

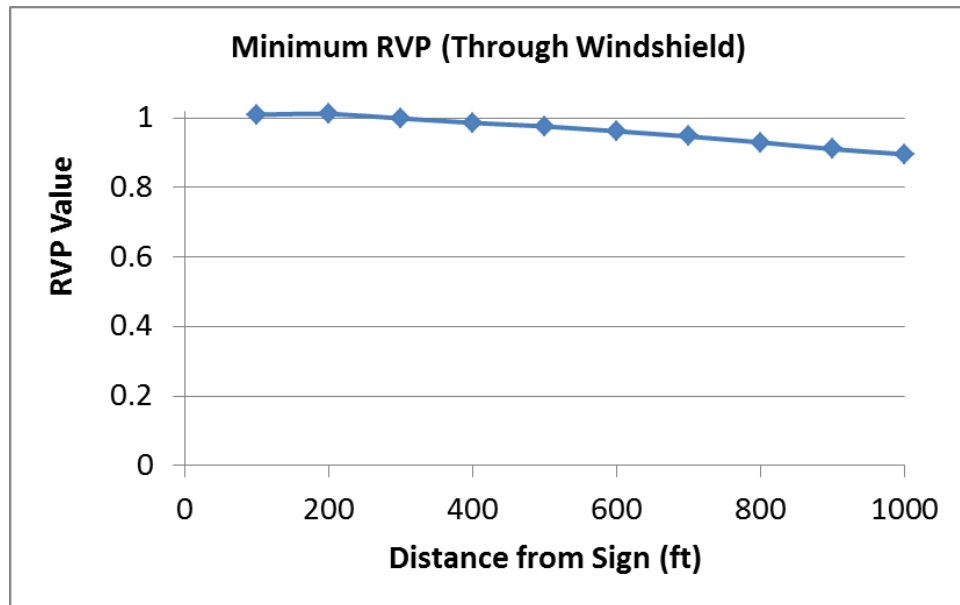


Figure 19. Minimum RVP values for ASTM Type XI orange barricade sheeting under low beam illumination for viewing distances between 100 and 1000 feet from the barricade.

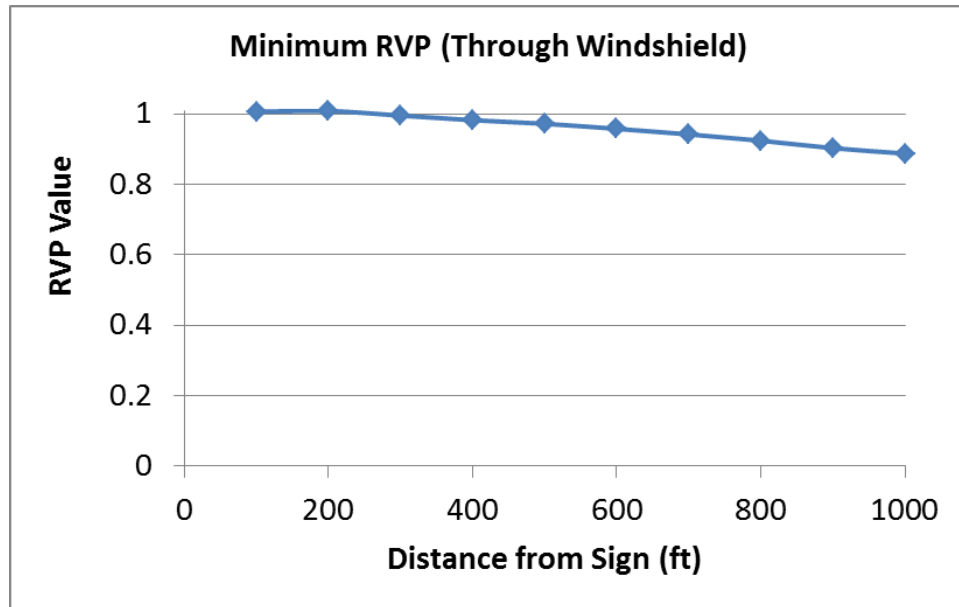


Figure 20. Minimum RVP values for ASTM Type XI orange barricade sheeting under low beam illumination for viewing distances between 100 and 1000 feet from the barricade, assuming 30% degradation in sheeting retroreflectivity.

## Barrels

Traffic barrels and drums used to delineate work zones and features such as lane change tapers are typically wrapped in concentric rings of orange and white retroreflective sheeting material, usually ASTM Type I (engineering grade). Materials using ASTM Type IV (prismatic) sheeting are also sometimes used to produce higher luminances.

The minimum luminance profile of the white wrapping material using ASTM Type I material is shown in Figure 21, and the corresponding minimum RVP profile is shown in Figure 22 (Figure 23 shows RVP for a 30% reduction in sheeting retroreflectivity). In these analyses it is assumed that the barrel is located to the left of the driving lane, on the ground.



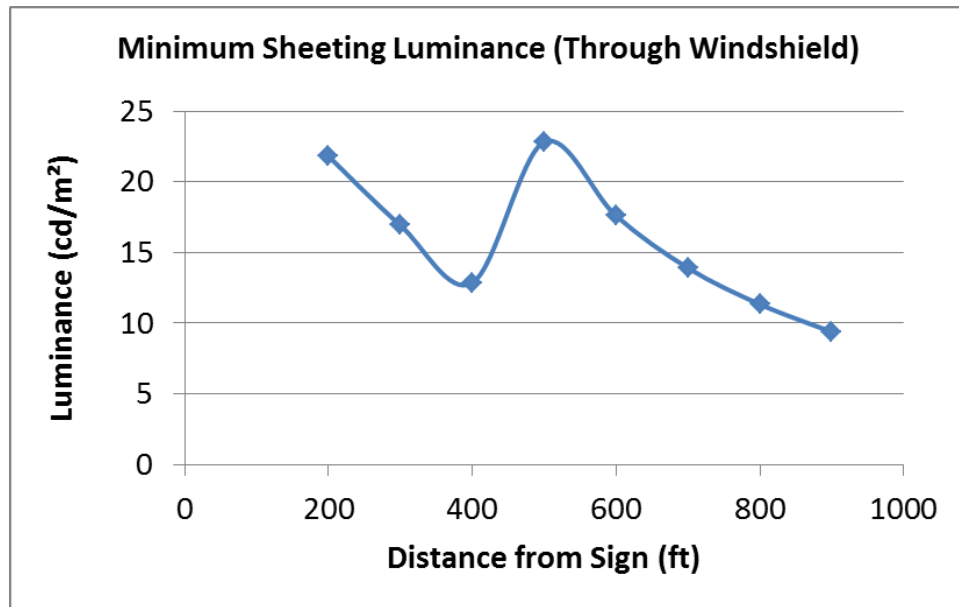


Figure 21. Minimum luminance of ASTM Type I white barrel wrap under low beam illumination for viewing distances between 200 and 1000 feet from the barrel.

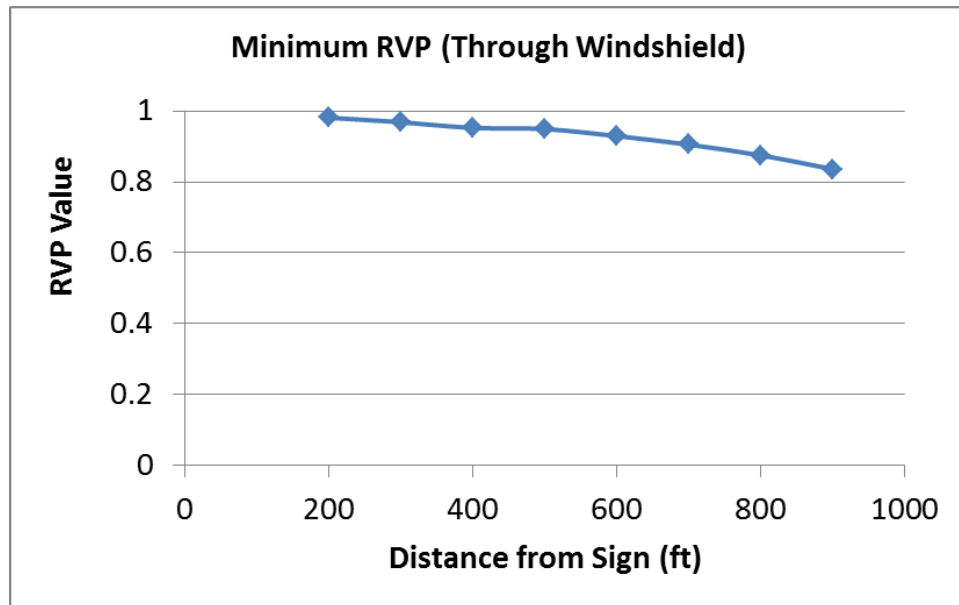


Figure 22. Minimum RVP values for ASTM Type I white barrel wrap under low beam illumination for viewing distances between 200 and 1000 feet from the barrel.

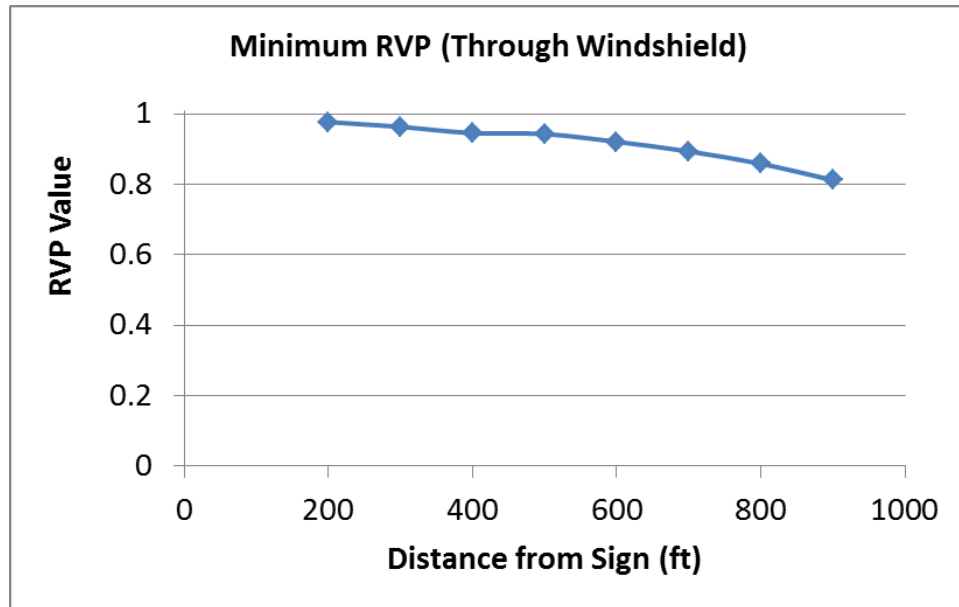


Figure 23. Minimum RVP values for ASTM Type I white barrel wrap under low beam illumination for viewing distances between 200 and 1000 feet from the barrel, assuming 30% degradation in sheeting retroreflectivity.

Figures 24, 25 and 26 show the same information as Figures 21, 22 and 23, respectively, but with ASTM Type IV sheeting material for the barrel wrap.

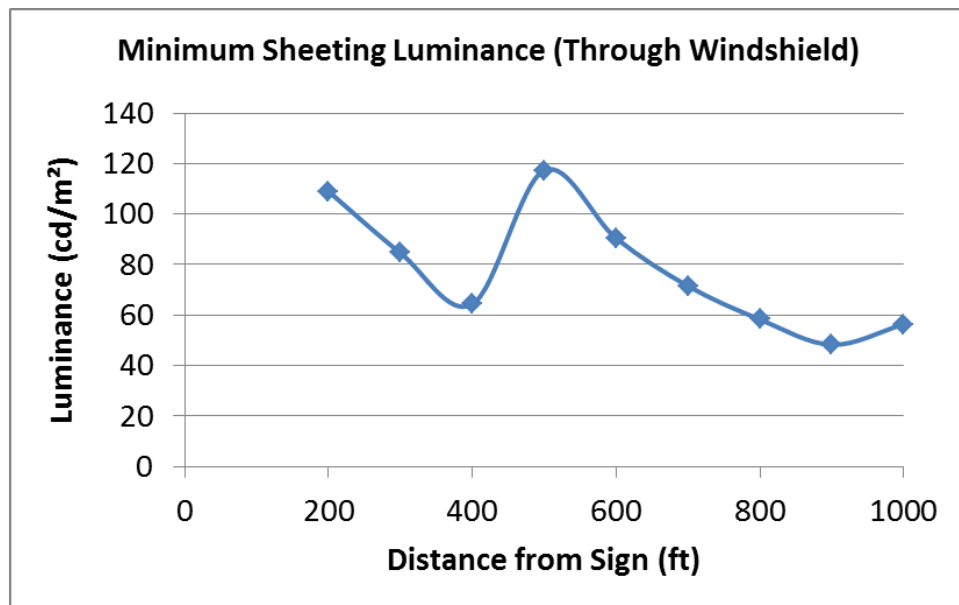


Figure 24. Minimum luminance of ASTM Type IV white barrel wrap under low beam illumination for viewing distances between 200 and 1000 feet from the barrel.

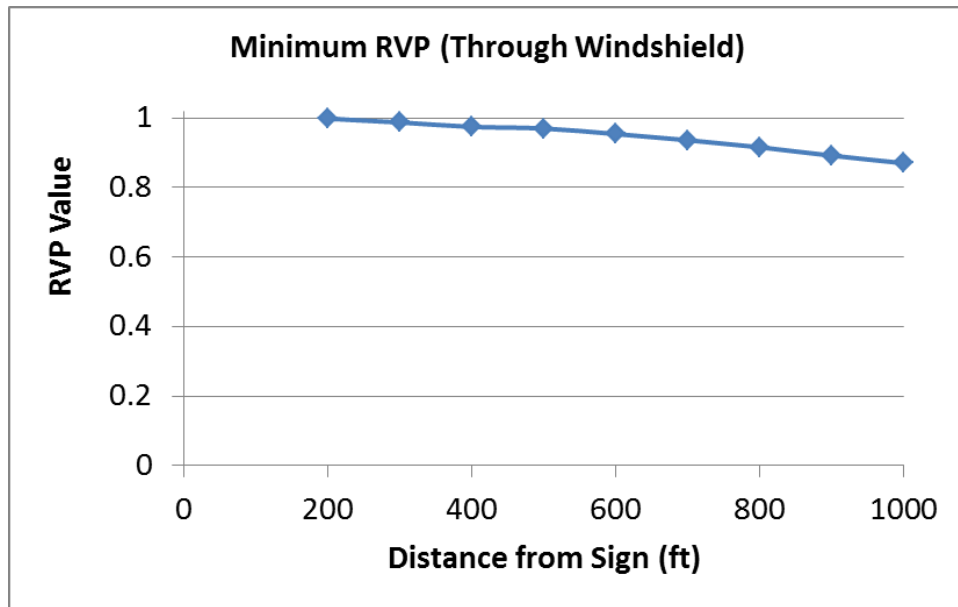


Figure 25. Minimum RVP values for ASTM Type IV white barrel wrap under low beam illumination for viewing distances between 200 and 1000 feet from the barrel.

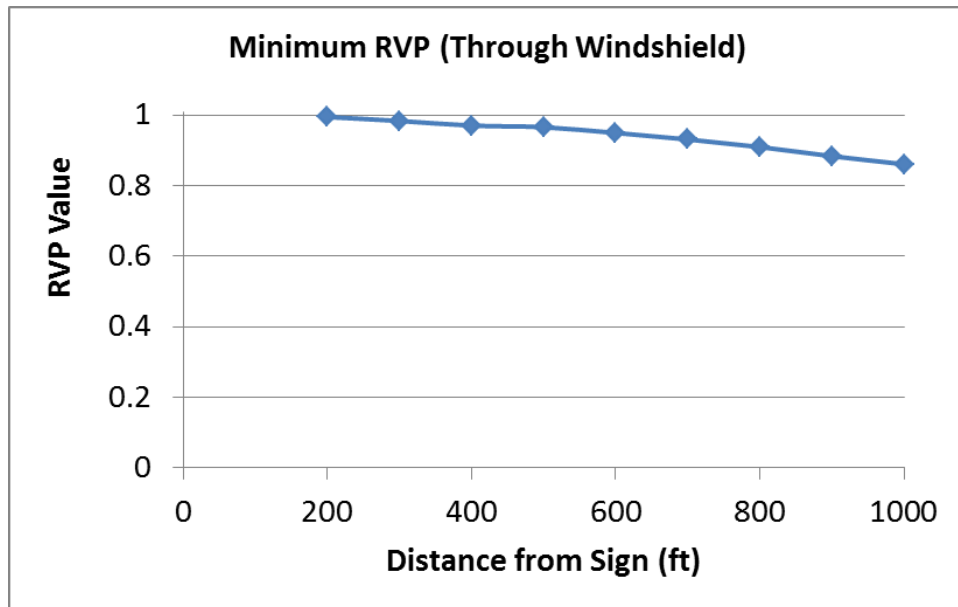


Figure 26. Minimum RVP values for ASTM Type IV white barrel wrap under low beam illumination for viewing distances between 200 and 1000 feet from the barrel, assuming 30% degradation in sheeting retroreflectivity.

## TECHNICAL ANALYSIS OF WARNING LIGHTS

Warning lights are used in work zones in a number of locations – on trucks and maintenance equipment, on traffic drums, on other delineators and barricades. Usually, these lights are yellow in color, although other colors have been investigated, such as green lights for snow plows used by the Ohio Department of Transportation,<sup>(19)</sup> and more recently, on a single test truck in New Jersey.

### Luminous Intensity Requirements

Several studies, as well as standards have addressed the luminous intensity of warning lights used as beacons on maintenance trucks and equipment. Standards for the performance of these beacons from the Society of Automotive Engineers (e.g., Standard J595) stipulate a minimum value for the peak luminous intensity of 600 cd regardless of whether the beacon is used during daytime or nighttime. Figure 27 shows response time data from a study of the detection of a yellow flashing light (50% duty cycle) varying in peak intensity from 80 to 530 cd against a daytime background scene or a nighttime background scene, when the location of the warning beacon was adjacent to the observer's line of sight.<sup>(20)</sup> It can be seen that the response times are all short regardless of the peak intensity of the warning light.

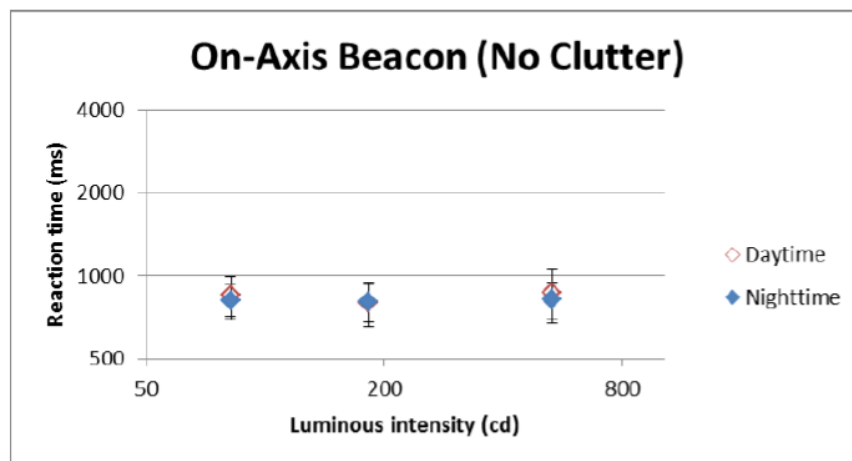


Figure 27. Response times to warning lights varying in peak intensity when viewed on-axis, against a daytime and a nighttime visual scene.

When the same warning lights were viewed 5° off-axis from the viewers' line of sight, the response times increase, and for the lowest peak intensities, were substantially longer than for the higher intensities (Figure 28) for lights viewed against a daytime background scene, but not at night.

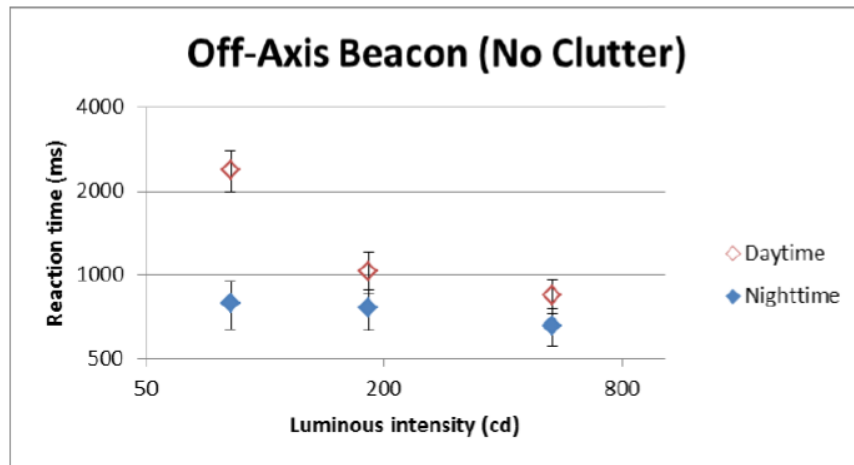


Figure 28. Response times to warning lights varying in peak intensity when viewed 5° off-axis, against a daytime and a nighttime visual scene.

The response times shown in Figures 27 and 28 were measured for roadway scenes that were relatively simple, with very little visual clutter present, such as might be encountered in a rural location. Figures 29 and 30 show corresponding response times for scenes in which competing flashing lights and blinking elements were present; it can be seen that even when viewed on-axis, response times to the lower-intensity warning lights against a daytime scene were increased.

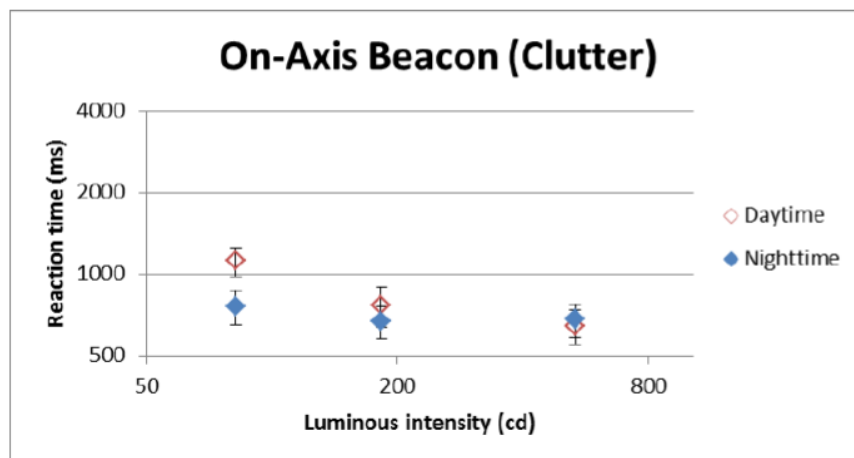


Figure 29. Response times to warning lights varying in peak intensity when viewed on-axis, against a daytime and a nighttime visual scene with clutter present.

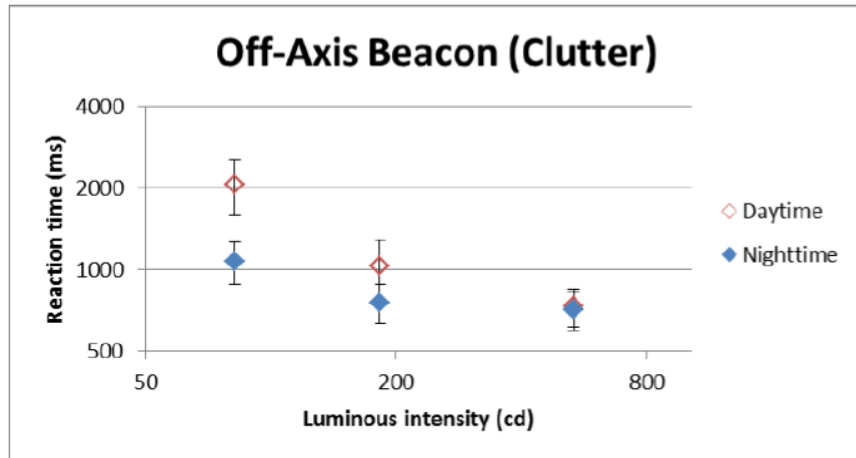


Figure 30. Response times to warning lights varying in peak intensity when viewed 5° off-axis, against a daytime and a nighttime visual scene with clutter present.

In general, the data in Figures 27 through 30 support the requirement for a minimum peak intensity of 600 cd for daytime viewing conditions, but suggest that for nighttime conditions, a peak intensity of only 200 cd might be needed to ensure short response times. These values can be converted to effective intensities,<sup>(21)</sup> which are an estimate of the steady-burning light intensity that has the same visual effectiveness as a flashing light. A flashing light with a duty cycle of 50% and a peak intensity of 600 cd has an effective intensity of approximately 430 cd; one with a peak intensity of 200 cd has an effective intensity of 140 cd.

Vehicle warning beacons can use halogen sources (about 60 W in rotating beacons) or LED sources (using only 6 W). Costs for halogen rotating beacons are approximately \$100/beacon, and for LED units are about \$200/beacon.<sup>(22)</sup>

As stated above, some warning lights are not used as vehicle beacons, but rather as delineating devices in work zones. Usually these are used in groups of lights rather than one or two lights on each vehicle, where only a single vehicle might be seen in isolation. There have also been studies to assess the intensity requirements for these types of warning lights, such as barricade lights. Bullough et al.<sup>(23)</sup> asked observers to judge the brightness of Type A (flashing – low intensity), Type B (flashing – high intensity) and Type C (steady – low intensity) barricade lights. Type B lights with an effective intensity of 35 cd (effective intensity is an estimation of a steady-burning intensity value with the same visual effectiveness as a flashing light; for an effective intensity of 35 cd, the barricade light had a peak intensity of 50 cd) were judged as suitable for brightly lighted areas, and would be too bright for dark areas. Type A lights (effective intensity 4 cd; peak intensity 6 cd) were judged as suitable for dark, unlighted areas but not lighted

areas. Type C steady lights with a luminous intensity of 2 cd were also judged as suitable for dark, but not lighted, areas (see Figure 31).

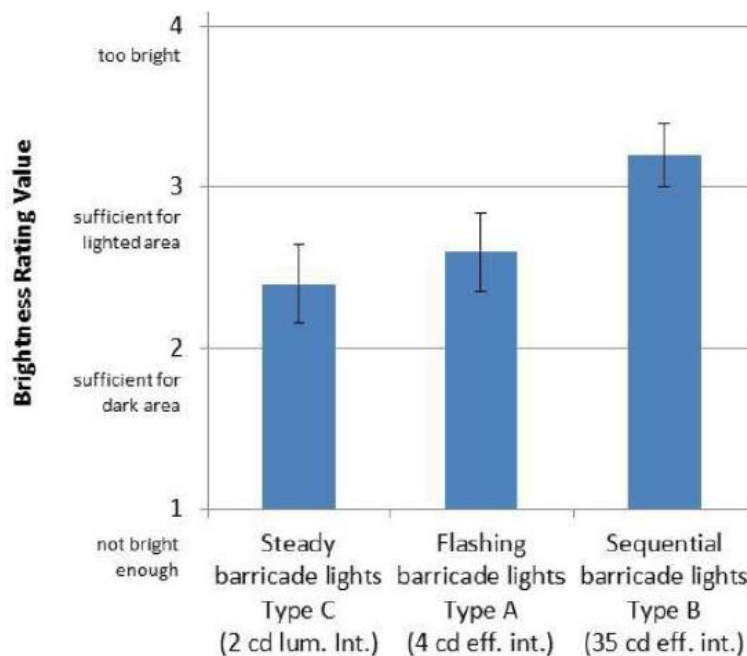


Figure 31. Brightness ratings for Type A, B and C barricade lights.

## Temporal Flashing Patterns

A number of studies have investigated the coordination of flashing warning lights when used for delineation (e.g., barricade lights) in situations such as lane closures, when the lights could be used in sequential formation, for example, to communicate to drivers that they should change lanes, and in which direction they should do so. Bullough et al.<sup>(23)</sup> asked observers to evaluate the informational clarity of barricade lights. Figure 32 shows the average ratings of informational clarity to roadway scenes with randomly flashing barricade lights (the default condition currently), to synchronized flashing lights where all lights flash in unison, and to sequential flashing lights where the sequence and order of the flashing indicate a direction.

Another aspect of temporal flashing patterns that can have relevance to work zone safety is the amount of modulation. When lights flash in an “on/off” pattern, drivers following a service vehicle (e.g., a snow plow) equipped with the flashing lights may experience difficulty judging the relative speed and direction of motion of the service vehicle. It has been demonstrated that closure detection times (the amount of time after a preceding vehicle slows down for a driver to notice that they are beginning to close in on the preceding vehicle) are reduced by up to 2.5 seconds when the flashing lights

maintain a minimum level of intensity at all times, such as 10% of the maximum intensity.<sup>(24)</sup>

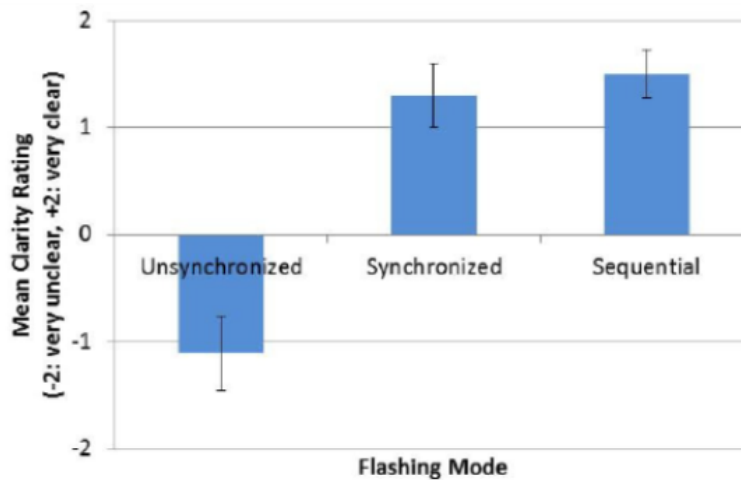


Figure 32. Informational clarity ratings to arrays of random, synchronized, and sequential flashing barricade lights.

## Warning Light Color

As mentioned previously, most warning lights used in work zone applications are yellow in color but green lights, for example, are used by some jurisdictions and New Jersey Department of Transportation is beginning to experiment with green flashing lights on maintenance trucks. In the context of traffic signals, there have been investigations of the intensity requirements of green versus yellow (steady-burning) signal lights under daytime conditions, and although higher intensities for green and yellow are needed to achieve the same response times to red signal lights, differences in response times between yellow and green lights are very small.<sup>(24)</sup> During nighttime conditions, yellow, green and red lights matched for intensity will elicit equivalent reaction times.<sup>(26)</sup>

With regard to glare from yellow and green lights at night, Bullough et al.<sup>(27)</sup> found that when equated for luminous intensity, green (steady-burning) signal lights were judged as more uncomfortable to view than yellow (steady-burning) signal lights. In fact, to be judged as uncomfortable by a majority of observers, a steady burning yellow light required a luminous intensity of 900 cd, whereas a steady-burning green light only required a luminous intensity of 450 cd (Figure 33). If this ratio of 50% intensity for the same level of discomfort glare also holds for flashing lights, it suggests that green lights when deployed at night should be used cautiously, perhaps by reducing their intensities at night. Of interest, observers judged yellow and green lights viewed under daytime conditions to be equally glaring when equated for intensity.<sup>(25)</sup>



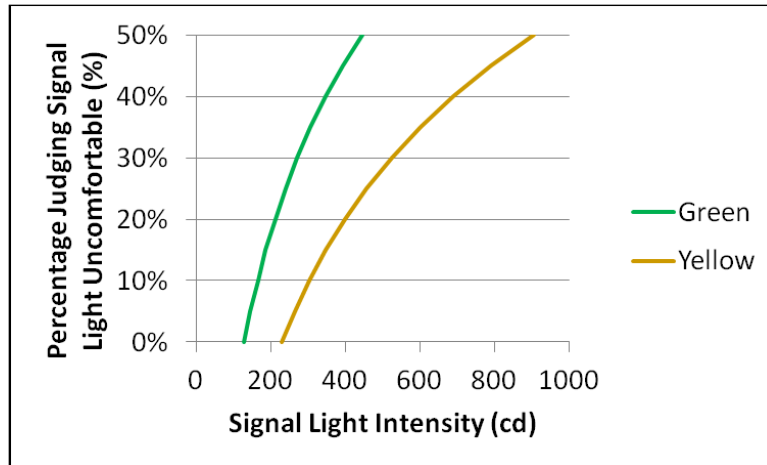


Figure 33. Percentage of observers judging steady-burning green and yellow lights as uncomfortable to view under nighttime conditions, as a function of their luminous intensities.

## **CONCLUSIONS**

The findings from the present study indicate that several new lighting and visual information technologies exist that can assist NJDOT with making work zones safer for workers and for drivers navigating them. For example:

Balloon lights offer substantial glare control compared to conventional trailer-mounted light towers, particularly light towers that are oriented toward oncoming traffic. Using Equation A-2 in the Appendix, it is possible to estimate the number of balloon lights of a given type, wattage and mounting height to achieve a minimum illuminance value.

For work zone signage and retroreflective delineation, conventional materials (Types I and III) are usually sufficient in terms of the luminances they produce when illuminated by low beam headlights. In very bright, visually complex environments, and when work zones are being set up without advance planning (e.g., urgent repairs, or accident scenes), more reflective materials (Types IV and XI) should be considered. When advanced signage is desired to be legible from greater than 600 feet away, letter sizes greater than 8 inches in height should be used.

For warning lights, peak luminous intensity should be limited to 200 cd at night to reduce glare. Sequential flash patterns of multiple barricade lights can be useful at conveying information about lane closures.

### **Statement on Implementation**

The Appendix to this report contains a set of guidelines for different work zone scenarios and ambient environments. The guidelines provide information on the selection of work zone illumination, signage and delineation materials, and flashing warning lights to help contribute to worker and driver safety in work zones. These guidelines can be distributed to work zone planning staff within NJDOT and to contractors who perform road repair and construction work. The guidelines are also summarized in the Project Brief, which is suitable for lamination and would provide an easy to use reference card on work zone lighting and visual guidance.

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## APPENDIX: PRELIMINARY GUIDELINES FOR WORK ZONE LIGHTING AND TRAFFIC CONTROL

This section of the present report contains preliminary guidelines for use by planners of work zone lighting and traffic control to provide sufficient illumination for worker visibility, while ensuring that signs and delineation are visible by adjacent drivers and that warning lights do not create glare or visual chaos. Three types of work zones are described:

- Long term, stationary projects
- Slow-moving operations
- Emergency incidents

For the first two types of work zone scenarios, guidance may differ depending upon whether the projects occur in urban locations with higher ambient light levels and more complex conditions including visual clutter, or in rural locations with lower ambient light levels and simpler visual conditions.

### Long Term, Stationary Projects

Long term, stationary projects include road construction and reconstruction, which are likely to occur over a period of several weeks to several months. Figure A-1 shows one example of a work zone involving a lane and shoulder closure.

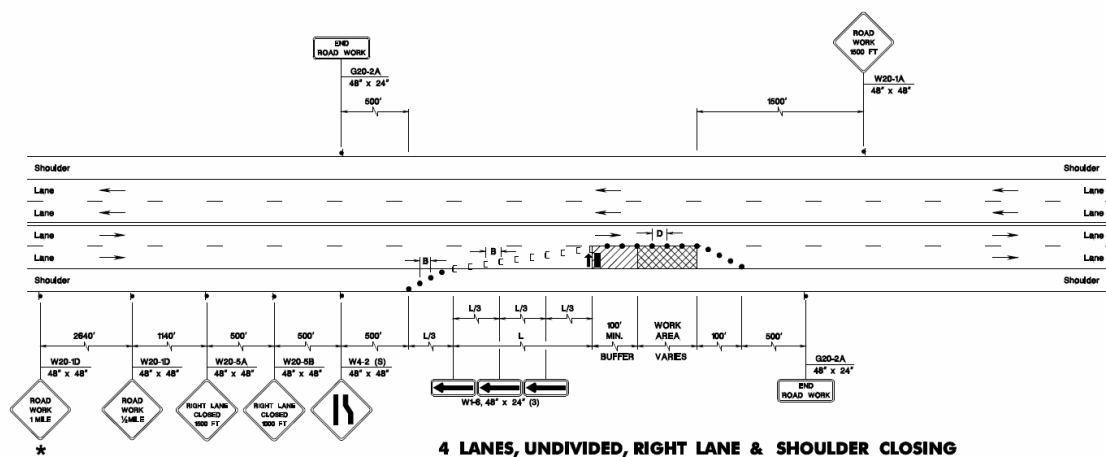


Figure A-1. Example of a work zone involving a lane and shoulder closure.

## **Illumination System**

The most common type of lighting system used to illuminate long term work zones are portable trailer mounted light towers. Based on *NCHRP Report 476*,<sup>(28)</sup> towers, each with three 1000 W metal halide (MH) lamps aimed perpendicularly to each other, could illuminate two lanes of traffic (or a traffic lane and a shoulder) to a level of 5 footcandles if they are spaced 110 feet apart along one edge of the work zone.

Particularly in locations with low ambient light levels where glare can be an important concern, work zone planners should consider using balloon lights. Active work zone areas where visual performance is critical could be illuminated to 5 footcandles. In such a situation, the following equation, modified and rearranged from Equation 1 for an arbitrary mounting height (H, in feet) and light output (L, in lumens) can be used to estimate the maximum distance (D, in feet) from the balloon light mounting location at which a particular illuminance value (E, in footcandles) would be produced:

$$D = \sqrt{\frac{18L}{250E} - \frac{H^2}{2}} \quad (\text{Equation A-1})$$

For example, if a balloon light produces 60,000 lumens (L = 60,000), is mounted 10 feet above the ground (H = 10), it would produce an illuminance of 2.5 footcandles (E = 2.5) at a distance of 41 feet from the light (D = 41). In order to maintain a minimum light level of 5 footcandles between balloon lights, the lights would have to be no more than twice this distance, or 82 feet, apart. Equation A-1 can be used as a rough guide in the planning of balloon light spacing for long term work zone illumination.

Semi-permanent high mast lighting should be considered for very long duration projects of several months or greater. An installation of 1500 W floodlights mounted on 70-foot poles, with floodlights mounted in a staggered formation 320 feet apart on each side of the highway, was able to provide a highly uniform, non-glaring illuminance of 10 footcandles throughout a six-lane freeway (three lanes in each traveling direction).<sup>(29)</sup> A safety concern with semi-permanent high mast lighting is the increased risk to drivers that may collide with the poles; having greater availability of space in a clear zone between the highway and the pole locations is beneficial. Table A-1 shows a checklist that can be used to help planners decide if and when to use semi-permanent high mast illumination for work zones.<sup>(30)</sup> A score of +4 or higher would indicate a potential benefit of this lighting approach. A negative score should not be considered; a score between 0 and +4 would require a more detailed analysis of the work zone site, considering the balance between improved illumination for workers and the risk of having large poles installed adjacent to the highway.

Table A-1 – Checklist for identifying the feasibility of semi-permanent high mast work zone lighting.

Consideration	Score: -1	Score: 0	Score: +1
Duration of project	Short: 1–2 months	Medium: 3 to 5 months	Long: 6+ months
Availability of space clear zone	Limited: Less than 30 ft	Medium: 30–50 ft	High: more than 50 ft
Number of traffic conflict points	High: urban and suburban location	Medium: rural location	Few: controlled-access highway
Type of curves	Small: traversed at low speed (<30 mph)	Medium: traversed at 30–40 mph	Large: traversed at high speed (40+ mph)
Presence of traffic barriers	Low: markings only	Medium: traffic cones and barrels	High: strong lane control and heavy barriers
Environmental considerations	High: very sensitive environmental or residential location	Medium: some residential areas nearby	Low: few or no sensitive areas nearby

### **Signage and Delineation**

Except in the most brightly illuminated urban areas where competing visual information in the form of commercial signs, streetlights, traffic signals and other light sources are present, conventional materials for retroreflective signage (ASTM Type III), barricade sheeting (ASTM Type I) and barrel wrap (ASTM Type I) are sufficient. In visually complex and bright ambient environments, using higher sheeting type materials (ASTM Type IV or XI for signs, ASTM Type IV for barricades and ASTM Type XI for barrel wrap) may be suitable to help drivers identify the locations of signs and delineators. These latter materials should be avoided in rural locations.

Using font sizes on signs in and approaching work zones larger than 8 inches could assist in making signs legible at greater distances, and will have a larger impact than increasing the luminance through higher ASTM Type materials.

### **Warning Lights**

The use of flashing lights to warn drivers of impending lane closures and of the presence of service and maintenance vehicles is recommended. Lights that flash in a “high-low” rather than an “on-off” pattern should be used on vehicles and in barricade lights, especially at night. For delineation, Type B flashing lights should be used in urban locations with higher ambient light levels and complex environments; Type A lights are sufficient for rural, dark locations. Using sequentially flashing lights at tapers to indicate the desired lane change direction when lanes are closed is recommended.<sup>(31)</sup>

A peak luminous intensity for vehicle and equipment mounted lights (see Figure A-2) of at least 600 candelas (or a minimum effective intensity of 430 candelas) is recommended for daytime detection. At night, a peak intensity of 200 candelas



(minimum effective intensity of 140 candelas) may be sufficient. Green flashing lights have similar detection performance as yellow lights during the daytime, but may appear glaring to drivers at night, especially in rural locations, if their intensities are not reduced. Green lights should be equipped with dimming controls. A combination of green and yellow lights might be preferable to the presence of green lights alone, since drivers are likely to be less familiar with green lights on maintenance and service vehicles. Consideration should also be given to turning some lights off when multiple vehicles are present and there is potential for confusion from many flashing lights.



Figure A-2. Vehicle mounted light-head used as a flashing warning light.

### **Slow-Moving Operations**

Slow moving operations include painting, road surface patching, and snow plowing, where the service vehicle is moving along the roadway at a reduced speed relative to the prevailing traffic speed (see Figure A-3). While illumination for worker visibility (at night) and warning lights are likely to always be used in such operations, signs and other delineators may or may not be used.

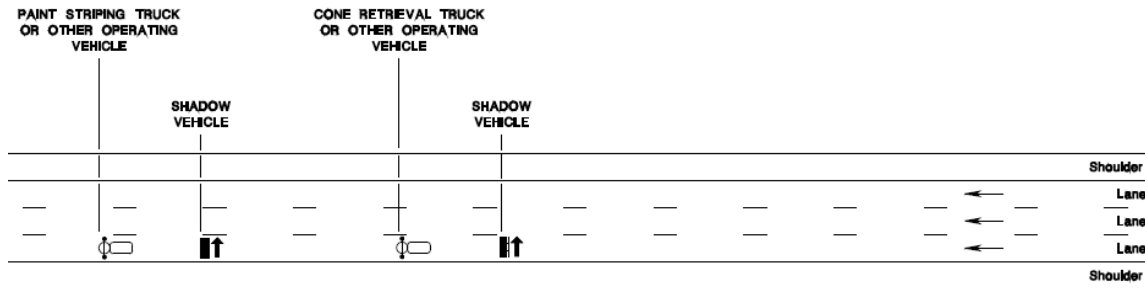


Figure A-3. Example of a slow moving work zone operation.

### **Illumination System**

If operations are conducted at night, illumination is needed to allow workers to perform their tasks. The use of vehicle mounted light towers is not recommended because these systems tend to provide excessive illumination for the task and create potentially severe glare hazards.<sup>(28)</sup> Balloon lights having smaller lumen packages than those used as stationary lights in work zones can provide useful levels of illumination while mitigating glare. Illuminance levels of 1 footcandle are sufficient 15 feet ahead of slow-moving equipment and 50 feet ahead of faster-moving equipment in non-active work areas.<sup>(28)</sup> Inspection of pavement for defects may require higher light levels such as 5 footcandles.

Equation A-1 can be used to identify the distance at which a particular illuminance can be produced by a balloon light for a given light output value and mounting height.

### **Signage and Delineation**

If retroreflective delineators such as drums are used, conventional materials (ASTM Type I) for items such as barrel wrap are likely to be sufficient except in the most brightly illuminated, complex nighttime environments.

### **Warning Lights**

All vehicles involved in the slow moving operation should be equipped with flashing warning lights. A peak luminous intensity for vehicle and equipment mounted flashing lights of at least 600 candelas (or a minimum effective intensity of 430 candelas) is recommended for daytime detection. At night, a peak intensity of 200 candelas (or a minimum effective intensity of 140 candelas) may be sufficient. Warning lights should flash in a "high-low" rather than an "on-off" temporal flash pattern so that at least 10% of the peak intensity remains on at all times, in order to assist drivers in judging closure distance and rate when approaching slow-moving vehicles.

Green flashing lights have similar detection performance as yellow lights during the daytime, but may appear glaring to drivers at night, especially in rural locations, if their intensities are not reduced. Green lights should be equipped with dimming controls. A combination of green and yellow lights might be preferable to the presence of green lights alone, since drivers are likely to be less familiar with green lights on maintenance and service vehicles. Consideration should also be given to turning some lights off when multiple vehicles are present and there is potential for confusion from many flashing lights.

## **Emergency Incidents**

When responding to emergency roadway situations such as a motor vehicle accident, fallen power lines or trees, time is of the essence and little time for planning lighting and traffic control is available. Moreover, lighting and traffic control equipment is often unavailable as well. Multiple vehicles may approach the incident scene, each with its own complement of warning lights, illumination systems, flares or other devices. Glare control and providing sufficient illumination at night are critical.

### **Illumination System**

Vehicle headlights may be the only illumination system available in many emergency incidents. To the extent possible, headlights should not be directed toward oncoming traffic. Headlights are highly directional light sources and prone to casting shadows in the incident scene. If a vehicle is equipped with floodlight or balloon light illumination, such systems would be preferable to mitigate against glare and harsh shadows. Vehicles not contributing illumination to the incident scene should consider switching headlights off (provided cornering lights are present).

### **Signage and Delineation**

Traffic cones or other delineators, if available, should be placed especially where traveling lanes are blocked or partially blocked. Since multiple service and emergency vehicles may be present, using higher ASTM Types of materials on cones (in contrast to ASTM Type I or III materials) may be beneficial regardless of the ambient environment.

### **Warning Lights**

When multiple vehicles are present at an incident scene (see Figure A-4), parked along the side of the road at convenient locations but not arranged formally in a specific

pattern to facilitate traffic control, consider adjusting the intensity of warning lights to a lower setting (peak intensity of 200 candelas, or an effective intensity of 140 candelas), or turning warning lights off on some vehicles, consistent with the New Jersey *Highway Incident Traffic Safety Guidelines for Emergency Responders*.<sup>(32)</sup> Flashing lights should operate with a "high-low" rather than an "on-off" temporal pattern, maintaining at least 10% of their peak intensity at all times. As time and situational details permit, arranging vehicles to create buffer and protected space can be performed.

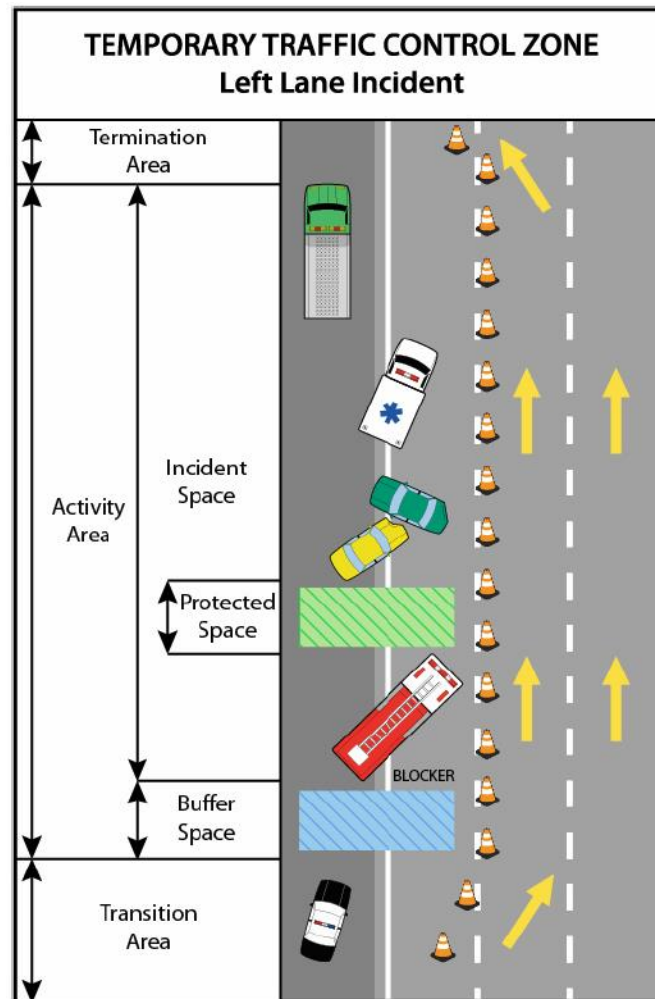


Figure A-4. Incident scene requiring a lane closure.

Self-organizing sequentially flashing barricade lights that will provide a sequential flash pattern across several lights to indicate the direction of travel in a lane closure situation are commercially available and will assist drivers in navigating around the incident scene; these can be stored in a vehicle where they are charged. Type B intensities are recommended to ensure they are visible among other flashing lights and light sources in the scene. Flares are another useful alternative to barricade lights at delineating full or partial lane closures or blockages.