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Guidelines for the Effective Use and Procurement of Advanced Warning Arrow Panels

This digest summarizes the results of NCHRP Project 5-14, "Advanced Warning Arrow Panel Visibility." The project evaluated the factors affecting the detection and recognition of arrow panels and developed a practical means for checking arrow panel visibility. This digest is based on a draft final report prepared by Douglas Mace, Mark Finkle, and Sara Pennak of The Last Resource.

INTRODUCTION

This digest provides procedures to ensure the proper visibility, deployment, and maintenance of advanced warning arrow panels. The digest also includes recommeded specifications for arrow panels.

Prior to the introduction of solar-powered arrow panels near the end of the 1980s, advanced warning arrow panels were considered to be a clear example of a conspicuous traffic-control device. These diesel-powered arrow panels could produce displays seen at great distances and wide angles. They also produced operational and maintenance headaches, creating environmental nuisances with fuel spills, fumes, noise, and glare. The lamps used in these diesel-powered units are typically automotive foglamps, easily purchased at an auto parts store but having little quality control for lens color, intensity, or filament orientation.

With the development of solar technology, solar-powered arrow panels were introduced as alternative traffic-control devices for use in roadway work zone areas. Tapping into the energy of the sun, these units were quiet and environmentally friendly, requiring no fueling and little maintenance relative to their diesel unit cousins. However, as with most new technology, performance and quality were spotty across the breadth of the early solar arrow panel manufacturers. Required to meet the same *Manual on Uniform Traffic Control Devices* (Federal Highway Administration, 1988) visibility standards as the diesel-powered arrow panels, issues of lamp intensity and lamp angularity emerged. Newer generations of solar arrow panels have furthered lamp technology research to address these concerns of visibility, and these concerns, in turn, have produced higher levels of quality control in lamp design and engineering.

This study was primarily designed to establish the minimum photometric requirements for Type C panels because Type C panels are the devices used in high-speed situations and comprise the largest part of the inventory of all arrow panels. The study's objective was not only to focus on the photometric requirements for Type C panels, but also to keep the specification as simple and generalizable as possible. The specification developed may be applied to all types of lamps and power supplies. It makes no reference to the type of light source (e.g., incandescent or light emitting diode) or to solar or diesel and makes no reference to wattage or type of reflector. There is no need for the specification to be concerned with this level of detail. An arrow panel will provide minimum visibility for most drivers in most situations if the following conditions are met:

- The light sources used on a Type C or B arrow panel meet the specification for intensity, angularity, and color and
- The panel itself meets some simple minimum criteria and is set up using a few simple field procedures.

Prior to this research, very little had been done to evaluate the luminous intensity necessary for the

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visibility of arrow panels. Concerns expressed about the performance of solar-powered arrow panels provided the impetus to study the visibility factors necessary for adequate arrow panel visibility, independent of technology or power source. This research focused on determining the minimum photometric levels required for arrow panel recognition during daylight and the maximum levels necessary to control glare at night. A photometric recommended specification for arrow panel lamps was developed based on (a) the minimum and maximum photometric levels determined by this research, (b) the analytic work that established angles under which arrow panels are viewed in extreme placements, and (c) the earlier research of others with regard to color, conspicuity, and minimum-intensity requirements at night. In addition to the recommended specification for arrow panel lamps, a set of very brief field procedures was developed to make certain that the lamps are installed properly and that the arrow panels are maintained and deployed in a manner that can satisfy driver needs.

TECHNICAL REQUIREMENTS FOR ARROW PANEL RECOGNITION

Overview

Given that the overall dimensions of the arrow panel are specified and that the background is flat nonreflective black, the only requirement for arrow panel visibility is that it have sufficient brightness to an observer at the necessary distance for safety. Brightness is a relative term that describes the appearance of an object to the eye. Regardless of how bright an object appears on any given day, the same object will appear brighter when the ambient light levels are lower. Luminance and luminous intensity are the photometric measurements that describe the performance of the arrow panel or the lamp without regard to ambient conditions and subjective evaluation.

The photometric requirements for arrow panels could be specified in terms of the entire panel or in terms of each individual lamp. Since it is much easier to test an individual lamp, the lamp became the focus for developing a specification to maintain minimum performance of the arrow panel. The photometric performance of a lamp can be represented in terms of luminous intensity (measured in candelas [cd]) or in terms of luminance (measured in cd/m^2). Luminous intensity was selected because at 300 m (984 ft) and beyond, the lamps on an arrow panel are clearly point-light sources. Therefore, it was decided to test and certify the lamps to meet both minimum and maximum luminous intensity requirements at the beam angles required for recognition at decision sight distance (DSD). These luminous intensity requirements will be referred to as simply intensity.

The requirement for minimum intensity over a range of beam angles is necessitated by the fact that arrow panel placements are not always on straight and flat roads where the arrow panel may be viewed essentially on-axis. Without any constraints on the placement of arrow panels, the beam angle requirements would be enormous. Clearly, some assumptions are necessary about the worst-case geometrics and placement of arrow panels in order to determine the maximum beam-width requirements.

Intensity Requirements

The minimum intensity requirements include requirements for on-axis and off-axis intensities. A minimum beam width is required to maintain recognition of the arrow panel in typical placement situations. The requirement for off-axis intensity ensures that the arrow panel is recognized by the alerted driver at potentially large off-axis angles. The off-axis intensity requirement has been based on the highest lamp intensity needed to obtain arrow panel recognition in a dynamic field study. The value chosen was the intensity needed to accommodate 95 percent of older drivers for the range of ambient conditions under which the dynamic study was conducted. This requirement has a safety factor built in and is not a threshold value. The safety factor may be derived by comparing the results of the static field study with those of the dynamic field study. The dynamic study yielded intensity results roughly four times higher than the results of the static study.

The on-axis requirement is needed to establish an intensity level necessary to make the arrow panel conspicuous to unalerted drivers in a visually complex environment. Threshold intensity was determined from the analysis of static and dynamic research studies. Based on previous research (Roper and Howard, 1938; Jenkins, 2000), a very conservative multiplier of 20 times (20x) the threshold minimum intensity for identification has been used to derive the minimum on-axis requirement.

Roper and Howard found that the detection distance of a pedestrian by unalerted drivers was half the distance of alerted drivers. The dynamic field study showed that arrow panels with lamp intensity 7.5x the threshold value of 100 cd were seen at more than 1,000 m by alerted drivers. According to Roper and Howard's study, these arrow panels would be noticed by unalerted drivers at distances greater than 500 m. Because the requirements for conspicuity involve cognitive as well as perceptual factors, generalizing from the study of one type of target to another is not always appropriate. The discussion by Jenkins will give the reader an excellent understanding of conspicuity and further suggests that, at least at night, a multiplier of 10x may be sufficient, even in complex backgrounds.

Daytime

To ensure arrow panel visibility, minimum values of illumination at the driver's windshield have been established by this research. These values apply regardless of the driver's position relative to the arrow panel. The intensity of an arrow panel display necessary to achieve a given level of illumination varies with the distance between the arrow panel and the driver, according to the "inverse square law." Two DSDs have been identified, applying to high-speed (100 km/h, or 63 mph) and low-speed (73 km/h, or 45 mph) roads, each one associated with a threshold illumination value and, hence, an intensity level requirement for the arrow panel display. These intensity levels must be satisfied at any point in space occupied by the driver. The usefulness of an arrow panel in the more challenging geometrics is related to its ability to achieve the required intensity levels at large angles "off-axis" (called "angularity").

High-Speed Roads

High-speed roads require longer DSD because of their high design speeds. Based on a nominal speed of 100 km/h (63 mph), a DSD of 457 m (1,500 ft) is used for this type of road. The dynamic field study found that the 95th-percentile recognition distance exceeded 457 m (1,500 ft) when the arrow panel lamps were at least 100 cd. This minimum intensity requirement, which is an off-axis requirement for recognition at 457 m (1,500 ft), represents a field factor of four or five times (4x or 5x) applied to the static threshold data. The static field study found that a 100th-percentile threshold intensity of approximately 25 cd is required for recognition by older drivers. The 20x-conspicuity multiplier results in a minimum on-axis requirement of 500 cd.

Low-Speed Roads

Low-speed roads, nominally 73 km/h (45 mph), have shorter DSD requirements. Intensity requirements for these types of road are based on a DSD of 300 m (984 ft). The dynamic field study found that the 95th-percentile recognition distance exceeded 300 m (984 ft) when the arrow panel lamps were 60 cd or greater. This minimum intensity requirement, which is an off-axis requirement for recognition at 300 m (984 ft), may also be arrived at by applying the 4x-field factor to the static field study data. Using a linear extrapolation of the static field results, 15 cd is required for threshold recognition. Using the 4x-field factor, the minimum off-axis requirement becomes 60 cd. The on-axis minimum intensity becomes 300 cd after applying the 20x-conspicuity multiplier to the 15 cd static threshold.

Nighttime

The requirements for nighttime arrow panel operation are similar to those for daytime with the addition of a requirement for the maximum intensity allowed. The reason for the additional requirement is to limit the amount of glare the arrow panel produces. The maximum intensity requirement must be met at the lamp "hot spot," which may or may not be on-axis with the optical center of the lamp. The nighttime glare studies found that the maximum tolerable total intensity combined from all arrow panel lamps was 5,500 cd. This intensity means 370 cd per lamp for a chevron display and 550 cd per lamp for an arrow display. Making the maximum intensity per lamp 370 cd ensures that glare will not be disturbing.

The nighttime requirements still include provisions for minimum on-axis and off-axis intensities. In previous work with nighttime requirements for traffic signals (Freedman et al., 1985), it was found that a nighttime level that was 30 percent of the daytime level did not reduce visibility of the signal. Applying this finding to the daytime arrow panel intensity gives a nighttime minimum intensity level of 150 cd on-axis and 30 cd off-axis for high-speed roads and 90 cd on-axis and 18 cd off-axis for low-speed roads (see Table 1).

Angularity Requirements

Three geometric configurations were used to determine the horizontal and vertical angles required for a variety of beam-width situations. Figure 1 shows the two configurations used to define vertical angularity. Horizontal angularity was defined using the configuration in Figure 2.

Vertical Angularity

In Figure 1, the arrow panel is assumed to be located at the beginning of the parabolic transition road section and the

TABLE 1 Summary of luminous intensity requirements

Situation	Minimum On-Axis	Minimum Off-Axis	Maximum Hot Spot
Low speed, day	300 cd	60 cd	NA
High speed, day	500 cd	100 cd	NA
Low speed, night	90 cd	18 cd	370 cd
High speed, night	150 cd	30 cd	370 cd

Note: NA = not available.

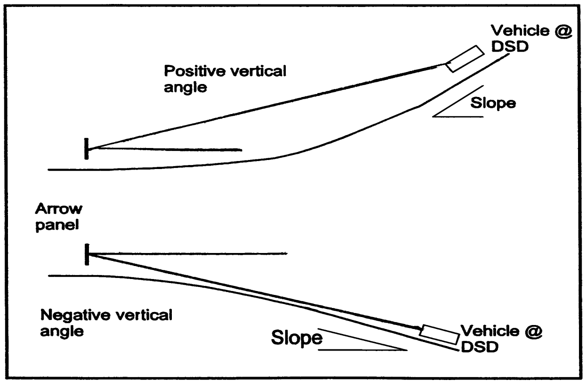

Figure 1. Vertical curvature.

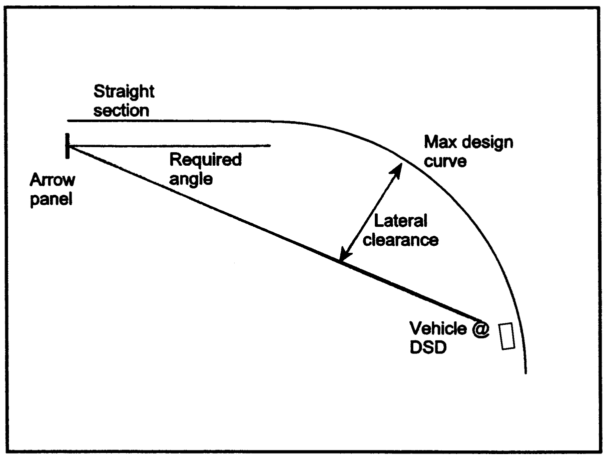

Figure 2. Horizontal curvature.

vehicle is located on the sloped section of road. If the locations of the vehicle and arrow panel were reversed, the resulting angles would be the same. Assuming that the arrow panel is at the beginning or end of a parabolic road section, the resulting angularity is the maximum that would be encountered. If a length of flat, straight road is placed between the observer and the arrow panel, then the angularity decreases as the flat length increases. Given the arrow panel placement, only the grade, or slope, of the road section is needed to calculate the required vertical angularity. The arctangent of the grade yields the required vertical angularity of the road section that is illustrated in Table 2 for several grades.

Horizontal Angularity

Figure 2 shows a portion of the required DSD on a straight section of road. The length of this straight section affects the viewing angle required at the DSD. If the straight section were equal to the DSD, the viewing angle would be at a minimum. When both the driver and the arrow panel are on the curve, there is no straight section and the viewing angle is maximum.

One alternative in specifying beam width is to make no assumption about the length of the straight section and to assume that the arrow panel is placed on a curve that extends for a length greater than the DSD. This placement of the arrow panel would require a useful beam width that very few arrow panels could meet. Without some straight section, the horizontal-beam angle requirements become very large. Further, a large beam width forces an assumption about the lateral clearance to an obstruction. The lateral clearance is the clear-zone width measured from the edge of the road that must be available in order to provide an unobstructed line of sight to the arrow panel. This clearance becomes important when trees and buildings line the shoulder of the road, blocking the line of sight. The effects of the design curvature and straight length on angularity and lateral clearance, respectively, are illustrated for low-speed roads in Tables 3 and 4 and high-speed roads in Tables 5 and 6. The essential difference between the high- and low-speed tables is the difference in the DSD required for each speed, which changes the separation distance between the arrow panel and the observer. This difference has the effect of changing the required beam width and lateral clearance when the degree of curvature remains unchanged.

As shown in Tables 3 and 4, a low-speed road, with an arrow panel on a 214-m radius curve, results in a 40-deg angle between the panel and the driver. For the driver to be able to view the arrow panel, a lateral clearance of 51 m (167 ft) is also required. This clearance reduces to 41 m (135 ft) if there is 100 m (328 ft) of straight-road section between the arrow panel and the curve. The required angularity also reduces significantly to 18 deg. Similar trends are shown in Tables 5 and 6 for high-speed conditions.

TABLE 2 Effect of grade on angularity (for low- and high-speed roads)

Grade (%)	Angle (deg)
2	1.1
4	2.3
6	3.4
8	4.6
10	5.7

TABLE 3 Angularity (deg) based on radius and straight length (for low-speed roads, when DSD = 300 m [984 ft])

Radius (m)	Straight Length (m)						
	0	**25**	**50**	**75**	**100**	**125**	**150**
214	40º	34º	28º	22º	18º	13º	10º
250	34º	29º	24º	19º	15º	12º	9º
300	29º	24º	20º	16º	13º	10º	7º
350	25º	21º	17º	14º	11º	8º	6º
400	22º	18º	15º	12º	10º	7º	5º
500	17º	14º	12º	10º	8º	6º	4º
650	13º	11º	9º	7º	6º	4º	3º
1000	9º	7º	6º	5º	4º	3º	2º

TABLE 4 Lateral clearance (m) based on radius and straight length (for low-speed roads, when DSD = 300 m [984 ft])

Radius (m)	Straight Length (m)						
	0	**25**	**50**	**75**	**100**	**125**	**150**
214	51 m	50 m	48 m	45 m	41 m	36 m	29 m
250	44 m	43 m	42 m	39 m	35 m	31 m	25 m
300	37 m	36 m	35 m	33 m	30 m	26 m	21 m
350	32 m	31 m	30 m	28 m	25 m	22 m	18 m
400	28 m	27 m	26 m	25 m	22 m	20 m	16 m
500	23 m	22 m	21 m	20 m	17 m	16 m	13 m
650	17 m	17 m	16 m	14 m	14 m	11 m	9 m
1000	12 m	12 m	11 m	10 m	9 m	8 m	7 m

TABLE 5 Angularity (deg) based on radius and straight length (for high-speed roads, when DSD = 457 m [1,500 ft])

Radius (m)	Straight Length (m)						
	0	**75**	**125**	**175**	**225**	**275**	**325**
437	20º	21º	16º	11º	8º	5º	2º
500	26º	18º	14º	10º	7º	4º	2º
550	24º	17º	13º	8º	6º	4º	2º
600	22º	15º	12º	8º	6º	3º	2º
750	20º	14º	11º	8º	5º	3º	2º
1000	13º	9º	7º	5º	3º	2º	1º
1550	8º	6º	4º	3º	2º	1º	1º

TABLE 6 Lateral clearance (m) based on radius and straight length (for high-speed roads, when DSD = 457 m [1,500 ft])

Radius (m)	Straight Length (m)						
	0	**75**	**125**	**175**	**225**	**275**	**325**
437	59 m	56 m	51 m	43 m	36 m	26 m	12 m
500	52 m	49 m	45 m	38 m	32 m	23 m	11 m
550	47 m	45 m	41 m	35 m	27 m	21 m	11 m
600	43 m	41 m	37 m	32 m	25 m	18 m	10 m
650	40 m	38 m	35 m	30 m	23 m	16 m	10 m
750	35 m	33 m	30 m	26 m	18 m	13 m	6 m
1000	26 m	25 m	23 m	19 m	14 m	11 m	5 m
1550	17 m	17 m	13 m	12 m	9 m	6 m	3 m

DEVELOPMENT OF A SPECIFICATION FOR ARROW PANEL LAMPS

Overview

Aside from color, the specification for an arrow panel lamp must designate both intensity and angular requirements. The previous section summarized the intensity requirements and pointed out that the required angularity was not a function of driver needs, but of the geometry of the roadway where the arrow panel is placed. Without restrictions on arrow panel placement, one cannot specify the required angles at which the driver may need to see the arrow panel. The purpose of this section is to make some assumptions about geometry and placement and to show how these assumptions are used to develop a sample specification.

In developing a specification for arrow panel lamps, a regulatory authority should first consider the geometric and placement conditions that are likely to be encountered in its jurisdiction. A "likely" condition should refer to a reasonable worst-case condition, such as one encompassing 85 percent of all conditions with sufficient lateral clearance to provide a line of sight. If the specification was developed to include the "worst-case" condition, there may be very few lamps that could meet the requirements. By using a reasonable worst case, many panels will be able to meet the specification. In those few cases when the geometry is worse than the specification assumes, the problem may be solved by moving the site, improving the aim of the arrow panel, or declaring it a special situation that should be reviewed by an experienced traffic engineer. The geometric and placement conditions considered must include the horizontal and vertical curvature, the length of straight section, and the lateral clearance expected.

Determination of Required Beam Width

The useful beam width of a lamp is defined as the portion of the lamp beam pattern that is capable of providing the necessary recognition of the arrow panel in which the lamp is installed. In other words, the useful beam width is the portion of the beam width that provides intensity greater than the minimum intensity required by alerted drivers at DSD. It is measured in terms of plus or minus a horizontal and vertical angle relative to the center of the lamp. The measurement provides an intensity greater than the minimum intensity required for recognition of an arrow display. The total beam width is the difference between the positive and negative components, which is typically twice the plus or minus value. Therefore, a lamp that provides sufficient intensity for recognition at ±12 deg has a total beam width of 24 deg.

The previous discussion showed that the beam width requirements differed among low- and high-speed roads. Low-speed roads require greater angularity than high-speed roads because the geometry of low-speed roads is likely to have a greater degree of curvature. Although arrow panels may require a larger beam width on low-speed roads, less intensity is required because the DSD is less. For example, situations encountered on a typical freeway would normally require a narrow beam width with greater intensity. In contrast to narrow-beam situations, wide-beam situations encountered on lower-speed arterials and local streets require a larger beam width and less intensity. In order to derive angular requirements for these situations, the research team used the geometric guidelines from AASHTO's 1994 *A Policy on the Geometric Design of Highways and Streets* (a.k.a. "Green Book"). Table 7 shows these geometric guidelines.

The previous section provided the information needed to determine the angular requirements for low- and high-speed conditions. The next two sections provide specific beam-width requirements for both high- and low-speed roads. A specification will then be given for one general-purpose lamp with multiple test points intended to meet the requirements of both low- and high-speed situations. A separate specification for a narrow-beam lamp that meets the requirements for only high-speed roads is also developed. This specification may be desirable if many of the arrow panels in a jurisdiction cannot meet the general-purpose requirements.

Required Angularity for High-Speed Roads

High-speed roads are assumed to have light to modest grade and curvature (see Table 7). Table 8 shows that, in high-speed situations (i.e., when DSD equals 457 m) with a maximum 437-m radius curve and no straight section (i.e.,

TABLE 7 Geometric assumptions (for low- and high-speed roads)

Speed	Radius	Grade	DSD
100 km/h	437 m	6 %	457 m
70 km/h	214 m	9 %	300 m

Note: DSD = decision sight distance. Guidelines taken from the American Association of State Highway and Transportation Officials, *A Policy on the Geometric Design of Highways and Streets* (a.k.a. "Green Book," Washington, D.C.: 1994).

TABLE 8 Effect of straight length on angularity and lateral clearance (for high-speed roads, with 437-m [1,434-ft] radius curve, 100-km/h [60-mph] design speed, and 457-m [1,500-ft] DSD)

Straight Length (m)	Angularity (deg)	Lateral Clearance (m)
0	30	59
50	24	58
100	18	54
150	13	47
175	11	43
200	9	39
225	8	36

with both driver and arrow panel on the curve), a beam angle of ±30 deg is required for recognition. Table 8 also shows that, for the same situation, the lateral clearance needed is 59 m. In most states, a 59-m lateral clearance is very rare. Even the 39-m (128-ft) lateral clearance required with a 200-m (656-ft) straight section may be difficult to find. Beam width is not useful when obstructions prevent a line of sight to the arrow panel. Therefore, even when the degree of curvature is well below the reasonable worst case that the specification is based on, when the lateral clearance is very restricted, it may be necessary to find a location with either a longer straight section or a gentler curve. Otherwise, a special situation exists where the services of an experienced traffic engineer are required. Special situations are discussed in the next section.

Table 8 suggests that, with the most extreme AASHTO geometry for high-speed roads, a ±8-deg beam width will provide recognition if there is a 225-m (738-ft) straight section and a lateral clearance of only 36 m (118 ft). If there is no straight section and both the arrow panel and the vehicle are on the curve, this same beam width will provide recognition for a 1,550-m (5,086-ft) radius curve with a 17-m (56-ft) lateral clearance (see Tables 5 and 6). The selection of the ±8-deg beam width was based primarily on the belief that a 36-m (118-ft) lateral clearance is probably more than will normally be available. It is also assumed that the arrow panel will be aimed parallel to the road and not aimed into the curve. By aiming the arrow panel, the effective beam width may be doubled. These situations for which the ±8-deg beam width provides recognition are diagramed to scale in Figures 3 and 4. The beam width for high-speed roads may be changed with two effects: (a) decreasing the beam-width angularity will result in greater lengths of required straight sections, an increase in the radius of curvature where the arrow panel is placed, or both and (b) increasing the angularity of the beam width will have the opposite effect. Although a larger beam width permits shorter straight sections, more severe curvature, or both, the beam width will not be useable unless there is sufficient lateral clearance. In other words, the excess beam width is wasted unless sites have the required lateral clearance.

Required Angularity for Low-Speed Roads

As stated previously, the methodology to determine the angularity for low-speed roads is the same as for high-speed roads except that a more extreme curvature should be assumed (see Table 7). Table 9 suggests that, with the most extreme AASHTO geometry for low-speed roads, a ±13-deg beam width will provide recognition if there is a lateral clearance of only 36 m (118 ft) and a 125-m (410-ft) straight section. If there is no straight section and both the arrow panel and the car are on the curve, this same beam width will provide recognition for a 650-m (2,133-ft) radius curve with a 17-m (56-ft) lateral clearance (see Tables 3 and 4). As with the angularity for high-speed requirements, the selection of the ±13-deg beam width was based primarily on the belief that a 36-m (118-ft) lateral clearance is probably more

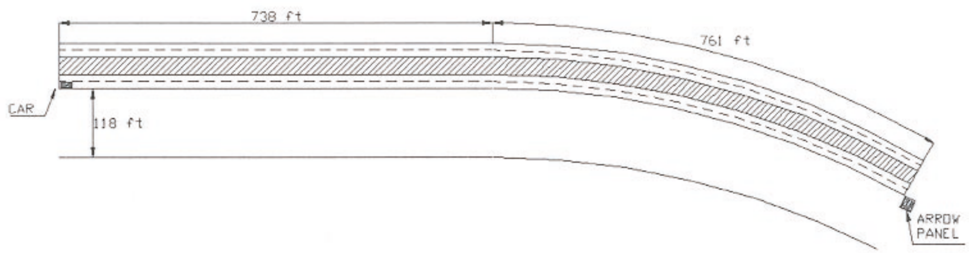

Figure 3. Arrow panel placement as seen at 457-m (1,500-ft) DSD on 437-m (1,434-ft) radius curve with 225-m (738-ft) straight section.

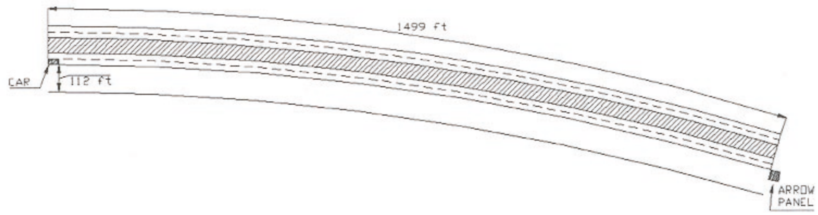

Figure 4. Arrow panel placement as seen at 457-m (1,500-ft) DSD on 1,550-m (5,090-ft) radius curve with no straight section.

TABLE 9 Effect of straight length on angularity and lateral clearance (for low-speed roads, with 214-m [702-ft] radius curve, 70-km/h [42-mph] design speed, and 300-m [984-ft] DSD)

Straight Length (m)	Angularity (deg)	Lateral Clearance (m)
0	40	51
25	34	50
50	28	48
80	22	44
100	18	41
125	13	36
150	10	29

than will be available. It is also assumed that the arrow panel will be aimed parallel to the road and not aimed into the curve. By aiming the arrow panel, the effective beam width may be doubled. These situations for which the ±13-deg beam width provides recognition are diagrammed to scale in Figures 5 and 6. The effects of changing the angularity are the same as for the narrow beam-width situation.

DEVELOPMENT OF A GENERAL ARROW PANEL SPECIFICATION

Two different specifications are presented in Appendix B. The first specification includes test points using two different horizontal angles and two different vertical angles to ensure that the arrow panel meets the recognition requirements on both low- and high-speed roads. A second narrow-beam specification with only one pair of horizontal and vertical angles (narrow-beam width) is included to allow for the fact that some arrow panels in use will not be able to meet the general specification, but may have sufficient intensity at narrow-beam angles to be used on high-speed roads.

Because a lateral clearance greater than 36 m (118 ft) seems unlikely, the sample specification shown in Appendix B includes a ±8-deg horizontal angularity requirement (16-deg beam width) for high-speed roads with a DSD requirement of 457 m (1,500 ft) and a ±13-deg horizontal

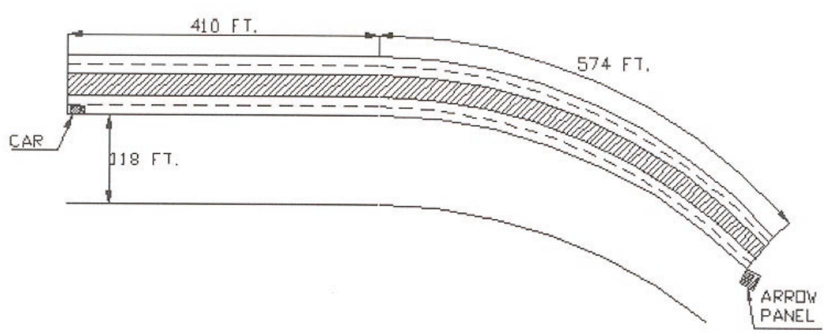

Figure 5. Arrow panel placement as seen at 300-m (984-ft) DSD on 214-m (702-ft) radius curve with 125-m (410-ft) straight section.

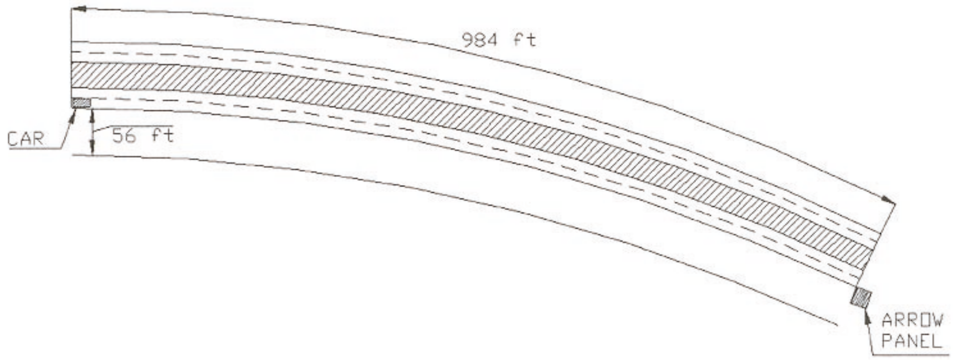

Figure 6. Arrow panel placement as seen at 300-m (984-ft) DSD on 650-m (2,132-ft) radius curve with no straight section.

angularity requirement (26-deg beam width) for low-speed roads with a DSD requirement of 300 m (984 ft). The vertical angularity requirement is ±3 deg for high-speed roads and ±5 deg for low-speed roads. These beam-width requirements, included in the sample specifications, are based on the worst-case scenarios shown in Figures 3–6 using the AASHTO recommendations contained in Table 7.

The most conservative criteria would require that all points in 1-deg increments within a rectangle defined by the horizontal and vertical angular requirements be equal or greater than the minimum intensity requirement. Given current technologies and the foreseeable future, beam patterns are and will continue to be elliptical, not rectangular. Also, it is highly unlikely that the road geometry will ever require the worst-case horizontal and vertical angles at the same location. The sample specification suggests modifying these requirements so that only 75 percent of the horizontal beam width is rectangular and suggests narrowing the vertical beam width beyond this point to 50 percent of the maximum vertical angle required, rounded upward to the nearest degree. Two areas can be defined: one for low-speed roads with a 60-cd requirement and one for high-speed roads with a 100-cd requirement. These areas are shown in Figure 7.

In addition to the intensity and angularity requirements discussed previously, the sample specification in Appendix B includes several other requirements. Most of these general

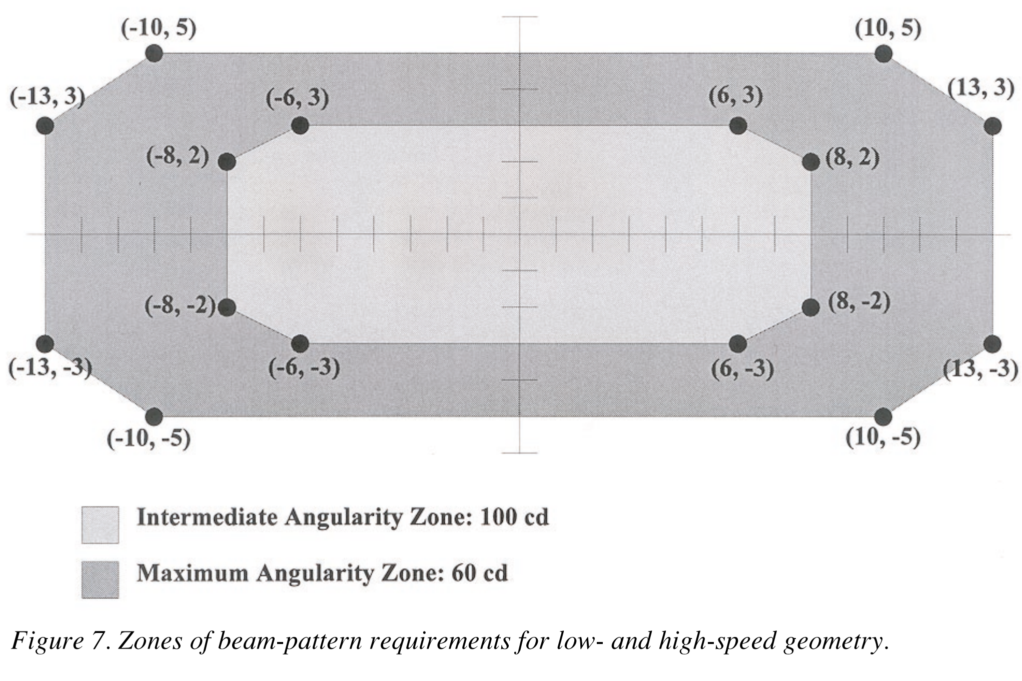

Figure 7. Zones of beam-pattern requirements for low- and high-speed geometry.

requirements, such as power supply, flash rate, and display configurations, already exist in current arrow panel specifications. However, a few of these general requirements either have never been precisely indicated or have only now been deemed necessary because of this research.

One notable example of a requirement that has not been precisely indicated in previous arrow panel specifications is lamp color. Most arrow panel specifications merely state that the color should be amber or yellow. The sample specification in Appendix B actually defines a color region based on the Commission Internationale De L'Eclairage (CIE) chromaticity diagram. The extent of the region was determined from a sample of current arrow panel lamps. A more conservative standard would have restricted the region to the CIE region for yellow; however, only one arrow panel lamp tested fit into this region. Because color discrimination is not a requirement for arrow panel recognition, a less conservative region was chosen that included five of the six arrow panel lamps tested, excluding only one (which appeared white to the entire research team).

Other requirements in the sample specification were introduced to allow field personnel to properly set up the arrow panel or verify conformance to the specification. For example, the sighting device aids in aiming the panel for maximum performance, while the voltage-testing controls indicate whether the lamps are being supplied with enough power to meet the intensity requirements in the specification. In addition, the ambient illumination level at which the arrow panel should be dimmed is also recommended according to the Institute of Transportation Engineers (ITE) specification for steady-burn and flashing warning lamps (Institute of Transportation Engineers, 1997).

PROCEDURES TO ENSURE PROPER ARROW PANEL VISIBILITY

The use of a specification and a procedure for certifying lamps does not in itself guarantee that arrow panels in use will have sufficient visibility to meet driver requirements. The lamp used and other characteristics of the hardware are critical to visibility, but do not necessarily ensure visibility. Additional steps are needed to ensure that the arrow panel is properly set up, maintained, and deployed. A frequent misconception is that arrow panels that use very bright lamps (i.e., lamps that exceed any specification by significant amounts) are more robust with regard to maintenance and placement issues. The truth is that all arrow panels, even the very brightest diesel panels, must be given the same attention with regard to maintenance and placement issues. Without the implementation of procedures, such as those that follow, even the best arrow panels may fail to provide adequate visibility to the driver.

The sample procedures presented in Appendixes C and D were developed with the contribution of a number of people with extensive field experience. The procedures were reviewed by construction supervisors and state DOT personnel in Pennsylvania and Maryland. Changes were made on the basis of these reviews and then taken to the field for verification again.

Procedures are provided for three broad purposes: First, the procedures ensure proper arrow panel operation, including the steps required for lamp and voltage verification. Second, the procedures help in aiming and verifying the visibility of the arrow panel, including a subjective evaluation of the arrow panel message and a field photometric procedure. Finally, the procedures provide guidance for using a special-purpose, narrow-beam lamp to help ensure that the panel is not placed where its visibility will not meet driver requirements.

Although each set of procedures or guidelines may have value for both yard and field personnel, some sets were written primarily for one group or the other. The arrow panel operation procedures are primarily written for yard personnel involved with arrow panel maintenance. These procedures include basic checks that should also be made by field personnel when replacing lamps or during scheduled maintenance. The verification of arrow panel visibility is primarily intended for field personnel after deployment so that arrow panel visibility is rated under the same conditions that the driver must view the arrow panel. However, there may be occasions when yard personnel may wish to verify visibility, perhaps to compare different arrow panels under the same conditions. The guidelines for determining the suitability of a special-purpose, narrow-beam arrow panel may be of use to both yard and field personnel. If possible, yard personnel should use their knowledge of a site and of the type of operation and should avoid sending a narrow-beam arrow panel to an inappropriate site. Sometimes, both general-purpose and narrow-beam arrow panels are delivered to a construction job. In this case, the guidelines will be useful for determining which panels to use where.

FINAL REPORT AVAILABILITY

The full agency report for NCHRP Project 5-14 will not be published in the regular NCHRP report series. However, loan copies of the agency report are available upon request from the National Cooperative Highway Research Program, Transportation Research Board, 2101 Constitution Avenue, NW, Washington, D.C. 20418.

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Resource, with Mr. Douglas J. Mace as the principal investigator.

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APPENDIX A: PHOTOMETRIC PROCEDURE

Photometric Measurement

The main purpose of this study was to establish the minimum photometric levels that should be incorporated into a standard for arrow panels. The minimum level will provide arrow panel recognition at the maximum distance necessary for safety at highway speeds. Experience suggests there will be no conflict between the minimum level found in this study and the maximum values established as a control for potential arrow panel glare effects. The minimum photometric levels necessary for recognition, even at long distances, should be well below those determined in the static field study to produce glare.

The purpose of this section is to describe the procedure for the photometric measurement of arrow panels. Each tangent-located arrow panel was placed in its testing position and directed upstream parallel to the road edge. Arrow panels that were not on tangents were intentionally misaimed to examine the effects of off-axis viewing. The angles tested were approximately ±15–20 deg horizontal.

Intensity levels were established using a Minolta LS-110 luminance meter. Because arrow panels are rectangular and the aperture of the LS-110 is circular, a portion of the arrow panel's background entered into the measurement (see Figure A1). The photometric levels were, therefore, established at night to ensure a uniform background for the photometer's aperture. Because luminance meters have fixed apertures, the length of the arrow and the diameter of the photometer's aperture restricted the selection of a measuring distance. Photometric measurements were taken at 457 m (1,500 ft). This distance is where the 2.1-m (7-ft) arrow fills the LS-110's one-third–deg aperture.

The research team converted the luminance measurement into an intensity-per-lamp value by dividing the measured luminance by the area contained in the aperture and dividing the result by the number of lamps in the measurement. Lamp intensity expressed in candelas was selected as the appropriate unit of measurement because it is the standardized method used to describe the characteristic distribution of light emitted from lamps.

Calculations

To calculate the total intensity of an object from the luminance measured for objects much smaller than the aperture of the luminance meter, the following equation for luminance can be used:

$$I = LA \tag{1}$$

where

I = total intensity (cd),
L = measured luminance (cd/m^2), and
A = area encompassed by the aperture at the measurement distance (m^2).

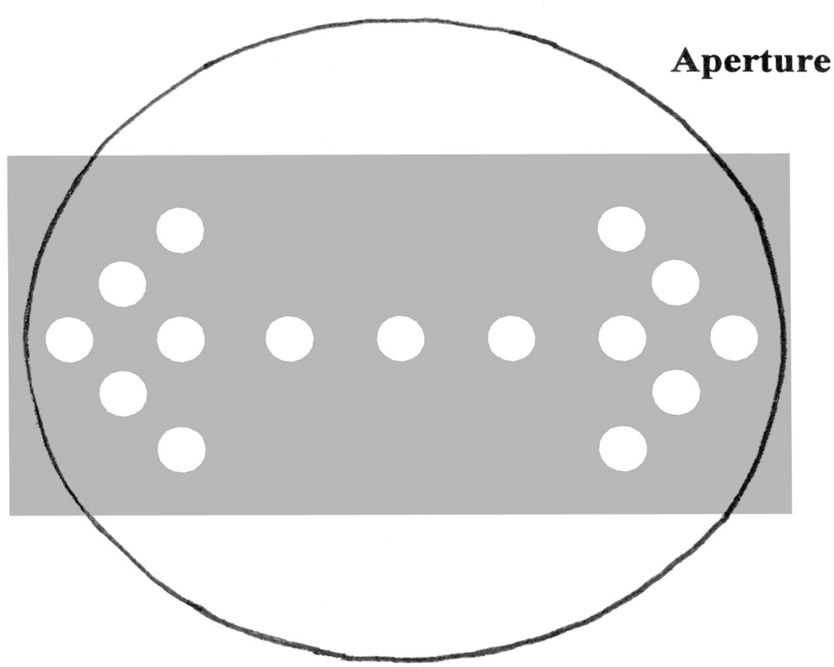

Figure A1. View of arrow panel from photometer.

The area encompassed by the aperture is found using the following equation:

$$A = [\tan(AP_{size}) \times D]^2\pi \qquad (2)$$

where

AP_{size} = aperture size (radians) and
D = distance between target and luminance meter (m).

If the target is larger than the aperture, then the area (A) is no longer the area enclosed by the aperture, but becomes the area of the target.

In the case of an arrow panel, the total intensity is the summed contribution of several lamps. To derive the intensity of an individual lamp, the total intensity of the arrow panel is divided by the number of lamps used to create the stimulus. This calculation assumes that each lamp contributes an equal portion of intensity, which is not true. There is variation in the amount of light coming from each lamp. This variation exists because some lamps are more off-axis than others are and because lamps may have slightly different colors.

Equipment

The luminance meter used during this study was a Minolta LS-110. The LS-110 has a one-third–deg aperture and a through-the-lens (TTL) viewing system that accurately indicates the area to be measured. The manual that comes with the LS-110 luminance meter states that the optical system is designed to reduce flare, so that measurements are "virtually unaffected by light sources outside the measurement area." The manual goes on to state that the actual amount of light that the meter picks up by a source outside the measurement area is less than 0.1 percent of the value that the meter would give if the source were in the measurement area. The meter uses a silicon photocell to measure the light and is filtered to closely match the CIE Relative Photooptic Luminosity Response.

The Minolta T-1 was the illuminance meter used in the validation tests. It, too, uses a silicon photocell and is filtered to closely match the CIE Relative Photo-optic Luminosity Response. The meter has a measuring range of 0.01–99,900 lux.

Validity of Photometric Measurements

Tests were conducted to validate the estimates of intensity from luminance measurements. Prior to conducting these tests, the research team checked the meter to ensure that the effects of flare were minimal by locating the aperture just outside a single lamp at a distance that included only the space between lamps.

The tests were conducted on 25- and 15-lamp arrow panels, as shown in Figure A2. The location of the arrow panel within the aperture was varied to test for uniform sensitivity of the photocell. The specific tests to validate this photometric technique were as follows:

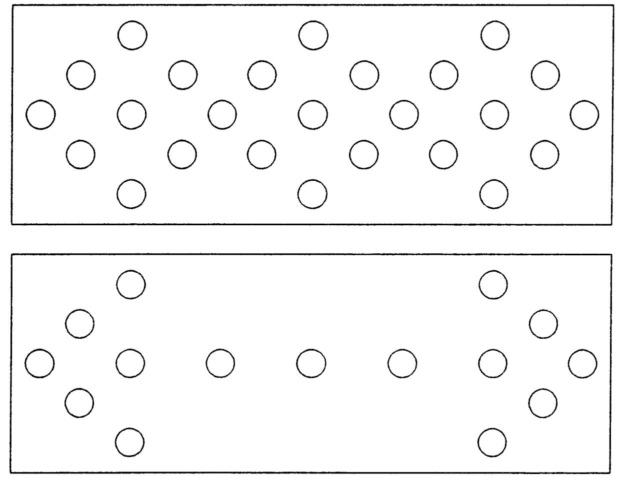

Figure A2. Arrow panel configurations with 25 and 15 lamps.

- Measure one panel mode from different distances, creating stimuli of various sizes in the aperture. Then calculate the per-lamp intensity of each mode (this intensity should remain constant).
- Measure different panel modes from a fixed distance. Then calculate the per-lamp intensity of each mode (this intensity should remain constant).
- Measure, from a fixed distance, the luminance and illuminance of different panel modes (the intensity calculated via both metrics should be the same).

The tests were repeated over several days.

A more comprehensive description of these tests can be found in M. Finkle's "Luminance-to-Intensity Measurement Method" (*Journal of Illuminating Engineering Society*, Vol. 26, No. 2, Summer 1997).

Changing Stimulus Size in Aperture Due to Distance

For this test, the measurement stimulus was an arrow panel located on a relatively straight, level section of roadway. This geometry reduced the effect of large changes in entrance angle as the distance from the arrow panel was increased. Luminance measurements of the entire panel were made at a distance greater than 457 m (1,500 ft) to decrease the size of the arrow panel relative to the aperture and to ensure that all lamps and their variation were included. As this distance was increased, the size of the stimulus in the aperture of the luminance meter was decreased. The calculated intensity of the stimulus should have remained constant regardless of the measurement distance.

Table A1 contains the results of the test. The results

TABLE A1 Changing stimulus size in aperture due to distance

Distance (m)	Luminance (cd/m^2)	Candela per Lamp (cd)	Percent of Aperture (%)
458	285	158	2.28
610	165	163	1.28
763	103	159	0.82
915	70	156	0.57
1068	50	151	0.42

indicate that the measurement procedure yielded consistent estimates of candelas per lamp. Variance in the readings is very small and could have resulted from a number of causes. The most likely cause would be small deviations from a straight-line approach to the arrow panel.

Changing Stimulus Size in Aperture at a Fixed Distance

This test was similar to the previous test in that the size of the stimulus in the aperture was varied. However, in the previous test the stimulus remained constant and distance to the arrow panel varied, whereas in this test the stimulus changed and the distance was fixed. By changing the stimulus, the amount of light filling the aperture could vary. Only the middle "diamond" of a 25-lamp arrow panel was used. Figure A3 shows the different stimuli used in the test.

The luminance meter was located 244 m (801 ft) from the arrow panel so that the "diamond" was just within the meter's aperture. Table A2 contains the results of this test. The candela per lamp is calculated from the measured luminance using Equation 1. Here again, the percent of aperture is a measure of the lighted area within the area enclosed by the aperture at the measurement distance. The results show that the greatest variance between the stimuli is 10 percent.

One explanation of why the candela-per-lamp value decreases as the number of lamps in the aperture increases is as follows: Stimulus 1 has only one lamp turned on, and, therefore, the total intensity calculated from Equation 1 is also the candela-per-lamp value. It is assumed that this stimulus is measured on-axis with the meter. When more lamps are turned on, as with the other three stimuli, the individual lamp intensities add together to produce a total intensity and, therefore, the measured luminance. Dividing Equation 1 by the number of lamps assumes that the individual contributions of all lamps are equal. This assumption is incorrect because a lamp that is on-axis with the meter gives a higher intensity than a lamp that is off-axis. As more off-axis lamps are added, this error increases.

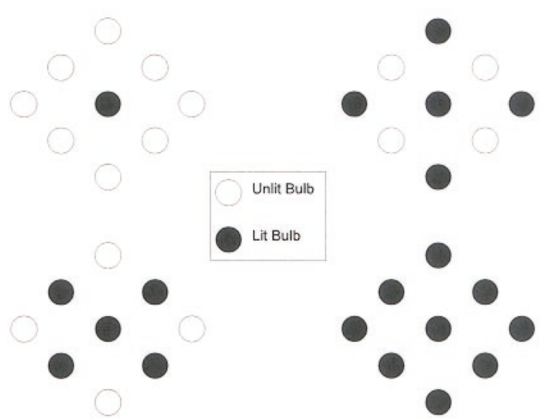

Figure A3. Different stimulus configurations tested at a fixed distance.

Using this explanation and the previous results, one can find that the expected total candela value for Stimulus 4 is closer to 1,874 cd. This value is only 5 percent off of the measured total candela value of 1,782 cd. The calculation required to find this value is as follows:

1. Subtract the total intensity of Stimulus 1 from Stimuli 2 and 3. The resulting values are "adjusted" total intensities of the off-axis portions of Stimuli 2 and 3.
2. Add the total intensity of Stimulus 1 and the "adjusted" intensities of Stimuli 2 and 3 to yield an "adjusted" value for Stimulus 4, which, in this case, is 1,874 cd.

Comparing Illuminance with Luminance

To achieve illuminance measurements high enough to make a stable comparison with luminance measures, readings were taken at 153 m (502 ft) and 61 m (200 ft) from the arrow panel. Because of the close proximity, only two stimuli were small enough to fit within the luminance meter's aperture: Stimuli 1 and 2 of the previous test. Luminance and illuminance readings were taken from the same location. Table A3 contains the total intensities calculated from illuminance and luminance at both distances.

Even though the variance in the readings is small, a large portion of the variance is because the illuminance measurements were very close to the threshold of the illuminance meter. In fact, the readings had only one significant digit. Documentation for the meter states that it is accurate to 2 percent of the CIE standard, ±1 digit in the last displayed position. This level of accuracy means that the candelas-via-lux values could vary by as much as 16 percent.

TABLE A2 Changing stimulus size in aperture at a fixed-distance (244-m, or 800-ft) stimulus

Stimulus	Luminance (cd/m^2)	Total Candela (cd)	Candela/Lamp (cd)	Percent of Aperture (%)
1 	140	221	221	0.8
2 	680	1075	215	4.0
3 	645	1020	204	4.0
4 	1130	1782	198	7.2

TABLE A3 Intensity (cd) calculated from illuminance (lux) versus intensity calculated from luminance (lum)

	61 m		153 m	
Stimulus	cd via lux	cd via lum	cd via lux	cd via lum
1 	192	214	232	247
2 	N/A (too close)	N/A (too close)	1160	1135

Conclusion

The results of the different tests satisfactorily validate the photometric procedure used to measure arrow panel signal strength at night. Until an instrument that is better suited becomes available, a luminance meter can be used for making such field measurements. However, it is unknown whether certain luminance meters may be better suited than others. For instance, the meter used in this study used a silicon photocell and not a phototransistor. A phototransistor performs differently and could alter the results of the tests. This fact, and others, must be considered before such atypical use of luminance meters becomes accepted.

APPENDIX B: RECOMMENDED SPECIFICATION FOR ADVANCED WARNING ARROW PANELS

1 Purpose

The purpose of this recommended specification is to provide the minimum and maximum photometric requirements for daytime and nighttime use of advanced warning arrow panels. This recommended specification applies to the equipment described in the next section.

2 Types of Arrow Panels

Various types of arrow panels are available, differentiated by size and number of lamps. The *Manual for Uniform Traffic Control Devices* (Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1998) specifies four different types:

- Type A for low-speed urban streets;
- Type B for intermediate-speed facilities and for maintenance or moving operations on high-speed roads;
- Type C for high-speed, high-volume construction projects; and
- Type D for use on authorized vehicles.

This recommended specification is intended for use with Type C arrow panels, but at some point may be generalized to Types A and B.

3 General Requirements

3.1 Support Panel

The support panel should be 1.22 m (48 in) high by 2.44 m (96 in) wide. The panel should contain a minimum of 15 lamps, the requirements of which are given in Section 7. The front of the panel should provide a flat black background for the lamps.

3.2 Hood Surrounds

Each lamp should be recessed mounted or equipped with a black surround of not less than 180 deg. The surround should extend a minimum of 10 cm (4 in) from the support panel or, alternatively, the lamps should be recessed at least 10 cm (4 in) into the panel.

3.3 Power Supply

The power supply should provide the unit with the power necessary for the lamps to meet the intensity requirements of Section 6. When the unit is to be operated by batteries, the power supply should provide the required current to keep the batteries in a charged state that allows the lamps to meet the intensity requirements of Section 6. (A minimum time period during which battery power supplies must maintain intensity requirements may be specified.)

3.4 Flash Rate

The arrow panel should flash at a rate of 25–40 flashes per minute with a dwell time of 50 percent of the cycle for flashing displays and 25 percent of the cycle for sequential displays.

4 Minimum Recognition Distances

The minimum required distance from the arrow panel at which a driver must be able to recognize the display mode is 457 m (1,500 ft) for roads with posted speeds above 70 km/hr and 300 m (980 ft) for roads with posted speeds of 70 km/hr and below.

5 Angularity Requirements

5.1 Useful Beam Width

The useful beam width of a lamp is defined as the portion of the lamp beam pattern that is capable of providing the required recognition distance for the arrow panel in which the lamp is installed. It is measured in terms of plus or minus a horizontal and vertical angle relative to the center of the lamp face.

5.2 General-Use Beam Width

Figure B1 shows the angular requirements for the intermediate and maximum beam-width zones that are necessary to meet driver requirements on all types of roads.

5.3 Limited-Use Beam Width

Arrow panels certified for use only on high-speed roads need only meet the angular requirements for the intermediate beam-width zone, shown in Figure B1.

6 Intensity Requirements

6.1 Luminous Intensity

The lamp-intensity requirements in Table B1 should be met during the specified operating conditions. The required angularity referenced in this table is specified in Section 5.

Nighttime maximum intensity assumes a chevron display mode. This intensity could be raised from 370 cd to 570 cd if an arrow display mode is used.

6.2 Testing Procedure

The intensity of the lamps should be tested as set forth in the most recent photometric testing standard of the Illu-

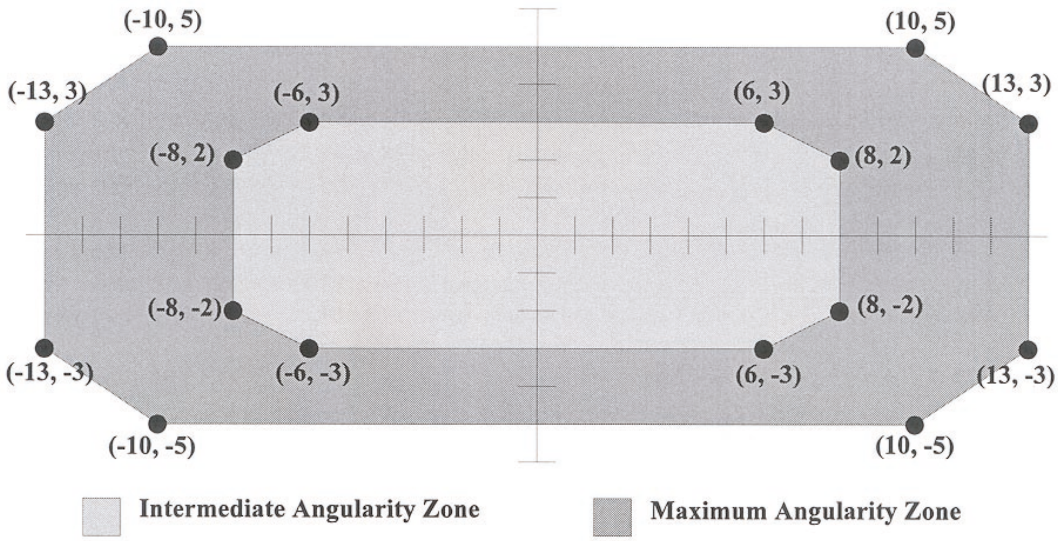

Figure B1. Beam-width zones (measurements in meters).

TABLE B1 Summary of luminous intensity requirements

Situation	Minimum On-Axis	Minimum Off-Axis	Maximum Hot Spot
Low speed, day	300 cd	60 cd	NA
High speed, day	500 cd	100 cd	NA
Low speed, night	90 cd	18 cd	370 cd
High speed, night	150 cd	30 cd	370 cd

Note: NA = not available.

minating Engineering Society or the Society of Automotive Engineers. The testing procedure should ensure that the lamps meet both the daytime and nighttime intensity levels. Lamps should be tested equipped with hoods or, if used in a recessed panel, with hoods that represent the recessed depth.

7 Lamp Requirements

7.1 Certification

The lamp should be certified for use in arrow panels by the state. This certification can be indicated through a certification label applied to the lamp or through placing the lamp on a list of certified lamps (this list would then have to be distributed throughout the state).

7.2 Lamp Size

The lamp should conform in size with either that of a PAR 46 or PAR 36 lamp, whichever the support panel is able to accept. Should other lamp sizes become available, they will be subject to the same intensity, angularity, and chromaticity requirements.

7.3 Lamp Chromaticity

Table B2 contains some recommended coordinates for the chromaticity of color for arrow panel lamps defined by the Commission Internationale de L'Eclairage (CIE) 1931 Standard Observer. These coordinates define a larger color box than the CIE box for yellow traffic signals because color discrimination for arrow panels is not as critical as color identification of traffic signals.

8 Electronic Controls

8.1 Dimming

The electronic controls should keep the intensity of the lamps at the nighttime requirement levels whenever the ambient light is at or below 215 lux. If the controls provided allow for continuous adjustment of lamp output with respect

TABLE B2 Color coordinates for arrow panel lamps using the CIE 1931 standard observer

X	Y
0.527	0.475
0.495	0.455
0.612	0.382
0.618	0.382

to ambient light level, then the lamp intensity may be linearly increased from the nighttime levels at 215 lux to the daytime levels at 35,000 lux. If continuous adjustment is not provided, then the electronic controls should keep the lamp intensity at the daytime requirement levels whenever the ambient light level is greater than 215 lux.

8.2 Display Modes

The electronic controls should permit the arrow panel to display (a) a flashing or sequential left and right arrow or left and right sequential chevrons, (b) double flashing arrows, and (c) a caution mode. The caution mode should consist of energizing the four outermost corners of the double-arrow mode.

8.3 Voltage Testing

The electronic controls should permit the user to test whether the system is supplying the lamps with the voltage required to meet the intensity requirements specified in Section 6. The user must be able to test both daytime and nighttime lamp supply voltage. If the arrow panel is equipped with a battery bank, the system must also allow the user to check the charge state.

Lamp voltage levels required to meet the specified intensity levels of Section 6.1 will vary among different types of lamps. Users should consider providing their personnel with a table of voltage values for the lamps they may encounter.

APPENDIX C: MAINTENANCE PERSONNEL PROCEDURES TO ENSURE PROPER VISIBILITY OF ARROW PANEL

The procedures for maintenance personnel to follow before delivery of arrow panels to the field include checks of the arrow panel operation (including lamp and voltage verification), verification of the arrow panel visibility (including a subjective evaluation or a field photometric performance test), and, for special-purpose, narrow-beam panels, a determination that the site geometry will not require a general-purpose arrow panel.

Arrow Panel Operation

Certain operational checks need to be made before the arrow panel is delivered and set up in the field. These checks are to ensure that the arrow panel is capable of providing the necessary levels of recognition and conspicuity for the current situation. The list of checks can be divided into two groups: lamp checks and voltage checks.

Lamp Checks

The lamps used in the arrow panel are vital to the panel's visibility. Each lamp should be certified by a state. A certification label is recommended to identify the lamp beam width and the daytime and nighttime operating voltages. The following is a list of checks that should be completed for each lamp. If a lamp fails any one of these tests, it should be considered "not functioning."

- The lamp should be certified as general purpose or narrow-beam-width only. Narrow-beam-width lamps must not be used in general-purpose arrow panels.
- The lamp should be the same as every other lamp on the panel.
- The lamp should be functional and should not appear weak compared with the other lamps on the arrow panel.
- The lens of the lamp should not have any obscuring material on its face or condensation inside its housing. Any dirt should be removed.
- The lamp should be seated properly in its socket. Use the indications on the lamp, such as the manufacturer name or even the word "TOP," to determine proper orientation.

Lamps that fail to meet the previous criteria are considered "not functioning." Arrow panels to be used in the flashing-arrow mode should have no more than one lamp "not functioning" in the stem and none in the head. In the chevron mode, not more than one lamp may be "not functioning" in any chevron segment. In caution mode, a minimum of four lamps should be functioning properly. If the arrow panel contains more "not functioning" lamps than allowed, then steps must be taken to correct the "not functioning" lamps.

Voltage Checks

An arrow panel operates at a minimum of two different voltages: a daytime voltage and a nighttime voltage. The type of lamp used in the arrow panel determines these voltages. The particular voltage levels that a lamp requires should be available either on the state certification label of the lamp or in the lamp manufacturer's literature. The voltage of interest is not the supply voltage of the batteries, but the voltage that is actually delivered to the lamps. If the arrow panel makes no direct provision for measuring this voltage, such as a separate voltmeter, then a handheld voltmeter should be used. The meter should be capable of measuring pulse-width-modulated signals. Choose a location that is easily accessible, such as the terminals of a lamp or the location where the lamp power cables connect to the controller. After compliance with the voltage requirements has been determined, the following checks should be made:

- The measured voltage at the daytime setting should be within the range specified for the type of lamps used in the arrow panel.
- The nighttime dimming control should be operational. When the ambient illumination falls below the specified level, the arrow panel should operate at the nighttime voltage level. Visual testing should be used to verify that the lamps are dimmed when the photocell is covered, which should put the arrow panel into nighttime mode.
- The measured voltage at the nighttime setting should be within the range specified for the type of lamps used in the arrow panel. If the arrow panel makes no provisions for directly testing the nighttime voltage, covering the photocell should put the arrow panel in its nighttime mode and the voltage level can be measured in the same way as the daytime voltage.

Guidelines for Determining Site Beam-Width Requirements

If special-purpose or narrow-beam panels are available, the guidelines and classification factors discussed in this section will assist in determining whether such panels may be used. If the jurisdiction certifies only one type of arrow panel, these guidelines will still be helpful in determining whether a special situation exists. Classification of each arrow panel location may be completed by maintenance personnel so that the appropriate arrow panel is sent to the field for each placement. If the maintenance personnel have no knowledge of the site requirements, they may send either a general-purpose panel or both general-purpose and narrow-beam panels to the field, where the field personnel will use the guidelines to assist in determining which panels to use at which locations.

Classification Factors

The simplest approach to site classification is to attempt to classify each site as a narrow-beam situation. If the site cannot be classified as narrow beam, then the site will require a general-purpose arrow panel or the site will be a special situation. The drive-through inspection conducted by field personnel may show the site to be a special situation that should be dealt with accordingly by an experienced traffic engineer.

Because of the limited angularity in which narrow-beam lamps provide adequate recognition, it is very important that the exact nature of the planned arrow panel location be known prior to installation. Design plans for the section of the highway in question provide the best source of information necessary to determine whether a general-purpose arrow panel will be required. An alternative to a review of site plans is a site visit and visual inspection. Also of great importance is the type of application for which the arrow panel will be employed. Some applications require general-purpose arrow panels regardless of roadway geometry.

The following sections describe the factors to be considered in the classification of a situation as requiring a narrow- or wide-beam arrow panel. If a narrow-beam arrow panel cannot satisfy the requirement of any one of these factors, a wide-beam arrow panel should be used.

Roadway Geometry. Horizontal alignment plays a crucial role in determining the viewing angle to the arrow panel. The viewing angle is highly important because, with all present technologies, light intensity diminishes rapidly as this angle increases. In some cases, roadway alignments having horizontal or vertical curves that are modest may accommodate narrow-beam lamps, particularly if there is some length of straight road leading up to the arrow panel. Aiming the arrow panel into a horizontal curve rather than aiming it perpendicular to the roadway can sometimes alleviate problems caused by otherwise unacceptable horizontal curves. In situations with extreme vertical curvature, narrow-beam arrow panels may also fail to meet visibility requirements.

In some situations, when geometric conditions prevent the use of narrow-beam lamps, the arrow panel and accompanying lane closure may be moved upstream to a location more suitable for narrow-beam lamps.

Access Ramps. On-ramps are a specific example of roadway geometry that presents problems for the use of narrow-beam arrow panels. The viewing angle for vehicles entering the highway is often greater than narrow-beam lamps can accommodate. Thus, any on-ramps located in the vicinity of the arrow panels merit special consideration to determine the possibility of using narrow-beam arrow panels. An exception to this situation arises when the arrow panel will be focused on or dedicated to only one of several lanes (e.g., an on-ramp) and when it is desirable not to have the arrow panel viewed by mainstream traffic. In this situation, a narrow-beam arrow panel would have a clear advantage.

Urban Streets. The visibility of arrow panels on urban streets can be affected by geometry conditions similar to those for highway on-ramps. In the urban setting, the likelihood exists that vehicles will be turning from cross streets, driveways, and parking lots onto the street where the arrow panel is located. The viewing angle for these vehicles is such that a general-purpose arrow panel should be used to ensure the greatest potential for the arrow panel to be seen.

Moving Operations. Spot maintenance, utility operations, and similar applications that employ arrow panels are inappropriate for narrow-beam lamps. These applications include those that involve moving maintenance operations, such as with lane striping, as well as those that consist of several short-term setups along a stretch of highway. These types of applications do not allow for the precise setup of the arrow panel that is required to ensure adequate recognition from narrow-beam lamps.

Multiple-Lane Closure. On wide roadways (i.e., roadways with more than three lanes in one direction) where multiple lanes will be closed, narrow-beam arrow panels may not provide adequate recognition distance or the necessary level of conspicuity.

Special Situations. A special situation is one that may result in a work-zone placement for which the arrow panel beam-pattern requirements are more extreme than the basic situations assumed by the sample specification. All of the situations that result in narrow-beam lamps being inappropriate are candidates for special situations. Extreme roadway geometry that is greater than AASHTO standards, situations with access ramps, multiple lane closures, urban streets, and moving operations are all conditions that make narrow-beam arrow panels inappropriate and that might create a special situation, a condition in which even a general-purpose arrow panel might not be appropriate.

The general-purpose arrow panel should be satisfactory in many of these conditions; however, all of these conditions involve unpredictable variability, requiring that an experienced traffic engineer review them. Extreme geometry will result in reduced speed, insufficient lateral clearance to produce a line of sight at 457 m (1,500 ft), or both. The beam width required by access ramps, multiple lane closures, moving operations, and urban streets may not be predicted. For this reason, in special situations, the arrow panel should only be used to supplement other traffic-control devices and the traffic engineer should design a complete traffic-control plan.

Summary of Site Classification Guidelines. The guidelines for the classification of a site should not be considered all inclusive with respect to factors that can be used to determine the required arrow panel beam pattern. Rather, the guidelines are intended to provide a framework to begin the process necessary to determine whether a narrow-beam arrow panel will provide sufficient visibility at a particular site or whether the site is a special situation that should be closely reviewed by an experienced traffic engineer.

Even under ideal geometric conditions, narrow-beam arrow panels must be carefully set up to ensure that adequate visibility will be provided. In terms of arrow panel aiming, any deviation from the correct setup dramatically reduces the visibility distance of the arrow panel. Furthermore, even if the use of a narrow-beam arrow panel is rejected in favor of a general-purpose arrow panel, the procedures in Appendix D must be followed. Remember that even general-purpose arrow panels will not meet driver visibility requirements under all conditions.

APPENDIX D: PROCEDURES FOR FIELD PERSONNEL TO DEPLOY TO MAINTAIN IN-SERVICE ARROW PANEL VISIBILITY

These procedures are for use by field personnel. If the maintenance yard has provided both general-purpose and narrow-beam arrow panels, the field personnel should refer to the guidelines for determination of site beam-width requirements for guidance as to which panel to use in which location. Three field procedures have been established. One procedure deals with proper setup and aiming of the arrow panel. Another procedure for visibility verification provides a method by which field personnel can establish that the panel being used is operating properly, is aimed correctly, and has adequate beam width for the demands of the site. A panel whose visibility is not verified may need to be moved, aimed differently, replaced with a wide-beam panel, or reclassified as a special situation. In addition to the visibility verification, a third procedure is included for lamp verification and replacement. The lamp verification procedure ensures that lamps on the panel are operating properly and provides some guidance for lamp replacement.

Aiming and Setup of Arrow Panels

Equally important to having a properly maintained arrow panel is its placement and aiming. The arrow panel should be placed according to state DOT guidelines for construction work-zone setup. The arrow panel should then be aimed toward the traffic it is attempting to inform of the lane closure. The objective is to make certain that the maximum light intensity is directed toward the oncoming traffic. This objective becomes especially critical in the areas of both horizontal and vertical curves. When placing an arrow panel, one should strive to aim the arrow panel at a point at least as far away as the DSD (457 m [1,500 ft] on high-speed roads) prior to the lane closure. Aiming should be done using the aiming device on the panel support structure. If the arrow panel does not have an aiming device, an inexpensive small caliber rifle scope may be used for this purpose. Once properly setup, the position of the arrow panel should be marked so that routine maintenance checks can verify the arrow panel placement.

Visibility Verification

Visibility verification needs to be done in the field in order to represent the same conditions with which the driver will see the arrow panel. Two methods are offered: (a) a method that requires only a subjective visibility rating and (b) a method that estimates light intensity using a relatively inexpensive luminance meter. Of primary concern is the angle at which the arrow panel is viewed.

Subjective Evaluation

After the operation of the arrow panel has been verified, an inspection drive-through should be made to verify that the arrow panel display is visible throughout the visibility distance of the site. The visibility distance is the distance interval between the arrow panel and the observer. In this distance, the arrow panel display should be clearly recognized. The upper end of the interval is the required DSD for the road speed condition, while the lower end is the minimum stopping sight distance (SSD) based on the road speed condition.

The following procedure will determine whether an arrow panel has been properly set up and aimed. Additionally, if the panel is certified as narrow beam, the procedure will determine whether a narrow-beam panel may be used at this site or whether a special-purpose arrow panel should be used instead. In choosing the time of day to perform this evaluation, field personnel should be aware that sun conditions affect visibility. When possible, the evaluation should be performed when the sun is out, not under overcast conditions. By choosing a time of day when the sun is directly on the arrow panel, the field personnel can check arrow panel visibility under the worst conditions.

The procedure for a drive-through inspection is simple. The inspector approaches the arrow panel from a distance that is twice the required DSD for the site and travels toward the arrow panel until the direction of the displayed arrow or chevron is clearly visible. If the arrow panel display does not become clearly visible to the inspector at the required DSD, then the arrow panel fails the drive-through inspection. If the panel display is clearly visible at the required DSD, the inspector should continue to drive toward the panel, making certain that the panel display remains clearly visible until the minimum SSD is reached. The recommended values for DSD and SSD are shown in Table D1.

The most difficult part of this procedure is knowing when a panel is clearly visible. For this purpose, the subjective visibility scale (see Table D2) will be of help. There should be no difficulty in identifying arrow panels that are "perfect," "poor," or "very poor" because it is obvious when the inspector has no idea or is guessing about what is on the panel or if the panel could not be any better. The difference between "clear" and "fair" is less obvious, but experience will help in making this distinction. If there is some doubt about whether the arrow panel is "clear" or "fair," the inspector should do the test under adverse sun conditions. If the inspector can definitely tell the direction of the arrow under these conditions, then the arrow panel visibility is acceptable.

There are two reasons why the panel display may not be clearly visible at DSD. First, the arrow panel itself may not be visible because there is no line of sight to the panel. The

TABLE D1 Recommended DSD and SSD

Posted Speed	DSD	SSD
> 45 mph	457 m (1,500 ft)	183 m (600 ft)
< 45 mph	300 m (984 ft)	91 m (300 ft)

TABLE D2 Subjective visibility scale

Arrow Panel Visibility Scale		
Perfect	5	Could Not Be Better
Clear	4	It Was Obvious
Fair	3	Could Just Make it Out
Poor	2	Could Guess
Very Poor	1	Had No Idea

absence of a line of sight may be caused by the presence of trees, buildings, or other obstructions or the existence of horizontal curvature. If there is not a line of sight to the arrow panel greater than the required DSD, then the location is considered a special situation. In this case, either the arrow panel should be moved or the site should be treated as a special situation for which the services of an experienced traffic engineer should be sought.

If there is an adequate line of sight but the direction of the arrow panel display mode is not clearly visible, then either the beam width is not adequate or the panel was not properly aimed or set up. If the particular site is not typical for some reason, such as extreme geometry, the arrow panel should be aimed to optimize its visibility range and the drive-through inspection should be repeated.

If, after being aimed, the arrow panel display is still not clearly visible throughout the required distance interval, then either the arrow panel location should be moved upstream of the lane closure or, if a narrow-beam panel is being used, a general-purpose panel should be sought. If these alternatives are not available, the site should be treated as a special situation for which the services of an experienced traffic engineer should be sought.

The drive-through inspection should be repeated daily throughout the life of the project. If ever the panel fails this inspection, the panel should be checked to determine the cause of the visibility loss. Individual lamps should be examined to determine whether lamp burnout has occurred. The panel should be checked for recent damage, and the batteries should be recharged if necessary. If all of the lamps appear to be operational and there is no apparent reason for the loss in visibility, the panel should be replaced and returned to the yard for a check of its voltage levels, charging system, and possibly lamp replacement.

Photometric Evaluation

An alternative method of testing the visibility of an arrow panel is to measure the luminous intensity emitted by the arrow panel at the required DSD and SSD. One method for taking this measurement involves measuring the luminance of the entire arrow panel with a luminance meter. This measurement requires a luminance meter with at least a 1-deg aperture because meters with smaller apertures would be unable to view the entire arrow panel at all the required DSD and SSD locations. (In fact, a 1-deg aperture fails to view the entire arrow panel at distances closer than 122 m [400 ft]). The procedure for this process is as follows:

1. With the meter attached to a tripod for stability, measure the luminance of the arrow panel with the lamps on and off. When taking the "on" measurement, set the meter to measure the peak reading. This setting overcomes the flashing nature of the arrow panel.
2. Subtract the "off" measure from the "on" measure.
3. Check the luminance measurement against the recommended values in Table D3.

Because the recommended values in Table D3 are per lamp, all measurements must be (a) divided by the number of lamps that are within the aperture and lit and then (b) compared with the appropriate value in Table D3. Because the SSD for low-speed roads is less than 122 m (400 ft), the aperture must be larger than 1 deg to include all the lamps. Because greater accuracy is obtained when the arrow panel fills the aperture, the larger aperture should not be used at distances greater than 122 m. If the largest aperture will not encompass all the lamps that are lit, multiple measurements may be made, each including a different set

TABLE D3 Recommended luminance

Type of Road	SSD	DSD
High-speed road	12 cd/m^2 at 183 m (600 ft)	2 cd/m^2 at 457 m (1500 ft)
Low-speed road	30 cd/m^2 at 91 m (300 ft)	2.8 cd/m^2 at 300 m (984 ft)

Note: These measurements are per lamp and should be multiplied by the number of lamps that are lit.

of lamps. Divide each measurement by the number of lamps being measured, and compare the average value with the appropriate value in Table D3. While not an ideal solution, the approximation that this procedure provides, coupled with a drive-through subjective evaluation, will provide a reasonable basis to ensure that driver needs are met.

Lamp Verification and Replacement

The lamps used in the arrow panel are vital to the panel's visibility. An inspector should check the functioning of each lamp at least once each day throughout the life of the project by repeating the visibility verification and again whenever scheduled maintenance is conducted. Whoever has responsibility for traffic-control devices in the work zone should check the arrow panel each day to make certain that each lamp is visible at the distance specified in the visibility verification.

The following checks should be made whenever a lamp is replaced:

- The lamp should be certified by the state as general purpose or narrow-beam-width only. Narrow-beam-width lamps must not be used in general-purpose arrow panels.
- The lamp should be seated properly in its socket. Use the indications on the lamp, such as the manufacturer name or even the word "TOP," to determine proper orientation.
- After replacement, the lamp should not appear weak compared with the other lamps on the arrow panel.

The following checks should be made as part of any scheduled maintenance on the arrow panel:

- The lens of the lamp should not have any obscuring material on its face or condensation inside its housing. Any dirt should be removed.
- Each lamp should not appear weak compared with the other lamps on the arrow panel.

Any lamps that fail to meet the previous criteria should be considered "not functioning." Arrow panels to be used in the flashing-arrow mode should have no more than two lamps "not functioning" in the stem and none in the head. In the chevron mode, not more than one lamp may be "not functioning" in any chevron segment. In caution mode, a minimum of four lamps should be functioning properly. If the arrow panel contains more "not functioning" lamps than allowed, then steps must be taken to correct the "not functioning" lamps.

Voltage Checks

Voltage checks should also be made as part of any scheduled maintenance on the arrow panel. An arrow panel operates at a minimum of two different voltages: a daytime voltage and a nighttime voltage. The type of lamp used in the arrow panel determines these voltages. The particular voltage levels a lamp requires can be found either on the state certification label of the lamp or in the lamp manufacturer's literature. The voltage of interest is not the supply voltage of the batteries, but the voltage that is actually delivered to the lamps. After adherence to the voltage requirements has been determined, the following three checks should be made (for reasons of safety, only the second check need be made in the field if the arrow panel makes no direct provision for measuring these voltages):

- The measured voltage at the daytime setting should be within the range specified for the type of lamps used in the arrow panel.
- The nighttime dimming control should be operational. When the ambient illumination falls below the specified level, the arrow panel should operate at the nighttime voltage level. Visual testing should be used to verify that the lamps are dimmed when the photocell is covered, which should put the arrow panel into nighttime mode.
- The measured voltage at the nighttime setting should be within the range specified for the type of lamps used in the arrow panel. If the arrow panel makes no provisions for directly testing the nighttime voltage, covering the photocell should put the arrow panel in its nighttime mode and the voltage level can be measured in the same way as the daytime voltage.