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PHOTOMETRIC REQUIREMENTS FOR ARROW PANELS

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16. Abstract

Arrow panels are often used in work zones to inform drivers of the need for a lane change or caution on the part of the driver. The *Manual on Uniform Traffic Control Devices* (MUTCD) requires that Type C arrow panels have a minimum legibility distance of 1 mile. The MUTCD does not provide an objective means for determining whether an arrow panel meets this criteria, nor are there industry photometric standards for message panels. The performance of Type C arrow panels was reviewed and photometric standards were developed to establish performance requirements. Photometric test methods were developed and recommended for use in evaluating the performance of arrow panels. This report provides documentation for the standards and procedures recommended, including results and descriptions of the field testing performed.

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CHAPTER 1. INTRODUCTION

The objective of this research project was to develop photometric test methods that provide an objective means of ensuring that arrow panels used on TxDOT projects meet the visibility needs of drivers. Additionally, TxDOT's current purchase specification for arrow panels was reviewed for potential changes. A review of the visual characteristics of arrow panels was undertaken and recommendations developed. The focus of the project was a Type C arrow panel, as defined in the *Texas Manual on Uniform Traffic Control Devices for Streets and Highways – Part VI* (*1*).

NEED FOR PROJECT

Arrow panels are often used in work zones to communicate important information to road users, indicating the need for a lane change or caution on the part of the driver. Although arrow panels have been used in traffic control applications for many years, there are no established photometric standards for the device that can be used as the basis for a procurement specification. The only provision related to visibility of arrow panels is a requirement in the *Texas Manual on Uniform Traffic Control Devices for Streets and Highways – Part VI* (*1*) that indicates the minimum legibility of a Type C panel is one mile. However, the manual does not provide instructions that indicate how that legibility distance is to be measured.

As a result of the lack of detailed measurement requirements, transportation agencies experience difficulty developing specifications that ensure all arrow panels purchased by the agency will communicate the desired information to drivers in an effective and consistent manner. This report presents the Texas Transportation Institute's (TTI) recommendations for test methods for measuring the photometric properties of Type C arrow panels. The intent of the test method is to provide TxDOT with a measurable criteria for qualifying arrow panels for use on TxDOT projects.

ORGANIZATION OF THE REPORT

To assist the reader, a brief description of this report is provided.

Chapter 1. A brief introduction of TxDOT's needs regarding arrow panels and the basic objective of the project;
Chapter 2. A review of background information available regarding arrow panels, focusing on visibility and conspicuity;
Chapter 3. An examination of angularity is provided, indicating angularity situations that might be encountered in the field;
Chapter 4. A review of a night visibility study conducted through pilot stages regarding arrow panel visibility;
Chapter 5. A review of a day visibility study conducted regarding arrow panel conspicuity;
Chapter 6. Recommendations and conclusions reached as a result of the studies and reviews conducted;

Chapter 7.	A critical review of and recommendation for changes in TxDOT's purchase specification; and
Chapter 8.	Recommended test procedures for use in the procurement and operation of arrow panels.

CHAPTER 2. ARROW PANEL VISIBILITY AND CONSPICUITY

Advance warning arrow panels are work zone traffic control devices that have been in use since the 1970s. Historically, arrow panels have been diesel generator powered devices that utilize incandescent lamps. As newer technology involving solar power and light emitting diode (LED) lamps emerges, concerns have arisen surrounding the effectiveness of the newer technologies. A large portion of previous research has focused on arrow panel placement within the work zone and their effectiveness in directing traffic to a different lane. Few research projects have addressed the performance of arrow panels with respect to the photometric properties.

Recently, a research project sponsored by the National Cooperative Highway Research Program (NCHRP) was conducted to evaluate the factors affecting the detection and recognition of arrow panels. Specifically, this research focused on determining the minimum photometric levels required for arrow panel recognition during the day and the maximum levels necessary to control glare at night. The NCHRP project (5-14) was conducted by The Last Resource, Inc. (LRI) who is the subcontractor for TTI on this project. The results of this research were the development of specifications and application guidelines for Type C arrow panels. Table 1 summarizes these recommendations, based on decision sight distance requirements for high-speed roads and the assumption that the arrow panel display must be properly identified by 95 percent of older drivers at 1500 ft.

Table 1. Summary of LRI Recommended Luminous Intensity Requirements (*2*).

Time of Day	Speed (mph)	Minimum On-Axis (candela/lamp)	Minimum Off-Axis (candela/lamp)	Maximum Hot Spot [a] (candela/lamp)
Day	≥ 45	500	100	NA
Night	≥ 45	150	30	370

[a] Maximum intensity requirement must be met at the lamp "hot spot," which may or may not be on-axis
NA Not applicable

The *Manual of Uniform Traffic Control Devices for Streets and Highways* (MUTCD) requires that a Type C arrow panel be legible from a distance of one mile (*3*). Prior to the NCHRP project described previously, there was little research to support the use of this distance. A paper addressing the human factors considerations of arrow panels (*4*) indicated that the optimal performance standard for high traffic density conditions should be that drivers identify the presence of flashing lights at 1.5 miles, and that recognition of the arrow symbol and direction occur at one mile. However, the researchers state that the study did not directly evaluate the recognition distance of the arrow symbol. Instead, the one-mile recognition distance was based on informal observations. It appears that the one-mile legibility requirement was implemented because the arrow panels of that time (i.e., diesel-powered) were legible to most individuals at one mile. With the advent of the use of solar power, arrow panels have had more difficulty meeting the legibility requirement and manufacturers have begun to question the origin and validity of the one-mile requirement for Type C arrow message panels.

The NCHRP arrow panel researchers (*2*) concluded that it was unnecessary for an arrow panel to have a mile of recognition distance and that often a mile of sight distance was not available. Instead, researchers substituted a minimum recognition distance of 1500 ft, which is consistent with the decision sight distance for high-speed roads in the original decision sight distance research (*5*) and the American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets* (*6*). Unlike the MUTCD criterion of one mile, the NCHRP research recommended 1500 ft of legibility for older drivers, from behind a windshield, and at any angle at which the panel might be viewed. It is thought that any arrow panel that meets this criteria (which is 20 times the threshold criteria) will also meet the one-mile criteria of the MUTCD if viewed on-axis, without a windshield, and by an observer with good visual acuity. The converse however is not true. Arrow panels that meet the MUTCD criteria may not meet the NCHRP 5-14 criteria, primarily because of limited angularity.

DECISION SIGHT DISTANCE

The concept of decision sight distance (DSD) was first addressed in a 1966 paper by Gordon (*7*). In his paper, Gordon discussed the concept of "perceptual anticipation." The concern was that the existing stopping sight distance values were too short for situations that required high decision complexity. Building on Gordon's argument, Leisch studied this concept further and defined the term "anticipatory sight distance" (*8*). This distance provides the necessary time for drivers to anticipate changes in design features (such as intersections, interchanges, lane drops, etc.) or a potential hazard in the roadway and perform the necessary maneuvers.

The term "decision sight distance" was first defined by Alexander and Lunenfeld (*9*). In the 1994 *Green Book*, decision sight distance is defined as follows (*6*):

> "...distance required for a driver to detect an unexpected or otherwise difficult-to-perceive information source or hazard in a roadway environment that may be visually cluttered, recognize the hazard or its potential threat, select an appropriate speed and path, and initiate and complete the required safety maneuver safely and efficiently."

Guidelines on DSD values were developed in a 1978 FHWA study by McGee, et al. (*5*). Recommended values for DSD were developed based on the hazard-avoidance model. This model was developed and modified in previous research efforts (*10, 11, 12*) and consists of the following six variables:

1. sighting - baseline time point at which the hazard is within the driver's sight line;
2. detection - time for driver's eyes to fixate on the hazard;
3. recognition - time for brain to translate image and recognize hazard;
4. decision - time for driver to analyze alternative courses and select one;
5. response - time for driver to initiate response; and
6. maneuver - time for driver to accomplish a change in path and/or speed.

The total time required from the moment that the hazard is visible to completion of maneuver is determined by adding all of the above variables together. Recommended values for each of the variables in the hazard-avoidance model were obtained from existing literature and then validated through field studies. The recommendations were first adopted and introduced in the 1984 AASHTO *Green Book* (*13*). They were updated in the 1990 *Green Book* (*14*) and remained unchanged in the 1994 revision.

The 1994 *Green Book* recommends that DSD be provided when drivers must make complex or instantaneous decisions, when information is difficult to perceive, or when unexpected or unusual maneuvers are required. Recommended values for DSD are shown in Table 2. These values are substantially greater than stopping sight distance because of the additional time allowed to maneuver a vehicle. The recommendations in this table are based on the location of the road (urban, suburban, or rural) and the type of maneuver required (change speed, path, or direction).

Since arrow panels serve as warnings of approaching hazards (i.e., lane closures), their displays must be recognizable from the recommended DSD values. As shown in Table 2, DSD increases as the design speed increases and as the location of the road changes from rural to urban. Thus, the DSD for the worst-case scenario (high speeds [i.e., 70 mph] and an urban location [i.e., E]) is 1450 ft.

Table 2. Recommended Decision Sight Distance Values (*6*, *14*).

Design Speed (mph)	Decision Sight Distance for Avoidance Maneuver (ft) [a]				
	A	B	C	D	E
30	220	500	450	500	625
40	345	725	600	725	825
50	500	975	750	900	1025
60	680	1300	1000	1150	1275
70	900	1525	1100	1300	1450

[a] A-Stop on rural road; B-Stop on urban road; C-Speed/path/direction change on rural road; D-Speed/path/direction change on suburban road; E-Speed/path/direction change on urban road

Table 2 supports the use of 1500 ft as the minimum distance that the arrow panel display should be recognized. While arrow panels should have sufficient brightness to be detectable at one mile, available sight distance and off-axis viewing may limit the distance at which it is practical to achieve recognition. Thus, the 1500 ft minimum criterion is appropriate for assessing available sight distance and off-axis intensity of the lamps.

PHOTOMETRIC TERMS AND TECHNIQUES

Photometry is a science that deals with measuring the intensity of light. As stated earlier, photometric characteristics of arrow panels have just recently begun to be investigated with the proliferation of solar and LED technologies. Throughout this report various photometric terms will be used. A few of the more common terms are described below.

- Brightness is a subjective term that refers to the attribute of light sensation by which a stimulus appears more or less intense or to emit more or less light.
- Illuminance (E) is the amount of light falling upon an object. It is derived from luminous intensity by the "inverse square law" ($E=I/d^2$) where d is distance. It is expressed in foot candles (fc) or lux (lx).
- Luminance (L) is the measure of light reflected from a surface or emitted by a light source, roughly equated to "brightness." It is not affected by distance and is derived from luminous intensity by dividing the luminous intensity by the source area. It is expressed in foot Lamberts (fL) or candelas per meter squared (cd/m^2).
- Luminous intensity (I) is a measure of the strength of a light source. It is expressed in candelas (cd), and is sometimes referred to as a candlepower.

Illuminance is measured with an illuminance meter. This is typically a small handheld device similar to what one is accustomed to seeing a photographer use. In the LRI study, an illuminance meter was used to verify the luminance-to-intensity conversion that will be detailed shortly.

Luminance is measured with a luminance meter. Most, if not all, luminance meters apply a weighting function (photopic luminous response curve) to the spectral power distribution of light being measured to render a measure of the perceived brightness of light. A luminance meter is different from an illuminance meter because it does not have a sensor area that a person places at the point to be measured. Instead, the luminance meters used in both the LRI research and the study documented in this report have "through the lens" capabilities that allow the researcher to focus the meter on the target to be measured. These "through the lens" meters are essential to the luminance-to-intensity method because they have a targeting aperture in which readings are recorded. Other types of luminance meters exist; however, none have been applied to arrow panel research at this time.

Luminance to Intensity Measurement Method

In the NCHRP arrow panel research (*2*), as well as an Illuminating Engineering Society of North America (IESNA) paper (*15*), Finkle introduced the luminance to intensity measurement method. This method presents the opportunity for the investigator to evaluate a light source (i.e., arrow panel) from the point of view of the observer or driver. Thus, an arrow panel can be photometrically evaluated at the applicable decision sight distance using Finkle's method. In addition, this new technique is imperative to the photometric evaluation of arrow panels because an illuminance meter measurement would be impractical at the distances involved due to ambient light (*15*). Instead, a luminance meter is used to estimate the source intensity of an arrow panel. Using a "through the lens" luminance meter an investigator targets the arrow panel so that the arrow panel display fills the targeting aperture and measures the luminance (Figure 1).

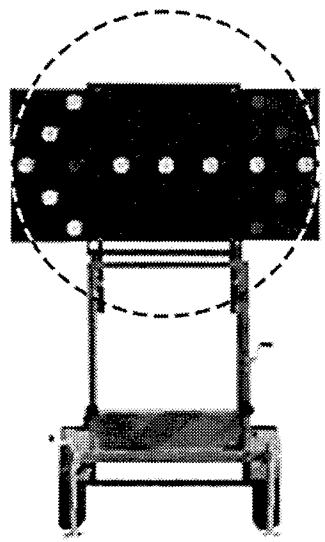


Figure 1. Arrow Panel within Luminance Meter Aperture.

After the luminance of the target arrow panel is recorded, the luminous intensity of the panel can be calculated through the use of the following formulae *(15)*:

$$I = L * A \qquad (1)$$

where: I = total intensity (cd)
L = measured luminance (cd/m^2)
A = area of the luminance meter aperture at target distance (m^2)

$$A = [\tan(APsize) * D/2]^2 * \Pi \qquad (2)$$

where: APsize = aperture size (radians)
D = distance between target and luminance meter (m)

As seen in Figure 1, the target aperture is not entirely filled by the arrow panel; thus, ambient or stray light may enter the meter making it necessary to take both a "target on" measurement and a "target off" measurement. The luminance measurement of the arrow panel is then the difference between two distinct luminance readings. Once the difference is obtained it can be entered into equation 1. This on/off measurement technique is necessary when taking readings during the day, or when a uniform black background cannot be provided for the arrow panel during nighttime testing.

The luminance to intensity measurement is a new estimation technique for luminous intensity estimation of field light sources. The measurement technique and calculations have been validated in laboratory experimentation as well as in the field evaluation of arrow panels during the NCHRP research (*2*) and in a symbolic traffic signal study sponsored by the Federal Highway Administration (*15*). Although nighttime measurements are preferred by TTI researchers because the background luminance is not as variant as during the day, the FHWA study concluded that daytime luminous intensity levels can be calculated from luminance measurements as accurately as nighttime intensities (*15*).

ADVANCED WARNING ARROW PANEL VISIBILITY – NCHRP 5-14 (*2*)

This report was prepared by LRI in December of 1996. The LRI research consisted of multiple studies that when combined allowed them to develop the photometric requirements documented in Table 1.

Laboratory Study

In the laboratory study, LRI evaluated the affects of the internal display characteristics of the arrow panel. This was done in an effort to determine the arrow panel characteristics that do not affect the recognition of the arrow panel message. The laboratory study utilized a simulated arrow panel on a personal computer. LRI researchers were able to investigate the effects of arrow and chevron stroke width and pixel density using the simulated arrow panel. The simulated conditions represent nighttime arrow panel usage where the arrow panel is operating well above the recognition threshold for both size and luminance. This study determined that a flashing arrow is the preferred display mode when compared with the chevron display. In addition, this study concluded that lamp size does not have any practical affect on arrow panel recognition.

Daytime Evaluations

Static Field Study

The static daytime field study was designed to examine the minimum intensity requirements in a controlled, but natural, environment. The minimum and optimum luminous intensity levels for both arrow displays and chevron displays were investigated in this study. Subjects were situated 1500 ft from a test arrow panel and presented with various displays that had differing luminance intensity levels. A subject was presented with high and low level displays and asked to correctly identify the display while the threshold intensity level was "bracketed." After the level was bracketed, the displays were presented in a stepwise manner from high to low in order to determine the threshold recognition level. This study surveyed 52 subjects, of whom 37 were older than 65 years old. This study concluded that there were no significant differences between young and old subjects. In addition, there was no significant difference between the arrow and chevron display modes. Based on the static daytime field study, it was determined that the minimum luminous intensity level for arrow panels be set at 30 cd/lamp for an 85th percentile recognition level or 50 cd/lamp for a 100th percentile level.

Dynamic Field Study

The objective of the dynamic field study was to validate the luminous intensity levels as determined in the static field study. This study utilized 63 older drivers between the ages of 60 and 85 years old. The drivers were driven through a closed course and asked to identify arrow panel displays at varying intensity levels. The researchers used the 95 percent recognition levels to ensure that the arrow panels were bright enough to be recognized by most drivers under the widest range of visibility conditions. At 100 cd/lamp, the arrow panel had a recognition distance of 1552 ft which is slightly greater than the DSD requirement for high speed roads.

Conclusion

To ensure safety, the 50 cd/lamp threshold value from the static study was rejected in favor of the 100 cd/lamp value (recommended minimum off-axis value). Additionally, the LRI researchers applied a multiplier to the threshold minimum intensity for identification to obtain the final recommended on-axis value (500 cd/lamp). The multiplier used accounts for the subjects' awareness that they were being tested and for the low visual complexity of the test area. Thus, the minimum on-axis value accounts for an unalerted driver in a visually complex location.

Nighttime Evaluations

Nighttime Glare Study

Two nighttime studies were conducted using older subjects to evaluate the effects of various arrow panel luminous intensity levels on both disability glare and discomfort glare. Disability glare is caused by a light level so intense that it results in a measurable reduction in the observer's ability to perform tasks requiring vision. Disability glare was measured in reference to the detection of a 7 inch square, 20 percent reflectance target at a distance of 150 ft (stopping sight distance) with the arrow panel 250 ft from the observer. When illumination at the drivers eye was kept below 0.68 lux there were no (100 percentile) measurable effects of disability among older drivers. To maintain illuminance under 0.68 lux at 250 ft, an arrow panel must have an intensity less than 374 cd/lamp (5611 cd/panel).

Discomfort glare is caused by a level of light that is intense enough to result in a measurable level of subjective pain or annoyance to the observer. Acceptable discomfort glare was defined at the illuminance level below which 85 percent of the drivers rated their discomfort at less than disturbing using the DeBoer rating scale. The average lamp luminous intensity at which 85 percent of the subjects found their discomfort from the arrow panel less than disturbing was 366 cd/lamp (5490 cd/panel). The actual illuminance level for this condition was 4.27 lux at the subjects' eyes at 100 ft.

Comparison of the results from each of the two glare studies showed that a panel intensity level no greater than 5500 cd would result in acceptable illuminance values for both disability and discomfort glare at any distance. This converts to an average lamp intensity of 550 cd/lamp for an arrow display (10 lamps) and 370 cd/lamp for a chevron display (15 lamps). Based on the worse case scenario of a chevron display at night, the study recommended a maximum nighttime lamp intensity of 370 cd/lamp.

Nighttime Minimum Luminous Intensity Levels

The LRI researchers also recommended minimum luminous intensity values for nighttime operation of arrow panels. They based these minimum values on previous traffic signal research which found that a 30 percent reduction in the daytime level did not reduce the visibility of the signal at night (*16*). Applying this 30 percent reduction to the daytime minimum intensity levels yields a nighttime minimum intensity level of 150 cd/lamp on-axis and 30 cd/lamp off-axis.

CONSPICUITY

Traditionally, an arrow panel has been thought of as a highly conspicuous sign that commands the driver's attention. Constructed using a matrix of lights which are capable of flashing or sequential displays of arrows or chevrons, arrow panels are intended to provide warning and directional information to assist in controlling traffic through or around a temporary traffic control zone. Diesel powered advance warning arrow panels represent a clear example of a high target value traffic control device capable of getting attention under the most demanding circumstances of visual noise, as well as adverse sun and traffic conditions.

The most recent revision of the MUTCD (*3*) refers to arrow displays instead of arrow panels and a matrix of elements instead of a matrix of lights. The intent is to broaden the definition to include new technologies and to recognize that even a changeable message sign can simulate an arrow panel. However, arrow panels on changeable message signs are thought to be not as effective due to their reduced brightness.

While the use of solar panels has lowered the target value of these devices by virtue of reduced brightness, it is safe to assume that under night work conditions almost any arrow panel will have high target value. However, if the arrow panel is to provide a net gain in traffic safety during daylight, the conspicuity of an arrow panel must be greater than other traffic control devices used for warning and guidance.

In order to test conspicuity, it is necessary to have a clear understanding of the term as it relates to the driving task. A driver is subjected to a vast amount of varied and complex visual information when driving; much more information than it is possible to notice. A driver's attention is directed to just a few of the visual stimuli available while most visual information is filtered or ignored. The practical question for a traffic engineer is how to ensure that a particular piece of visual information (e.g., an arrow panel) is noticed at an appropriate distance, allowing time for the driver to take appropriate action.

A conspicuous object, according to Cole and Jenkins (*17*) is one that will, for any given background, be seen with certainty probability ($p > 0.9$) within a short observation time ($t < 0.25$ seconds) regardless of the location of the target with respect to the line of sight. Hughes and Cole (*18*) cite the work of Engel (*19*), who drew attention to the sensory conspicuity of an object. The sensory conspicuity depends upon the physical prominence of the object's physical properties compared with its background, and cognitive conspicuity which Engel saw as dependent on the information content of the object and the psychological state of the observer. Mace and Pollack (*20*) made a similar observation when they suggested that the conspicuity of a sign depends upon the motivation and expectancy of the driver, so that restaurant signs are more conspicuous to the hungry driver and "Stop Signs" following "Stop Ahead" warning signs are more conspicuous, as are all signs at intersections compared with those midblock. This is why Hughes and Cole (*21*) found that the conspicuity of an object depended upon the instructions given to an observer, and this is why researchers have difficulty generalizing the results of research to new situations.

Hughes and Cole (*18*) defined two kinds of conspicuity: attention conspicuity and search conspicuity. Attention conspicuity is the capacity of the target to attract attention when the observer's attention is not directed to its likelihood of occurrence. Search conspicuity is defined as the accessibility of the target when the observer was explicitly directed to look for the object. Since most drivers are not expecting lane closures, practitioners need to be concerned more with the attention conspicuity of arrow panels than the search conspicuity.

Attention Conspicuity

The physical prominence of an object's properties compared with its background determines its attention conspicuity. While the internal layout or graphic quality of an object will affect its conspicuity, the color, shape, size, and design of the arrow panel is fixed and not subject to manipulation. The only methods of manipulating the attention conspicuity of an arrow panel is by increasing its brightness or placing the panel in a less visually complex background.

The visual complexity of the highway environment is as critical as external contrast in determining the conspicuity of traffic control devices. Mace, et al. (*22*) found that when visual complexity of the scene is high, the complexity is a more significant determinant of sign detection than the contrast of a sign with its surround. When visual complexity is low, target contrast and size play the larger role in detection. Jenkins (*23*) explained it this way, "No object is conspicuous per se. It can only be conspicuous in a certain background; if the background changes then the object may or may not remain conspicuous."

The data collected by Hughes and Cole (*21*) suggest that traffic control devices are considerably less conspicuous in shopping center environments than other types of roads and less conspicuous in arterial roads than residential roads. They argue that visual clutter is the most likely explanation for reduced attention conspicuity and not the added demands of the driving task.

In order to determine the brightness required to maintain conspicuity of an arrow panel, it is necessary to control both the complexity of the background as well as the motivation and expectancies of the subjects. If subjects are sensitized to look for traffic control devices, the task becomes one of search or cognitive conspicuity which is not what is needed for the arrow panel to provide the level of safety desired.

CHAPTER 3. ANGULARITY EFFECTS ON ARROW PANEL VISIBILITY

A review of potential angularity effects due to lane positioning and roadway curvature was undertaken by examining the effects of viewing angle and lateral clearance between vehicles and arrow panels in various positions.

STUDY DESIGN

In this examination, standard dimensions of the roadway and the radius of curves were taken from the *Green Book* (*14*) and used to develop an understanding of the effects of roadway alignment on arrow panel angularity.

Viewing Angle

In this context, viewing angle means the angle between the driver's eye and the perpendicular face of the arrow panel. This is a very important factor because as the viewing angle increases the apparent brightness of the arrow panel is reduced and the driver may not be able to clearly see the arrow panel and understand its message.

Case 1: Straight Road With Arrow Panel Positioned 90 Degrees to the Roadway

The following assumptions were made:

- center of arrow panel is located at a distance of 6 ft from the roadway edge,
- lane width is 12 ft, and
- the driver views the arrow panel from the middle of the 12 ft lane (i.e., at a 6 ft offset from the lane edge or lane line).

The arrow panel was placed at an angle of 90 degrees to the roadway, facing the oncoming traffic. The viewing angle at distances of 500, 1000, 1500, and 2500 ft from the arrow panel was then calculated. Four lanes were considered for this analysis and the change in viewing angle with respect to the position of the car on the lane was also found.

The viewing angle is given by the following relationship:

$$\theta = \tan^{-1}(TD / LD) \tag{3}$$

where:

TD = Transverse distance of car from arrow panel
LD = Longitudinal distance between car and arrow panel

Table 3 gives the viewing angles for various longitudinal and transverse distances and is plotted in Figure 2.

Table 3: Arrow Panel Placed at 90 Degrees to the Roadway (Facing Shoulder).

Longitudinal distance of car from arrow panel (ft)	Lane position of car	Transverse distance of car from center of arrow panel (ft)	Viewing angle (deg)
500	Lane 1	12	1.37
	Lane 2	24	2.75
	Lane 3	36	4.12
	Lane 4	48	5.48
1000	Lane 1	12	0.69
	Lane 2	24	1.37
	Lane 3	36	2.06
	Lane 4	48	2.75
1500	Lane 1	12	0.46
	Lane 2	24	0.92
	Lane 3	36	1.37
	Lane 4	48	1.83
2000	Lane 1	12	0.34
	Lane 2	24	0.69
	Lane 3	36	1.03
	Lane 4	48	1.37
2500	Lane 1	12	0.28
	Lane 2	24	0.55
	Lane 3	36	0.83
	Lane 4	48	1.10

As shown in Table 3, the viewing angle increases as the driver approaches the arrow panel, although the effects are relatively modest. With the arrow panel aimed straight down the shoulder, the maximum angularity that would be encountered in lane one is 1.37 degrees and in lane two is 2.75 degrees. Looking at extremes, in lane four the maximum angularity encountered by the driver is 5.48 degrees at 500 ft from the arrow panel. Figure 2 illustrates the effects of lane and longitudinal position (with respect to the arrow panel) of the motorist on angularity.

A conservative value for PIEV (perception, intellection, emotion, and volition) is 3 seconds (*24*). At 70 mph a motorist travels 308 ft in 3 seconds; at 50 mph a motorist travels 220 ft in 3 seconds. The increase in angularity for the motorist traveling at these speeds and with this value for PIEV is minimal, as shown in Table 3.

Case 2: Arrow Panel Placed on a Horizontal Curve

Although the preferred placement of an arrow panel is on a straight section of roadway to provide an unfettered view of the arrow panel, occasionally there arises a need to place an arrow panel on a horizontal curve. The effect of roadway horizontal curvature on viewing angles is discussed in this section. The effects of varying the curve radius for rural highways and high speed urban streets was considered for the effect on angularity. Table 4 provides the angularity experienced by the driver when an arrow panel is placed perpendicularly to a

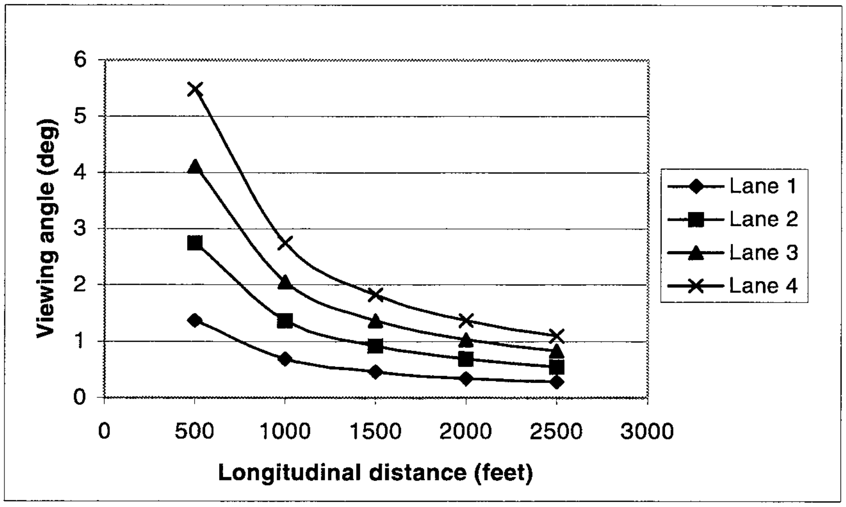


Figure 2. Change in Viewing Angle with Longitudinal Distance and Position of Car in Lane.

1910 ft radius curve, the maximum radius for a superelevation rate of 0.08 and design speed of 70 mph.

The following inferences can be drawn from Table 4.

- Vehicles in the farthest lanes have larger viewing angles.
- For a given position of arrow panel, the viewing angle decreases as the distance between the vehicle and the arrow panel decreases, as the vehicle traverses along the curve.
- For a given position of the car on the curved road, the viewing angle reduces as the distance of the arrow panel from the point of tangent (PT) is increased.

Following the approach of Mace et al. (*2*) and adopting decision sight distance as the minimum sight distance requirement for the arrow panel, 1500 ft was used as a critical value for arrow panel visibility. At this minimum distance the viewing angle must be within reasonable limits so that the driver is able to see the arrow panel. From Table 4, however, it is shown that the viewing angle is quite high and could have a significant impact on the apparent brightness of the arrow panel.

Requiring the orientation of an arrow panel to be perpendicular to the roadway when that roadway is in a horizontal curve would appear to be unreasonable, however. If the arrow panel is oriented toward the driver at a distance appropriate to that required for decision-making (i.e., 1500 ft) then the changes in viewing angle might be calculated for vehicles on the curved roadway. Figure 3 shows an arrow panel set up in such a manner. Calculating the viewing angle for two extreme cases (70 mph and 1910 ft radius; 50 mph and 764 ft radius), changes in viewing angle of 4.7 degrees and 7.6 degrees were derived (Φ in Figure 3). The viewing angle changes were calculated using the assumed speeds and PIEV of 3 seconds.

Although greater than the viewing angles observed on straight roadways, the relatively small changes determined for arrow panels on the 1910 ft and 764 ft radius curves generally appear acceptable if the arrow panel is oriented toward the position of the driver at 1500 ft away, along the roadway. It is noted that for the driver to view the arrow panel on curves of these radii it is necessary that the curve be cleared of obstructions that could block the driver's view. For the 1910 ft radius curve the roadway would have to be cleared of obstructions within 145 ft; for the 764 ft radius curve, 340 ft.

Table 4: Viewing Angle on Curved Roads, Arrow Panel Perpendicular to Roadway Curve.*

				Arrow panel position relative to start of curve (e.g., 500 ft into the curve)			
Distance of car along the curve* from PT (feet)	Longitudinal distance of car from PT (feet)	Lane Occupied by Car	Transverse Distance of car From center of arrow panel (ft)	PT	500 ft	1000 ft	1500 ft
				Viewing angle (deg)	Viewing Angle (deg)	Viewing angle (deg)	Viewing angle (deg)
500	494.31	Lane 1	77.07	8.86	4.43	2.95	2.21
		Lane 2	89.07	10.21	5.12	3.41	2.56
		Lane 3	101.07	11.56	5.81	3.87	2.90
		Lane 4	113.07	12.88	6.49	4.33	3.25
1000	954.94	Lane 1	267.85	15.67	10.44	7.81	6.23
		Lane 2	279.85	16.33	10.89	8.15	6.51
		Lane 3	291.85	16.99	11.35	8.50	6.78
		Lane 4	303.85	17.65	11.80	8.84	7.06
1500	1350.50	Lane 1	571.35	22.93	17.17	13.67	11.34
		Lane 2	583.35	23.36	17.51	13.95	11.57
		Lane 3	595.35	23.79	17.84	14.22	11.80
		Lane 4	607.35	24.21	18.18	14.50	12.03
2000	1654.04	Lane 1	966.87	30.31	24.19	20.03	17.05
		Lane 2	978.87	30.62	24.45	20.26	17.25
		Lane 3	990.87	30.92	24.72	20.48	17.45
		Lane 4	1002.87	31.23	24.98	20.71	17.65
2500	1844.88	Lane 1	1427.47	37.73	31.35	26.66	23.12
		Lane 2	1439.47	37.96	31.56	26.85	23.30
		Lane 3	1451.47	38.19	31.77	27.04	23.47
		Lane 4	1463.47	38.42	31.99	27.24	23.64

* Radius=1910 ft.

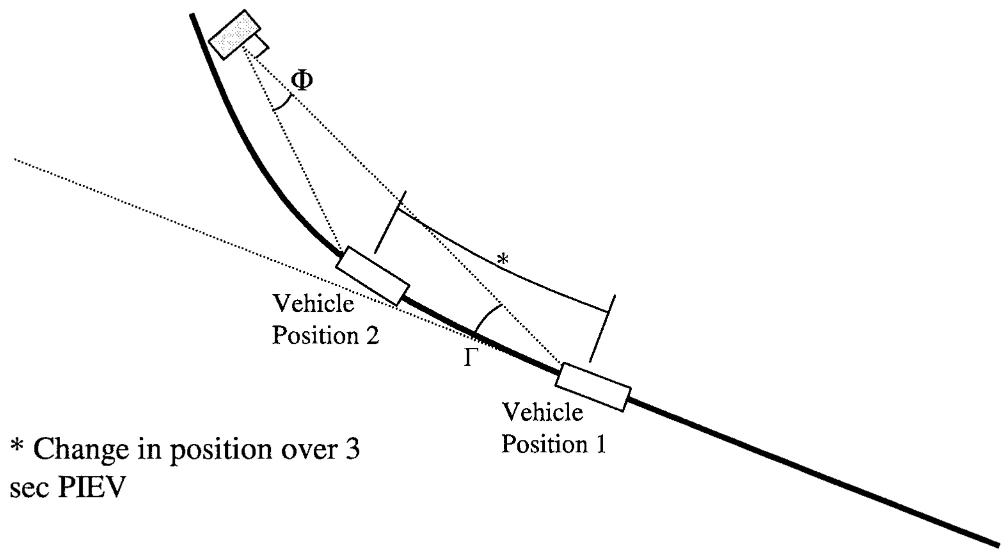


Figure 3. Viewing Angle on Horizontal Curve.

CONCLUSION

From the analysis performed it can be concluded that the viewing angle between the driver's line of sight and the face of an arrow panel as that arrow panel is approached on a straight roadway is relatively small. The viewing angle is much greater on curves (depending on the radius) when the arrow panel is oriented perpendicularly to the tangent of the curve at the arrow panel, but the angle can be reduced greatly by realigning the arrow panel to be perpendicular to the driver's line of sight at the distance desired for observation. If this setup practice is followed, the viewing angle is greatly reduced and potentially adverse effects on panel luminance are minimized.

CHAPTER 4. NIGHTTIME MINIMUM INTENSITY STUDY

This chapter details the experimental design and findings for the nighttime minimum luminous intensity study conducted at TTI's Proving Ground Facilities at the Texas A&M University Riverside Campus in Bryan, Texas, during May 2000. The main objective of this study was to determine the minimum luminous intensity required by young and old drivers for nighttime recognition of arrow panels.

BACKGROUND

In the NCHRP 5-14 report, recommendations were prepared regarding arrow panel luminous intensity for various conditions. Table 5 contains the photometric recommendations for individual lamps used in a Type C arrow panel. These recommendations are based on decision sight distance requirements for high-speed roads, which state that the arrow panel display must be properly identified at 1500 ft (*2*).

Table 5. Summary of NCHRP Recommended Luminous Intensity Requirements (*2*).

Time of Day	Speed (mph)	Minimum On-Axis (cd/lamp)	Minimum Off-Axis (cd/lamp)	Maximum Hot Spot [a] (cd/lamp)
Day	≥ 45	500	100	NA
Night	≥ 45	150	30	370

[a] Maximum intensity requirement must be met at the lamp "hot spot," which may or may not be on-axis
NA Not applicable

Most of the recommendations in Table 5 are directly derived from the studies performed in the NCHRP project. The exceptions, however, are the recommendations for minimum nighttime recognition luminous intensity. To obtain the nighttime minimum intensities, the daytime minimum values were reduced by 30 percent. This 30 percent reduction was based on previous nighttime traffic signal research that found this reduction in the daytime level did not reduce the visibility of the signal (*16*).

Based on these findings, TTI researchers decided to develop an experiment that would directly examine the nighttime minimum luminous intensity needed for Type C arrow panel recognition. The specific tasks of this study were to:

- modify an experimental arrow panel (diesel with incandescent lamps) so it is capable of producing displays at various luminous intensities,
- develop a glare source to simulate oncoming headlights, and
- conduct human factors studies to determine the minimum luminous intensities necessary for nighttime recognition of the arrow panel display.

STUDY DESIGN

TTI's research utilized human factors studies at the TTI facility on the Texas A&M Riverside Campus. The human factors studies were divided into two phases referred to as "Phase I: Pilot Study" and "Phase II: Nighttime Recognition Study." The objectives of Phase I were to determine a range of luminous intensity values that would be further explored during Phase II and to examine the effectiveness of the study design.

TTI Proving Ground

This study was conducted at night at the TTI facility on the Texas A&M Riverside Campus. The TTI Proving Ground facility is a 2000-acre complex of research and training facilities located at the Texas A&M University Riverside Campus, which is 12 miles northwest of the University's main campus. The proving ground is a former military aircraft base comprised of four major runways and associated taxiways (Figure 4). These concrete runways and taxiways are ideally suited for experimental research and testing in the area of work zone traffic control devices. Runway 35C was used for this study.

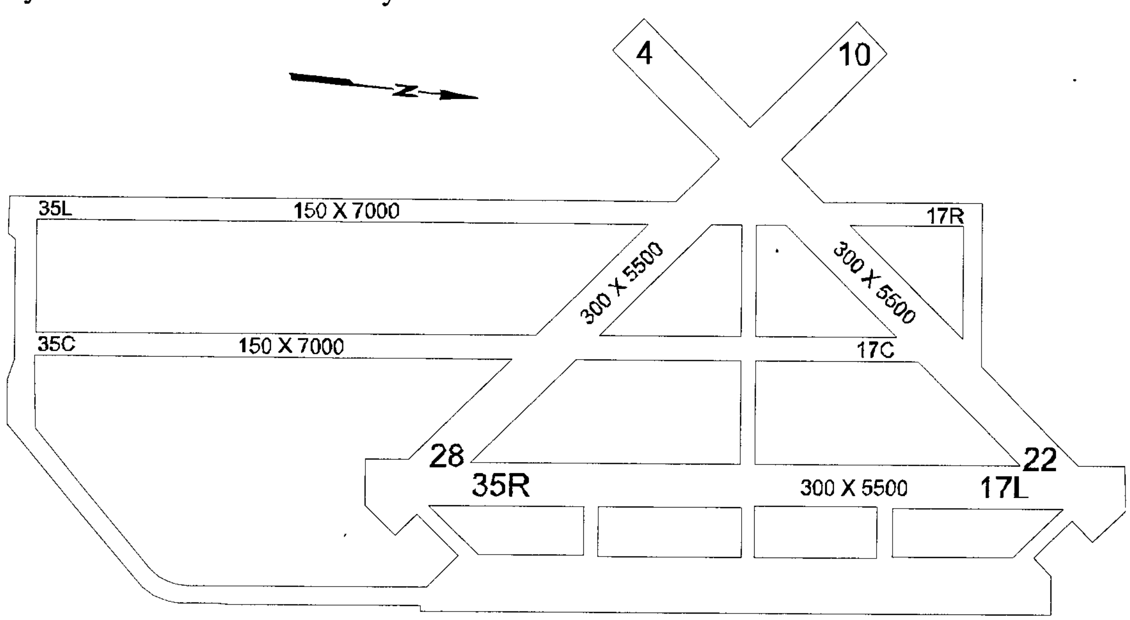


Figure 4. Runway Layout at Texas A&M University Riverside Campus.

Modified Arrow Panel

For the nighttime minimum luminous intensity study, a diesel powered Type C arrow panel with PAR 46 incandescent lamps was obtained and modified. In order to provide various and precise intensity levels from the sealed beam lamps, the manufacturer was contacted to provide information about the controller on the arrow panel. The manufacturer was reluctant to provide any information with respect to the controller or how the controller could be modified to meet the needs of this research. Thus, researchers decided to replace the original controller with a new one designed at the TTI Proving Ground. Figure 5 shows the new controller.

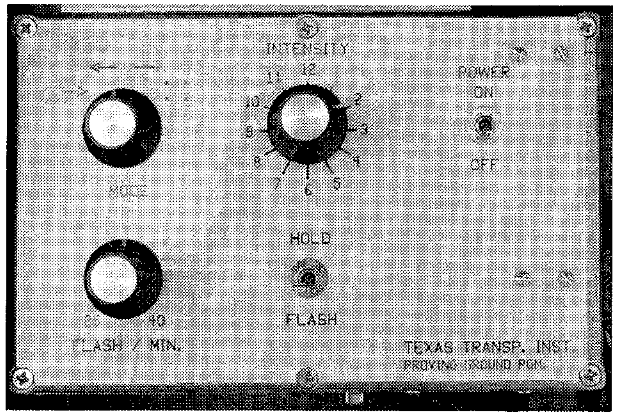


Figure 5. New Controller.

The new controller utilizes an imbedded micro processor which is programmed to provide four displays (right arrow, left arrow, caution bar, and four corner caution). These displays are then controlled by the operator to either flash or remain steady for light measurement purposes. The rate of flash is adjustable from 25 to 40 flashes per minute. The intensity can be varied between 0 and 100 percent by changing the ratio of off-to-on square waves that are alternating at 1000 cycles per second by the processor (referred to as pulse width modulation). At 1000 cycles per second the human eye does not recognize the on-and-off cycles but perceives a change in light intensity. The intensity level is adjusted using a switch with a maximum of 12 positions which are calibrated to known intensity levels.

In order to determine the minimum luminous intensity necessary for recognition of the arrow panel display, it was desirable to set the arrow panel at very low intensities (less than 6 cd). However, the light output from the panel at these intensities was not uniform across the 10 lamps that form a flashing left or right arrow (i.e., some lamps produced a much higher intensity than others). Thus, the complete flashing arrow display was not always recognizable. Proving ground staff attempted to determine the cause of the lamp's variability and successfully ruled out voltage and lamp angularity.

Given the uncertainty of the panel at extremely low luminous intensity levels, the research team decided to set four intensities that were lower than normal operational levels, yet higher than the point at which the panel became unstable. Table 6 contains the four intensities. These values were used to determine if the panel was visible at 1500 ft at night, with and without the glare source.

To obtain the panel intensities in Table 6, researchers used a luminance-to-intensity method developed by Finkle (*15*). This method involves measuring the target with a luminance meter and using the resulting luminance measurement to calculate the estimated intensity of the target. Researchers used a Minolta LS-100 luminance meter with a fixed circular aperture (1 degree). To obtain the luminance of the entire arrow panel display (flashing left or right arrow), the complete display must be encompassed in the aperture. Researchers found that at approximately 500 ft this was accomplished; however, a portion of the arrow panel's background, as well as the surrounding background, is also captured in the luminance meter aperture (since the panel is rectangular). To ensure that a uniform black background is in the luminance meter aperture, measurements were taken at night.

Table 6. Panel Photometric Properties Tested in Phase I.

Photometric Properties	Setting 1	Setting 2	Setting 3	Setting 4
Measured Panel Luminance (cd/m^2) [a]	2	9	19	57
Calculated Panel Intensity (cd)	12	56	118	354
Calculated Lamp Intensity (cd/lamp) [b]	1.2	5.6	11.8	35.4

[a] Displaying a left or right flashing arrow (i.e., 10 lamps illuminated)
[b] Calculated by dividing the panel intensity by the number of lamps illuminated

Glare Source

TTI proving ground staff constructed a glare source that when affixed to the driver's side of a vehicle's hood simulates the glare illuminance on the driver's eye of a continuous stream of oncoming cars (Figure 6). The glare source is comprised of two small flashlight bulbs that are elevated above the hood of the test vehicle by using a small wooden dowel. The dowel is mounted in a swivel base, which has a large suction cup on the underside. The glare source was calibrated to simulate low-beam headlights of an oncoming passenger car at a distance of 164 ft at a fixed glare angle. This distance was chosen because it corresponds to the "glaring" point in the beam pattern that caused the largest glare illuminance (*25*). Table 7 contains the dimensions of the simulated headlamps and the glare source.

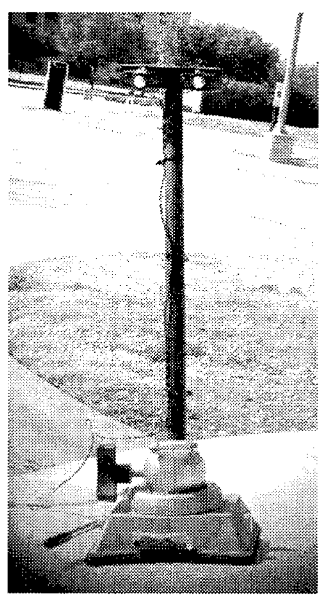


Figure 6. Glare Source.

Table 7. Dimensions of the Simulated Headlamps and Glare Source (*25*).

Parameter	Dimensions	
Lane width	12 ft	
Lateral distance between observer's eyes and car center	1.1 ft	
Height of observer's eye above the road surface	3.8 ft	
	Simulated Oncoming Car	Glare Source
Distance headlamps and observer's eye (measured parallel to driving direction)	164 ft	7.2 ft
Headlamp height	4.7 in	0.21 in
Headlamp width	9.4 in	0.42 in
Distance between headlamp centers	3.6 ft	1.9 in
Height of headlamp center above the road surface	2 ft	--

Method of Study

Figure 7 depicts the setup of the study. The arrow panel was placed 1500 ft downstream of the subjects. As discussed previously, this distance is based on decision sight distance requirements for urban high-speed roads (i.e., worst case scenario). Subjects viewed the panel from the driver's seat of the stationary vehicle, which was offset horizontally from the arrow panel to simulate the position of an arrow panel on the shoulder, and the test vehicle in the left lane of a simulated four-lane road (i.e., two lanes in each direction). The low-beam headlights of the test vehicle were "on." It should be noted that other than the arrow panel, test vehicle's headlights, and the glare source, no other lighting was present during the study.

Drivers were subjected to right- and left-flashing arrow displays at various intensities. Subjects viewed these displays with and without the glare source. The trials were randomly selected from a counter-balanced set of displays.

PHASE I RESULTS

The primary objective of Phase I was to evaluate the scale of luminous intensities that the panel would display during Phase II of the study. Four test subjects (two TxDOT employees, one retired faculty member, and one volunteer from the community) and four researchers observed the panel at the four intensities in Table 6. All eight individuals correctly identified the displays at the lowest panel intensity (12 cd). These individuals covered a variety of ages, with at least one being under 25 and one being over 65.

Based on the Phase I results, it was determined that the NCHRP recommendations for nighttime minimum luminous intensities (Table 5) were more than adequate for recognition of a Type C arrow panel display at night in a rural environment (i.e., low complexity). Thus, the research team concluded that it was not necessary to continue with Phase II of the study. Instead, researchers decided to focus on the luminous intensity required for conspicuity—the ability of an object to attract attention in a complex environment. Chapter 5 discusses the conspicuity studies.

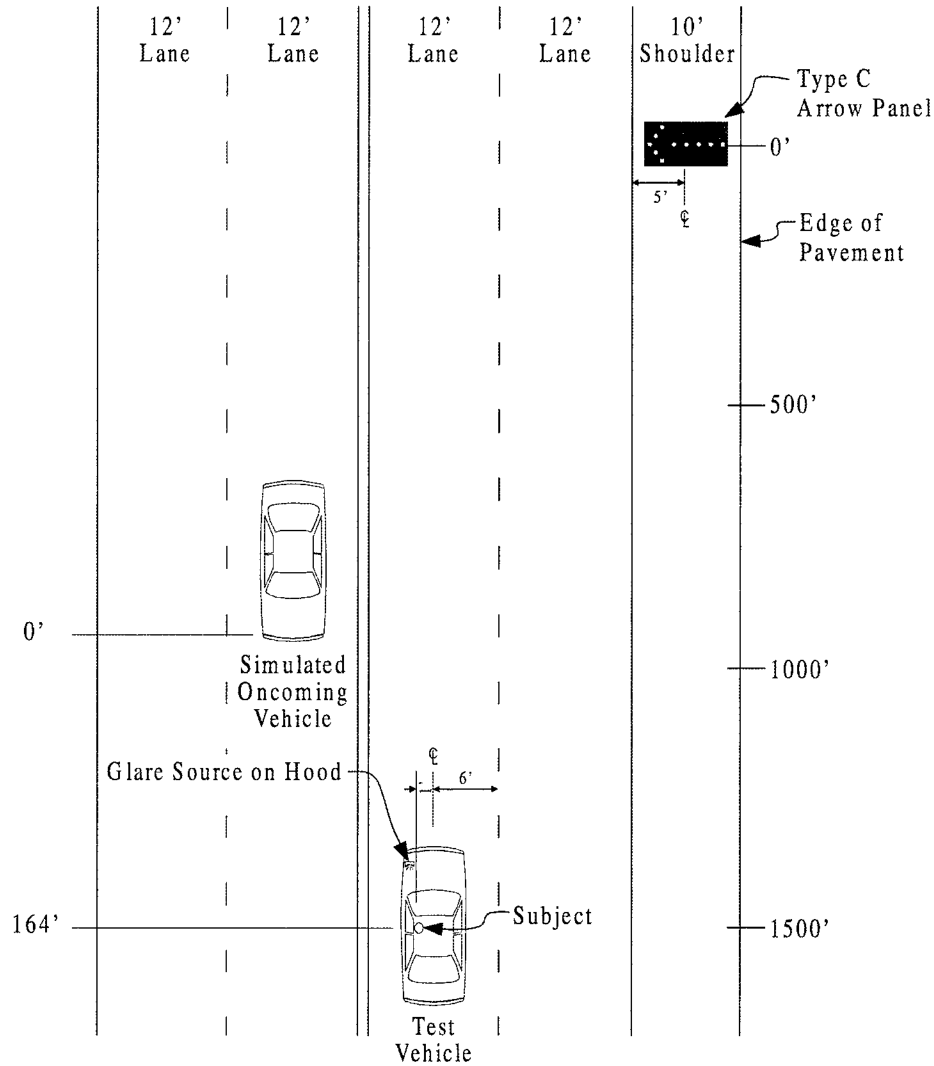


Figure 7. Nighttime Minimum Luminous Intensity Study Setup.

CHAPTER 5. DAYTIME CONSPICUITY STUDY

The experimental design and initial findings for the daytime conspicuity study are documented in this chapter. The main objective of this study was to determine the minimum luminous intensities required for daytime conspicuity of arrow panels under various levels of visual complexity.

BACKGROUND

As discussed previously, the NCHRP 5-14 study included various static and dynamic daytime studies on the recognition distance of Type C arrow panels; however, these studies did not include any empirical evaluation of luminous intensity required for conspicuity – the ability of an object to attract attention in a complex environment. Instead, based on previous research multipliers were applied to the threshold minimum intensity for identification to achieve the minimum on-axis intensity in Table 8 (500 cd/lamp). The multipliers were used to account for the study subjects' awareness that they were being tested and for the low visual complexity of the test area.

Table 8. NCHRP Recommended Daytime Luminous Intensity Requirements (*2*).

Speed (mph)	Minimum On-Axis (cd/lamp)	Minimum Off-Axis (cd/lamp)
≥ 45	500	100

In the 1980s, Jenkins and Cole (*26*) researched the daytime conspicuity of road traffic control devices using target discs and signs. They found that the main variables affecting daytime conspicuity are size, contrast with the immediate surrounding background, and the complexity of the background. Also, in the 1980s, Olson (*27*) assessed the minimum luminance levels of signs that could be detected and recognized at adequate distances under nighttime conditions with varying degrees of background complexity. The three levels of background complexity used were high, medium, and low which referred to urban, suburban, and rural conditions, respectively. Olson found that surround complexity, subject age, retroreflective efficiency, and sign color all had an effect on sign conspicuity.

Based on these findings, TTI researchers decided to develop an experiment to evaluate the effect visual complexity has on the daytime minimum luminous intensity needed for Type C arrow panel conspicuity. The specific tasks of this test were to:

- modify an experimental arrow panel (solar with LED lamps) so it is capable of producing displays at various luminous intensities; and
- conduct field studies to determine the minimum luminous intensity necessary for daytime conspicuity of the arrow panel display under various visual complexities.

STUDY DESIGN

Study Factors

Intensity

The NCHRP 5-14 recommendations for the daytime minimum on-axis and off-axis intensities are 500 cd/lamp and 100 cd/lamp, respectively. However, TxDOT preferred an intensity measurement for the entire arrow panel instead of per lamp. For the conspicuity study, a Type C arrow panel was used to display either a flashing left or right arrow. Both of these displays have 10 lamps (five lamps in the head and five lamps in the stem) "on" at one time. Thus, the equivalent NCHRP 5-14 daytime minimum on-axis and off-axis intensities for the entire panel are 5000 cd and 1000 cd, respectively. This calculation assumes that each lamp contributes an equal portion of intensity, which is not necessarily true.

To determine if the solar-powered arrow panels currently being used by TxDOT and contractors on TxDOT construction projects meet the 5000 cd recommendation, a small photometric study was conducted. Researchers visited three work zones in the Bryan/College Station area, and collected on-axis luminance measurements for four solar/LED arrow panels (used by contractors). Researchers also measured a brand new solar/LED arrow panel at the TxDOT Bryan District Office. Table 9 contains the calculated panel intensities of the five solar arrow panels.

Researchers again utilized Finkle's method (*15*) of converting measured luminance-to-intensity; however, the daytime measurement process consists of a "display off" measurement (i.e., ambient light) which is subtracted from a "display on" measurement. The difference between these measurements is used to calculate the intensity. As mentioned previously, it is assumed that each lamp is contributing an equal portion of intensity to the panel measurement. However, in reality when measuring the entire panel with a luminance meter all of the lamps are not directly on-axis; thus, each lamp is not contributing an equal amount of intensity.

Table 9. Panel Photometric Properties of Solar-Powered LED Arrow Panels.

Panel	Average Measured "On" Luminance (cd/m^2) [a]	Average Measured "Off" Luminance (cd/m^2) [a]	Average Measured Panel Luminance (cd/m^2)	Average Calculated Panel Intensity (cd)
1	928	765	163	902
2	2956	2156	800	4447
3[b]	2172	1785	387	2152
4[b]	1605	1055	551	3060
5[c]	2280	1460	820	4556

[a] Distance between target and luminance meter was 500 ft
[b] Same arrow panel model
[c] New TxDOT panel

These results show that two of the arrow panels (2 and 5) where relatively close to NCHRP 5-14 recommendation of 5000 cd (4447 cd and 4556 cd, respectively). However, in contrast, the average intensity of panel 1 was only 902 cd. Based on the results of this photometric study, researchers decided that a panel intensity of 2000 cd should be tested. This intensity will represent solar-powered arrow panels that are currently being used in work zones.

Researchers also wanted to examine an intensity that was representative of diesel arrow panels. Thus, they conducted another small photometric study to determine the average panel intensity of diesel-powered arrow panels currently being used by TxDOT. Table 10 contains the calculated panel intensities of two diesel arrow panels. Based on these results, researchers decided to include a panel intensity of 10,000 cd in the study.

Table 10. Panel Photometric Properties of Diesel-Powered Arrow Panels.

Panel	Average Measured "On" Luminance (cd/m^2) [a]	Average Measured "Off" Luminance (cd/m^2) [a]	Average Measured Panel Luminance (cd/m^2)	Average Calculated Panel Intensity (cd)
1	2637	468	2169	9505
2	3354	1426	1928	8224[b]

[a] Distance between target and luminance meter was approximately 500 ft
[b] The top lamp in the head of the right arrow display was not lit (i.e., only 9 bulbs were measured).

Visual Complexity

Researchers believed it was important to evaluate the intensities over a range of visual complexities. Visual complexity refers to characteristics of a site, such as geometric, traffic, visual noise (e.g., other signs and signals, buildings, etc.), and work zone conditions, that make an arrow panel more or less conspicuous. Following the Taguchi approach in which extreme conditions should be evaluated first, researchers targeted the following two complexities:

- high (i.e., urban facility characterized by more complex geometry, high traffic volumes, and a large amount of visual noise); and
- low (i.e., rural facility with simple geometry, low traffic volumes, and a small amount of visual noise).

Overall, the daytime conspicuity study was to examine four panel intensities (10,000 cd, 5000 cd, 2000 cd, and 1000 cd) and two visual complexities (high and low). To achieve the desired intensities both diesel (incandescent bulbs) and solar-powered (LED) panels were used. The eight different conditions that were to be evaluated are shown in Table 11. All studies were to be performed under daytime conditions on high-speed roadways (i.e., ≥ 45 mph).

Table 11. Evaluation Matrix.

Arrow Panel Type	Bulb Type	Arrow Panel Intensity (cd)	Background Complexity	
			High	Low
Diesel	Incandescent	10,000	✓	✓
Diesel	Incandescent	5000	✓	✓
Solar	LED	2000	✓	✓
Solar	LED	1000	✓	✓

Modified Arrow Panels

As previously discussed in Chapter 4, a diesel powered Type C arrow panel with PAR 46 incandescent lamps was modified such that the intensity of the lamps could be varied. Since the light output of the diesel panel was not uniform at lower intensities, a solar powered Type C arrow panel with LED lamps was obtained and modified similar to the diesel panel.

To achieve the needed intensity levels (0 to 100 percent, where 100 percent is the original daytime intensity) the original controller was slightly modified. Once again a programmable micro processor was used to pulse width modulate the low side of the power going to the lamps while the original controller modulated the high side of the voltage. This unobtrusive modification allowed the operator to enter the percentage of light desired using a keypad (see Figure 8). The percentage of light entered was then displayed on a liquid crystal display. Since the LED lamps require no warm up or cool down (as do the incandescent lamps), the ratio of the on-to-off cycles represent the same light output ratio. Again, at 1000 cycles per second the human eye does not recognize the on and off cycles but perceives a change in light intensity.

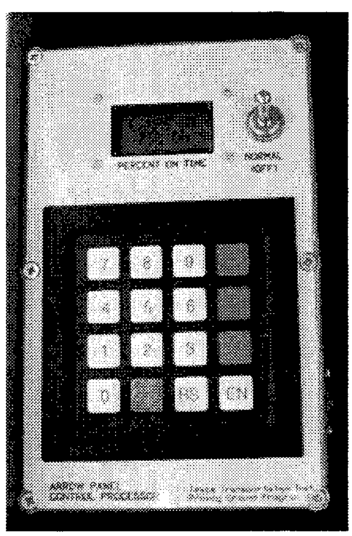


Figure 8. Solar Panel Intensity Controller.

Another small modification made to the solar panel was the addition of a three-way switch that controlled the automatic dimming function of the arrow panel. The three conditions programmed into the switch were "auto," "day," and "night." The "auto" setting allowed the panel to operate normally, while the "day" and "night" settings were representative of the automatic dimming function being "off" and "on," respectively.

Method of Study

In order to evaluate the four arrow panel intensities and two complex backgrounds, researchers planned to locate a minimum of two active daytime work zone lane closures which represent the two background complexities (i.e., one site per complexity). However, due to a lack of suitable sites data were collected at only two low-complexity sites.

The primary focus of the field study was the operational measures of performance immediately upstream of the lane closure. Researchers identified whether the intensity of the arrow panel resulted in significant differences in the following measures:

- lane choice statistics upstream of the taper (percent distributions at several points upstream, percent of last-minute lane changes); and
- erratic maneuvers and vehicle conflicts.

As a minimum, lane choice statistics were computed 1500 ft upstream, 1000 ft upstream, 500 ft upstream, and at the beginning of the lane closure (i.e., last-minute lane changes). Erratic maneuvers were also assessed over the 1500 ft distance upstream of the beginning of taper. As a minimum, to evaluate driver lane choice, researchers obtained between 500 and 1000 vehicle samples per intensity.

The secondary focus of the field study was a motorist survey comprised of three questions related to the brightness of the arrow panels being studied (see Appendix A for the motorist survey). The survey targeted motorists that had just driven through the work zone. It should be noted that the motorists did not receive monetary compensation for their participation in the survey.

STUDY RESULTS

Test Site 1 – College Station, Texas

Test Site 1 was located on State Highway (SH) 6 south of College Station, Texas. An overlay project required that the southbound direction of SH 6 be reduced from two lanes to one lane. A right-lane closure upstream of the overlay work was installed by the contractor according to Texas MUTCD requirements. Figure 9 illustrates the test site.

This section of SH 6 is a rural facility with simple geometry (relatively straight alignment). The posted speed limit is 70 mph. The sight distance to the beginning of the taper exceeded 2000 ft, and there was a relatively small amount of visual noise located in the area (e.g., some shopping centers and restaurants). Thus, this test site was located in a low-complexity area.

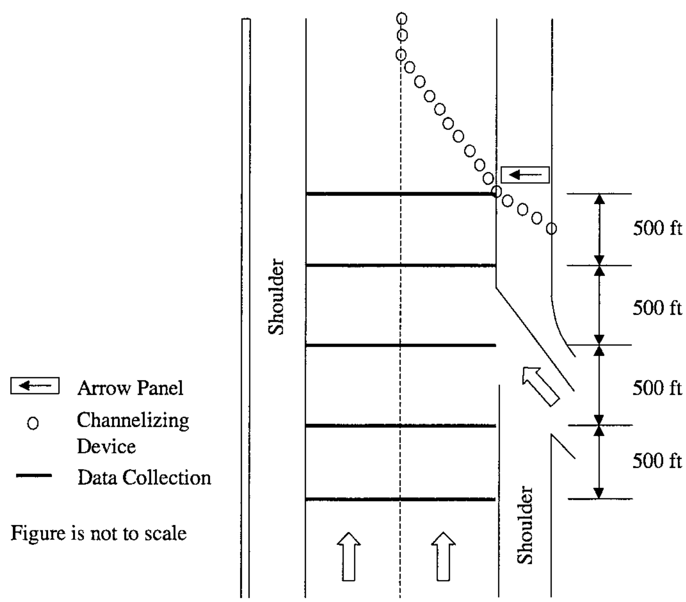


Figure 9. Test Site 1 on SH 6 Southbound, College Station, Texas.

It should be noted that the overlay project began in the fall of 2000; thus, the southbound left lane and inside shoulder of SH 6 had been closed prior to this study. However, the left lane/shoulder closure did not occur each day. Data for this project were collected the first and second day of the right lane/outside shoulder closure.

Data Collection

The operational measures of performance were collected for the four intensities (10,000 cd, 5000 cd, 2000 cd, and 1000 cd) during the day. Lane choice and erratic maneuver data were collected manually 2000 ft upstream, 1500 ft upstream, 1000 ft upstream, 500 ft upstream, and at the beginning of the taper by the data collection team (see Figure 9). The lane choice data collected at 1000 ft upstream, 500 ft upstream, and at the beginning of the taper did not include the vehicles that entered SH 6 via the entrance ramp located approximately 1000 ft upstream of the beginning of the lane closure taper.

The lane choice data were recorded for passenger vehicles and trucks, separately. The data for trucks were documented separately because the eye level of a truck driver is higher than that of a passenger vehicle driver. Researchers recognized that truck drivers may see and react to the lane closure differently than the drivers of passenger vehicles.

The motorist survey was conducted at a site on Greens Prairie Road (first exit after lane closure), which is approximately 2.5 miles from the beginning of the lane closure. The selection criteria were that the subject had driven through the entire work zone and had a current valid driver's license. Motorists that entered SH 6 at the Rock Prairie Road (see Figure 9) entrance were not surveyed. The survey administrator verbally asked the participant three survey questions and documented the subjects' answers on the survey form. The survey took approximately 5 minutes to conduct per subject. Subjects were at least 18 years old, and both males and females were surveyed.

Test Site 2 – Corsicana, Texas

Test Site 2 was located on Interstate 45 south of Corsicana, Texas. A reconstruction project required that the northbound direction of I-45 be reduced from two lanes to one lane. The contractor installed a right-lane closure upstream of the construction according to Texas MUTCD requirements. Figure 10 illustrates the test site.

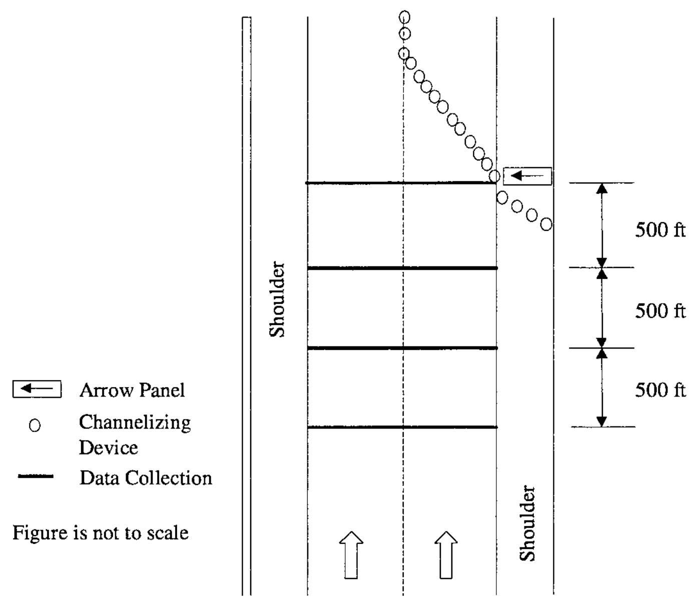


Figure 10. Test Site 2 on I-45 Northbound, Corsicana, Texas.

This section of I-45 is a rural facility with simple geometry (relatively straight alignment). The posted speed limit is 70 mph. The sight distance to the beginning of the taper was approximately 1800 ft because of a slight horizontal/vertical curve located upstream of the lane closure. Compared to the College Station site, there was even less visual noise located in the immediate area surrounding the lane closure; thus, this test site was also considered to have low-complexity.

Data for this project were collected on March 5, 2001. It should be noted that the reconstruction project began on April 25, 2000, and that the northbound lane closure had been in place since July 31, 2000 (seven months prior to this study).

Data Collection

The operational measures of performance were collected for the four intensities (10,000 cd, 5000 cd, 2000 cd, and 1000 cd) during the day. Lane choice and erratic maneuver data were collected manually 1500 ft upstream, 1000 ft upstream, 500 ft upstream, and at the beginning of the taper by the data collection team (see Figure 10). The lane choice data were recorded for passenger vehicles and trucks, separately. The data for trucks were documented separately because the eye level of a truck driver is higher than that of a passenger vehicle driver. Researchers recognized that truck drivers may see and react to the lane closure differently than drivers of passenger vehicles. The motorist survey was not conducted at this site, because an appropriate survey location could not be identified.

Lane Distribution Results

The analysis examined the influence of the following factors (together with their expected effects) on the percentage of traffic in the inside (open) lane:

- intensity, in candela–the higher the intensity the greater the percentage of traffic in the inside lane;
- distance from arrow panel, feet–the greater the distance the lower the percentage of traffic in the inside lane; and
- site–used as a blocking variable.

An analysis using the multivariate analysis of variance (MANOVA) was used to determine whether the percentage of cars present in the inside lane was significantly related to the intensity of the arrow panel. The use of MANOVA was required to correctly account for the correlation present in the data. The correlation is present in the data within a given treatment (intensity) level because the proportions of vehicles in the respective lanes were measured at five locations (distances) for the same traffic flow during the 15-minute interval. MANOVA requires that all cells have data, leading to two different analyses being completed because of the available data. First, data from Site 1 were analyzed using information available at distances ranging from 0 to 2000 ft; second, data from Sites 1 and 2 were analyzed together using information available at distances ranging from 0 to 1500 ft. This was required because no data were collected at 2000 ft for Site 2 due to site conditions.

The intensity levels of the arrow panels were set at 1000 cd (an aggregate reading of the 10 lamps present in a flashing arrow display), 2000 cd, 5000 cd, and 10,000 cd. The analyses reported results from comparisons of the percentage of vehicles in each of the 15 minute blocks of data collected, and typically include four 15-minute blocks per intensity; the intensity levels 1000 cd and 10,000 cd were tested twice, however, and have more data available. The data result from a total traffic count of over 7000 cars and 1800 trucks.

The analysis of the results of the study centered around the effect of varying the arrow panel intensity on the percentage of vehicles in the inside, or open, lane. A box-plot was prepared to show an overall picture of the effects of intensity on lane distribution for passenger cars, and is shown in Figure 11. The effect of distance is clearly illustrated, with higher percentages of cars as they get closer to the arrow panel. Arrow panel intensity also appears to have an effect, with higher percentages of cars present in the inside lane when the arrow panel intensity was higher. Figure 12 illustrates the effects of distance and arrow panel intensity on trucks. Although generally similar results are observed, the influence of intensity is not as consistent. Table 12 provides the mean percentages of cars observed in the inside lane, while Table 13 provides the mean percentages of trucks observed in the inside lane. Figures 13 and 14 provide a visual comparison of the effects of site on the percentage of cars and trucks in the inside lane, respectively.

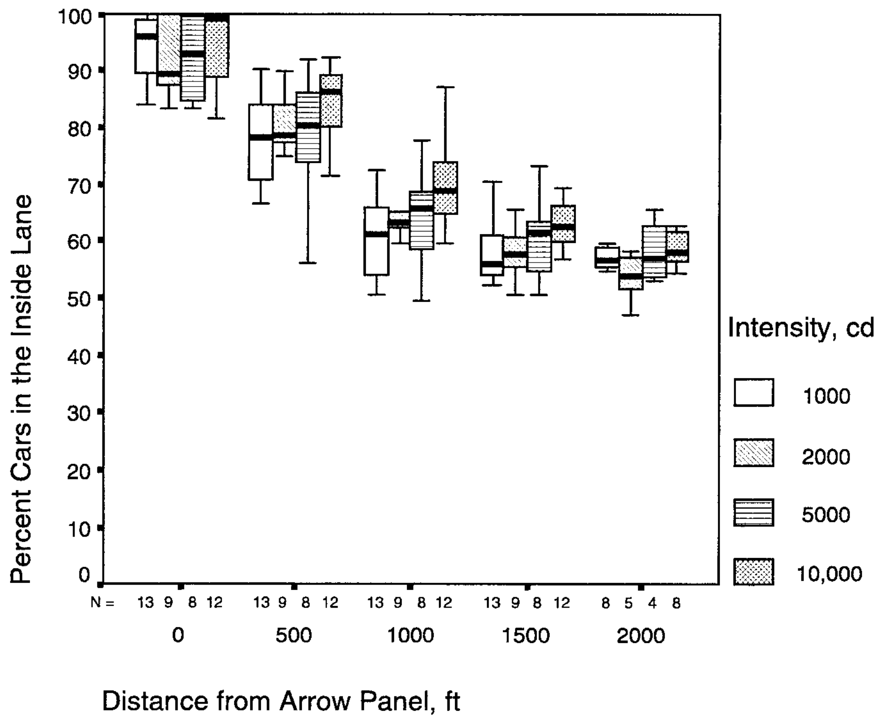


Figure 11. Effect of Intensity and Distance on the Percentage of Cars in the Inside Lane.

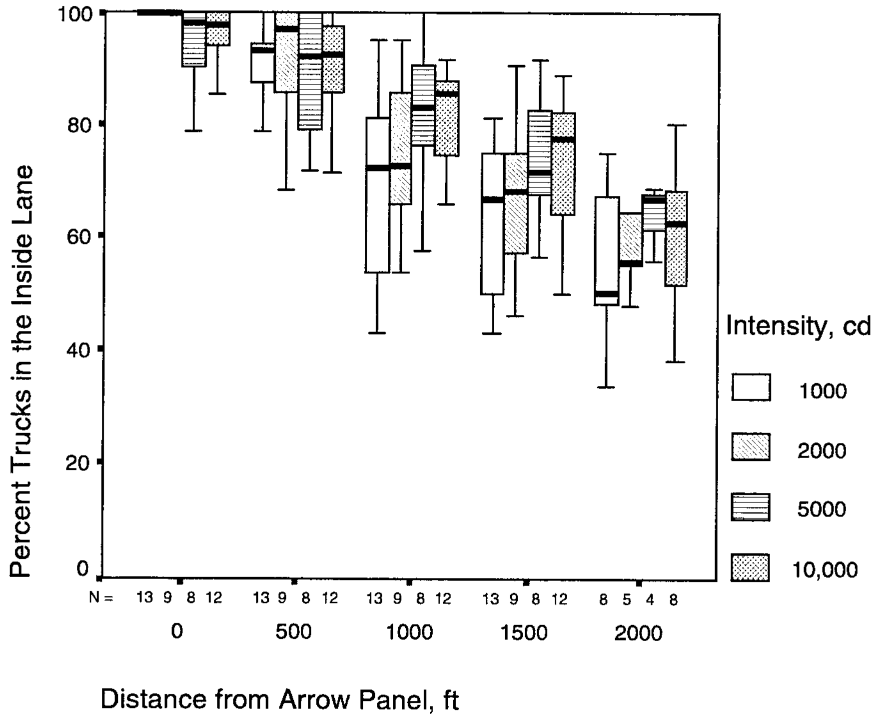


Figure 12. Effect of Intensity and Distance on the Percentage of Trucks in the Inside Lane.

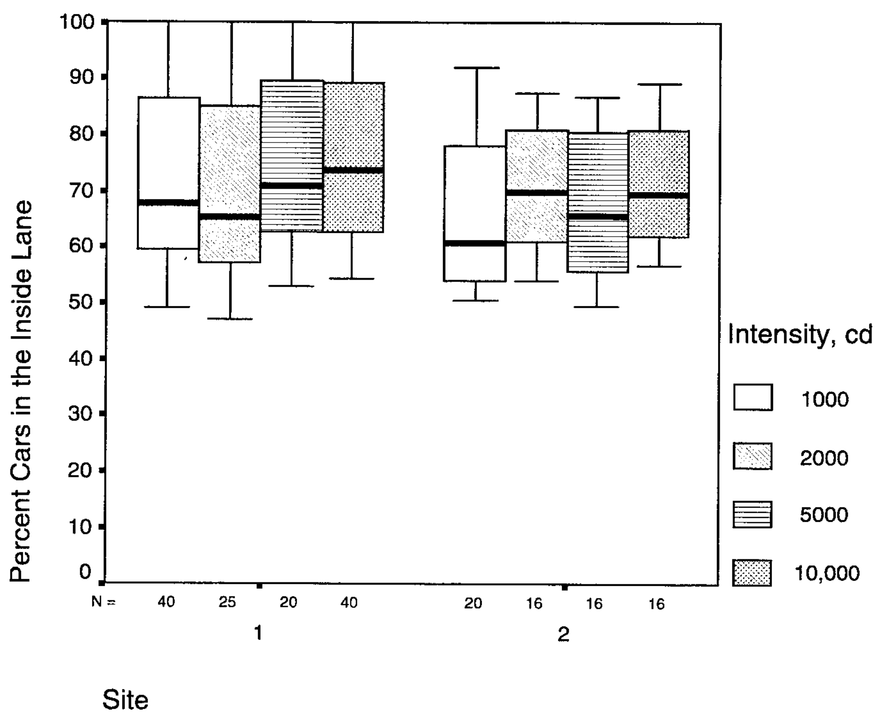


Figure 13. Boxplot Comparing Sites 1 and 2 Using Percent Cars.

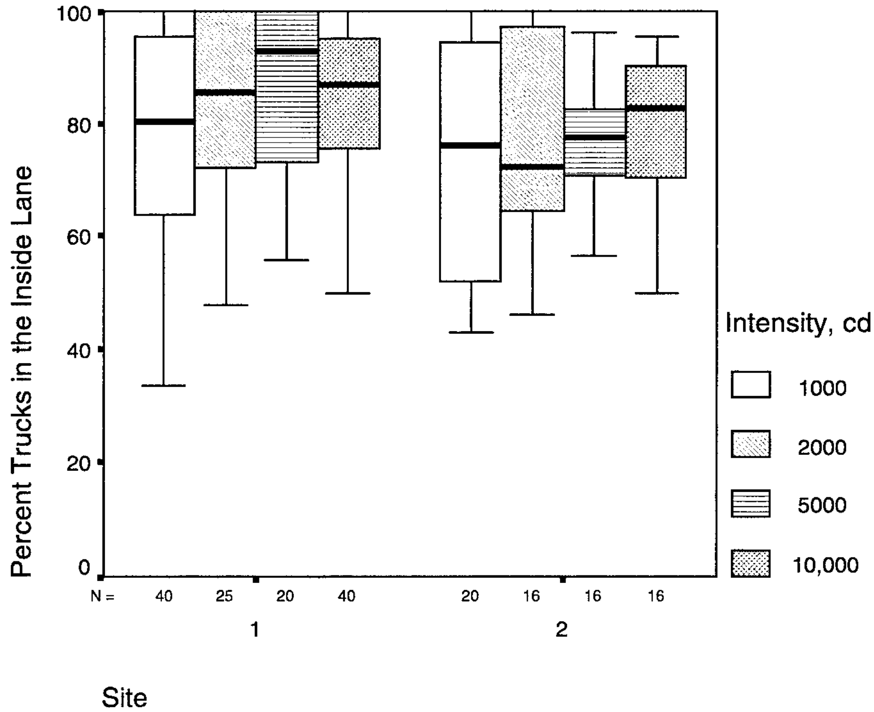


Figure 14. Boxplot Comparing Sites 1 and 2 Using Percent Trucks.

Table 12. Percentage of Cars in the Inside Lane.

Distance from arrow panel, ft	Intensity, cd	Percentage of Cars in Inside Lane
0	1000	93.9
	2000	92.4
	5000	92.2
	10,000	94.9
500	1000	77.7
	2000	80.9
	5000	78.6
	10,000	84.1
1000	1000	61.3
	2000	65.6
	5000	64.1
	10,000	69.9
1500	1000	57.8
	2000	57.9
	5000	60.4
	10,000	63.8
2000	1000	57.0
	2000	53.6
	5000	58.1
	10,000	59.6

Table 13. Percentage of Trucks in the Inside Lane.

Distance from arrow panel, ft	Intensity, cd	Percentage of Trucks in Inside Lane
0	1000	98.0
	2000	97.9
	5000	94.4
	10,000	96.5
500	1000	89.1
	2000	90.7
	5000	89.3
	10,000	90.8
1000	1000	69.7
	2000	74.9
	5000	82.2
	10,000	81.8
1500	1000	62.6
	2000	67.0
	5000	74.0
	10,000	73.2
2000	1000	54.9
	2000	61.6
	5000	64.5
	10,000	60.3

The results of the MANOVA used to analyze the passenger car data for Site 1 reveals that intensity was a significant factor. Differences between levels of intensity were then tested in *post hoc* analyses to determine where the differences were. Unless otherwise noted, significance is judged based on alpha=0.05:

- 500 ft: The percentage of cars in the inside lane is significantly different for intensity levels 1000 and 10,000 cd.
- 1500 ft: The percentage of cars is significantly different for intensity levels 1000 and 10,000 cd, and for intensity levels 2000 and 10,000 cd.

Using 1500 ft as the appropriate minimum legibility criterion, the percentage of vehicles in the inside lane at low levels of intensity (1000 and 2000 cd) was found to be significantly lower than the percentage of vehicles at the high level of intensity (10,000 cd). A MANOVA analysis was also completed for the percentage of trucks in the inside lane, but intensity was not found to be a significant factor.

Next, an analysis was completed using data from both Sites 1 and 2. Because no data at 2000 ft were available for Site 2, the data were analyzed only at distances of 0, 500, 1000, and 1500 ft. The analysis of the percentage of cars in the inside lane revealed that intensity was again a significant influence. Specific differences were reviewed in *post hoc* analyses:

- 500 ft: The percentage of cars in the inside lane is significantly lower for intensity level 1000 cd when compared to that for 10,000 cd. The percentage was also significantly lower at intensity levels 5000 cd when compared to that for 10,000 cd. In an alternative test, Tukey's Studentized Range test found that only intensity 1000 cd and intensity 10,000 cd were significantly different.

Plots for Site 2 data (see Figure 13) show that the mean percentage of cars in the inside lane is higher for intensity 2000 cd than that for intensity 5000 cd. A large variability in the sample proportions (there are only four) for intensity 5000 cd at Site 2 is also noted.

Analyzing the combined truck data at Sites 1 and 2, intensity was found to significantly influence the percentage in the inside lane. The results were somewhat different, but with certain similarities to that found for cars:

- 0 ft: The percentage of trucks in the inside lane is significantly different for intensity levels 1000 and 5000 cd.
- 1000 ft: The percentage of trucks in the inside lane is significantly different at intensity levels 1000 and 5000 cd. The percentage is also significantly different at intensity levels 1000 and 10,000 cd.
- 1500 ft: The percentage of trucks in the inside lane is significantly different at intensity levels 1000 and 5000 cd. The percentage is also significantly different at intensity levels 1000 and 10,000 cd.

In general, the percentage of trucks in the inside lane for 1000 cd was found to be significantly lower than the percentage for the mid-range (5000 cd) and high level of intensity (10,000 cd). The percentage of trucks in the inside lane was not found to be significantly different when comparing the effects of 5000 and 10,000 cd.

Conclusion

Intensity was generally found to be a significant influence on the percentage of vehicles in the inside (i.e., open) lane. As intensity was increased, the percentage of vehicles in the inside lane typically increased. More specifically, the percentage of vehicles in the inside lane at 1000 cd was frequently found to be significantly lower than the percentage observed at 5000 and 10,000 cd. Differences in the percentage of vehicles in the inside lane were not generally statistically different for observations at 2000, 5000 and 10,000 cd.

It is apparent that arrow panels brighter than 1000 cd have a beneficial effect at the sites studied (low complexity). However, the benefits of arrow panels brighter than 2000 cd were not clearly demonstrated, since researchers were not able to conduct this study in an urban setting (high complexity). To ensure that the minimum intensity requirements are adequate for both low- and high-complexity situations, researchers recommend a minimum on-axis panel intensity of 4000 cd. Based on previous human factor research, this intensity should satisfy the needs of motorists in more complex settings.

Driver Survey Results

A limited number of surveys were completed at Site 1. A larger number of drivers were approached, but most declined to participate. The drivers appeared to be impatient and were not receptive to participating in the survey. An acceptable field location to conduct the survey was not available at Site 2. Researchers went to the nearest off-ramp and attempted to conduct the survey, but abandoned the effort when no drivers had exited after an hour. The next off-ramp was after traveling through an extended lane closure with many different types of traffic control devices; it was judged that motorist responses would not provide a good measure of the performance of the arrow panel at that location.

Of the 33 surveys completed at Site 1, the percentages were very similar for those motorists who reported seeing the arrow panel under various intensity levels:

- 1000 cd: 89 percent;
- 2000 cd: 81 percent; and
- 10,000 cd: 83 percent.

In response to the question "Were you able to see the arrow panel far enough in advance to take the appropriate driving action needed? If not, why?" most drivers reported that they were able to see the device satisfactorily, with little or no difference due to intensity.

When motorists were asked "Do you feel that the arrow panel was bright enough to grab your attention?" one driver commented that if the "brightness" level of the arrow panel was greater it would be more readily seen.

CHAPTER 6. CONCLUSIONS

The performance of arrow panels in lane closures is important to enhance the safety and efficiency of traffic operations in construction zones. Ensuring that the arrow panels meet their objectives of providing a clear, commanding directive to the driver to change lanes at an appropriate location is critical. Alternately (depending on the situation and the display chosen), they alert the driver to situations that require extra caution or care.

A number of characteristics are critical to the performance of arrow panels. The reviews of previous work and studies described in the previous chapters of this report provide information regarding those characteristics. The critical characteristics in question are described below, together with appropriate conclusions and recommendations.

DAYTIME LUMINOUS INTENSITY LEVELS

A satisfactory level of on-axis luminous intensity for daytime operation of arrow panels in a low complexity area is 2000 cd/panel. This level has been shown to exhibit satisfactory performance in on-road evaluations oriented toward testing conspicuity. More specifically, findings from these field studies show that a luminous intensity of 2000 cd/panel provided an acceptable level of response that was not distinguishable from higher levels of intensity (5000 cd/panel and 10,000 cd/panel).

However, the performance of the 2000 cd intensity in a high-complexity area was not demonstrated, since researchers were not able to conduct this study in an urban setting. To ensure that the minimum intensity requirements are adequate for both low- and high-complexity situations, researchers recommend a minimum on-axis panel intensity of 4000 cd. Based on previous human factor research, this intensity should satisfy the needs of motorists in more complex settings.

When converting the on-axis panel intensity to an on-axis lamp intensity, it is assumed that each lamp contributes an equal portion of intensity to the panel measurement. However, in reality, when measuring the entire panel with a luminance meter researchers find that some of the lamps are not directly on-axis; thus, each lamp is not contributing an equal amount of intensity. Consequently, the panel intensity cannot be simply divided by the number of lamps illuminated (i.e., 10 for a flashing left or right arrow) to obtain a minimum lamp intensity since in reality the lamp intensity would be more than this calculated value.

Researchers recommend a minimum on-axis lamp intensity of 500 cd. Using the assumption of equal lamp contribution, the on-axis lamp intensity would equate to an on-axis panel intensity of 5000 cd. Thus, the minimum recommended on-axis panel intensity (4000 cd) is 80 percent of the lamp intensity. This difference accounts for the violation of the assumption as discussed above.

Based on test track performance reported at LRI (*2*), a minimum off-axis luminous intensity of 100 cd/lamp is recommended. This level satisfied both static and dynamic requirements in testing for recognition. Equating this off-axis lamp intensity to an off-axis panel intensity (using the method described previously, which accounts for the fact that each lamp does not contribute an equal amount of intensity) results in a minimum off-axis panel intensity of 800 cd.

NIGHTTIME LUMINOUS INTENSITY LEVELS

Researchers recommend that the minimum on and off-axis levels of nighttime luminous intensity be 150 cd/lamp (1200 cd/panel) and 30 cd/lamp (240 cd/panel), respectively. These values were derived by applying a 30 percent reduction factor as recommended in the literature (*16*). Recognition testing confirmed that luminous intensity levels could be greatly reduced from the daytime values.

The maximum level of nighttime on-axis luminous intensity is recommended to be 5500 cd/panel to prevent unacceptable levels of glare (*2*). Limiting the luminous intensity with specific values prevents the introduction of problems presented by nighttime glare. Table 14 summarizes the recommended daytime and nighttime photometric requirements.

Table 14. Recommended Photometric Requirements.

Time of Day	Speed (mph)	Minimum On-Axis		Minimum Off-Axis		Maximum On-Axis
		cd/lamp	cd [a]	cd/lamp	cd [a]	cd [a]
Day	≥ 45	500	4000	100	800	NA
Night	≥ 45	150	1200	30	240	5500

[a] Intensity requirements for the entire panel when displaying a left or right flashing arrow (10 lamps illuminated)
NA Not applicable

ANGULARITY

Based on the literature (*2*) and analysis reported in Chapter 3, angularity values of +/- 4 degrees horizontally and +/- 3 degrees vertically are recommended as minimal values for specification purposes. If arrow panels are aimed at the roadway at the distance of primary interest, these angularity values should provide acceptable performance in almost all cases. A plot of the recommended lamp performance is provided in Figure 15. The limits of the shaded region should meet the minimum off-axis luminous intensity levels.

LEGIBILITY DISTANCE

The legibility of arrow panels should be assured through the provision of readily verifiable, measurable photometric characteristics. The provision of the recommended luminous intensity values at the angularity values described will provide acceptable legibility performance for arrow panels.

COLOR

The color of traffic control devices is an important part of the overall scheme of the MUTCD (*3*), enhancing motorist understanding and acceptance of the message presented by those devices. Based on testing reported by Mace et al. (*2*), the use of the Commission Internationale de

L'Eclairage (CIE) color box developed at LRI is recommended (see Figure 16). The lamp color should fit within that color box to ensure that the panel lamps are perceived as "yellow."

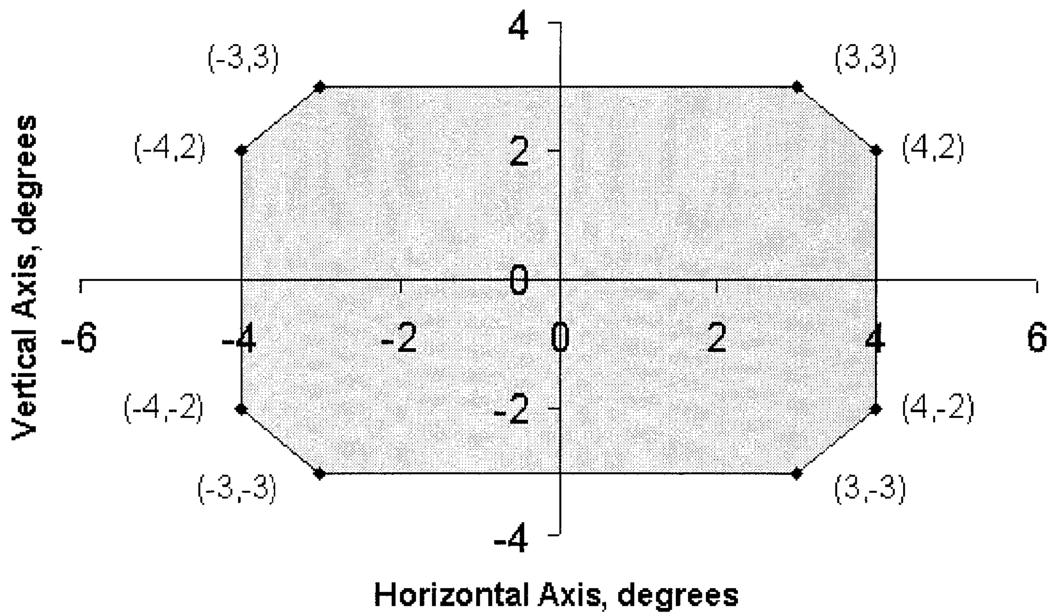


Figure 15. Shape of Angularity Requirement.

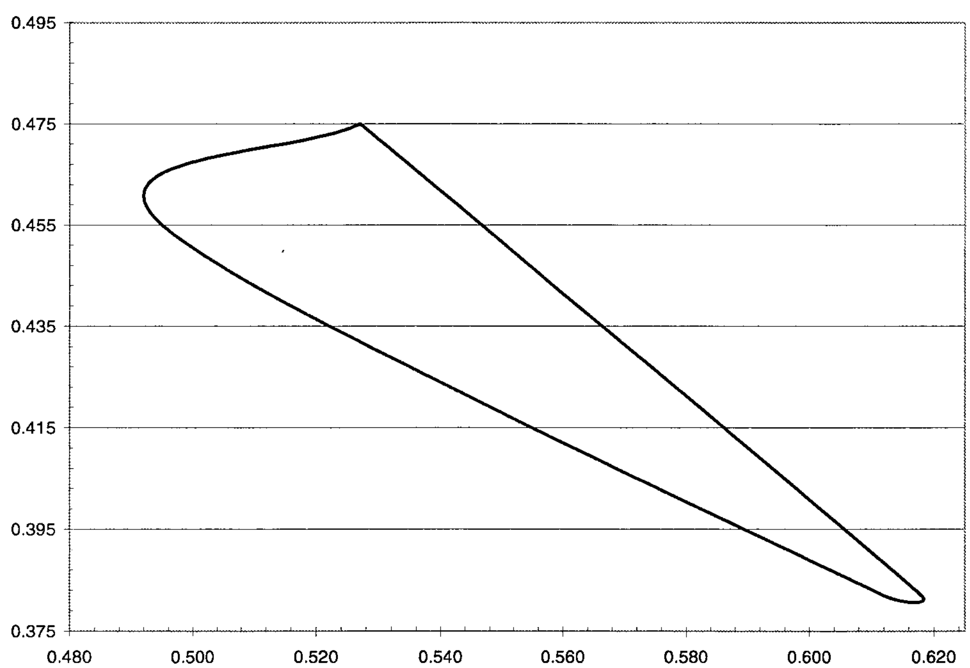


Figure 16. CIE Chromaticity Plot for Arrow Panel Lamp Color (Unitless).

CHAPTER 7. ANALYSIS OF ARROW PANEL SPECIFICATIONS

This chapter provides an analysis of the TxDOT diesel powered arrow panel and solar powered arrow panel specifications. In addition, an analysis that correlates the two TxDOT purchase specifications with previous specifications developed in national research is documented. Recommendations for changes to the current TxDOT specifications are made as a result of the analysis.

It should be noted that information contained in this chapter was submitted to TxDOT in Technical Memorandum 7-4940-2. The researchers acknowledge that both arrow panel specifications were revised accordingly in September 2000.

TxDOT TYPE C ARROW PANEL PURCHASE SPECIFICATIONS

TxDOT has two purchase specifications related to Type C trailer-mounted arrow panels. The specifications are differentiated primarily by power source. The solar/battery powered arrow panel purchase specification is Specification No. TxDOT 550-14-77 and was last revised in December 1998 (*28*). The diesel powered arrow panel is Specification No. TxDOT 550-14-74 and was last revised in June 2000 (*29*). As the diesel specification is the most current version of the two specifications, it will be used as the base reference in terms of language and contextual comparison of the specifications. The majority of the solar specification mirrors the diesel specification in terms of content; thus, minor differences in word usage or organization are not noted. However, while the specifications are very similar, there are some key differences. The sections below outline these differences.

Towing

The issue of towing an arrow panel is addressed in *Part II Specification – Scope* of the specifications. The solar specification states that the arrow panel must be mounted on a "trailer suitable for safe towing at highway speeds up to 60 mph, in the stored position" (*28*). The diesel powered arrow panel specification reads slightly different and requires safety "at highway speeds up to 70 mph in either the upright or stowed position" (*29*).

The first notable difference in the specification is the stipulation of two different towing speeds. Currently the maximum speed limit in Texas is 70 mph, so it is conceivable that an arrow panel could be towed at speeds of 70 mph. This is reflected in the diesel specification but not in the solar specification. Another difference in the specification is with respect to the towing position. The solar specification makes reference to the panel only being towed in the stored position, while the diesel panel specification references both a stored and upright position.

Towing is also referenced in *Part II Specification – Sign Panel Mounting* of both specifications. In contrast with the diesel specification, which maintains the prior towing descriptions, the "upright" position has been added to the towing position in the solar specification. Uniformity in the design of the two trailers is a necessity because of the nature in which panels are moved from site to site.

Recommendation

The solar specification should be modified to reflect the towing operations as described in the diesel specification in order to ensure uniform towing behavior for all TxDOT trailer mounted arrow panels. Specifically, Part II of the solar specification should be revised as follows:

> *Part II Specifications – Scope*
> All components shall be mounted on a trailer suitable for safe towing at highway speeds up to ~~60~~ 70 mph (113 km/h), in either the upright or stowed position.
>
> *Part II Specifications – Sign Panel Mounting*
> Shall be adequately supported when towed at road speeds up to ~~60~~ 70 mph (113 km/h) in the upright and stowed positions.

Dimming

Dimming the arrow panel displays is addressed in *Part II Specifications – Sign Panel* and *Part II Specifications – Circuitry and Controls.* The solar specification states that the "*maximum* dimming shall be 50 percent of lamp light output" (*28*) while the diesel specification specifies that the "*minimum* dimming shall be 50 percent of lamp light output" (*29*). This is a notable discrepancy in that the two statements imply such different meanings.

The MUTCD and TxMUTCD both state that an arrow panel should be capable of a minimum 50 percent dim and still fulfill the one-mile minimum legibility requirement during nighttime operation (*1, 3*). Thus, the solar specification contradicts the two MUTCDs.

Recommendation

The TxDOT solar purchase specification should reflect the wording of both manuals. Thus, the word "maximum" should be removed from the TxDOT solar specification and replaced with "minimum." The recommended text for the solar specification appears below:

> *Part II Specifications – Sign Panel*
> ~~Maximum~~ Minimum dimming shall be 50 percent of lamp light output, at or below five foot candles (of available ambient light), so that the minimum legible visibility of one mile (1.6 km), shall be maintained during nighttime operation.
>
> *Part II Specifications – Circuitry and Controls*
> ~~Maximum~~ Minimum dimming shall be 50 percent of lamp light output, at or below five foot candles (ambient light).

TYPE C ARROW PANEL SPECIFICATIONS FROM PREVIOUS RESEARCH

At least two previous research projects have recommended or created a general trailer mounted Type C arrow panel specification to assist state DOTs in writing purchase specifications. The two projects that were used to evaluate the current TxDOT solar and diesel powered arrow panel specifications were:

- *Procurement Specification and Application Guidelines for Arrow Panels* – TTI Project 7350 (*30*); and
- *Advanced Warning Arrow Panel Visibility* – The Last Resource, Inc. (*2*).

Table 15 contains the comparison of the current TxDOT trailer mounted Type C arrow panel specifications with the general specifications found in the aforementioned reports. While the specifications are very similar, the key differences among the specifications are discussed in the following sections.

Display Mode

The "sequential chevron" is an allowable display mode in the TxMUTCD (*1*). In addition, TxDOT construction standards allow for the use of the sequential chevron display during daylight operations (*31*). However the "sequential chevron" is not addressed in either TxDOT specification. The TxMUTCD also states that the "warning bar" is a permissible display mode. However, there is the potential for this display mode to be interpreted as a malfunctioning directional arrow. For this reason, the TxDOT construction standards state that the caution mode is the "four corner" display (*31*). In addition, the 2000 edition of the MUTCD specifies that a flashing caution is a "four corner" display and no longer provides the "warning bar" as a valid display (*3*).

Recommendation

Either the "sequential chevron" should be removed from the TxMUTCD list of permissible displays or the TxDOT specifications should specify that the "sequential chevron" is an acceptable display mode. Since the "warning bar" may potentially confuse drivers, it would be desirable to eliminate it from the TxMUTCD and the TxDOT specification. Suggested text revisions for the solar and diesel purchase specifications are below:

> *Part II Specifications – Sign Panel*
> Arrow board display options shall include:
> 1. Left arrow (five lamps in arrowhead).
> 2. Right arrow (five lamps in arrowhead).
> 3. Double arrow.
>   ~~Warning bar.~~
> 4. Four corner signal.
> 5. Sequential Chevron (25 lamp panels only).

Table 15. Comparison of Type C Trailer Mounted Arrow Panel Specifications.

	LRI	TTI - 7350	TxDOT SOLAR	TxDOT DIESEL
DESCRIPTION		Type C arrow panel, in conformance with MUTCD and State MUTCD. Trailer Mounted with arrow panel, mounting frame, rotating mechanism, control switches + circuitry, control box housing electronics, trailer, and power supply.	Type C, flashing arrow board panel, solar/battery powered, electrically lighted (15 or 25), trailer mounted meeting MUTCD and TxMUTCD.	Type C, flashing arrow board panel, diesel powered, electrically lighted (15 or 25), trailer mounted meeting MUTCD and TxMUTCD.
PANEL	48" x 96". Front - Flat black in color.	4' x 8'. Front and Back - Flat black, non-reflective color. Wiring is corrosion resistant and attached every 8". Height should be 7-9' above roadway surface.	Aluminum, 96" x 48", weather resistant flat black. Bottom of panel 7' off ground. Top 11'. Pipe-type sight gauge.	Aluminum, 96" x 48", weather resistant flat black. Bottom of panel 7' off ground. Top 11'. Sight tube/sight gauge.
DISPLAY	Left, Right Flashing or Sequential Arrow. Left or right Chevron if 25 Lamp display. Double Sided Flashing Arrow. 4-Corner Caution	Controls shall provide flashing arrows, L,R,+Dbl, and provide 4-corner caution may provide sequential arrow and/or chevron.	Flashing Left, Right and Double Arrow. Warning Bar, Four corner Signal.	Flashing Left, Right and Double Arrow. Warning Bar, Four corner Signal.
LAMPS	Certified by State. PAR 36 or PAR 46	PAR 36 or PAR 46. Min. 15, 25 if for chevrons.	15 LED assemblies. Screw or push type lamps. 25 for chevron	15 LED assemblies. Screw or push type lamps. 25 for chevron
HOODS	Minimum 180 degrees. 4" hood or recessed lamp	4" hood or recessed lamp. 360 degrees.	Hooded or visored lamps (easily replaceable)	Hooded or visored lamps (easily replaceable)
VOLTAGE/ POWER	Controls must permit testing to ensure Panel provides necessary voltage to meet intensity. If Panel has battery bank, it must allow for checking of charge state.	Supply adequate power to ensure legibility requirements met.	Battery life of 21 days without sun.	Battery life of 2 hours without alternator working. 12 volt 61 amp negative ground automotive alternator. Engine ships with muffler, amp meter, and throttle control. Fuel tank should provide 90 hours of operation
FLASH RATE/ DWELL TIME	25-40 fpm. Dwell = 50% cycle for flash, 25% for chevron.	25-40 fpm. Dwell = 50% cycle for flash, 25% for chevron.	25-40 fpm. Dwell = 50% +- 5% cycle for flash.	25-40 fpm. Dwell = 50% +- 5% cycle for flash.
DIMMING	Automatic at or below 215 lux. (20 ft-candle)	Automatic at or below 54 lux of light. Maximum dim of 50% of daylight output.	Maximum dim of 50%. At or below 5 ft-candles (54 lux) of available ambient light.	Minimum dim of 50%. At or below 5 ft-candles (54 lux) of available ambient light.
CONTROL/ WIRING		On/off, dim/bright selector, operation mode, and photocell. Electronics protected by fuses or circuit breakers. Cables and control are salt-resistant and waterproof.	On/off, dim/bright selector, operation mode, and photocell. Electronics protected by fuses or circuit breakers. Cables and control are salt-resistant and waterproof.	On/off, dim/bright selector, operation mode, and photocell. Electronics protected by fuses or circuit breakers. Cables and control are salt-resistant and waterproof.
OTHER		Indicator lamp, upper corner, and driver side. Towed in stored at 60mph. When deployed withstand 60mph wind.	Mode indicator lamps that indicate to workers what message is being displayed. Battery indicator gauge. Towed in stored or upright position at 60mph. When deployed withstand 60mph wind. Lamp intensity regulator	Mode indicator lamps that indicate to workers what message is being displayed. Battery indicator gauge. Towed in upright or stored position at 70mph. When deployed withstand 60mph wind.

Number of Lamps

The TxDOT specifications require 15 lamp assemblies for arrows and 25 for chevrons.

Recommendation

If the sequential chevron display is not added to the TxDOT specifications as a permissible display mode, all references to the 25-lamp configuration should be removed from the TxDOT specifications.

Lamp Size

The TTI and LRI reports both state that the lamps used in the arrow panel should be either PAR 36 or PAR 46 in diameter. A PAR 36 lamp is typically 4.5 inches in diameter, while a PAR 46 lamp is typically 5.75 inches in diameter. However, the TxDOT purchase specifications do not address lamp diameter. If this could be an item of contention with a supplier, the lamp diameter may need to be specified.

Recommendation

The TxDOT purchase specification should specify that the arrow panel be comprised of PAR 36 or PAR 46 size lamps. Because neither specification currently specifies lamp size, suggested text for both the diesel and solar specifications follows:

> *Part II Specifications – Scope*
> <u>The lamp shall conform in size with either a PAR 36 or PAR 46 lamp.</u>

Hoods

The TxDOT purchase specification only states that there shall be "hooded or visored" lamps. The MUTCD and TxMUTCD require that arrow panel lamps either be recess mounted or equipped with "an upper-hood of not less than 180 degrees" (*1, 3*). In addition, the LRI report and TTI report recommend either 4-inch recession or 4-inch hoods (*2, 30*). The TTI report further recommends that the hood be 360 degrees in coverage.

Recommendation

At a minimum, the TxDOT specification should be revised to reflect the 180 degree hood requirement in the MUTCD and TxMUTCD. Specifying that the hoods be 4 inches and 360 degrees should also be considered based on previous research. Suggested text for the specifications appears below:

> *Part II Specifications - Sign Panel*
> <u>Each lamp shall be recess mounted 4 inches or equipped with a 4 inch upper-hood of not less than 180 degrees.</u>

Dwell Time

Dwell time refers to the "lamp on-time." TxDOT specifies that the dwell time be 50 percent ± 5 percent of the cycle time whereas previous research, the MUTCD, and the TxMUTCD all specify 50 percent dwell time for flashing operation (*1, 2, 3, 30*). Also, the TTI and LRI reports include a cyclic dwell time of 25 percent for the chevron display modes. The MUTCD and TxMUTCD specify that "equal intervals of 25 percent" shall be provided for sequential phases.

Recommendation

To be consistent with the specified values of the MUTCD and TxMUTCD the TxDOT specifications should remove the ±5 percent dwell time requirement. Because the sequential chevron can be used during daytime operations, both purchase specifications should be amended to reflect the 25 percent dwell time for the sequential chevron display mode.

> *Part II Specifications – Sign Panel*
> Lamps shall flash at a rate not less than 25 or more than 40 flashes per minute, with a minimum lamp "on time" of 50 percent ~~± five percent~~ of the cycle. Minimum lamp "on-time" during sequential phases shall be 25 percent of the cycle.

ADDITIONS TO SPECIFICATION BASED ON RESEARCH

The research documented in this report investigated the photometric properties of Type C advance warning arrow panels. The results of this research should be incorporated into the TxDOT purchase specifications. Items researched are discussed in the following sections.

Luminous Intensity

Based on previous research and the field studies conducted as part of this research project, TxDOT should incorporate the luminous intensity requirements shown in Table 16 into the arrow panel purchase specifications.

Table 16. Recommended Luminous Intensity Requirements.

Time of Day	Speed (mph)	Minimum On-Axis		Minimum Off-Axis		Maximum On-Axis
		cd/lamp	cd [a]	cd/lamp	cd [a]	cd [a]
Day	≥ 45	500	4000	100	800	NA
Night	≥ 45	150	1200	30	240	5500

[a] Intensity requirements for the entire panel when displaying a left or right flashing arrow (10 lamps illuminated)
NA Not applicable

Angularity

In addition to intensity, the angular requirements of an arrow panel lamp must be specified. The useful beam width of a lamp is defined as the portion of the beam pattern that provides an intensity greater than the minimum off-axis intensity required for recognition of an arrow display. It is measured in terms of plus or minus a horizontal and vertical angle with respect to the center of the lamp.

Based on findings from previous research (*2*) and the analysis presented in Chapter 3, the minimum angularity permitted for a Type C arrow panel should be stated as +/- 4 degrees in the horizontal plane (8 degree beam width) and ± 3 degrees in the vertical plane (6 degree beam width). These recommendations are based on the assumption that the AASHTO guidelines for maximum curvature are met. Without restrictions on the placement of arrow panels, assumptions about geometry and placement must be made since the required angularity is not a function of the driver but of the geometry of the roadway. If arrow panels are aimed at the roadway at the distance of primary interest, these angularity values should provide acceptable performance in almost all cases.

Based on the recommended angularity above, all points within the defined rectangle should be equal to or greater than the minimum off-axis intensity requirements. However, current technologies produce beam patterns that are elliptical, not rectangular. Thus, the requirements were modified such that only 75 percent of the horizontal beam width is rectangular, and the vertical beam width beyond this point is 50 percent of the maximum vertical angle required (rounded to the nearest degree). The practical minimum angularity requirements are shown in Figure 17. The limits of the shaded region should meet the minimum off-axis luminous intensity levels.

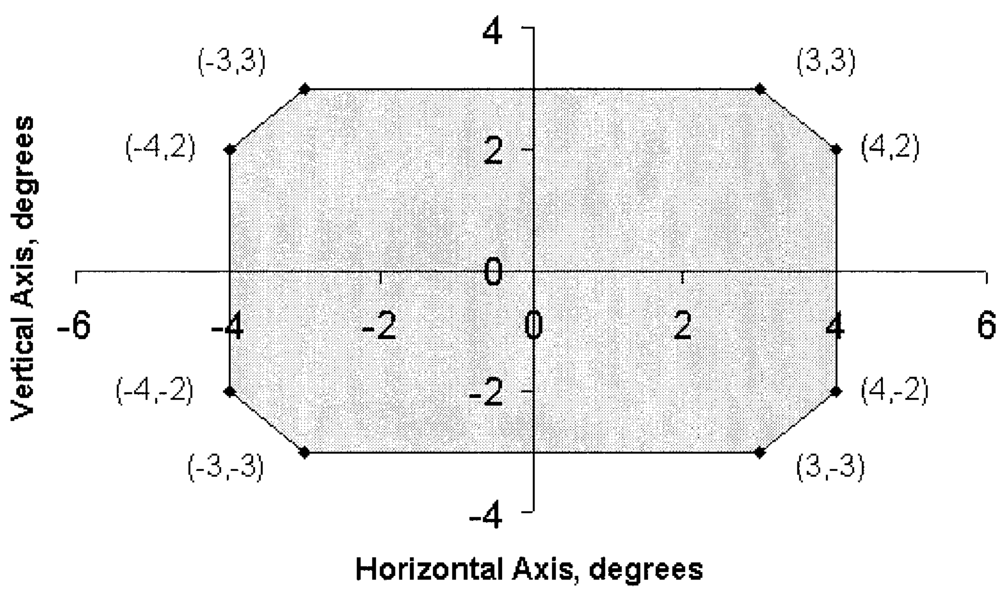


Figure 17. Minimum Angularity Requirements.

Color

Currently the MUTCD and TxMUTCD specify that the panel lamps shall be "yellow" in color (*28, 29*), while the TxDOT purchase specifications state that the lamps shall be "amber/yellow" in color (*31*). However, none of these documents define the tri-linear coordinates of the CIE standard. Based on a field sample of lamps from six different arrow panels, LRI recommended the CIE color box in Figure 18 (*2*).

The researchers recommend that the LRI color box be incorporated into the TxDOT purchase specification for arrow panels. Lamp color should fit within the color box to ensure that the panel lamps are perceived as "yellow."

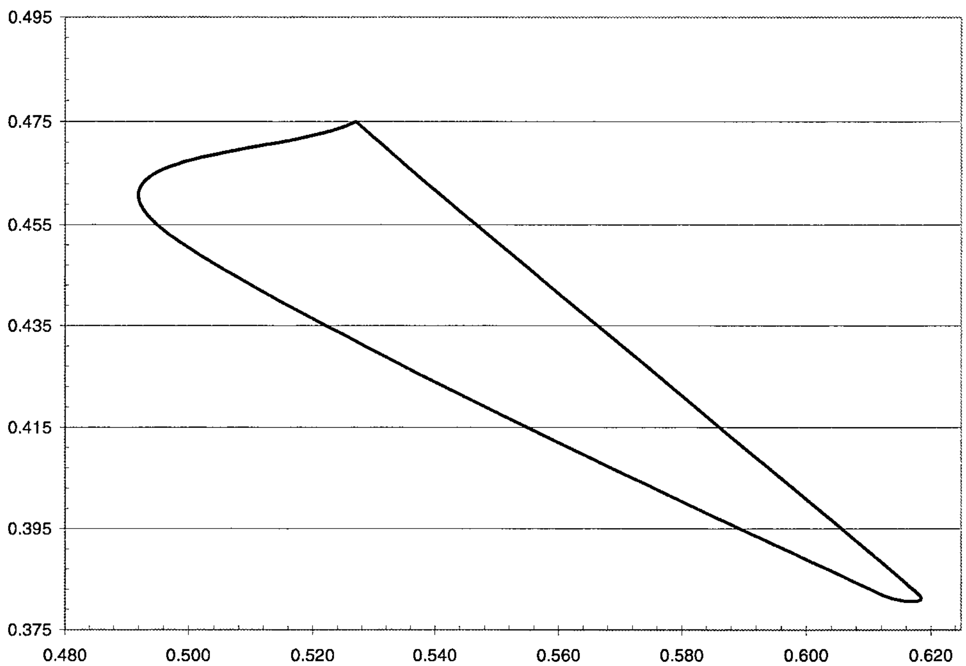


Figure 18. CIE Chromaticity Plot for Arrow Panel Lamp Color.

Dimming

Ideally, the luminance measurement of an arrow panel is performed at night. This ensures a uniform dark background in the luminance meter aperture. However, in order to measure daytime intensities at night a manual override of the automatic dimming function will be needed. Thus, it is recommended that TxDOT specify that a method for overriding (turning off) the automatic dimming function be provided.

CHAPTER 8. PHOTOMETRIC TESTING PROCEDURES

The purpose of this chapter is to describe the recommended photometric procedures to be used when measuring the luminous intensity of Type C arrow panels. This chapter will detail both a panel testing procedure and a lamp testing procedure.

PANEL TESTING PROCEDURES

When determining the luminous intensity of an arrow panel, the "Luminance-to-Intensity Measurement Method" must be utilized to calculate the luminous intensities from the arrow panels (*15*). This measurement method, and the resulting photometric procedures are discussed below.

Luminance-to-Intensity Measurement Method

Luminous intensity is the measure of the strength of a light source. It is expressed in candelas, and is sometimes referred to as a candlepower. Typically the intensity of a source is derived from an illuminance measurement; however, at the distances involved in arrow panel assessment, the use of an illuminance meter is not practical. Instead, a luminance meter is used to estimate the source intensity of an arrow panel. Utilizing the following formula, the measured panel luminance and area are converted to panel intensity:

$$I = L * A \tag{4}$$

where: I = total intensity (cd)
L = measured luminance (cd/m^2)
A = area of the aperture at target distance (m^2)

The area of the luminance meter aperture is found using the following:

$$A = [\tan(\text{APsize}) * D/2]^2 * \Pi \tag{5}$$

where: APsize = aperture size (radians)
D = distance between target and luminance meter (m)

To determine a lamp intensity, the panel intensity calculated must be divided by the number of lamps that were illuminated during the test (e.g., 10 for a flashing left or right arrow display). This method assumes that each lamp contributes an equal amount of intensity to the panel reading. However, due to the variation among lamps and the position of the luminance meter with respect to each lamp, this is not necessarily true. Thus, a lamp intensity calculated using the panel testing procedure will not be equal to the on-axis lamp intensity measured during the lamp testing procedure.

When the arrow panel is measured during the day or in lit areas, a second luminance measurement must be taken. This second measurement is taken when the arrow panel is "off," and represents the ambient light. This measurement is then subtracted from the "on" measurement to yield the panel luminance used to derive the panel intensity in Equation 4.

The luminance meter used in the panel testing procedure should include the following attributes:

- an aperture of 1 degree,
- a continuous reading function,
- a peak reading function,
- allow for mounting on a tripod, and
- a through-the-lens targeting system.

Panel Measurement Procedure

The procedure outlined in this section should be followed to measure the daytime and nighttime luminance of a Type C arrow panel, and determine if the panel intensities meet the minimum daytime and nighttime requirements, respectively. In addition, the form in Appendix B has been developed to aid the testing procedure.

Ideally, luminance measurement of an arrow panel is performed at night. This ensures a uniform dark background in the luminance meter aperture. However, in order to measure daytime intensities at night a manual override of the automatic dimming function will be needed. Though not recommended, the panel can be measured during the day or in lighted areas. However, in these situations measurements must be taken with the arrow panel both "on" and "off" so that the peak luminance values may be adjusted for ambient light. It is strongly recommended that these measurements not be made on days with partly cloudy conditions as the ambient light changes too rapidly to obtain accurate measurements.

Step 1: Set Up of Arrow Panel

Raise the arrow panel into position and level it by adjusting the jack stands and stabilizer bars. Turn either a left or right flashing arrow display "on" and make sure all ten lamps (five in the head and five in the stem) are illuminated. Measure and document the vertical distance from the road surface to the center of the lamps that form the stem in a flashing arrow display (should be approximately 9 ft).

Step 2: Set Up of Luminance Meter

In order to obtain repeatable measurements, a tripod must be used to stabilize the luminance meter because slight differences in aperture placement can affect the luminance readings. Attach the luminance meter to a tripod and setup the tripod so that the luminance meter is stationed 500 ft upstream of the arrow panel. This distance must be measured in a precise manner in order to accurately calculate the luminous intensity. After the distance is verified, document the distance between the arrow panel and luminance meter.

To measure the arrow panel luminance, the panel must be centered in the aperture of the luminance meter so that the display is completely contained in the aperture (Figure 19). Thus, both the horizontal and vertical position of the meter must be established with respect to the arrow panel. If it is not possible to capture the complete arrow panel within the aperture, check each of the following:

- measuring a Type C arrow panel,
- using a one degree aperture, and
- the distance between the luminance meter and arrow panel is 500 ft.

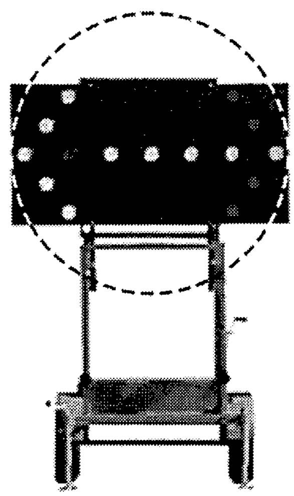


Figure 19. Luminance Meter Aperture Relative to Arrow Panel.

For on-axis measurements, the horizontal position of the luminance meter should be located using a surveying instrument to establish a straight line parallel to the arrow panel and a perpendicular crossing line (Figure 20). The arrow panel should be oriented so that the face of the panel is centered on the straight line and directly over the crossing line. For tests of off-axis performance, the crossing line should be set at the desired angle and the face of the panel set directly over the crossing line. A sight tube or other device as provided on the arrow panel can be used as an aid to initial aiming efforts, but the use of surveying instruments is recommended to ensure that the luminance meter is in the correct position to record the photometric measurements.

To position the luminance meter vertically, the distance between the road surface and the center of the meter aperture should be equal to the distance between the road surface and the center of the arrow panel lamps that form the stem in flashing arrow displays (measured and documented in step 1). Note that the terrain between the arrow panel and luminance meter should be relatively flat.

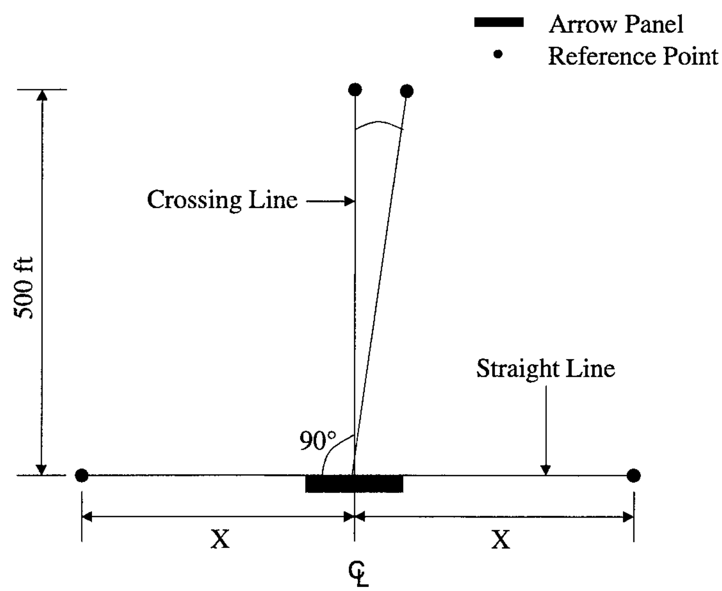


Figure 20. Horizontal Position of Luminance Meter.

Step 3: Measuring the Luminance of the Panel

Turn the luminance meter on and check to ensure that the following settings (if available) are selected:

- measuring luminance without color correction,
- units are in cd/m^2,
- preset calibration,
- absolute measuring mode, and
- peak intensity function (cannot use a continuous measuring method with a flashing device).

Measure the luminance of the flashing display continuously for one minute. After one minute the peak luminance reading should be recorded. This procedure should be repeated a minimum of three times.

If the measurements are being collected during the day or in a lighted area, a peak "off" measurement (arrow panel display is not illuminated) should be taken immediately after each peak "on" measurement (arrow panel display is illuminated) in order to minimize the effects of the sun or movement of clouds on the measurements. However, it is best to eliminate the effects of clouds by taking measurements on an overcast day. In any event, the "off" measurement represents the ambient light of the area, and is subtracted from the "on" measurement to yield the panel luminance.

Step 4: Calculate the Luminous Intensity of the Panel

Calculate the average peak luminance value and area of the luminance meter aperture (Equation 5). Calculate the peak intensity using Equation 4.

Step 5: Determine if the Panel Meets the Intensity Requirements

Using Table 17 determine if the calculated peak luminous intensity meets the minimum on- and off-axis requirements, as well as the maximum nighttime requirement. With respect to the minimum requirements, the panel intensities must be equal to or greater than the requirements to meet the specification (i.e., pass the test). With respect to the maximum requirement, the panel intensity must be equal to or less than the requirements to meet the specification.

Table 17. Panel Intensity Requirements [a].

Time of Day	Speed (mph)	Minimum On-Axis (cd)	Minimum Off-Axis (cd)	Maximum On-Axis (cd)
Day	≥ 45	4000	800	NA
Night	≥ 45	1200	240	5500

[a] When displaying a left or right flashing arrow (10 lamps illuminated)
NA Not applicable

LAMP TESTING PROCEDURES

In this test, an individual lamp element complete with hood is tested in a photometric laboratory. A table of intensity values is measured with the hood mounted on the lamp with no tilt. Measurements of lamp intensity are made from +/- 10 degrees vertical to +/- 25 degrees horizontal in one-degree increments.

The performance of the lamp is dependent on the voltage at which it is tested. This voltage should be based on the performance of the arrow panel in the field. Measurements should be made at the daytime and nighttime settings of the arrow panel. Covering the photocell of the arrow panel should provide a nighttime voltage level if other provisions have not been made by the manufacturer. The measurements are made in a photometric laboratory using a goniometer utilizing type B geometry (*32*). In this system the light source turns about a fixed vertical axis and also about a horizontal axis following the movement of the vertical axis. All measurements are made with the lamps powered at the specified voltage and with hoods mounted on the lamps. Hoods reduce the luminous intensity of these lamps as the observer moves off-axis with the lamp.

The practical minimum angularity requirements for a Type C arrow panel are shown in Figure 21. Thus, all points within the defined rectangle must be equal to or greater than the minimum off-axis lamp intensity requirements in Table 21 to meet the specification (i.e., pass the test).

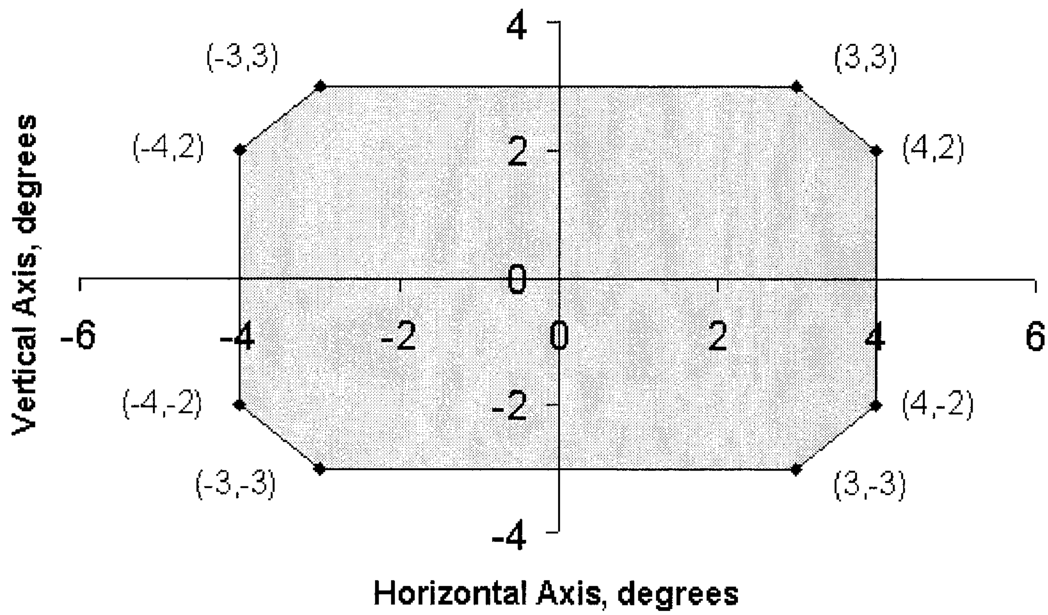


Figure 21. Angularity Requirements.

Table 18. Lamp Intensity Requirements.

Time of Day	Speed (mph)	Minimum On-Axis (cd/lamp)	Minimum Off-Axis (cd/lamp)
Day	≥ 45	500	100
Night	≥ 45	150	30

Examples of Test Results

The results of testing the daytime luminous intensity of two lamps is shown in Figures 22 and 23. The daytime intensity levels were determined for 1071 test points arranged in a rectangular matrix of horizontal and vertical angles defined in relation to the axes of each lamp. The horizontal axis was measured from 25 degrees left to 25 degrees right in steps of one degree. The vertical axis was measured from 10 degrees up to 10 degrees down, again in steps of one degree. Figure 22 presents a graphic description of a solar lamp used by TxDOT, and Figure 23 shows a popular diesel lamp.

A comparison of Table 18 with Figures 22 and 23 shows that both lamps satisfy the on-axis daytime requirement of 500 cd; as the hot spot of the solar lamps is 542 cd and the hot spot of the diesel lamp is 3005 cd. Both lamp types meet the 100 cd off-axis requirement at the coordinates shown in Figure 21.

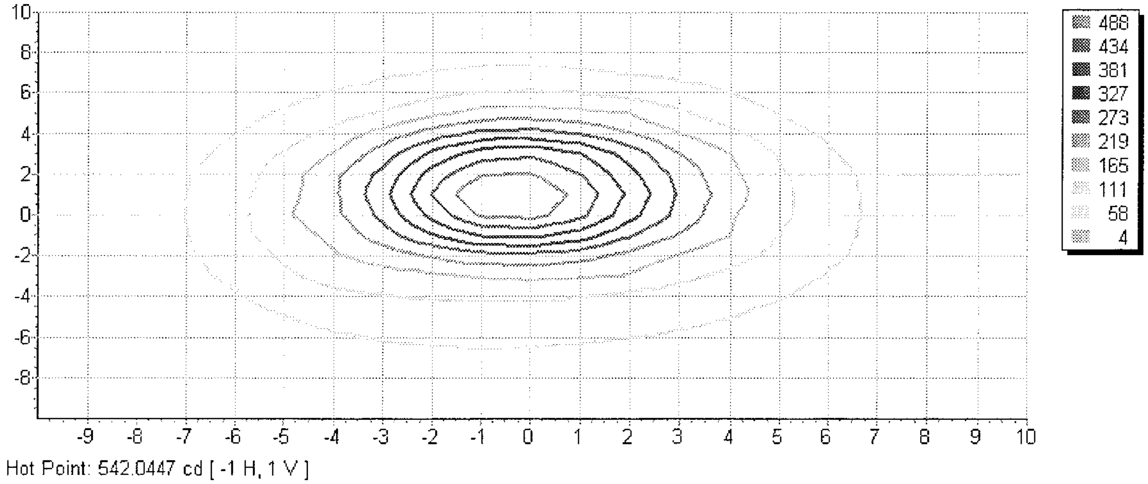


Figure 22. Results of Test of Solar Lamp.

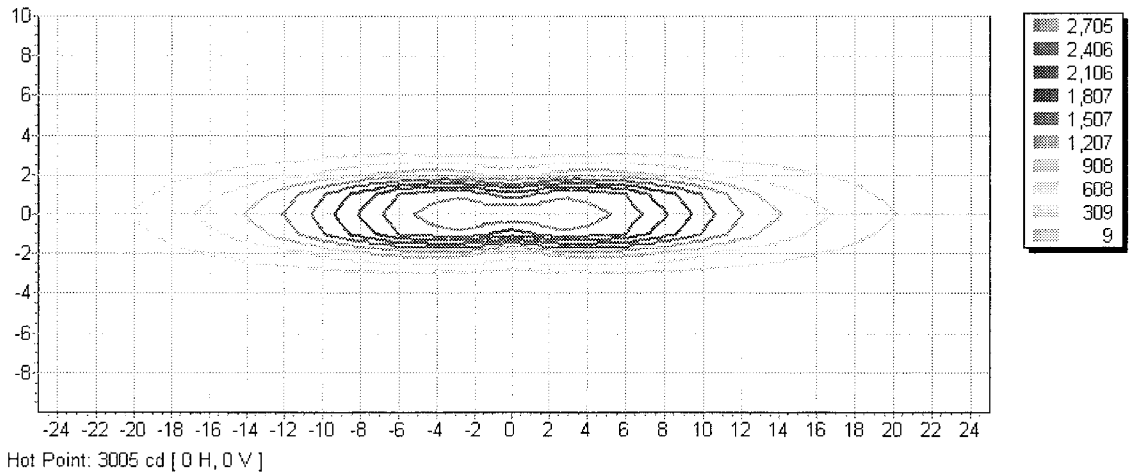


Figure 23. Results of Test of Diesel Lamp.

REFERENCES

1. *Texas Manual on Uniform Traffic Control Devices for Streets and Highways, Part VI.* Texas Department of Transportation, Austin, TX, 1995.

2. Mace, D., M. Finkle, and S. Pennak. *Advanced Warning Arrow Panel Visibility.* Final Report prepared for the National Academy of Sciences by The Last Resource, Inc., December 1996.

3. *Manual on Uniform Traffic Control Devices for Streets and Highways, Part VI.* U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 2000.

4. Knapp, B. G. and R. F. Pain. Human Factors Considerations in Arrow Board Design and Operation. In *Transportation Research Record 703*, Transportation Research Board, National Research Council, Washington D.C., 1979, pp. 1-8.

5. McGee, H. W., W. Moore, B. G. Knapp, and J. H. Sanders. *Decision Sight Distance for Highway Design and Traffic Control Requirements.* Report FHWA-RD-78-078. Federal Highway Administration, U.S. Department of Transportation, 1978.

6. *A Policy on Geometric Design of Highways and Streets.* American Association of State Highway and Transportation Officials, Washington, D.C., 1994.

7. Gordon, D. A. Perceptual Bases of Vehicular Guidance. *Public Roads*, Vol. 34, No. 3, August 1966, pp. 53-57.

8. Leisch, J. E. *Dynamic Design for Safety.* An Institute of Traffic Engineers Seminar, 1975.

9. Alexander, G. J. and H. Lunenfeld. *Positive Guidance in Traffic Control.* Federal Highway Administration, U.S. Department of Transportation, April 1975.

10. Baker, J. S. and W. R. Stebbins. *Directory of Highway Traffic.* Traffic Institute, Northwestern University, Evanston, IL, 1960.

11. Leisch, J. E. *Communicative Aspects in Highway Design.* Presented at 8th Summer Meeting, Transportation Research Board, Ann Arbor, MI, August 1975.

12. Pfefer, R. C. New Safety and Service Guides for Sight Distances. *Transportation Engineering Journal*, ASCE, November 1976, pp. 683-697.

13. *A Policy on Geometric Design of Highways and Streets.* American Association of State Highway and Transportation Officials, Washington, D.C., 1984.

14. *A Policy on Geometric Design of Highways and Streets*. American Association of State Highway and Transportation Officials, Washington, D.C., 1990.

15. Finkle, M. Luminance-to-Intensity Measurement Method. *Journal of the Illuminating Engineering Society*, Vol. 26, No. 2, Summer 1997, pp. 13-19.

16. Freedman, M., P. S. Davit, L. K. Staplin, and M. E. Breton. *Traffic Signal Brightness: An Examination of Nighttime Dimming*. Report RD-85/005. Federal Highway Administration, U.S. Department of Transportation, 1985.

17. Cole, B. L. and S. E. Jenkins. Conspicuity of Traffic Control Devices. *Australian Road Research*, Vol. 12, No. 4, December 1982, pp. 223-238.

18. Hughes, P. K. and B. I. Cole. Search and Attention Conspicuity of Road Traffic Control Devices. *Australian Road Research*, Vol. 14, No. 1, 1984, pp. 1-9.

19. Engel, F. L. Visual Conspicuity as an External Determinant of Eye Movements and Selective Attention. Unpublished doctoral thesis, Technische Hogeschool, Eindhoven, 1976.

20. Mace, D. J. and L. E. Pollack. Visual Complexity and Sign Brightness in Detection and Recognition of Traffic Signs. In *Transportation Research Record 904*, Transportation Research Board, National Research Council, Washington D.C., 1983, pp. 33-41.

21. Hughes, P. K. and B. L. Cole. What Attracts Attention When Driving? *Ergonomics*, Vol. 29, No. 3, 1986, pp. 377-391.

22. Mace, D. J., K. Perchonok, and L. Pollack. *Traffic Signs in Complex Visual Environments*. Report FHWA/RD-82/102. Federal Highway Administration, U.S. Department of Transportation, 1982.

23. Jenkins, S. E. Considerations of the Effects of Background on Sign Conspicuity. In Proceedings of the 11th Conference of Australian Road Research Board, Vol. 11, Part 5, pp. 182-205. Australian Research Board, Melbourne, Australia, 1982.

24. *Traffic Control Devices Handbook*, U.S. Department of Transportation, Federal Highway Administration, 1983.

25. *The Relation Between Discomfort Glare and Driving Behavior*. Report DOT HS 808 452. NHTSA, U.S. Department of Transportation, April 1996.

26. Jenkins, S. E. and B. L. Cole. Daytime Conspicuity of Road Traffic Control Devices. In *Transportation Research Record 1093*. TRB, National Research Council, Washington, D.C., 1980, pp. 74-80.

27. Olson, P. L. *Minimum Requirements for Adequate Nighttime Conspicuity of Highway Signs*. Report UMTRI-88-8. University of Michigan Transportation Research Institute, February 1988.

28. *TxDOT Purchase Specification No. TxDOT 550-14-77*: Sign, Arrow Board, Solar/Battery Powered, Trailer Mounted. Texas Department of Transportation, Austin, TX, December 1998.

29. *TxDOT Purchase Specification No. TxDOT 550-14-74*: Sign, Trailer Mounted, Arrow Board, Diesel Powered. Texas Department of Transportation, Austin, TX, June 2000.

30. Fontaine, M. and H. Hawkins. *Procurement Specification and Application Guidelines for Arrow Panels*. Submitted to NCHRP. Texas Transportation Institute, College Station, TX, 1999.

31. *Standard Plans BC(4)-99: Barricade and Construction Standards*. Texas Department of Transportation, Austin, TX, February 1998.

32. *Lighting Handbook, Reference & Application.* M. S. Rea Ed., Illuminating Engineering Society of North America, New York, 1993.

APPENDIX A

Project 4940　　*Form Code: 1 2*　　*Subject ID Code: ______*

Subjective Survey Form

This research study is being conducted by the Texas Transportation Institute, part of the Texas A&M University System. It is sponsored by the Texas Department of Transportation. The study is being conducted to determine the needed minimum requirements for various traffic control devices. The compensation for your participation in this survey will be a Texas roadmap.

Did you just drive through the entire work zone that is located upstream of here? Yes No
Do you have a current driver license? Yes No
NOTE: If the subject did not drive through the ENTIRE work zone or does not have a current driver license, he/she does not qualify to participate in the study. Thank them for their time.

The study will take approximately 5 minutes to complete. You will be asked to verbally answer three questions about the work zone you just drove through. If you are uncomfortable answering any questions, please let me know. Also, if you choose not to continue to participate in the research for any reason, you are free to quit at any time. For demographic purposes, can you tell me what age category you are in?

Subject Age: 18-34　　35-55　　55+　　Subject Gender: Male　　Female

Question 1: Which of these work zone traffic control devices did you see in the work zone you just traveled through? *Show the subject the pictures of five traffic control devices.*

Sign 1　　Sign 2　　Arrow Board　　Panel　　Barrel

Question 2: Were you able to see the arrow board far enough in advance to take the appropriate driving action needed? If not why?

____

____

Question 3: Do you feel that the arrow board was bright enough to grab your attention?

____

____

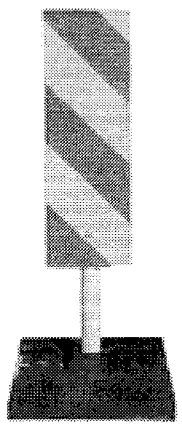
Comments: ____

____

That is all the questions I have for you. Do you have any questions about the survey? Thank you for participating. Have a good day!
Fill out this portion of the form immediately after the survey has been conducted!

Date: ____________			*Recorder: ______________*	
Location: ______________________________				
Weather Conditions: ______________________				
Arrow Panel Intensity (cd):	*1000*	*2000*	*5000*	*10,000*

FORM 1



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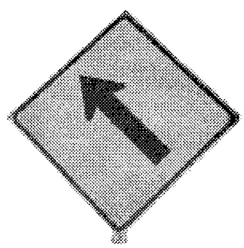
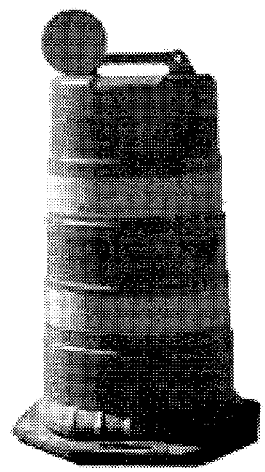
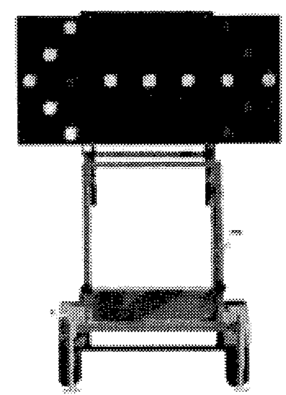


Sign 1



Barrel

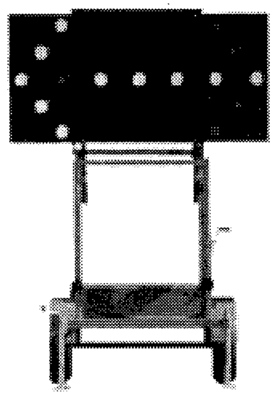


Arrow Board

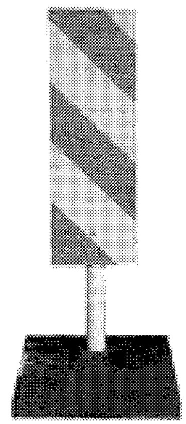
Sign 2

FORM 2

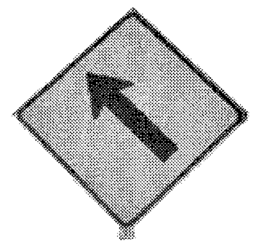
Sign 2



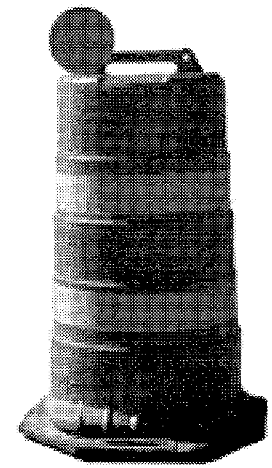
Arrow Board



Panel



Sign 1



Barrel

APPENDIX B

Type C Arrow Panel Intensity Test

Date: ____________________ Time: ________________________

Test Administrator: ____

Recorder: ____

Location of Test: ____

Manufacturer: ____

Model No.: ____________________________ Serial No.: _____________________________

Intensity Tested (circle one): Day Night

Angle Tested (circle one): On-axis Off-axis

Step 1: Set Up of Arrow Panel

Vertical distance from road surface to the center of the lamps that form the stem in a flashing arrow display (should be approximately 9 ft) _______________ ft

Step 2: Set Up of Luminance Meter

Horizontal distance between arrow panel and luminance meter ______500______ ft

Step 3: Data: Measuring the Luminance of the Panel

"On" Peak Luminance Measurement 1 _______________ cd/m^2 (*A*)
"Off" Peak Luminance Measurement 1 _______________ cd/m^2 (*B*)
Peak Luminance Measurement 1 (subtract *A-B*) _______________ cd/m^2 (*C*)

"On" Peak Luminance Measurement 2 _______________ cd/m^2 (*D*)
"Off" Peak Luminance Measurement 2 _______________ cd/m^2 (*E*)
Peak Luminance Measurement 2 (subtract *D-E*) _______________ cd/m^2 (*F*)

"On" Peak Luminance Measurement 3 _______________ cd/m^2 (*G*)
"Off" Peak Luminance Measurement 3 _______________ cd/m^2 (*H*)
Peak Luminance Measurement 3 (subtract *G-H*) _______________ cd/m^2 (*I*)

NOTE: The peak luminance measurements (*C*, *F*, and *I*) should be similar. If one is very different, another set of readings should be taken. This would most likely occur when measuring the arrow panel during the day, but could also happen at night due to transient light.

"On" Peak Luminance Measurement 3 _______________ cd/m^2 (__)
"Off" Peak Luminance Measurement 3 _______________ cd/m^2 (__)
Peak Luminance Measurement 3 (subtract __-__) _______________ cd/m^2 (__)

Step 4: Calculate the Luminous Intensity of the Panel

Average Peak Luminance Measurement = $(C+F+I)/3$ = ______________ cd/m^2 (J)
Area of Luminance Meter Aperture = $[\tan(\text{APsize}) * D/2]^2 * 3.14$ = 5.56 m^2 (K)
where APsize = 1 degree and D = 152.4 m (500 ft)
Peak Intensity = $J * K$ = _________ cd (L)

Step 5: Determine if the Panel Meets the Intensity Requirements

Minimum On- and Off-Axis Measurements

Is the calculated peak intensity (L) _________ cd equal to or greater than the minimum requirement found in Table 1 __________ cd (circle one)? YES NO

Maximum Measurements

Is the calculated peak intensity (L) _________ cd equal to or less than the maximum requirement found in Table 1 __________ cd (circle one)? YES NO

Table 1. Panel Intensity Requirements. [a]

Time of Day	Speed (mph)	Minimum On-Axis (cd)	Minimum Off-Axis (cd)	Maximum On-Axis (cd)
Day	≥ 45	4000	800	NA
Night	≥ 45	1200	240	5500

[a] Panel intensity requirements when displaying a left or right flashing arrow (10 lamps illuminated)
NA Not applicable

Does the arrow panel intensity pass the current specification (question in Step 5 was answered "YES")? PASS FAIL

____

Signature of Test Administrator Date

____

Print Name of Test Administrator