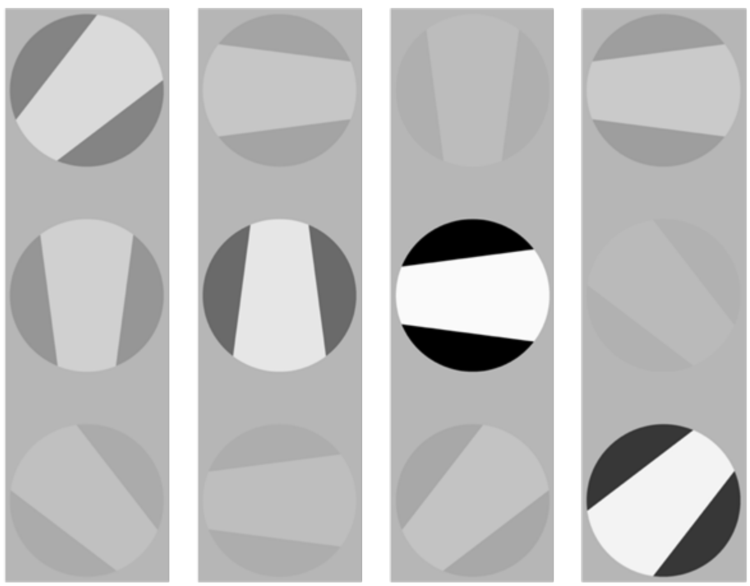
U.S. Department of Transportation

Federal Railroad Administration

Compliance Testing for Locomotive LED Headlights and Auxiliary Lights, Phase II

Office of Research, Development, and Technology
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)
With the development of new lighting technologies, such as light-emitting diodes (LED), the safety requirements stipulated in 49 CFR §229.125 may not adequately accommodate the introduction of LED lamps to the railroad industry. Consequently, it is necessary to better understand the current state of LED technology with respect to such safety requirements. The purpose of Phase II was to evaluate visibility and glare aspects of human-sized objects in lighting conditions produced by different lamps in a stationary locomotive. Visibility aspects were evaluated via contrast discrimination. Results showed that LED lamps provide better contrast discrimination than halogen lamps along the tracks, but worse contrast discrimination than halogen lamps at an angle offset of 7.5° from the centerline of the locomotive. Discomfort glare was evaluated using the De Boer scale. For glare rating in bright mode, results showed no statistically significant differences between LED and halogen lamps. However, for glare ratings made in dim mode, statistically significant differences between both headlamp types were found, with LED lamps producing worse glare ratings than halogen lamps.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

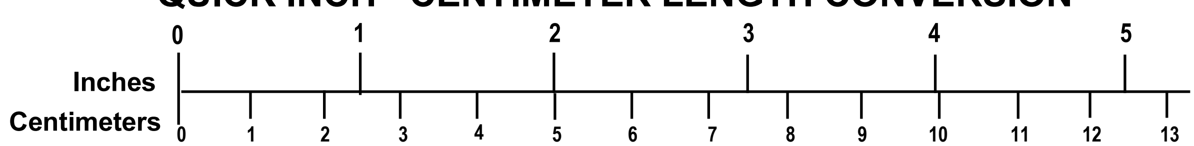
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



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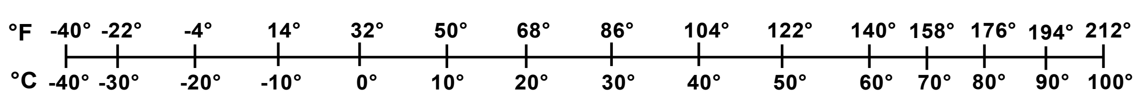

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

This report describes the work performed through the Phase II compliance testing of manufacturer-supplied prototype light-emitting diode (LED) fixtures as locomotive headlights and auxiliary lights. The testing described within this report was conducted by a team of engineers from Engineering Systems Inc. (ESi) and ENSCO, Inc. between September 2018 and March 2019. The research team utilized a locomotive provided by the Monticello Railway Museum to conduct static subjective lighting tests.

Phase II involved field-testing prototype LED and production halogen lamps on stationary locomotives. The purpose of this phase was twofold:

1. To evaluate visibility aspects of human-sized objects in lighting conditions produced by different locomotive lamps.
2. To evaluate aspects of discomfort glare produced by LED and halogen lamps at different distances and orientations.

The research team evaluated visibility aspects using contrast discrimination. Results showed that LED lamps provide better contrast discrimination than halogen lamps along the tracks, but worse contrast discrimination than halogen lamps at an angle offset of 7.5° from the centerline of the locomotive.

The team evaluated discomfort glare using the De Boer scale. For glare ratings in bright mode, results showed no statistically significant differences between LED and halogen lamps; however, for glare ratings made in dim mode, researchers found statistically significant differences between both headlamp types.

In accordance with Federal Railroad Administration regulations, locomotive headlights and auxiliary lights shall comply with 49 Code of Federal Regulations §229.125, which applies directly to locomotives equipped with incandescent lamps, including currently used halogen lamps produced for the rail industry. With the development of new lighting technologies, such as LED, the safety requirements stipulated in §229.125 may not adequately accommodate the introduction of LED lamps to the railroad industry. Therefore, railroads and policymakers should better understand the implications of this technology with respect to visibility and discomfort glare.

1. Introduction

The railroad industry has started to introduce light-emitting diode (LED) technology for locomotive headlights. The present report corresponds to the second phase of such efforts. As with Phase I, LED and halogen samples developed by all participating suppliers were provided to an independent engineering entity staffed by Engineering Systems, Inc. (ESi) and ENSCO, Inc., to evaluate visibility and glare aspects related to LED headlights and auxiliary lights in locomotives.

1.1 Background

In accordance to the Federal Railroad Administration (FRA) regulations, locomotive headlights and auxiliary lights shall comply with 49 Code of Federal Regulation (CFR) §229.125, which applies directly to locomotives equipped with incandescent lamps. With the development of new lighting technologies, such as LED, the safety requirements stipulated in section §229.125 may not adequately accommodate the use of LED lamps in the railroad industry. Consequently, railroads and policymakers should better understand the current state of LED technology with respect to such safety requirements. Phase I addressed photometric characteristics in terms of luminous intensity and colorimetry of LED and halogen lamps.

1.2 Objectives

Phase II of the compliance testing of LED locomotive headlights and auxiliary lights focused on field-testing with stationary locomotives. Two main objectives for this phase were:

1. To evaluate visibility aspects of human-sized objects in lighting conditions produced by different locomotive lamps.
2. To evaluate aspects of discomfort glare produced by LED and halogen lamps at different distances and orientations.

1.3 Overall Approach

The research team chose the objectives described above to fulfill and exceed specific requirements and general guidelines established by the Technical Advisory Group (TAG). The team simultaneously collected experimental data from the same set of conditions for both contrast sensitivity (visibility) and discomfort glare.

Researchers studied visibility aspects associated with the lighting conditions produced by each type of lamp through perceptual evaluations of human-sized contrast targets made by observers located inside the locomotive cabin. They analyzed these observations using multinomial regression to compare the different contrast levels that were detectable for each lamp.

The team examined glare aspects associated with each of the lamps through perceptual evaluations made by test subjects at different distances and angles from the headlights and auxiliary lights. Observers rated the level of discomfort glare using the De Boer scale. These ratings were analyzed using ordinal regression and other statistical methods to test the differences between lamps of perceived glare.

1.4 Scope

The research team limited this study to stationary conditions of two types of locomotives. Testing included only those lamps that were operable in at least bright mode. Phase III testing, a future study, will include visibility aspects during dynamic (moving on track) conditions of the locomotive.

1.5 Organization of the Report

Section 2 provides a brief overview of relevant scientific literature related to contrast sensitivity and glare. Section 3 describes the methodology used during field testing. Section 4 provides an analysis of the data collected, and a discussion of the implications of such results. General conclusions are presented in Section 5.

2. Literature Review

Researchers conducted a literature review to evaluate existing academic research in the field of lighting and human perception, as well as regulatory statutes applicable to the use of LED lighting in locomotives. Investigators reviewed contrast-sensitivity charts to determine the most appropriate evaluation of visibility from onboard the locomotive. Test personnel considered quantitative and qualitative methods of evaluating glare as well as reviewed locomotive lighting regulations contained within 49 CFR §229.125 to establish the procedures used throughout Phase II testing.

2.1 Brief Regulation Overview: 49 CFR §229.125

Relevant portions of Section 229.125, that directly relate to visibility, are addressed. For instance, paragraph (a) states that during road service, "Each headlight shall be aimed to illuminate a person at least 800 ft ahead and in front of the headlight." In addition, with regard to locomotives used in yard service, paragraph (b) states, "Each shall be aimed to illuminate a person at least 300 ft ahead and in front of the headlight."

Currently, there are no regulations in § 229.125 regarding discomfort glare. Nonetheless, the testing designed and the conclusions drawn in this study were based on the scope of work established by the TAG committee members and the scientific literature available to date.

2.2 Review of Contrast-Sensitivity Charts

Compliance with 49 CFR §229.125, as previously mentioned, can be quantified by measuring the amount of light falling on a surface or plane (illuminance) that approximately represents the area of a person. That illuminance, measured in lux (lx) per SI units, or foot-candles (fc) in SAE units, can then be compared to an established threshold. For instance, standard SAE J2829 uses a threshold for distance and illuminance detection of 3 lx (approximately 0.279 fc), and based on such a threshold, low-beam headlamps for the U.S. automotive industry are designed to project at least 3 lx of illuminance at 100 meters in front of the vehicle (SAE, 2009). This amount of light approximates the amount of natural light before sunrise and after sunset, also known as civil twilight.

In addition to this quantifiable characteristic of light, and per the requirements established in the scope of work for this study, a subjective aspect to the evaluation of LED lamps was considered. In general terms, the TAG committee posed the following question: how visible is a human-sized object when illuminated by locomotive lamps? The answer to this question requires some level of quantification for a subjective concept of visibility – more specifically, visibility under low-illumination conditions. Under these conditions, our perceptual abilities are hindered and our ability to detect visual information otherwise available during higher-illumination levels is degraded (Andre & Owens, 2001; Owens & Tyrrell, 1999; Owens, Wood, & Owens, 2007). During nighttime driving, for instance, the ability of a driver to detect a pedestrian on or near the road depends greatly on the contrast between the pedestrian and the surrounding background. For example, if a pedestrian is wearing dark clothing, a driver is less likely to detect the pedestrian due to the lower contrast ratio typically produced between the nighttime background and the dark clothing.

One approach to measure this visual function is by means of contrast sensitivity. Contrast sensitivity can be defined as the ability to discriminate between a lighter and a darker spatial area. Contrast sensitivity varies among individuals; the higher the contrast sensitivity an observer possesses, the smaller the threshold amount of detectable contrast is required. Contrast sensitivity is an important function for the visual system and its ability to detect lines, edges, and ultimately shapes, especially under low illumination. In fact, contrast-sensitivity charts have been developed to match the observations made by an observer in a low-illumination scene to a visual representation of such scene – e.g., photographs, videos, or virtual renderings (Ayres & Kubose, 2015; Sprague, Meza-Arroyo, Shibata, & Auflick, 2019). The underlying principle that makes a contrast-sensitivity chart effective is that contrast sensitivity is a function of spatial frequency and the overall illumination of a scene (Ayres & Kubose, 2015). As previously mentioned, the overall illumination of a scene refers to illuminance, while spatial frequency refers to a spatial relationship between the dark and light areas that define contrast. Spatial frequencies are characterized by gratings comprised of a sequence of alternating light and dark bands, which are measured in cycles per degree – i.e., the number of light-dark pairs in one degree of visual angle. These gratings are often generated through the implementation of Gabor filters. Figure 1 shows three gray scale gratings based on a Gabor patch at different spatial frequencies and orientations. Spatial frequencies decrease from left to right, with left-most grating having the highest frequency. For each of the three gratings, contrast increases towards the center of the image and it decreases towards the edges.

These gratings are the basic components of contrast-sensitivity charts. A widely used chart in the field of forensic engineering is that proposed by Ayres (Ayres, 1996) (see chart *a* in Figure 2) includes six contrast levels at two spatial frequencies over a 0.20 relative luminance background. More recently, Ayers and Kubose (2015) presented an update to this chart with the inclusion of additional spatial frequencies and a background with different luminance value (see chart *b* in Figure 2). This revised version extended the range of usability in relatively brighter lighting conditions. A recent study presented a series of enhancements to the contrast-sensitivity charts proposed by Ayres (Sprague et al., 2019). These enhancements extended the range of usability even further and added a layer of testability for contrast perception and validation of visual representations under low-illumination conditions.

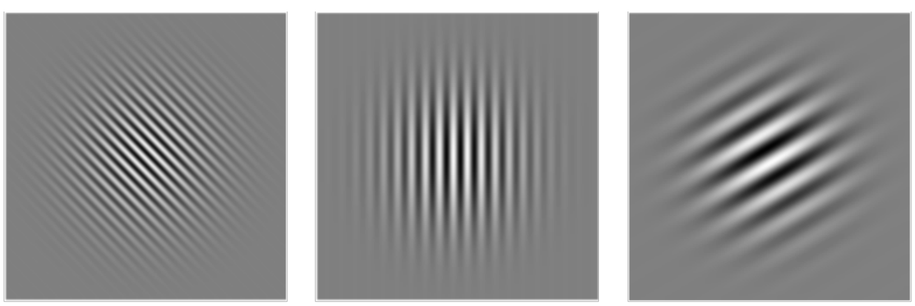
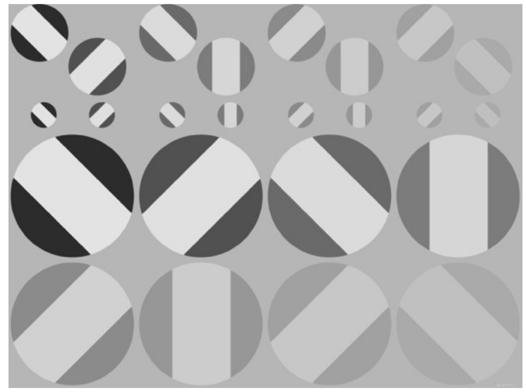
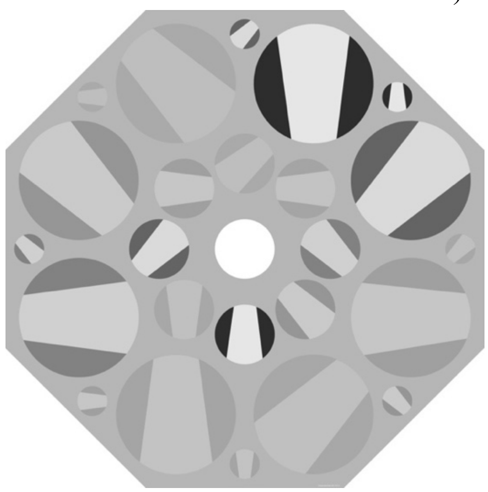


Figure 1. Example gray scale gratings based on a Gabor patch

a) Original Ayres Chart



b) Revised Ayres Chart



c) Sprague Chart

Figure 2. Examples of contrast-sensitivity charts

This latter version of a contrast-sensitivity chart was the basis for the quantification of visibility under the lighting conditions produced by different locomotive lamps (see chart *c* in Figure 2) includes eight contrasts levels at three spatial frequencies over a 0.47 relative luminance background. The contrast chart implemented in the present study allowed a relationship to be established between the level of lighting produced by different locomotive lamps and the contrast perception of different observers under such conditions.

2.3 Review on Glare

Glare is a visual condition created by the sub-optimal distribution of luminance across an observer's field of view. Glare conditions can occur two ways: when luminance is too high (i.e., too much light) and when the range of luminance across the visual field of an observer is too large (IES, 2019). There are known effects associated with headlamp glare. For instance, glare reduces visibility by creating a layer of scattered light over the field of view of observers (Bullough, Van Derlofske, Dee, Jie, & Akashi, 2003). This is often referred to as disability glare, and its effect can be accentuated in older individuals due to age-related visual impairments, surgical procedures, and other visual medical conditions. Similarly, glare can also increase discomfort to nearby observers, which may affect the performance of their task-at-hand – e.g., driving, navigating, or handling machinery. This perception or sensation of glare is referred to as discomfort glare (National Highway Traffic Safety Administration, 2007). Different models to characterize and predict glare can be found in the literature. However, discrepancies have been found between these models when attempting to predict or characterize glare (Clear, 2012). Different factors can affect the performance of different models, such as luminance size, the number of light sources, and the overall complexity of the scene.

The body of literature regarding glare also includes a vast number of studies focused on transportation systems and the safety implications of its light sources. Glare produced from locomotive lights, for instance, is a safety concern for regulatory bodies and standards organizations in the transportation industry. A 1995 FRA study identified glare as a safety concern for auxiliary alerting lights and recommended considering glare when specifying minimum and maximum levels of luminous intensity (Carroll, Multer, & Markos, 1995). Similarly, in 2001, the National Highway Traffic Safety Administration (NHTSA) initiated research efforts to investigate complaints regarding headlamp glare and its effects on driving performance (Bullough et al., 2008, 2003; National Highway Traffic Safety Administration, 2007).

It would be expected that perceived glare is a function of the amount of light falling on an observer's eye, with glare increasing as illuminance also increases. A previous study found that the successful detection of targets decreased as illuminance increased from 0.2 to 5 lx (Bullough et al., 2003). However, according to that same study, the relationship between a light source and its perceived glare can be more complex, especially with respect to discomfort glare. For instance, a previous study found that two different light sources, a halogen and a high-intensity discharge (HID) headlamp, were perceived differently at the same level of luminous intensity, with the HID headlamp perceived as more uncomfortable (Bullough, Fu, & Van Derlofske, 2010).

One the most common tools to quantify discomfort glare is the De Boer scale (De Boer, 1967). This tool is a subjective rating scale, including 9 measurement points arranged as follows:

Table 1. De Boer scale

1. Unbearable
2.
3. Disturbing
4.
5. Just permissible
6.
7. Satisfactory
8.
9. Just noticeable

In this scale, the worst case of perceived glare is given a rating of 1 (Unbearable), while the best case is given a rating of 9. In an experimental setup, observers exposed to a potential source of glare are asked to provide a numerical rating from the De Boer scale to evaluate the discomfort produced by the source. Despite being a subjective response that depends on the particular sensation of an observer, previous studies have produced consistent results when using this scale (Bullough et al., 2008, 2003; Sivak, Schoettle, Minoda, & Flannagan, 2005). Moreover, the ubiquitous presence of the De Boer scale in the scientific literature has produced prediction models based on objective measurements. As shown in the study sponsored by NHTSA (Bullough et al., 2003), one such model is expressed by the following equation:

$$GR = 5 - 2\log \frac{E_v}{0.02\left(1+\sqrt{\frac{L_v}{0.04}}\right)\theta^{0.46}} \tag{1}$$

Where *GR* is the glare rating in the De Boer scale, E_v is the illuminance (lx) at the observer's location, L_v is the luminance (cd/m^2) of the glare source, and θ (in degrees) is the orientation of the observer with respect to the glare source. This implies that, under specific conditions, glare can be described mathematically. In addition, different De Boer ratings have been associated with specific levels of illuminance. For instance, a previous study found that a rating of 4 in the De Boer scale was produced when illuminance at the eye of an observer was at approximately 1 lux (Bullough et al., 2010). The De Boer scale and mathematical model expressed in Equation 1 served as the basis for glare evaluations in the present study. Further details, methods, and results are discussed in subsequent sections of this report.

3. Methodology

The test methodology to evaluate the illuminance, contrast sensitivity and glare of LED headlamps on stationary locomotives is described in this chapter. Lamp samples submitted by the participating suppliers were installed on a stationary locomotive and measurement points established at various distances from the locomotive and angular offsets from the track centerline. These measurement points were used for both subjective evaluation of glare and contrast as well as quantitative measurement of illuminance.

3.1 Lamp Samples

All samples submitted during Phase I of testing were also used for Phase II testing. Additional samples and substitution of some were required due to technical difficulties encountered during installation and operation of the samples on the locomotives. Additions and substitutions were as follows:

- All four halogen samples provided by CML were substituted for new 75-volt lamps.
- Original LED samples provided by Railhead/Divvali were refurbished on site by the supplier to run appropriately with the locomotives.
- Additional LED samples developed at a higher luminous intensity (approximately 200,000 cd) were provided by Railhead/Divvali.

Further details about each of the samples tested can be found in Appendix F.

3.2 Testing Protocol

Experimental Setup

Testing was done at the facilities of the Monticello Railway Museum in Monticello, IL. The section of railway used for testing was selected based on the following criteria:

- Relatively flat terrain
- Straight section of at least 1,000 ft in length
- Unobstructed visibility for at least 1,000 feet in front of the locomotive and for at least 300 feet to one of the sides of the railway

Prior to testing, the railway selected was surveyed, and the relevant points for testing were marked for later reference. The testing site and locomotives were documented and preserved using a Faro X330 laser scanner to collect 3D point cloud data and a DJI Phantom 4 Pro drone for photographs/HD video.

Overall Procedure

The logistics of the test were not trivial. The testing protocol was designed such that contrast evaluations were done at the same time as glare ratings. During testing, at least three key roles were fulfilled by four people:

1. ***Contrast operator***: A person located inside the cabin who provided participants with specific instructions related to the contrast detection task. Before each trial, this operator documented the lighting conditions via validated photography, using the contrast targets

as references for exposure. This person also coordinated the overall logistics and flow of testing.

2. ***Fixture operators***: Two operators who rotated their assigned contrast fixtures to a specific sequence as mandated by the contrast operator.
3. ***Glare operator***: A person who provided participants with instruction regarding glare ratings. This person walked to the randomly assigned measurement locations and guided participants through specific sequence.

A fourth role that had to be additionally filled by either the contrast or glare operator was the photometer operator. This person oversaw recording illuminance and luminance measurements at different distances and orientations (see image ***a*** in Figure 5). In addition to these specifically assigned roles, ESi personnel and individuals from TAG, UP, and NS also coordinated the logistics related to the proper function and operation of the locomotives, as well as the installation of lamp samples. Volunteers from the Monticello Railway Museum also assisted as needed.

Testing Requirements

1. Perceptual evaluations from inside the locomotive cabin (contrast) included the following two conditions:
    a. Locomotive lamps in bright mode with a contrast target located on the railroad at 800 feet away and in front of the locomotive.
    b. Locomotive lamps in both dim and bright mode with a contrast target located at 300 feet away and 7.5° to the right of the observer.
2. Perceptual evaluations from outside the locomotive cabin (glare) included the following conditions:
    a. Locomotive lamps in bright mode with measuring points at two different distances away from the light source: 300 feet and 800 feet, and three different angle offsets of 0.0°, 7.5°, and 20° for each distance.
    b. Locomotive lamps in dim mode with measuring points at two different distances away from the light source: 100 feet and 300 feet, and three different angle offsets of 0.0°, 7.5°, and 20° for each distance.

Testing Participants

Participants were volunteers from the Monticello Railway Museum and local residents of Monticello, IL. Consent forms and bio-sheets were filled and signed for each participant, and a unique, randomized subject number was assigned for each one them. A total of 11 subjects participated in the study.

Apparatus

Tools and equipment used for this experiment included contrast charts, cameras, light meters, and scanners. One camera was set up outside the nose-door of the locomotive cabin to capture validated photography. Two photometers were used – an Extech HD450 light meter to measure illuminance and a LiteMate PR-524 PhotoResearch photometer to measure luminance. A Faro scanner was used to obtain precise geometry of the locomotives and the terrain in which the testing was performed. A drone was used to obtain aerial views of the extended area in which the experiment was performed.

Additional tools needed for testing included office supplies, flashlights with red lenses to minimize disruptions to dark adaptions, distance measurement devices, tripods, cones, chalk paint, conspicuity vests, and custom fixtures for the rotating contrast charts.

3.3 Contrast Sensitivity Evaluations

As mentioned previously, contrast evaluations were made from within the locomotive cabin to determine the visibility aspects of a human-sized object under the various lighting conditions produced by the different locomotive lamps. To achieve this goal, two contrast-sensitivity fixtures, each containing 12 different circular targets, were developed. One fixture was set at 800 feet away with a 0° offset angle from the locomotive cabin, and a second one set at 300 feet away with a 7.5° angle offset. The location of the latter fixture was based on the CFR regulations in §229.125, regarding the luminous intensity that a headlight should provide at 7.5° from the centerline of the locomotive, and the projected illuminance maps developed during Phase I. Moreover, placing the contrast fixture at an orientation of 20° would have produced an immediate floor effect, and placing the fixture at an orientation of 0° would have produced, for most contrast levels, a ceiling effect on the targets. In other words, contrast targets placed too far to the side (at 20°) under minimal to nonexistent illuminance conditions would have made detection of even the highest contrast targets unlikely, while a contrast fixture placed at 300 feet in front of the locomotive would have made all of the contrast targets detectable.

The contrast fixtures were based on contrast-sensitivity charts used for validating low-illumination photography, often used in the forensic engineering field. Each circular target was composed of a lighter, center wedge and two darker flanks, with contrast balanced around 0.47 relative luminance for the background. The contrast relationship for these two components followed an exponential function, with the circular target labeled "CL.1" having the highest contrast and "CL.12" the lowest (see Figure 3). As the targets decreased in contrast, their relative luminance values approached that of the background luminance.

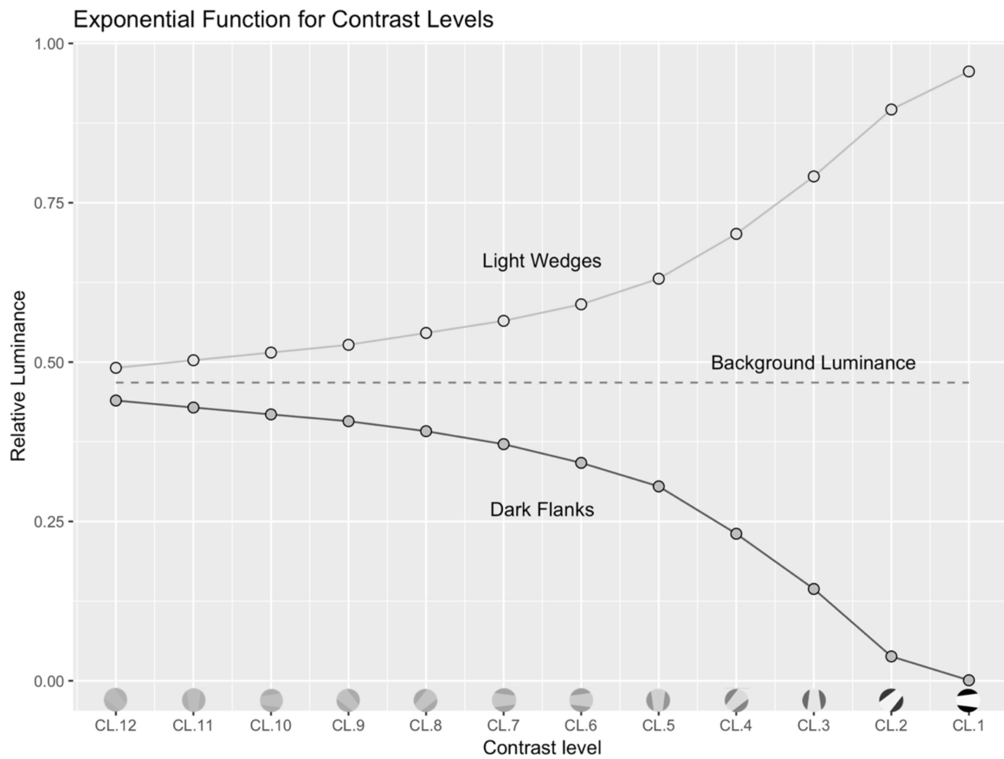


Figure 3. 12-Point contrast function

The contrast fixtures shown in Figure 4 were developed specifically for this study. Each side of the contrast fixture had a specific "gray card" with 3 circular contrast targets, making a total of 12 distinct contrast levels (one for each circular target). The lighter center in the form of a wedge added a testable aspect of visibility. While the adjacent light and dark components tested contrast-sensitivity, the center wedge allowed a relative level of acuity to be tested. The wedge was used to convey a sense of directionality, similar to an arrow. For this experiment, subjects were instructed that the shorter end of the wedge conveyed such direction. For both fixtures, gray cards were labeled from A to D, as shown in Figure 4. During the experiment, the fixture operator could then rotate the fixture to the card assigned by the contrast operator.

As part of the testing protocol, for each exposure to a gray card containing three circular targets, participants were asked to determine the number of circular targets that they could detect, and the direction of the light, center wedge within each target. As an experimental addition, during random trials, the fixture operator (wearing dark clothing) at 330 feet away stood on one side of the fixture (to the left or right of the contrast fixture), and at the end of such trial, the participant, making contrast evaluations, was asked about the location of the fixture operator without having to look again at the fixture. Participants provided their evaluations on answer sheets prepared in advance (see Appendix C – Visibility Sheet). They were asked to draw an arrow on the corresponding circle in their answer sheet if they could perceive the direction of the wedge. If they could discern the contrast between the center wedge and the darker flanks but not the direction of the wedge, they were asked to draw a check mark. If they could discern neither the contrast nor the direction of the wedge, they were instructed to leave blank that circle on their answer sheet.

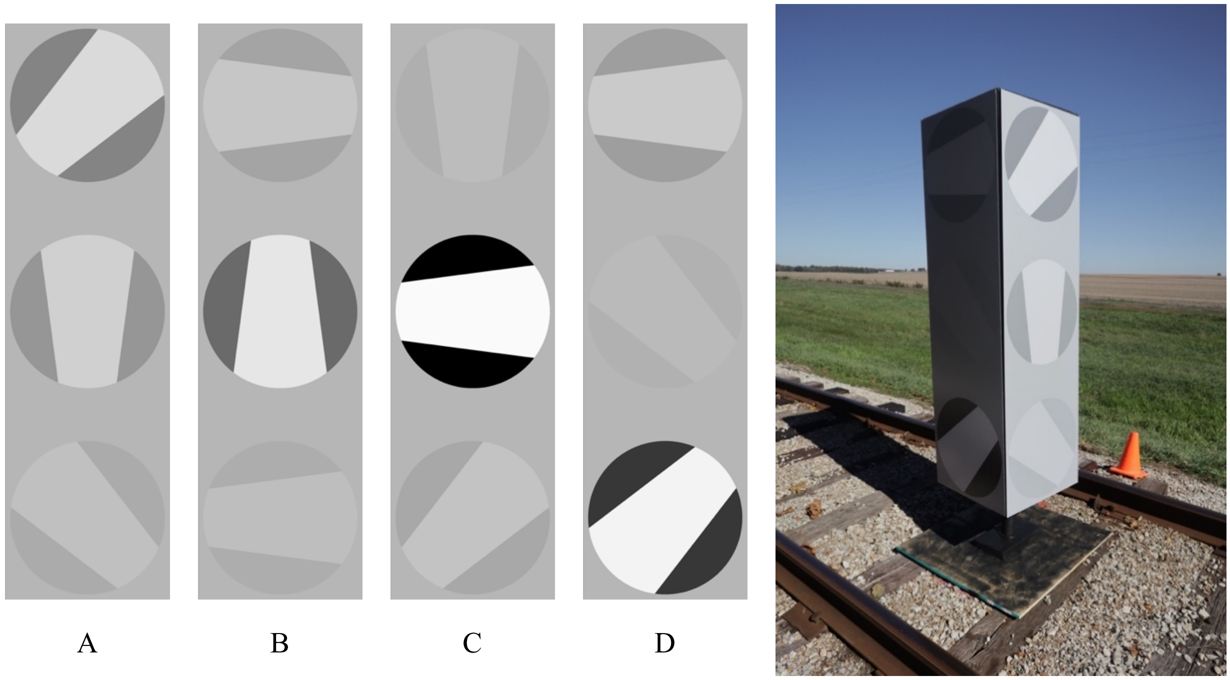
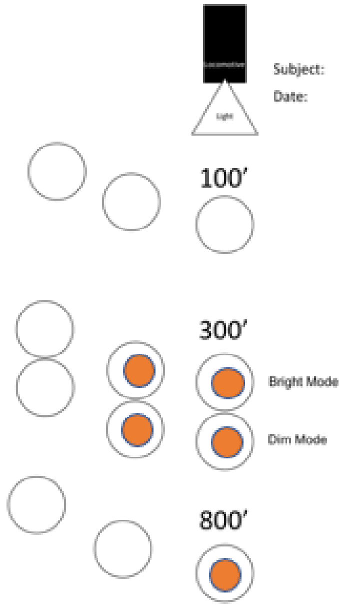


Figure 4. Contrast targets and contrast fixture at testing site

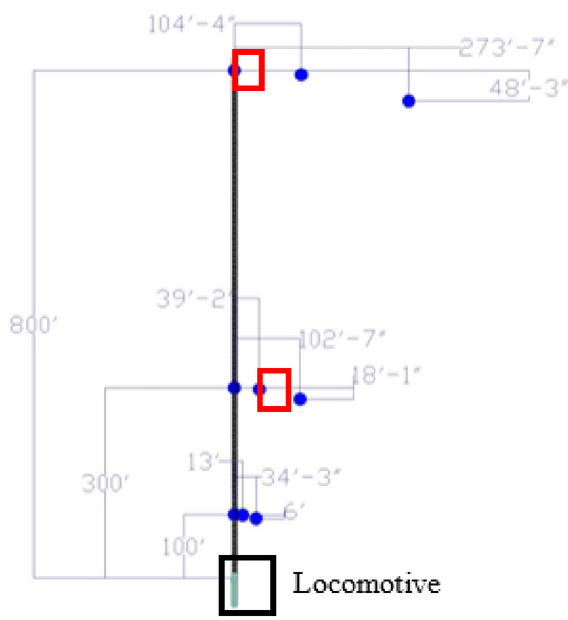
3.4 Glare Ratings – De Boer Scale

Glare ratings were made from outside the locomotive cabin. To evaluate aspects of discomfort glare produced by LED and halogen lamp samples, participants were asked to make judgments using the De Boer scale. These judgments were made from three different distances (100 feet, 300 feet, and 800 feet) and three different angles (0°, 7.5°, and 20°) from the light source, with a total of nine different measuring locations (see Figure 5). Three locations per trial were assigned at random to each participant. At each location, they were asked to report their rating verbally, and the glare operator recorded the rating using an answer sheet previously prepared with the specific measuring locations (see Appendix D – Glare Ratings Sheet).

Figure 5 shows an NTS diagram of the testing layout for glare and contrast judgments. The solid circles indicate the locations where participants made glare ratings. Red squares show the locations where the two contrast fixtures were located. The orange circles in image *a* represent the locations where illuminance measurements were recorded.



a) Answer sheet for recording glare ratings and illuminance measurements. The orange circles represent the illuminance measuring locations.



b) Scaled sketch of testing setup and testing locations

Figure 5. Glare, contrast, and illuminance measuring locations

4. Analysis and Discussion

Test personnel analyzed the results of test results using a static locomotive to determine relevant characteristics of light intensity and distribution at various distances and angles under evaluation. Combined with the results of subjective contract detection tests, these analyses provide a thorough characterization of each sample's suitability for use as a locomotive headlamp.

4.1 Illuminance Analysis

Per the requirements established by the TAG, researchers took illuminance measurements at 800 feet in front of the locomotive with the headlight set to bright mode and at 300 feet in front of the locomotive with the headlight set to dim mode. In addition to these two measurement locations, illuminance measurements at 300 feet with an offset angle of 7.5° in bright and dim mode were also taken – adding to a total of five illuminance measurements per lamp trial. Illuminance measurements were taken at 4.5 feet above the ground surface at each measuring location, which is approximately sternum height.

At each location and for each lamp model, sequential illuminance measurements were recorded. The results reported in this section include an average of those measurements for each unique tested condition. Note that the names of the participating suppliers were not matched to their corresponding results. This avoided potential future misrepresentation of the characteristics and performance of the lamps, as the outcomes reported in this report may not reflect the changes made by each supplier to their lamps after undergoing this set of tests.

Of all measurements taken, the highest values corresponded to LED lamps with illuminance conditions produced above 60 lx (see Appendix I). Most illuminance measured for both LED and halogen lamps were found to be below 25 lx. The geometric arrangement between the headlight and the auxiliary lights was different between locomotives. The headlight in the UP locomotive was located on the nose of the locomotive, and it was equipped with a dual-lamp headlight in a vertical arrangement. The NS locomotive was equipped with a dual-lamp headlight in a horizontal arrangement located above the cabin windows.

UP Locomotive (a)   NS Locomotive – headlamp only (b)

Figure 6. Difference in headlamp arrangements

Illuminance Measurements in Bright Mode

When in bright mode, both locomotives powered a total of four lamps, a dual-lamp headlight and two auxiliary lights. The highest values of measured illuminance corresponded to LED lamps at 300 feet away and directly in front of the locomotive. This was expected, as illuminance decreases inversely proportional to the square of the distance from the light source (inverse-square law).

The lowest values of measured illuminance corresponded to LED lamps at 300 feet and at an angle of 7.5° from the centerline of the locomotive. Figure 7 shows illuminance levels measured at 0° and 7.5° from centerline plotted versus an arbitrary order of the data (Measurement Index). The dashed line in Figure 7 represented an arbitrary threshold equal to 3 lx. This result matched the laboratory findings reported in Phase I, where LED lamps produced lower levels of luminous intensity at 7.5° and 20° orientations and halogen lamps exhibited a wider lateral spread of illuminance.

For measurements taken at 800 feet, LED lamps also exhibited the highest comparative illuminance values. However, unlike measurements at 300 feet, most of the lowest measurements corresponded to halogen lamps. Figure 8 shows these measured illuminance levels taken at 0° from centerline along with an arbitrary reference illuminance level of 3 lx. This result is also consistent with the findings reported in Phase I, where LED lamps exhibited a photometric distribution more focused along the tracks and ahead of the locomotive.

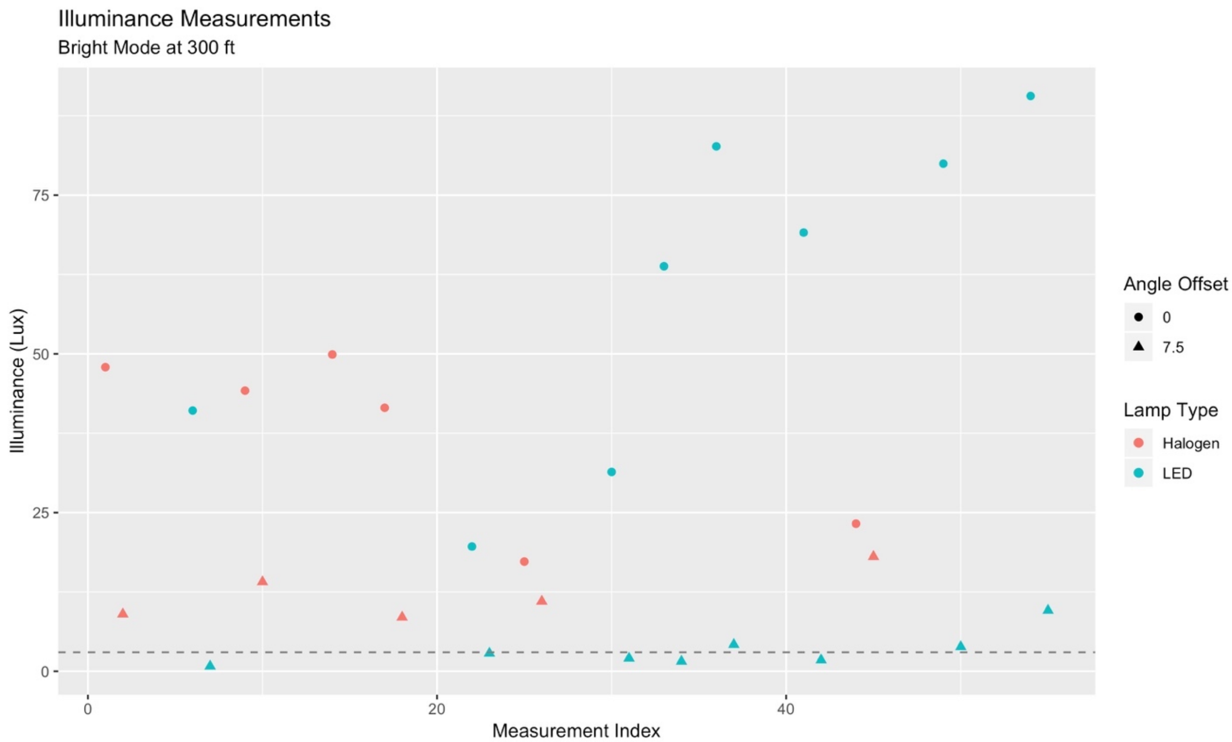


Figure 7. Illuminance measurements in bright mode at 300 feet

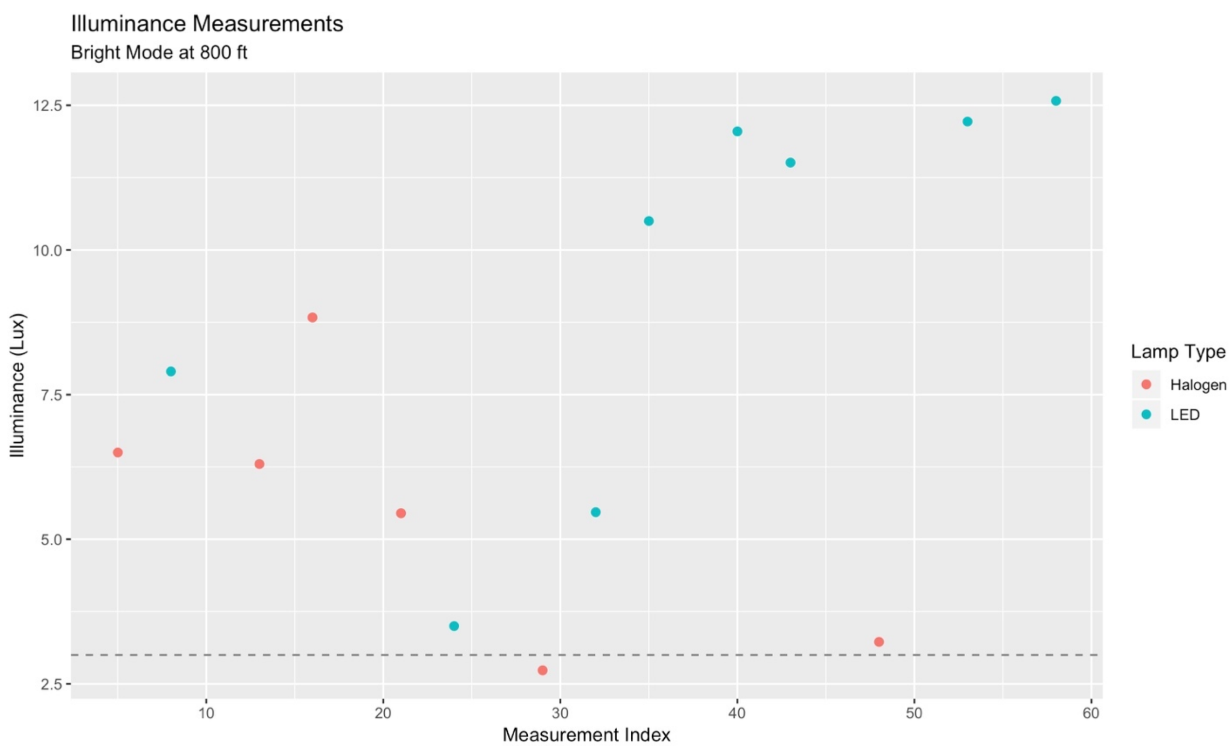


Figure 8. Illuminance measurements in bright mode at 800 feet

Illuminance in Dim Mode

All measurements in dim mode were taken at 300 feet away and at two orientations (0° and 7.5°) from the centerline of the locomotive. The highest illuminance values, as was the case for values in bright mode, corresponded to LED lamps. Illuminance measurements for halogen lamps, however, remained below arbitrary reference illuminance of 3 lx at both orientations 0° and 7.5° (see Figure 9).

Note that lamps from only one LED supplier could be tested. All other LED lamps were not able to engage dim mode in either of the locomotives. This was a concern raised during laboratory testing of Phase I, due to the various mechanisms found for engaging dim mode. Some lamps could be dimmed by reducing the voltage, while others required series resistance that simulated the locomotive circuitry.

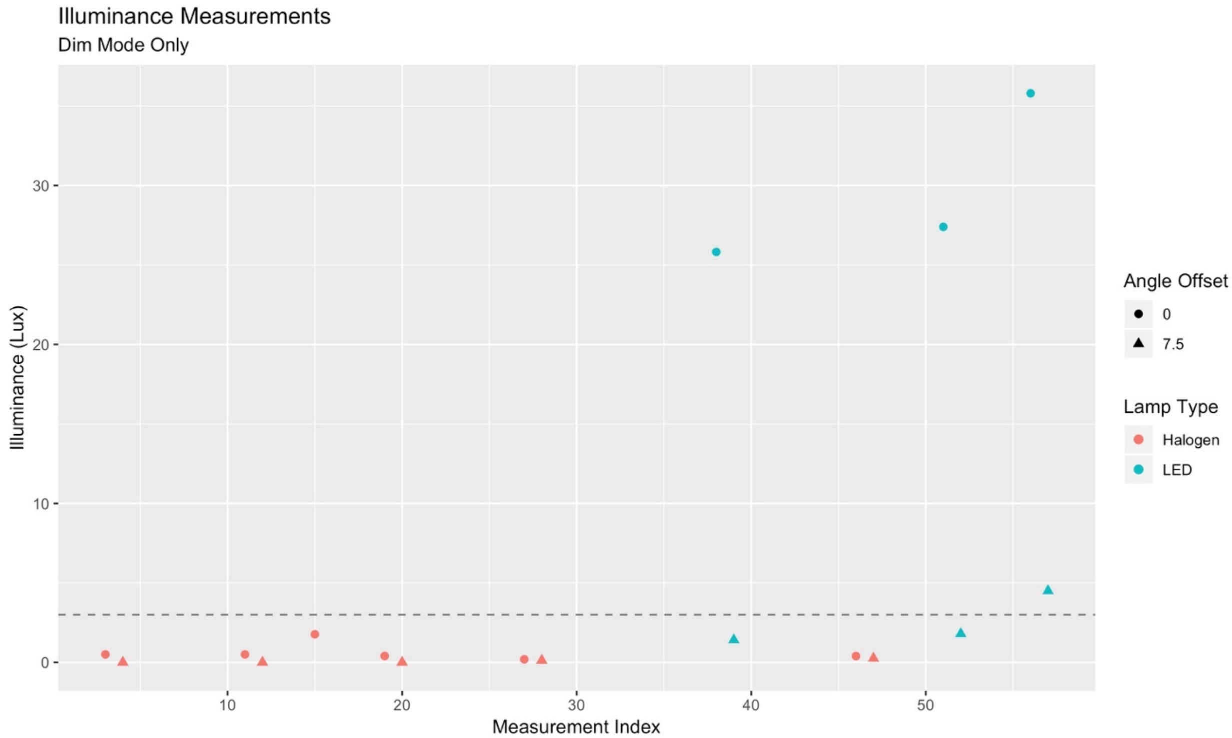


Figure 9. Illuminance measurements in dim mode at 300 feet

Illuminance Comparison with Laboratory Testing

During Phase I testing, illuminance maps were developed for each of the participating lamps. In this section, measurements from field testing are compared to illuminance calculations made from laboratory measurements of luminous intensity. Average measured illuminance values at 300 feet centerline, 300 feet 7.5º angle offset, and 800 feet centerline in both dim and bright mode and for both the UP and NS locomotives were tabulated and compared to the data gathered in Phase I laboratory testing as shown in Table 2. The data from Phase I was generated considering a height of 4.5 feet above the rails. Note, only lamps with both Phase I and Phase II measurement values are reported here.

Some differences were found between laboratory and field measurements. These differences may have been due to four potential reasons: power differences, human variability, unleveled terrain, and headlamp aiming. First, the manner in which lamps were powered may have been different.

During laboratory testing, lamps were powered using direct current; during field measurements, lamps were powered through the internal circuitry of the locomotive, which may have provided less constant voltage. Second, potential error due to human variability may have originated from inherent inconsistency in the height, location, and orientation of each measurement. Third, although the testing site tracks were relatively flat, the surrounding terrain was not. Hence, slight changes in the terrain would translate into differences in the overall geometry between light sources and measuring points. And fourth, lamp-aiming would have been different between laboratory and field-testing conditions. During field-testing conditions, lamp-aiming would have been subject to slight differences in installation procedures.

Suppliers' names and their corresponding lamp models were coded. A total of six suppliers were included in this analysis, three for halogen and three for LED. Halogen lamps were assigned the letter **X**[1] and numbered from one to three for each supplier. LED lamps were simply assigned the acronym **LED** and assigned letters A to C. Suppliers A and C provided two different lamp models. The total number of tested model lamps, including halogen and LED, was eight.

Table 2. Illuminance comparison between laboratory and field testing[2]

UP Locomotive Illuminance (lux)							
		300 ft., 0°		300 ft., 7.5°		800 ft., 0°	
	Supplier	Phase I	Phase II	Phase I	Phase II	Phase I	Phase II
Halogen-Bright	X1	40.24	44.2	9.51	14.07	3.27	6.3
Halogen-Bright	X2	34.49	23.25	1.78	18.06	3.86	3.23
Halogen-Bright	X3	37.13	49.9	6.10		3.83	8.83
LED-Bright	LED A1	29.08	63.8	0.73	1.55	3.56	10.5
LED-Bright	LED A2	34.45	31.4	0.88	2.15	4.53	5.47
LED-Bright	LED B	20.44	19.65	1.70	2.83	2.89	3.5
LED-Bright	LED C1	41.77		1.59		3.49	
LED-Bright	LED C2		90.62		9.58		12.58
LED-Dim	LED C1	20.70		0.47			
LED-Dim	LED C2		35.8		4.5		

[1] In chemistry, the letter X is often used to refer to any halogen element.
[2] Laboratory testing for halogen lamps did not include dim mode. Lamps from supplier LED B were operable in the NS locomotive.

NS Locomotive Illuminance (lux)							
		300 ft., 0º		300 ft., 7.5º		800 ft., 0º	
	Supplier	Phase I	Phase II	Phase I	Phase II	Phase I	Phase II
Halogen	X1	33.91	41.5	8.74	8.5	6.76	5.45
Halogen	X2	22.71	17.28	1.61	11.00	7.44	2.74
Halogen	X3	26.34	47.9	5.79	9.0	7.38	6.5
LED-Bright	LED A1	14.34	41.07	0.66	0.8	6.59	7.9
LED-Bright	LED A2	16.90	69.1	0.88	1.77	8.01	11.51
LED-Bright	LED C1	34.77	82.68	1.13	4.2	7.32	12.05
LED-Bright	LED C2		79.95		3.86		12.22
LED-Dim	LED C1	15.64	25.82	0.38		3.72	1.41
LED-Dim	LED C2		27.4				1.8

4.2 Analysis of Contrast Sensitivity Evaluations

As described in Section 3.2, participants reported their contrast evaluation on a specific answer sheet. These written responses were then captured in a digital database. The evaluations made by participants for each contrast level were coded into an ordinal scale to perform multinomial regression analysis. Correct responses made about the direction of the wedge were assigned the value "3." Responses where participants drew an arrow with the incorrect direction[3] along with a checkmark corresponding to contrast detection were assigned the value "1." Finally, blank responses in which participants were not able to detect a given contrast level were given the value "0."

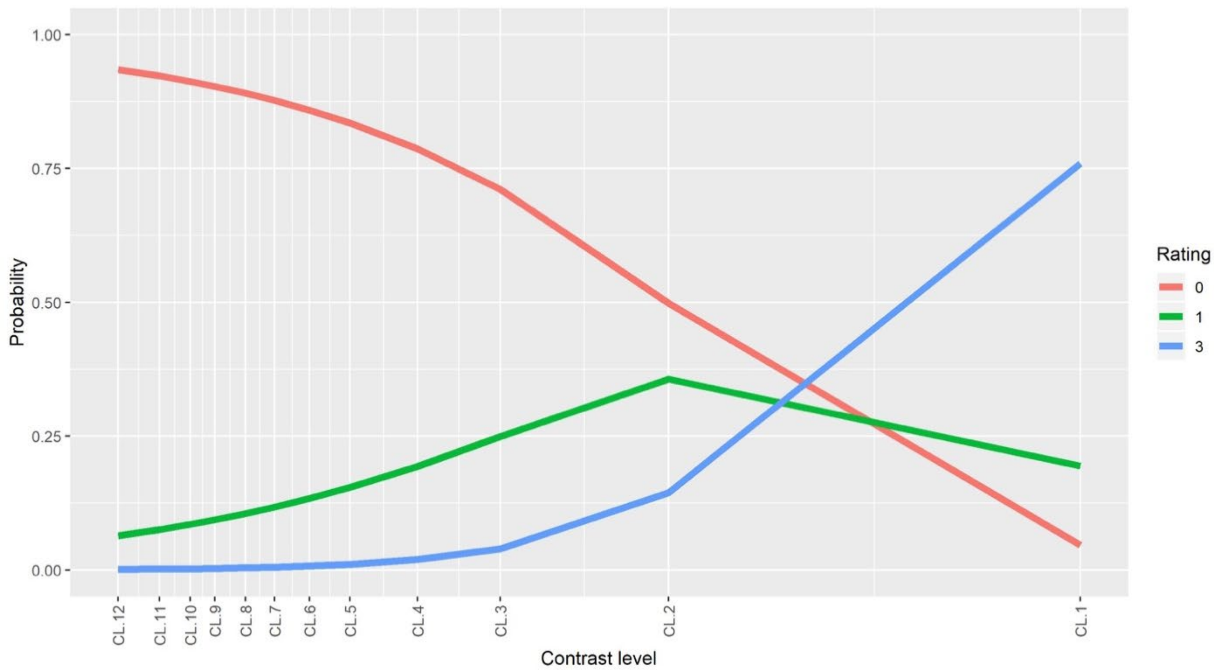
These data were analyzed using the R programming language. The general purpose of the analysis was to characterize the probability of detecting a given contrast level under the lighting produced by each set of locomotive lamps, and to determine if contrast-sensitivity differences existed between each set of lighting conditions. The rationale behind this approach was that performance differences, in terms of visibility conditions, would be expressed by differences in the probability of detecting a given contrast level. In other words, a set of lamps producing better visibility conditions would reflect higher probabilities of contrast detection than lower performing lamps.

For instance, Figure 10 shows a sample comparison of contrast performance between two different sets of lamps with contrast increasing from left to right. Take the rating 0 curves (red curves) for comparison. To reiterate, a contrast rating of 0 corresponds to responses of no contrast detection. The red curve in the bottom graph decreases at a lower contrast ratio than the red curve on the top graph. This implies that the probability of not detecting any contrast level is lower in the better contrast performing lamp. And the same time, the probability of detecting not

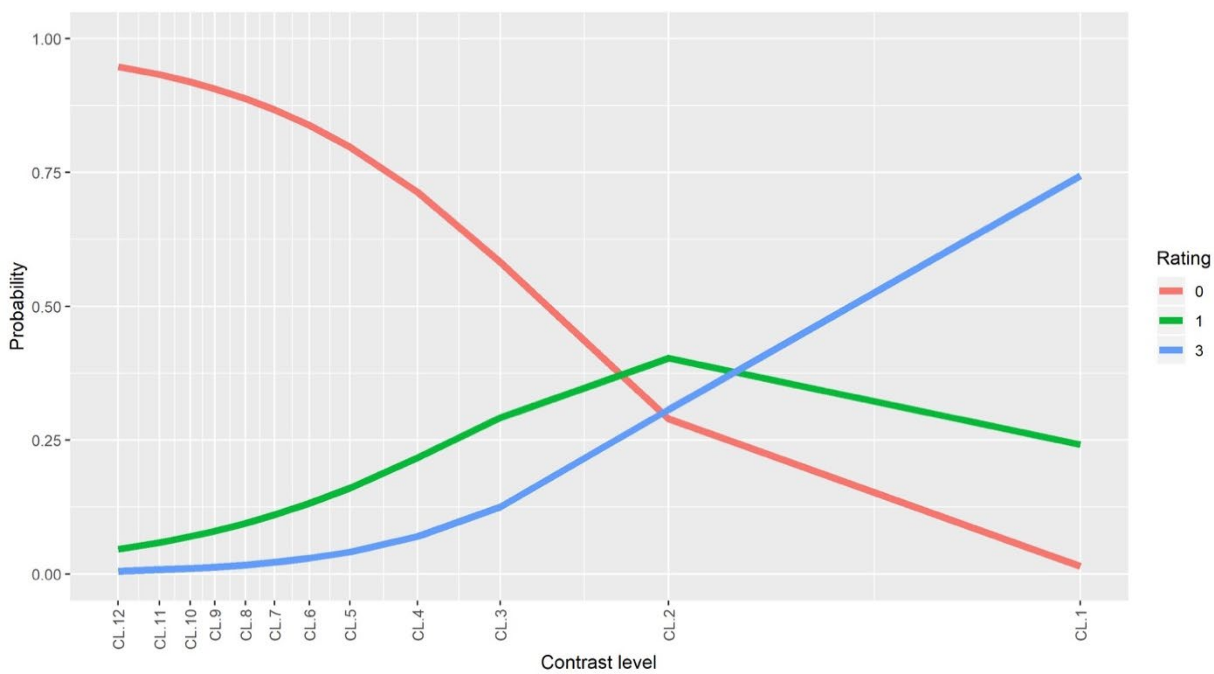
[3] Responses with incorrect arrows drawn were initially given a value of 2; however, after a preliminary analysis these responses were merged with checkmark responses (1), which all corresponded to contrast detection only.

only contrast levels, but higher acuity details (depicted by the blue curve, rating 3) is higher in the better performing lamp.

As described previously, lamp geometry between locomotives was different. The data analyzed showed no significant differences between headlamp and auxiliary light arrangements. Therefore, all subsequent analyses included combined data from both locomotives.



a) Poorer contrast performance lamp



b) Better contrast performance lamp

Figure 10. Sample comparison of contrast performance for two different lamps

Contrast Sensitivity Evaluations at 800 feet

Contrast sensitivity evaluations at 800 feet away were made only in bright mode and at a 0° angle offset. For blank responses, contrast rating 0, LED lamps (with the exception of halogen supplier X1) exhibited lower probabilities of not detecting contrast levels. This implies that, in general, LED lamps provided better contrast detection along the train tracks, at 800 feet away and in front of the locomotive. This result corroborates Phase I findings on the general differences in photometric distributions between LED and halogen lamps (see Figure 11).

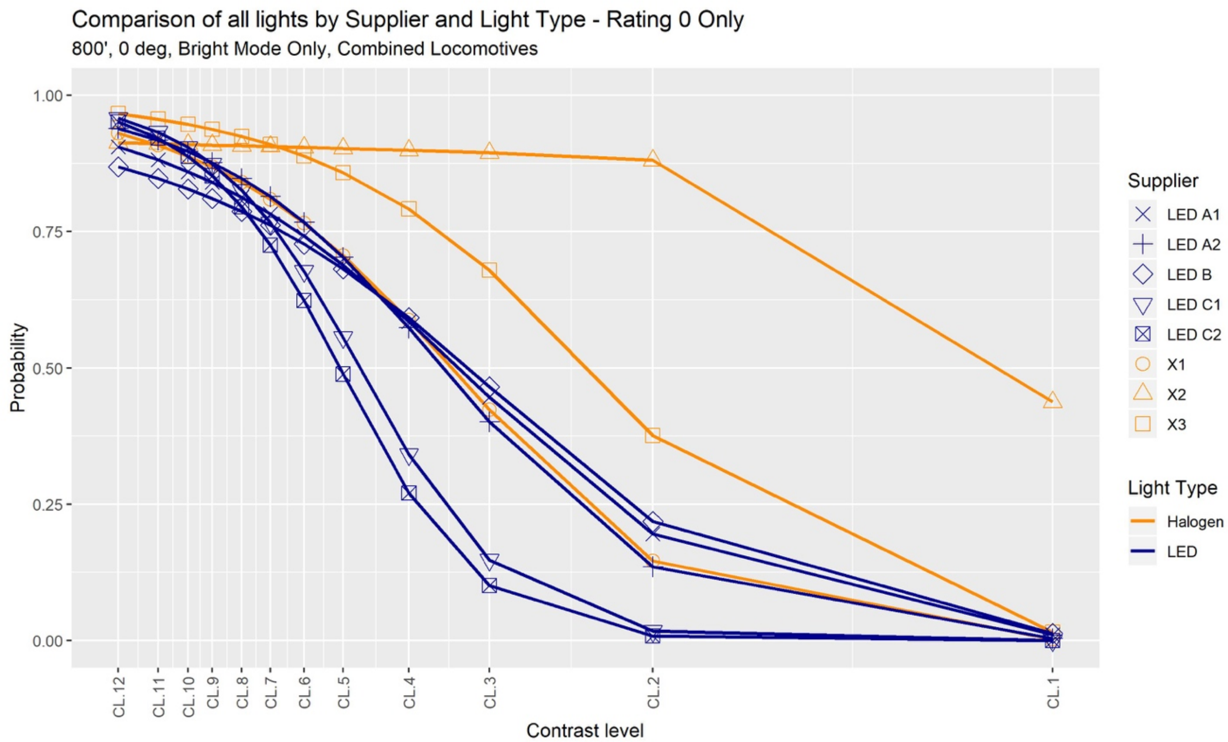


Figure 11. Probability functions for null contrast detection by supplier

For rating 1 responses, detection of only contrast levels, halogen lamps (with the exception of supplier X2) demonstrated higher probabilities of contrast detection than LED lamps (see Figure 12). This, however, does not imply better contrast performance for halogen lamps. As shown by the results for contrast rating 3, all LED lamps demonstrated higher probabilities of detecting higher acuity details for all contrast levels (see Figure 13). Since responses were mutually exclusive (i.e., only one type of response per contrast level allowed), the ability to determine the correct direction of a wedge implies also the ability of discerning the corresponding contrast level. In general, LED lamps provided better contrast performance at 800 feet and in front of the locomotive.

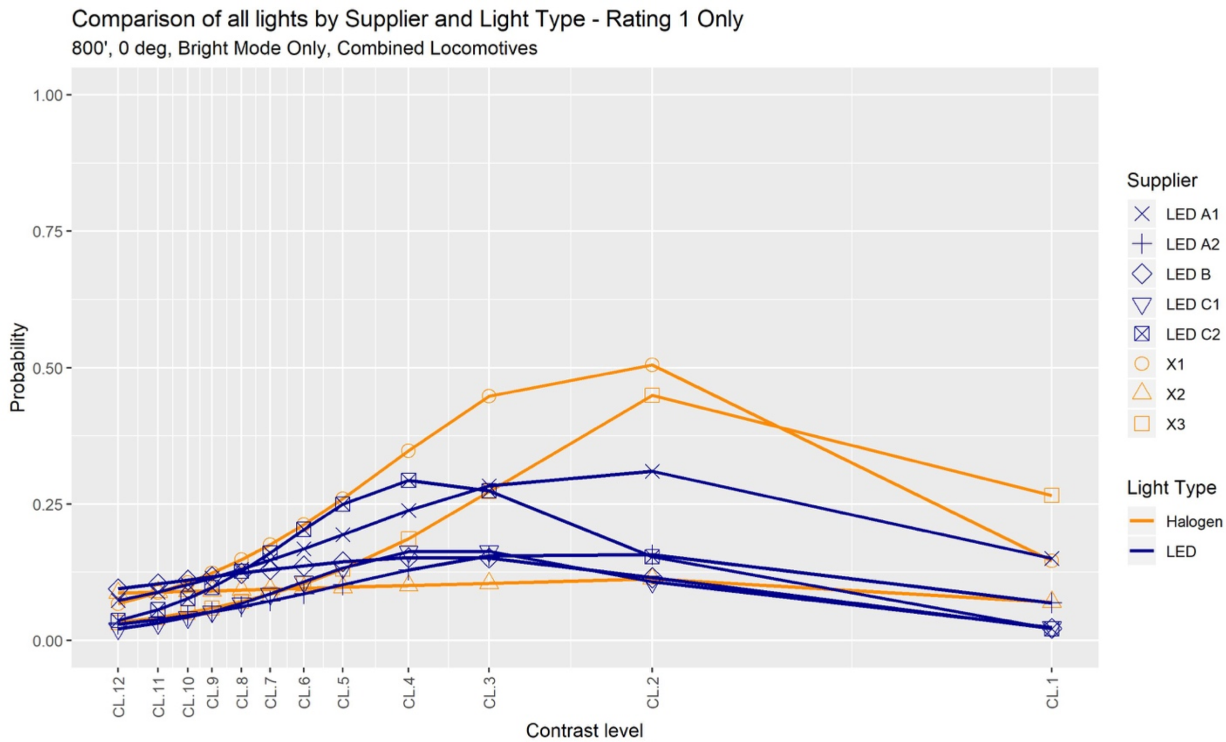


Figure 12. Probability functions for contrast detection only by supplier

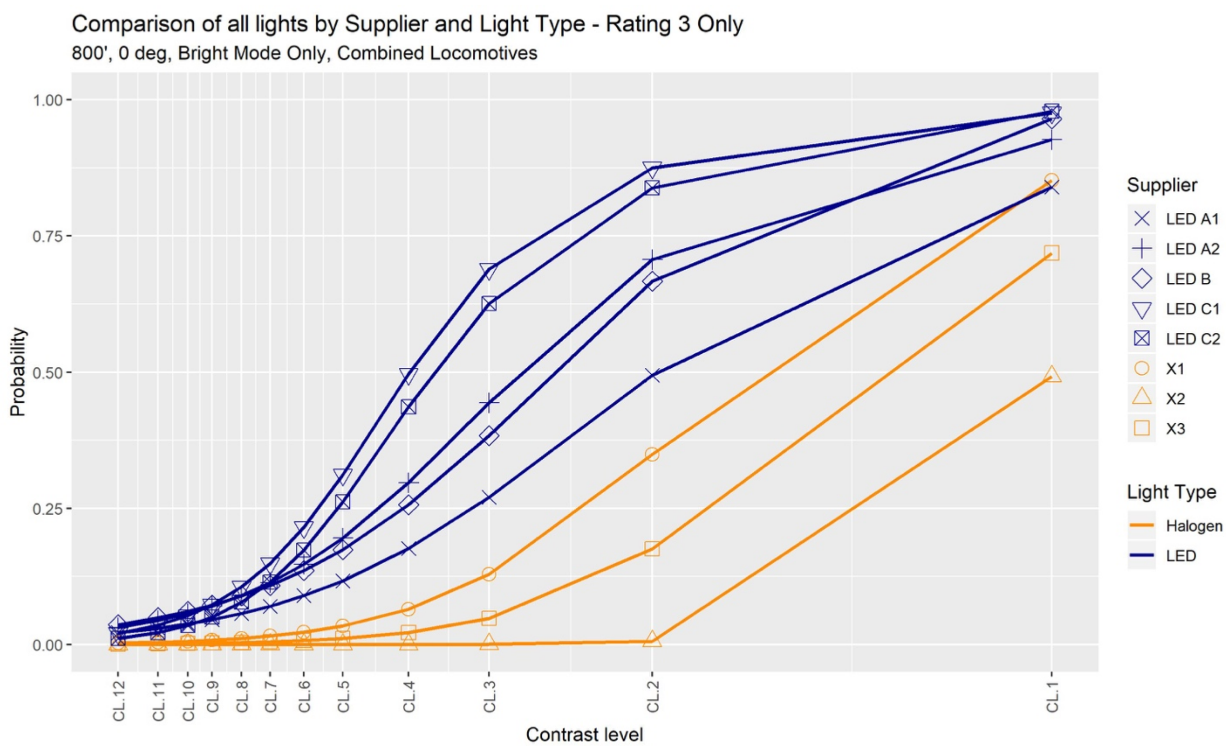


Figure 13. Probability functions for high-detailed contrast detection by supplier.

Contrast Sensitivity Evaluations at 300 feet

Contrast sensitivity evaluations at 300 feet away were made in bright and dim mode at a 7.5° angle offset. In contrast with the results shown for contrast sensitivity at 800 feet, halogen lamps (with the exception of supplier LED C) provided better contrast performance at an offset angle of 7.5°. This result implies that halogen lamps provide better contrast performance to the sides of the track. This correlates with the photometric properties of halogen lamps seen in Phase I testing, which resemble that of a flood light – i.e., a wider lateral spread of illumination. As also expressed in Phase I findings, supplier LED C exhibited the closest contrast performance to that shown by halogen lamps.

As shown in Figure 14, the probability of not detecting lower contrast levels (CL.12 – CL.2) was higher for suppliers: LED A and LED B. Figure 15 shows that the probability of just detecting the lowest contrast levels CL.12 through CL.7 was higher for halogen lamps (X1 and X2). As contrast levels increased (up to CL.2), LED lamps also increased the probability of just detecting those contrast levels. However, at those same contrast levels halogen lamps offered high-detailed contrast level detection (see Figure 16).

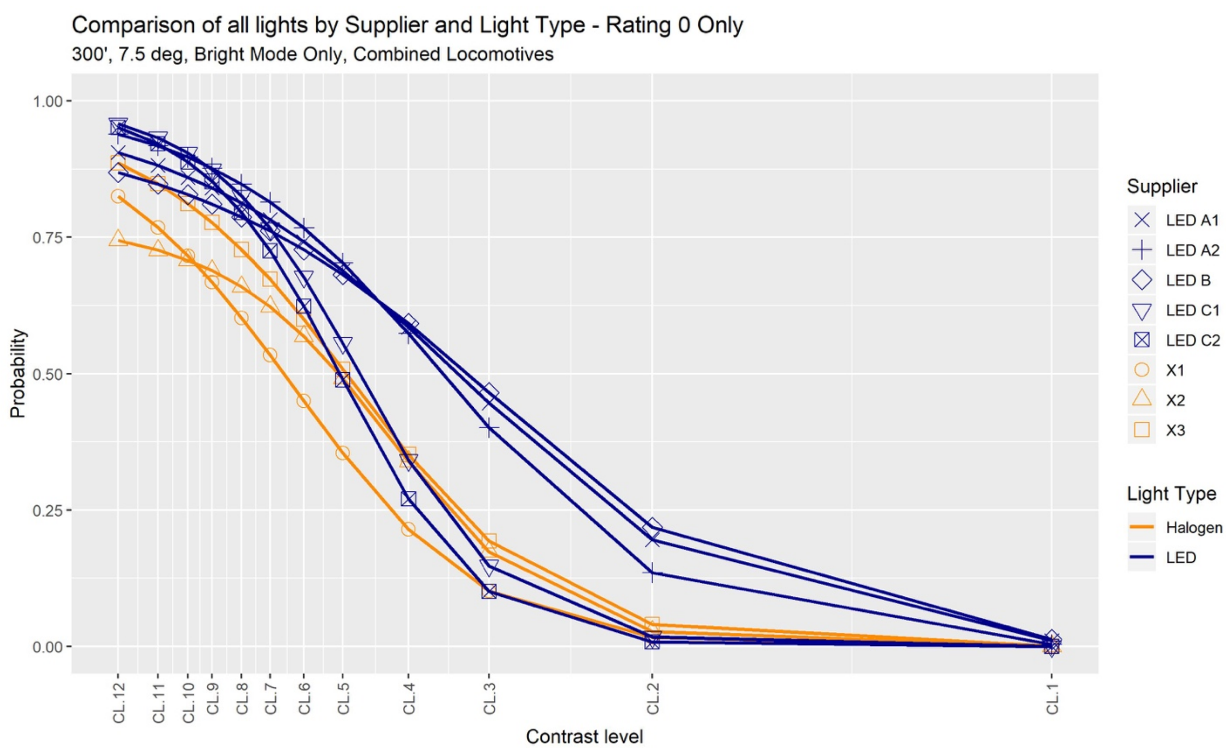


Figure 14. Probability functions for null contrast detection by supplier

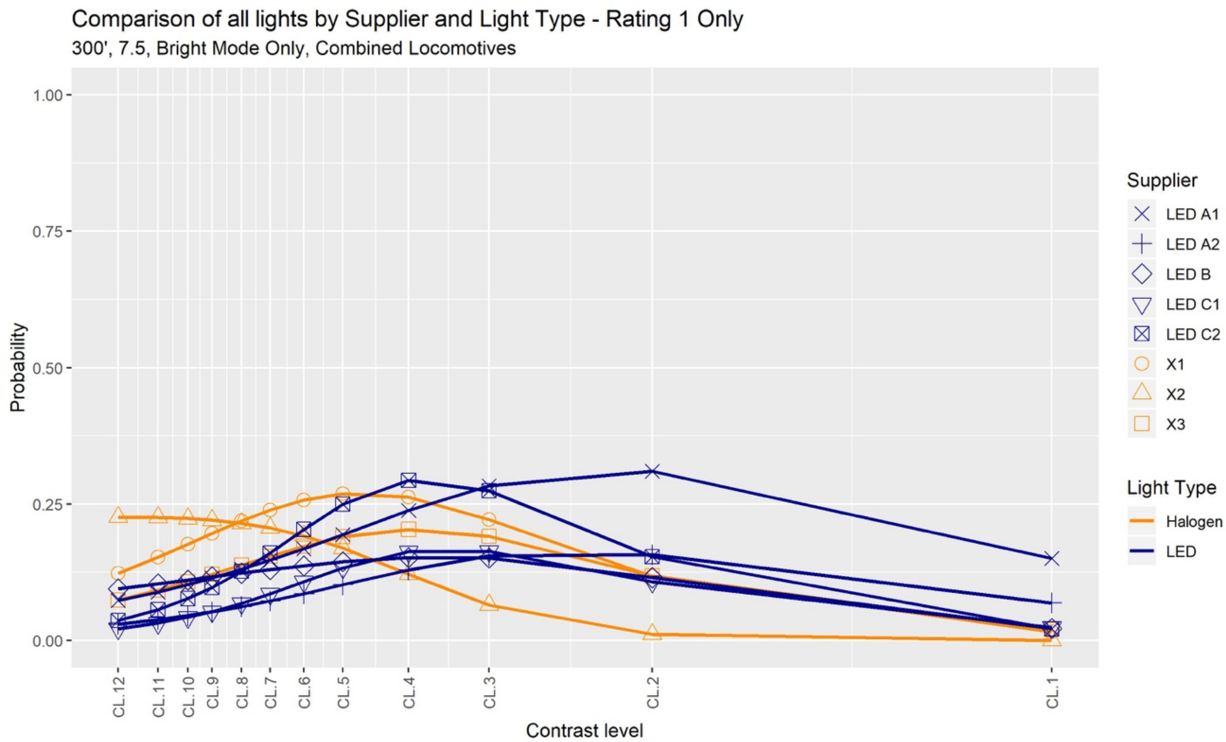


Figure 15. Probability functions for contrast detection by supplier

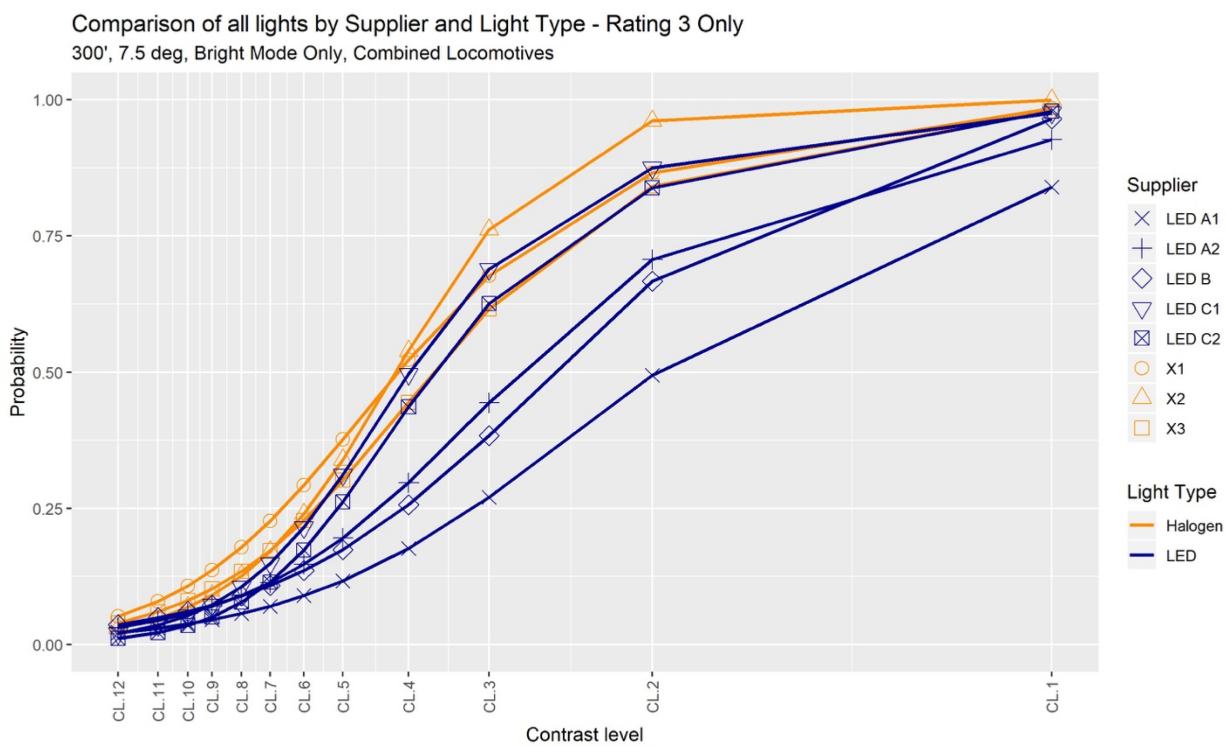


Figure 16. Probability functions for high-detailed contrast detection by supplier

Notes on Contrast Sensitivity Evaluations in Dim Mode

Because fewer measurements were taken in dim mode, the multinomial regression approach presented in the previous section was not feasible. Nonetheless, counts of the responses made by participants with respect to different contrast targets can offer some insights in the contrast discrimination differences between lamp models. Table 3 shows the sum of contrast evaluations for the three highest contrast levels in a contrast fixture (highlighted circles shown in Figure 17). As shown in Table 3, both LED lamps (LED C1 and LED C2) produced greater counts of high-detailed contrast detections. Only halogen lamp X3 produced comparable results to LED lamps. At the same time, all halogen lamps produced greater counts of null contrast detections, suggesting that LED lamps provided better contrast discrimination in dim mode.

Table 3. Sum of the response count for the 3 highest contrast levels

Supplier	Null Contrast Detection (Rating 0)	Contrast Detection (Rating 1)	High-Detailed Contrast Detection (Rating 3)
X1	18	0	2
X2	22	2	0
X3	14	8	14
LED C1	3	1	7
LED C2	4	1	17

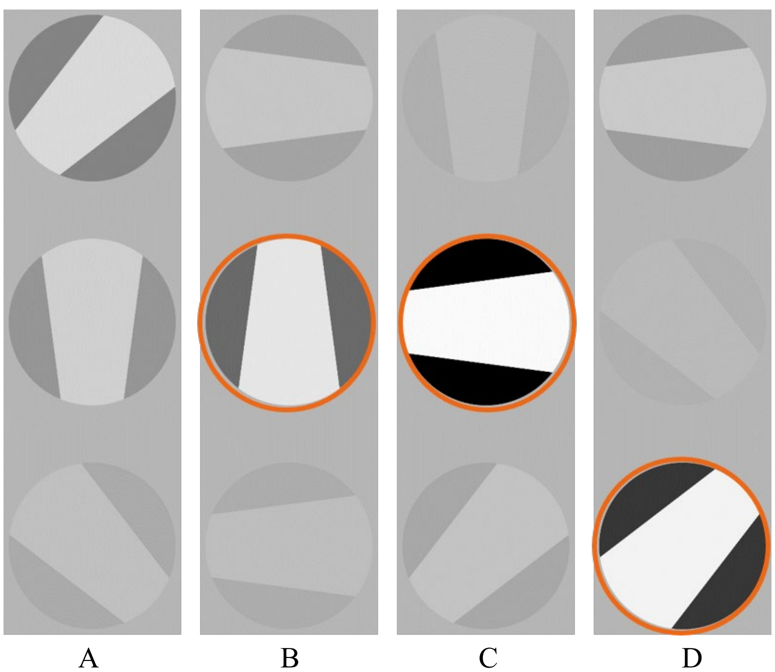


Figure 17. Contrast levels included in the response counts for contrast sensitivity evaluations in dim mode

Notes on Visibility and Other Human Factors Considerations

On 15 randomly chosen trials, a person wearing dark clothing stood to either the left or right of a contrast fixture located 300 feet away with a 7.5° offset from the centerline of the locomotive (see Figure 18). At the end of the trial, participants were asked if they could remember a person standing next to contrast fixture, and if so, on which side. For 7 of the 15 trials (46.7 percent, almost half of the trials), participants either did not remember seeing a person standing next to the contrast fixture or incorrectly recalled the side on which the person was standing.

Figure 18. Nighttime view from the nose of the locomotive with dark clad person standing next to the contrast fixture

The purpose of this exercise was to expand and clarify the differences between the visibility aspects included in the present study and other human factors considerations that may be associated with detecting human-sized objects under low-illumination conditions. Visibility, in this study, was quantified and represented using contrast sensitivity judgments. These judgments provided a method for comparing differences in the lighting conditions produced by each lamp – i.e., better lighting conditions would be reflected by better contrast sensitivity judgments. While participants were able to discern different levels of contrast in approximately almost half of the trials, participants failed to detect the darkly clad person standing next to the contrast targets. This result not only reflects aspects associated with contrast sensitivity, but also aspects of inattentional blindness (or change blindness), expectancy, and conspicuity.

There are multiple studies on inattentional blindness. One of the most notable examples is the invisible gorilla test (Chabris & Simons, 2010). In that test, participants were asked to watch a short video of two different groups of people passing a basketball. Participants were tasked with counting the number of passes between one of the groups. In the video, as the ball is passed around group members, a person wearing a gorilla outfit walks through the scene. At the end of the video, participants were asked to immediately report the number of passes. Then, participants were given the following series of questions: 1) While you were doing the counting, did you notice anything unusual on the video? 2) Did you notice anything other than the group members? 3) Did you see anyone else (besides the group members) appear on the video? And 4) Did you see a gorilla walk across the screen? Surprisingly, 50 percent of the participants reported not seeing the gorilla in the video, suggesting a significant level of inattentional blindness.

Another aspect associated with failing to see the person standing next to the contrast fixture is expectancy. Expectancy is based on past experiences (Wickens, Lee, Liu, & Gordon-Becker, 2003). It depends on a top-down process of perception that is supported by prior knowledge and associations to a given stimulus. In this subject study, participants had no expectation of a darkly clad person standing next to the contrast fixture.

Finally, conspicuity was also an important factor in the ability to detect the darkly clad person. Conspicuity refers to the salient features of an object likely to attract attention. In this case, the darkly clad person lacked any salient features that could attract the participant's attention. Given these conditions and findings from previous studies, a relatively low percentage of detection was expected. For instance, a previous study focused on a driver's ability to detect pedestrians during nighttime. This study reported significant differences in detection performance due to clothing configuration, with a 5 percent detection rate for pedestrians who wore black clothing and a 100 percent rate for pedestrians who wore retroreflective clothing (Wood, Tyrrell, & Carberry, 2005). Retroreflective clothing increases contrast between the user and its background, in most cases accentuating features of biological motion. This finding relates to the importance of contrast detection in low-illumination conditions, and better contrast discrimination can translate into better detection of relevant objects in a scene.

4.3 Analysis of Glare Ratings

As described in Section 2.3, the De Boer scale has been used to effectively characterize discomfort glare. A significant factor on how an observer may rate the glare produced by a light source is the amount of light falling (illuminance) on the observer's plane of observation. From Equation (1), illuminance, along with luminance and orientation, can also be shown to be a significant factor for predicting De Boer glare ratings. Therefore, higher levels of illuminance should correlate with lower glare ratings (i.e., in the De Boer scale, a glare rating of 1 is defined as Unbearable glare).

Data collected in the present study was no exception to such a relationship. Figure 19 shows the relationship between glare ratings provided by participants and measured illuminance for all halogen and LED lamps in both bright and dim mode, taken at 300 feet and 800 feet, at locations offset 0° and 7.5° from the locomotive centerline. The data points are jittered (slightly offset from each other) for visual clarity. The solid lines represent a local weighted average, with the only purpose of showing the trend of observations. As seen in this figure, halogen lamps produced higher glare ratings (towards just noticeable glare) than LED lamps. But at the same time, LED lamps produced higher levels of illuminance.

To find specific differences between lamp models, glare data was first parsed in bright mode, and dim mode. The data was then compared using pairwise Wilcoxon tests. These findings are discussed in the next sections.

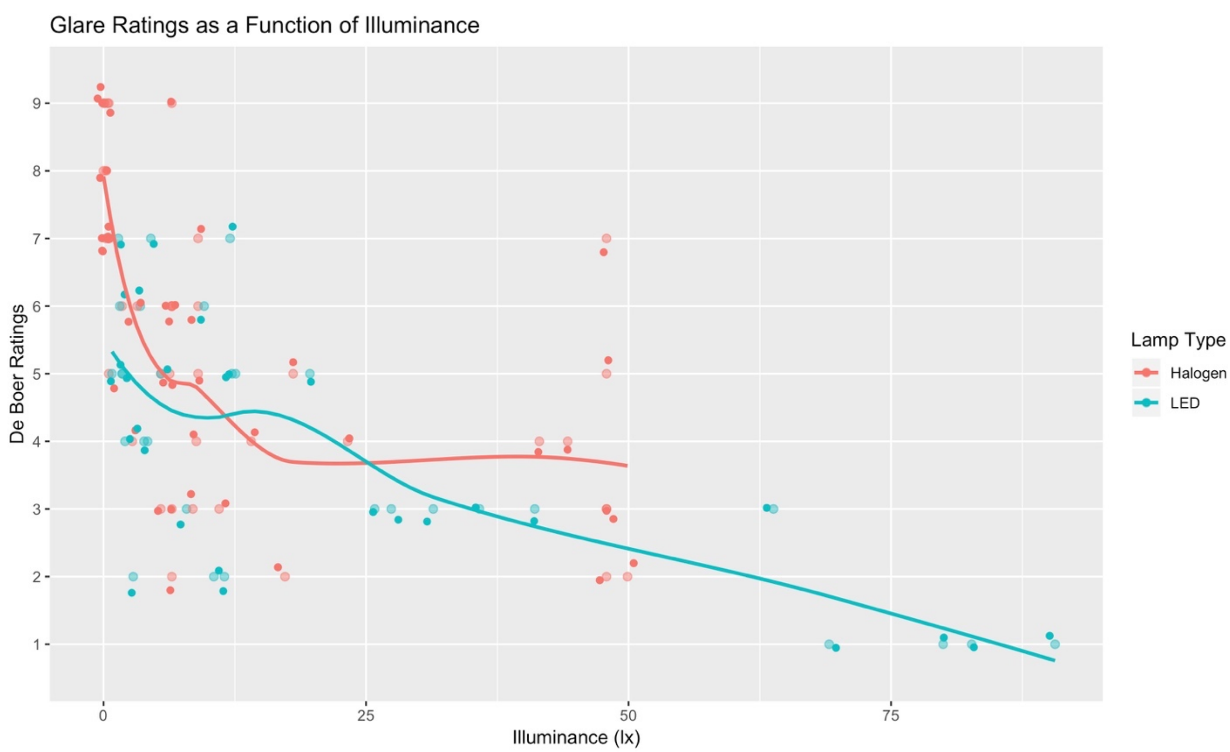


Figure 19. De Boer glare ratings for all halogen and LED lamps as a function of illuminance

Glare Ratings in Bright Mode

Glare ratings corresponding to bright mode were made at two distances (800 feet and 300 feet away from the locomotive) and all three orientations (0°, 7.5°, and 20° from the centerline of the locomotive).

Pairwise Wilcoxon tests for comparing glare differences in glare ratings showed no significant differences between lamp models. However, note that, although not statistically significant, the LED lamp model with the highest color temperature produced lower *p*-values when compared to halogen lamps.

Figure 20 contains a 2 by 8 grid plot showing the relationship between De Boer ratings, angle offset, and distance from the locomotive for all lamp models. Worse levels of glare are represented by lower De Boer glare ratings, with 1 labeled as "Unbearable". The gray solid line represents a local weighted average to accentuate any trends in the data. As seen in this figure, glare ratings increase as the angle offset also increases. The more oblique the angle is between the observer and the center line of the light source, the less "unbearable" discomfort glare becomes. Distance, however, did not produce differences in trends. Both distances, 800 feet and 300 feet, seemed to exhibit similar glare ratings.

All lamp models exhibited similar trends, except from lamp supplier X3. This lamp produced more scattered glare ratings when viewed at a 0° angle offset. The reason for this result is uncertain. However, variability due to the nature of human perception could be the sole reason.

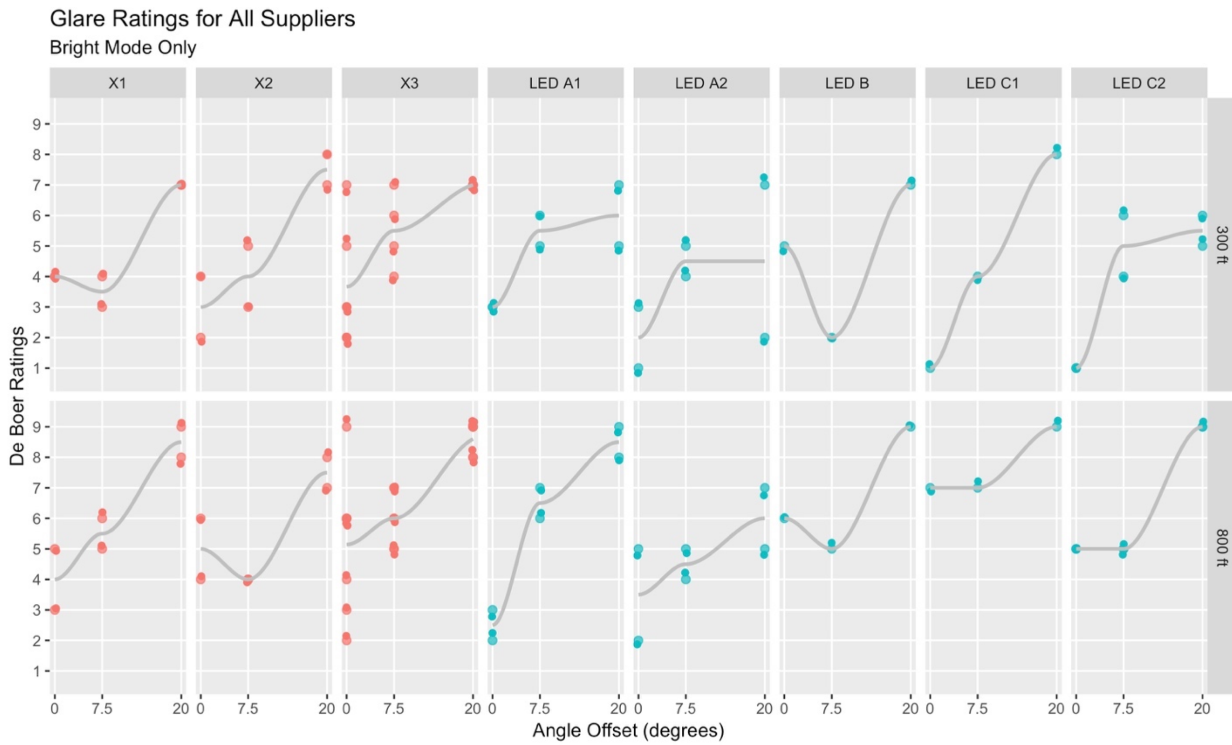


Figure 20. Glare ratings in bright mode for all lamp models

Glare Ratings in Dim Mode

Glare ratings corresponding to dim mode were made at two distances (300 feet and 100 feet away from the locomotive) and all three orientations (0°, 7.5° and 20° from the centerline of the locomotive).

In contrast with glare ratings in bright mode, pairwise Wilcoxon tests for comparing glare ratings did show significant differences between LED and halogen lamps. Table 4 shows the *p*-values for the pairwise comparisons between lamp models. LED C1 was significantly different (at a 95 percent confidence level) than halogen lamps X1 and X2. LED C2 was significantly different than all halogen lamps. The reason for this difference can be traced to Figure 9, in which LED lamps are shown to produce higher levels of illuminance in dim mode, and also to Figure 19, which demonstrates the relationship between illuminance and glare ratings.

Table 4. Table of *p*-values for pairwise comparisons

Supplier	X1	X2	X3	LED C1
X2	0.7465	-	-	-
X3	0.1087	0.0824	-	-
LED C1	**0.0337**	**0.0328**	0.0824	-
LED C2	**0.0096**	**0.0096**	**0.0323**	0.9244

Figure 21 contains a 2 by 5 grid plot showing the relationship between De Boer ratings, angle offset, and distance from the locomotive for all lamp models. Like the ratings in bright mode, glare ratings in this case also increased as the angle offset increased, with more oblique angles relating to less “unbearable” discomfort glare. Distance also did not produce any differences in trends. Both distances, 300 feet and 100 feet, exhibited similar glare ratings.

The significant differences shown in Table 4 can be graphically observed by the gray solid lines in Figure 21. As shown by these lines, both LED lamps produced lower glare ratings at 0° and 7.5° angle offsets and at the 100 feet and 300 feet distances.

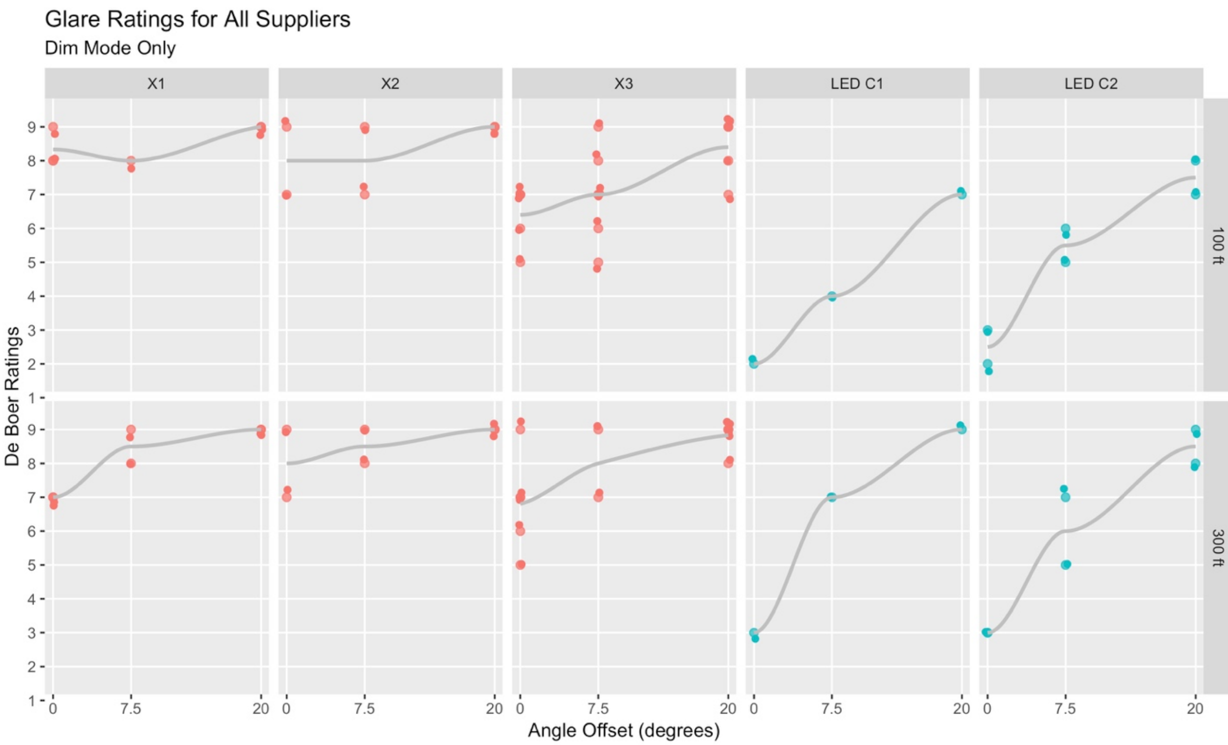


Figure 21. Glare ratings in dim mode for all lamp models

5. Conclusion

The purpose of this study was twofold. First, to evaluate visibility aspects of human-sized objects in lighting conditions produced by different locomotive lamps. This was mainly achieved by using contrast-sensitivity charts to evaluate human contrast discrimination. The data collected was analyzed using multinomial regression. In general, results showed that LED lamps provide better contrast discrimination than halogen lamps along the tracks, but worse contrast discrimination than halogen lamps at an angle offset of 7.5° from the centerline of the locomotive.

And second, to evaluate the discomfort glare produced by LED and halogen lamps at different distances and orientations. This was achieved by implementing the De Boer scale. Glare ratings were analyzed using pairwise Wilcoxon comparison. For glare ratings made in bright mode, results showed no statistically significant differences between LED and halogen lamps. However, for glare ratings made in dim mode, results showed statistically significant differences between both headlamp types.

In terms of contrast sensitivity, the implementation of LED lamps as headlights and auxiliary lights in locomotives may have advantages over halogen lamps. However, careful considerations must be made about the luminous intensity produced in dim mode and the lateral spread of the illumination of LED lamps. For the latter, if the purpose of an LED lamp is to resemble the photometric characteristics of a halogen lamp, its lateral spread of illumination must be wider. For considerations regarding the luminous intensity produced in dim mode, a balance must be made between contrast discrimination and discomfort glare. LED lamps did provide better contrast and more illuminance when in dim mode, but at the same time produced significantly worse levels of discomfort glare.

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Appendix A.
Testing Scripts

Visibility – Contrast Evaluations

Greet and/or thank participant…

In this part of the testing, you will be shown circular visual targets at various distances from the locomotive. The circular visual targets will be similar to the ones in this chart (*show participant small chart)*. As you can see in this small chart (*point at the small chart*), the targets are composed of two main parts, a lighter center wedge and its darker flanks. For this experiment, we will assume that the smaller end of the wedge inside the target defines a direction. For instance, this particular target has a wedge that points to the: (*show direction of target in small chart*). For some trials it may be that you cannot determine the direction, but you may be able to see the lighter and darker flanks, and that is ok!

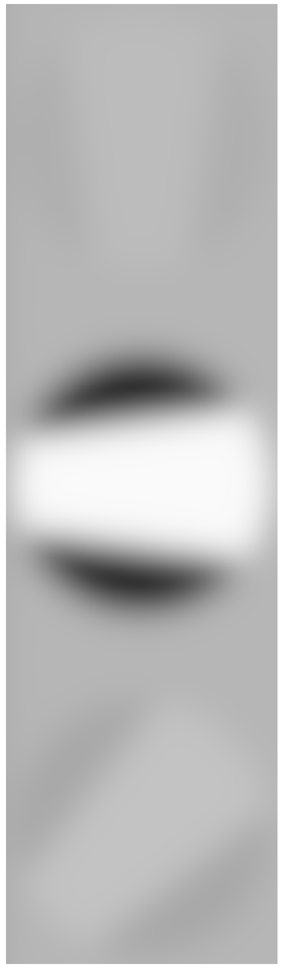
To complete your answers, you will use this answer sheet (*show participant answer sheet*). In it, I would like you to try your best to reproduce the targets that will be presented to you. You will have a limited amount of time, and we will repeat the exercise a few times. As an example, let's look at this image that I have here (*show participant fuzzy printed chart*). In this image, the top circular target is NOT visible, so you would leave this spot on your answer sheet blank. The second target in the middle is a bit fuzzy, but you can get a sense of most details like the wedge direction, so you would draw an arrow as such (*show participant with example sheet*). The third target at the bottom is a bit more difficult to see, perhaps you can may be able to see that there is a circular target, but you don't get a good sense of the direction of the wedge. If that is the case, you just put a check mark on this spot. Got it?

Any questions? Ready? (*Get fixture side ready over radio and set timer for 10 seconds. Participant may be finished before 10 seconds*)

GO!... up to 10-second wait… STOP! (*Get next fixture side ready…*)

The following is only asked once at the end of the contrast evaluation and at randomly assigned trials:

Did you notice the person standing next to the visual target? On which side?



Fuzzy chart

Glare – De Boer Evaluations

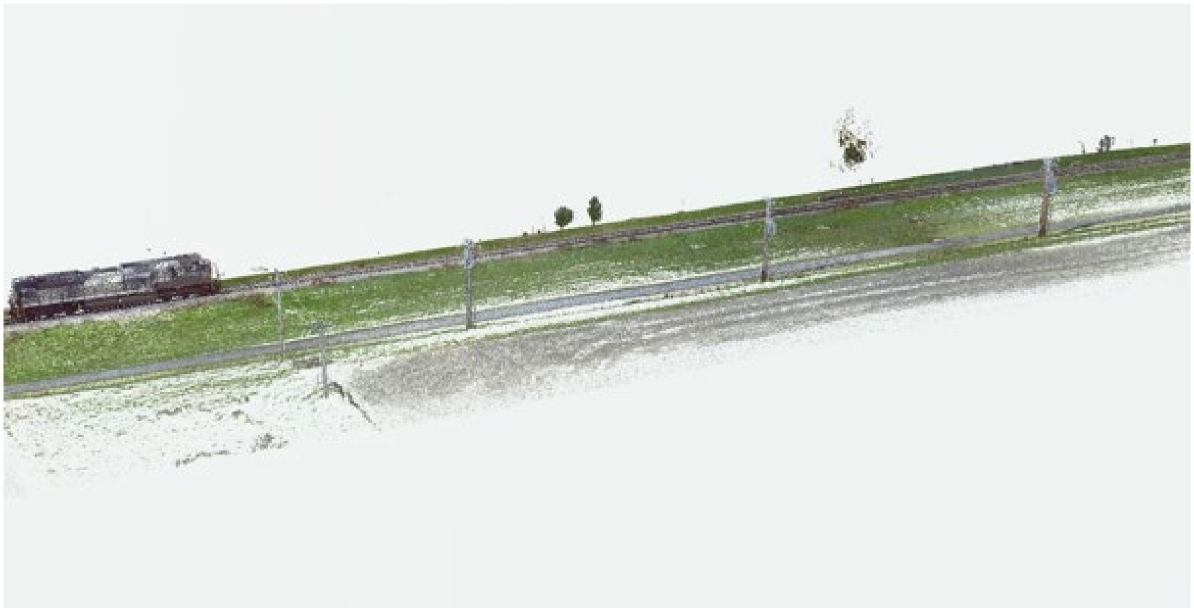
Greet and/or thank participant…

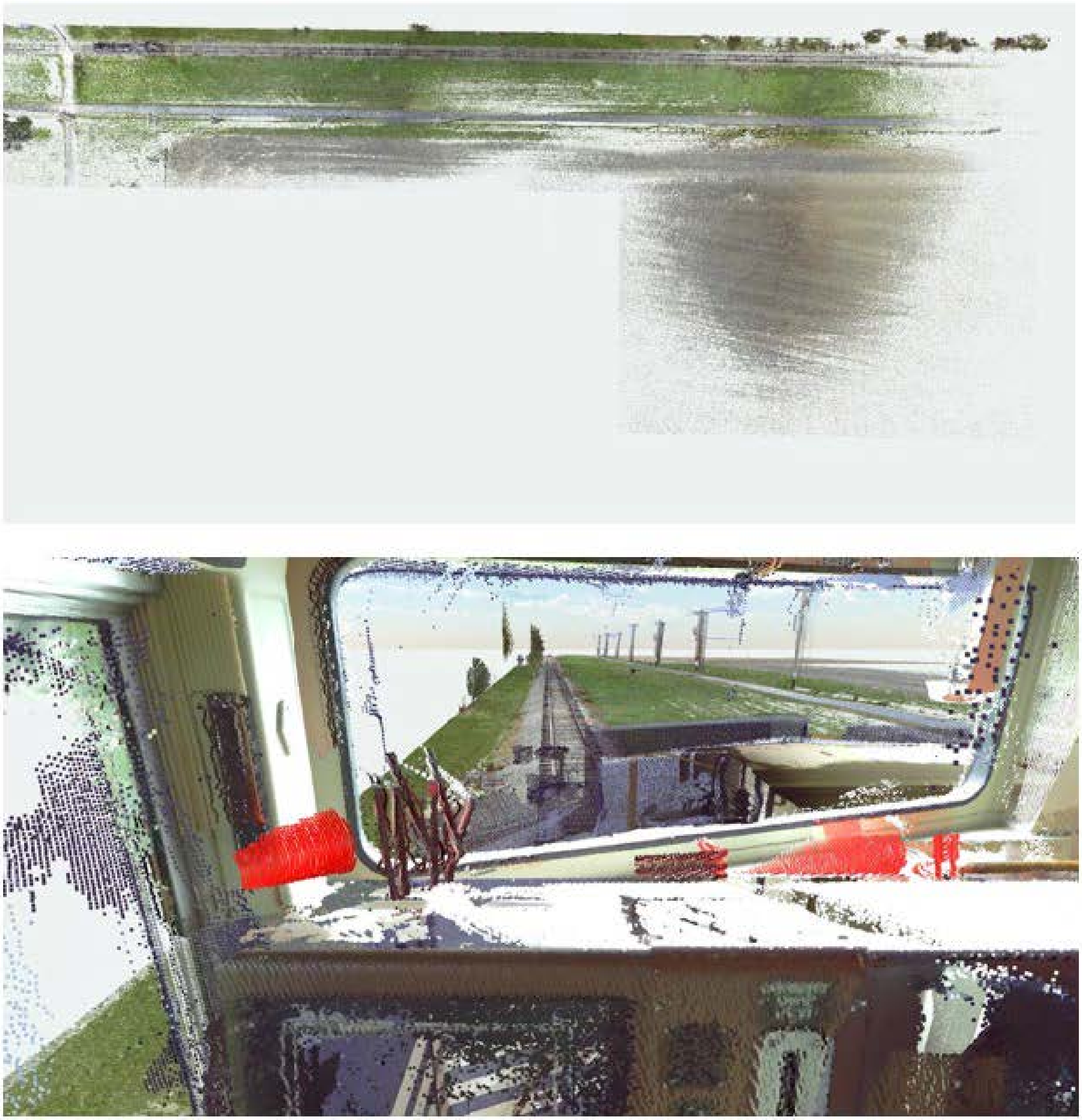
In this part of the testing, you will have to rate the level of discomfort glare that the locomotive headlight produces. To give your rating, think of the following question: **How disturbing is the light source?**

To answer that question, here is the glare scale that you will be using. This scale has 9 levels (*instruct subject on a couple of contrast levels and give an example*). When doing these ratings, hold the scale next to the light source at arm's length. Do not stare directly into the light, instead look at the scale in front of you and verbally give your response. There is a specific sequence that we will guide you through. Any questions?

Appendix B.
Photos of Experimental Setup

Aerial views of experimental setup





Views from 3D Laser Scanner

Appendix C.
Contrast Answer Sheet

Subject:
Date:

1 2 3 4

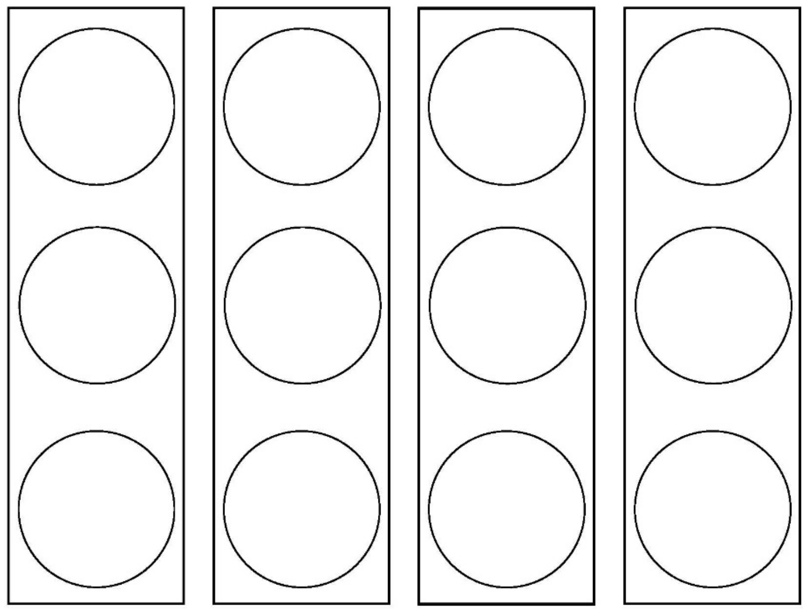
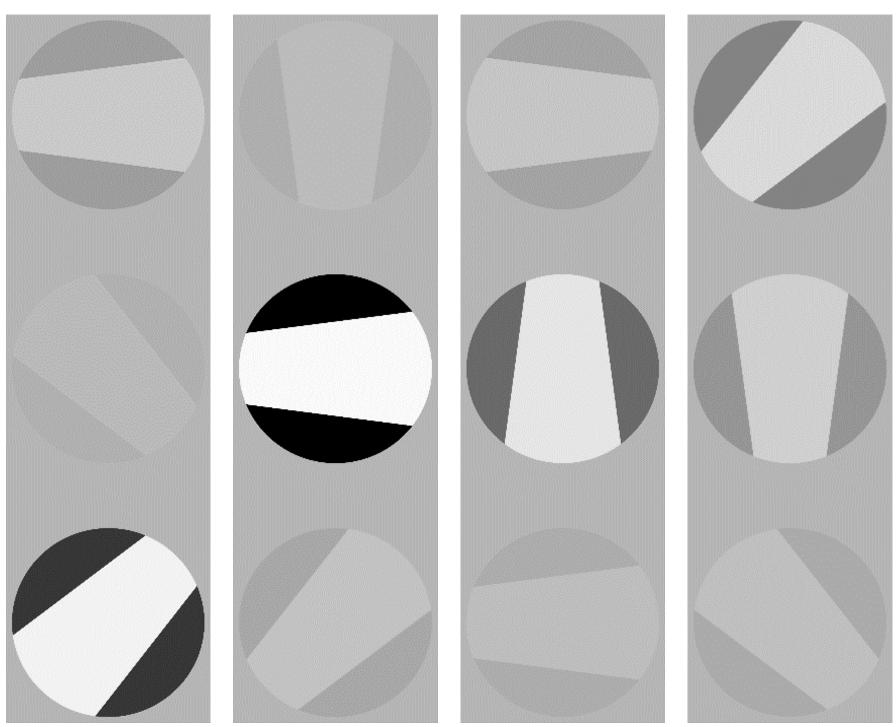
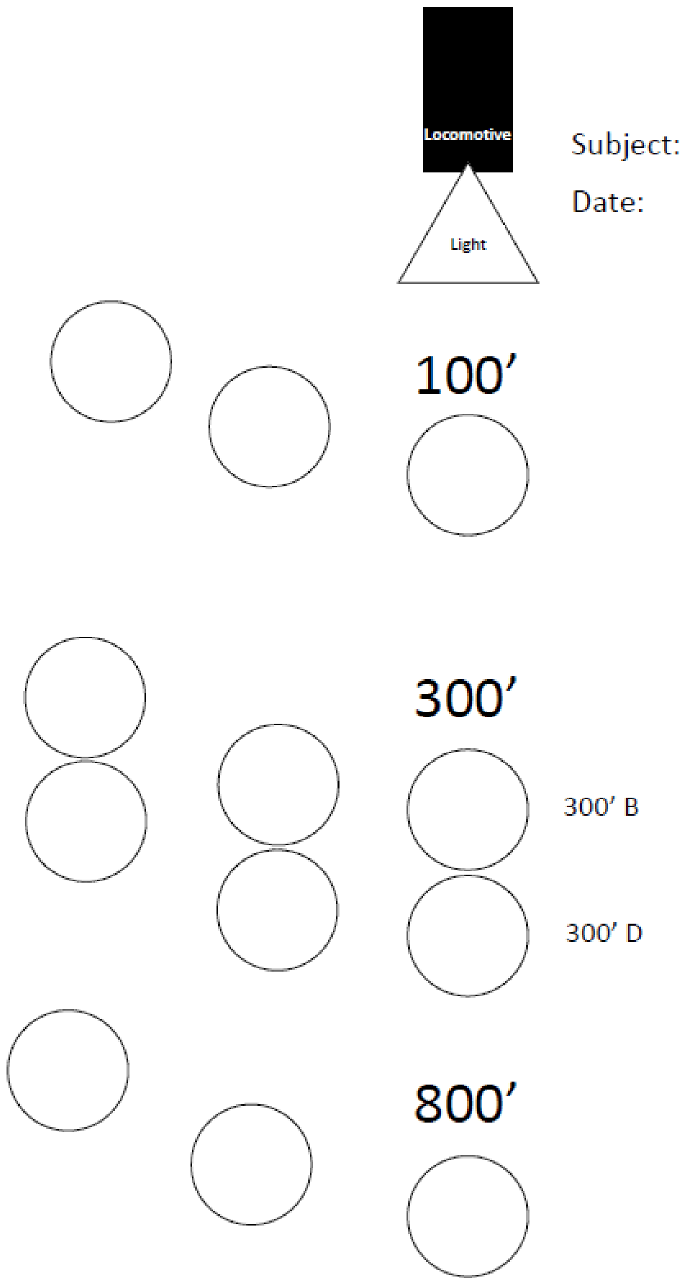


Chart sequence:



Appendix D.
Glare Ratings Answer Sheet and Scale



Subject:

Date:

Field Testing Example for Glare Ratings

Appendix E.
Locomotive Documentation

NORFOLK SOUTHERN (NS 7284)

UNION PACIFIC (UP 6335)

Appendix F.
Lamp Documentation

<table>
<tr>
<td></td>
<td>Supplier: J.W. Speaker – LED Sample

Model: 554601

Specifications summary:

Input voltage: 50-90V DC
Operating voltage: 75V DC
Current Draw: 1.25A @ 50V DC, 0.85A @ 75V DC, 0.70A @ 90V DC.
Candela output: 200,000 min.
Nominal LED color temperature: 5000 °K
</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>J.W. Speaker as headlamp and auxiliary lamp</td>
<td>J.W. Speaker as auxiliary lamp</td>
</tr>
</table>

Supplier: **J.W. Speaker** – LED Sample

Model: **554601**

Specifications summary:

- Input voltage: 50-90V DC
- Operating voltage: 75V DC
- Current Draw: 1.25A @ 50V DC, 0.85A @ 75V DC, 0.70A @ 90V DC.
- Candela output: 200,000 min.
- Nominal LED color temperature: 5000 °K

Supplier: **Hydra-Tech International** – LED Samples

Models: **HYD-LOC001.28K** (Hydra-Tech 2800 °K) and **HYD-LOC001** (Hydra-Tech 7000 °K)

Specifications summary:

- Wattage: 35 W
- Input voltage: 14-30V DC
- Amp draw: 1.09 A @ 32V DC
- 32-75V DC Max brightness ditch light
- Output (cd): Exceeds 200,000 cd Requirement
- Color temperatures: 7000 ºK & 2800 ºK

Hydra-Tech single auxiliary light on locomotive

Hydra-Tech auxiliary lights on locomotive

Supplier: **J.W. Speaker** – LED Sample

Model: **554601**

Specifications summary:

- Input voltage: 50-90V DC
- Operating voltage: 75V DC
- Current Draw: 1.25A @ 50V DC, 0.85A @ 75V DC, 0.70A @ 90V DC.
- Candela output: 200,000 min.
- Nominal LED color temperature: 5000 °K

Supplier: **Railhead/Divvali –** LED Sample

Model: **KE-PAR56 75V LED**

Specifications summary:

- Wattage: 50W
- Input voltage: 75 VDC
- CCT: 5500K
- Candela: 174,000
- 7 ½ off center brightness (2x the brightness)
- 20° beam cut off

Railhead/Divvali auxiliary lights on locomotive

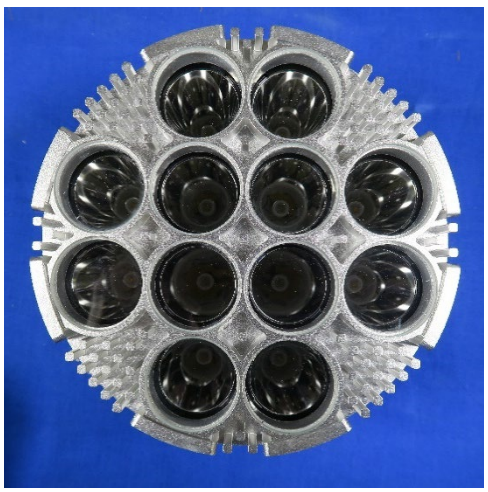
Railhead/Divvali as auxiliary lamp

Supplier: **J.W. Speaker** – LED Sample

Model: **554601**

Specifications summary:

- Input voltage: 50-90V DC
- Operating voltage: 75V DC
- Current Draw: 1.25A @ 50V DC, 0.85A @ 75V DC, 0.70A @ 90V DC.
- Candela output: 200,000 min.
- Nominal LED color temperature: 5000 °K

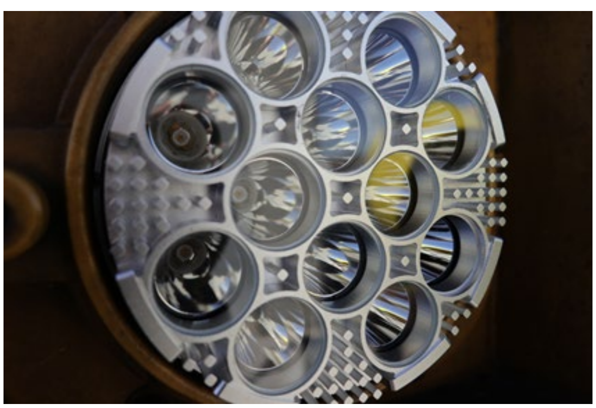


Supplier: **Smart Light Source Co. –** LED Sample

Model: **SLS-75VDC-60W-LED-PAR56**

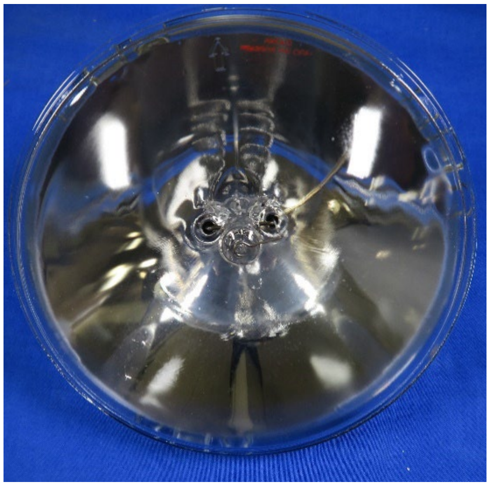
Specifications summary:

- Operating voltage: 75V DC
- Rated wattage: 60W
- Average bulb life: 50,000 hours
- Color temperature: 3000 °K



Smart Light Source headlamp sample

Smart Light Source lamps on locomotive



Supplier: **AMGLO** – Halogen Sample

Model: **AHQV56-75V350WCS**

Specifications summary:

- Design voltage: 75V
- Design watts: 350
- Minimum candela: 200,000
- Lab life: 2,000 hours

Supplier: **CML** – Halogen Sample

Model: **CMQ5630250**

Specifications summary:

- Design voltage: 75V
- Design Power: 250W
- Cd peak: 200,000 min.
- Cd ± 7.5°: 3,000 min.
- Cd ± 20°: 400 min.
- Average life: 2,000 hours

Supplier: **ePowerRail** – Halogen Sample

Model: **FRA350PAR56-SP**

Specifications summary:

- Average life: 4,000 hours
- Candela: 200,000
- Wattage: 200
- Input voltage: 75V

Appendix G.
Technical Difficulties

The following is a list of general issues experienced by all headlamps used during testing. The issues were documented and compiled by ESi and members of the TAG committee present at the time of testing.

- Locomotives do not supply "clean" power; voltage conditioners must be used to protect headlight/auxiliary light circuitry, as is done for all other on-board locomotive electronic devices.
- Headlight/auxiliary lights must not be affected by low-voltage ground situations.
- Auxiliary light flash controllers must not affect headlight/auxiliary light operation.
- Alignment tabs in the headlight/auxiliary light positions are not consistent from locomotive to locomotive or even from position to position on a single locomotive.
    - GEC44AC UP6335 upper headlight index slots are 90°, 135°, 135°.
    - GEC44AC UP6335 lower headlight index slots are 120°, 120°, 120°.
- Consider using a single alignment tab to prevent headlight/auxiliary light rotation within the housing.
    - This might only be possible for headlight/auxiliary lights that do not have a defined "top" position.

The following list is comprised of issues experienced by specific headlamps during testing. These issues were documented and compiled by ESi and members of the TAG committee present.

- Condensation was noted on the inside of the lens on the morning following testing.
- No heat noticed from lens during operation.
- Lamp index tabs are 120°.
- Smaller tabs to the sides of the alignment tabs do not allow the fixture to seat properly. (They were installed oriented properly and pressure seated.)
- Lugs are #4; halogen are #6 (#4 is difficult to install).
- Connectors should discourage contact with the exterior of the housing.
- Ditch lights did not shut off on both NS & UP units.
- Ditch light did NOT flash on UP; did flash on NS.
- Headlights would not dim on NS or UP units.
- Top is notated; does not line up with tabs in the headlight position. Each headlight is lined up to a different, non-up position. (On UP GE unit). Ditch light tabs do line up and LEDs are installed in the proper orientation.
- Only works on BRIGHT setting.
- Not certain how to use integrated jumper wire for DIM mode.
- Auxiliary lights stay lit when the headlight is off (UP unit).
- Conductor ditch brighter than all others; might have resolved after connecting jumper wire.
    - 30k lx on the conductor side from ~10 feet
    - 12.5k lx on the engineer side from ~10 feet
- Spring clips are not acceptable; use a flat terminal base with threaded lug.

- Glue/film visibly obscures portion of inside of lens.
- Lens is easily scratched.
- Connectors require mechanical separation and should discourage contact with the exterior of the housing.
- Failed functional test – suffered catastrophic failure when connected to power. The fixture burned up internally and smoked.
- Circuitry had to be changed out to accommodate flasher control module.
- “Gaskets” are not an option for fitment.
- Bulky design does not allow easy clearance of the light retainer ring.
- Back cable interferes with the installation process.
- Connectors require mechanical separation.
- Front heat sink and lens protrudes into the walkway of the UP unit.
- Front heat sink and lens protrudes into the glare deflector on the over-windshield headlight on the NS unit. Installed without completely tightening down the enclosure.
- One of the small lenses popped out when the locomotive door was slammed.
- Lens protrudes ~1.5 inches.
- The rough exterior (heat sink) poses a safety hazard in that it could snag clothing. It could also become packed with flying debris, reducing its heat transfer capabilities. Even on the back, the heat sink is capable of “trapping” loose screws.
- Failed functional test – LED flickered briefly when power was applied and then would not illuminate in the auxiliary light position.
- Slight warmth noted from lens during operation.
- Binding posts were loose.
- Bottom headlight on UP loco was loose (possibly due to retainer ring failure on locomotive).
- Orientation of fixture is not specified (i.e., no “top”).
- Standoff tube loose.
- Did not fit well in headlight housing.
- Index tabs 90°, 135°, 135°.
- Headlight dimmed inexplicably.
- Lower headlight on UP locomotive was intermittent on/off.
- Pigtail connector should be removed for North American railroads.

Appendix H.
Additional Testing Documentation

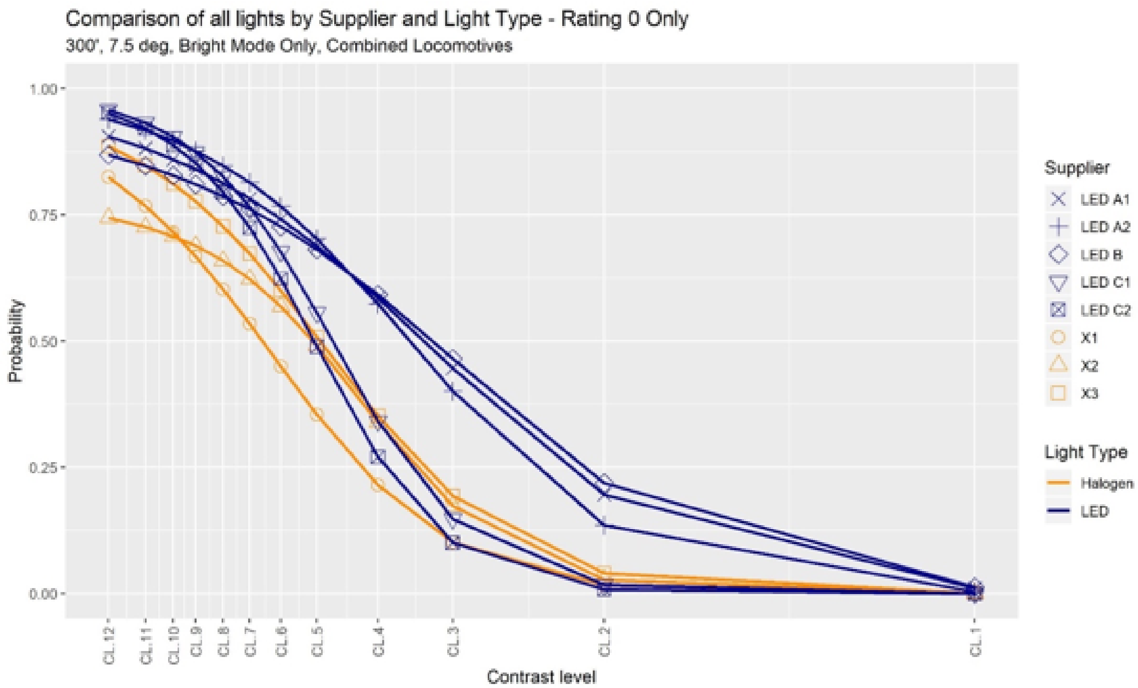
Photography Documentation

Nighttime Validated Photography Samples

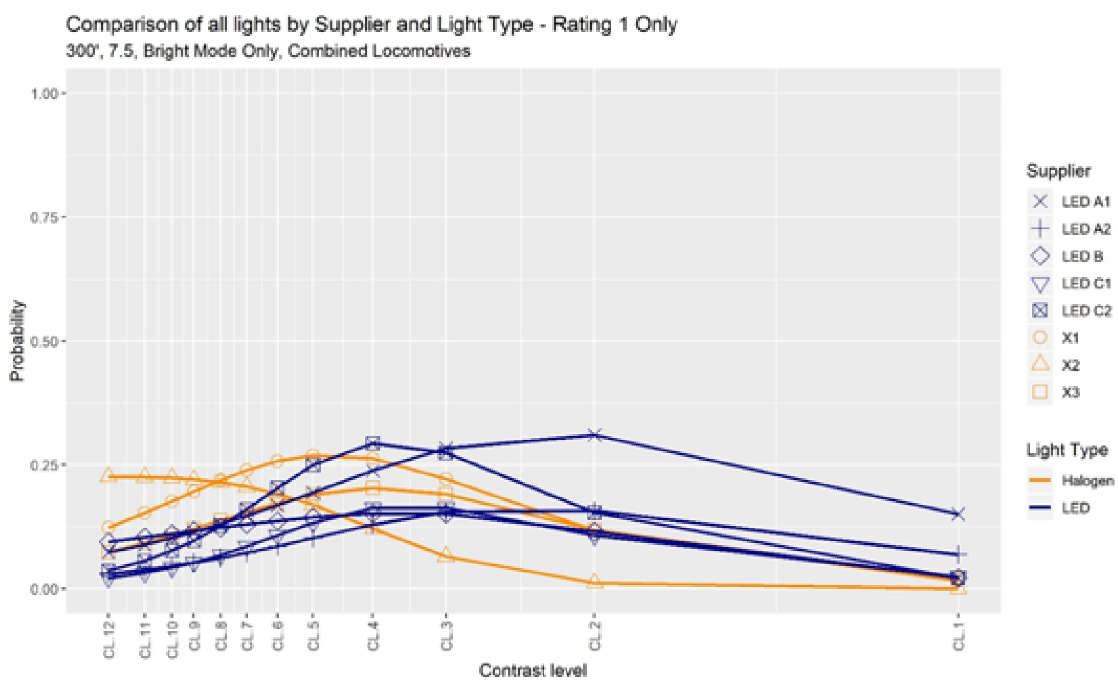
Lighting Conditions Produced by Sample Halogen Lamp

Lighting Conditions Produced by Sample LED Lamp

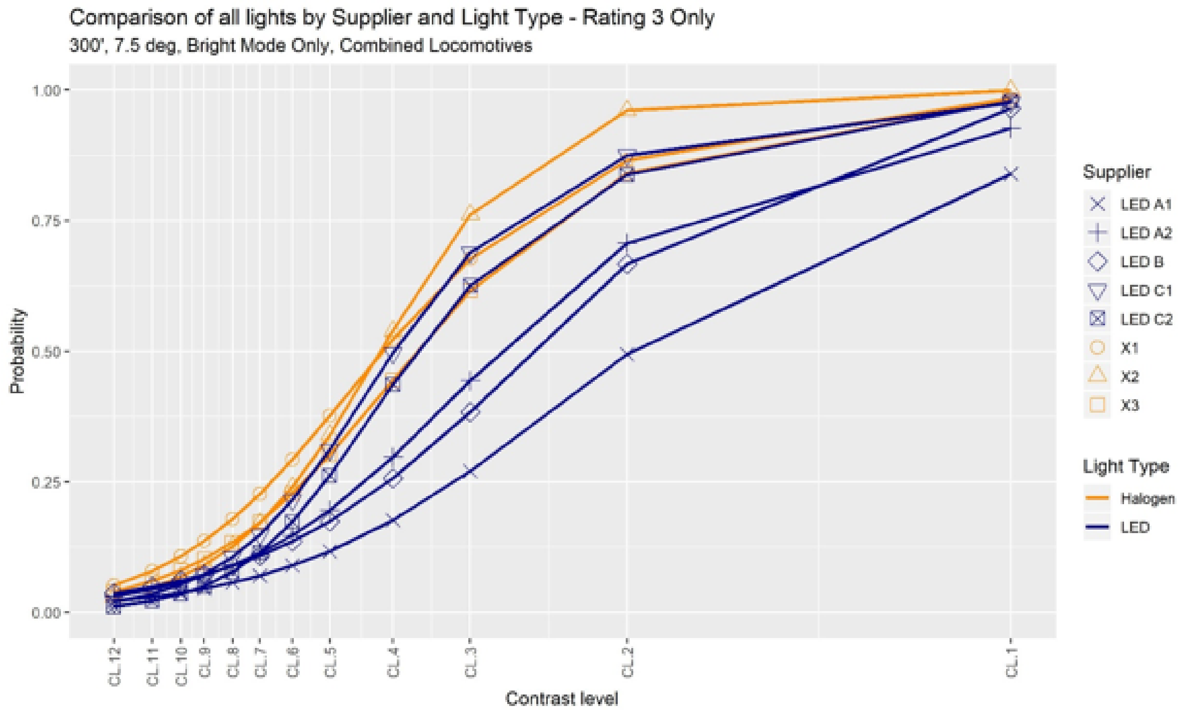
Appendix I.
Additional Graphs and Plots



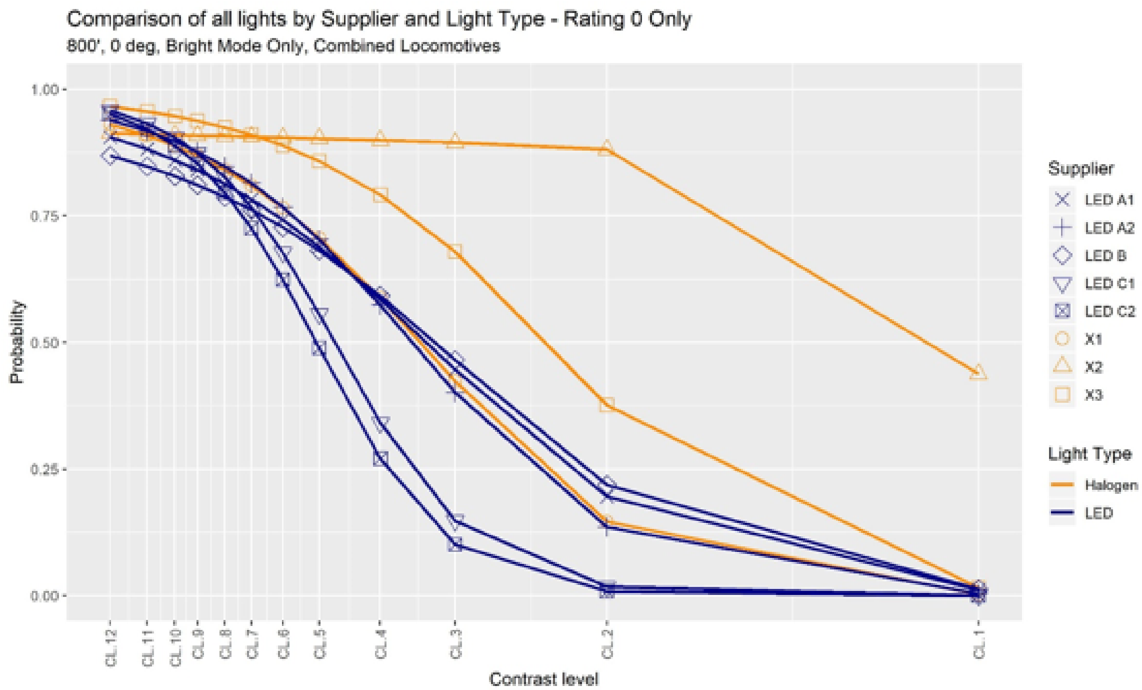
Probability function for null contrast detection applied to all Suppliers at 300 ft.



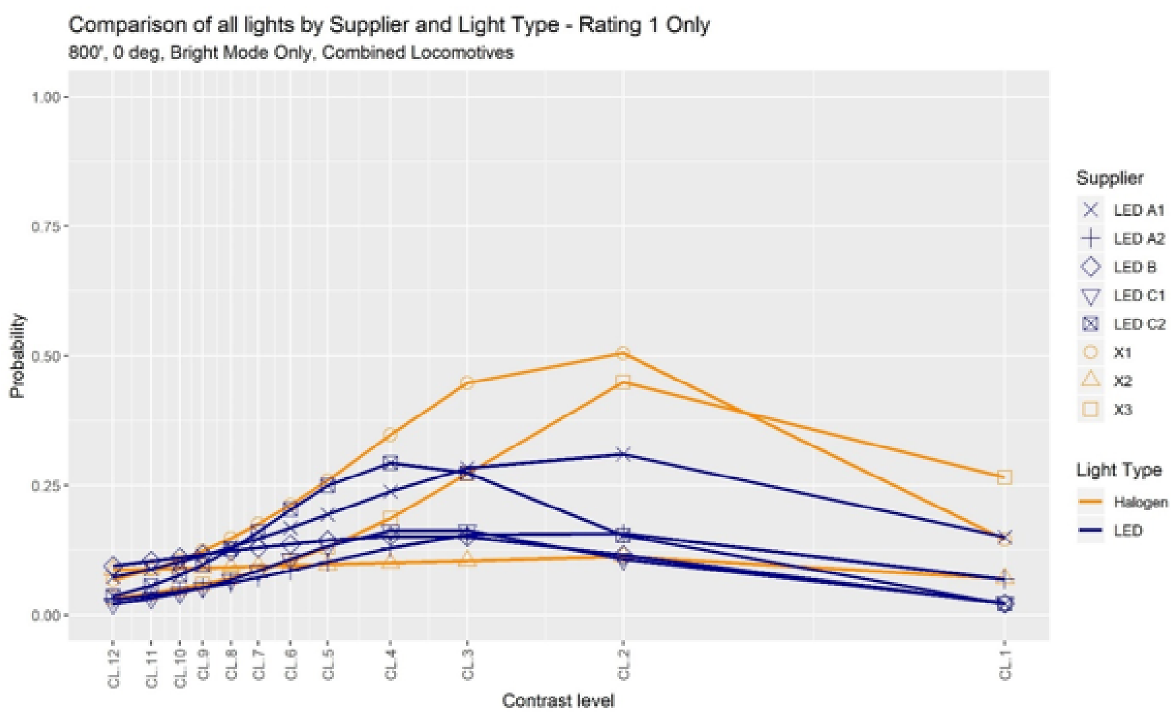
Probability function for contrast detection only applied to all Suppliers at 300 ft.



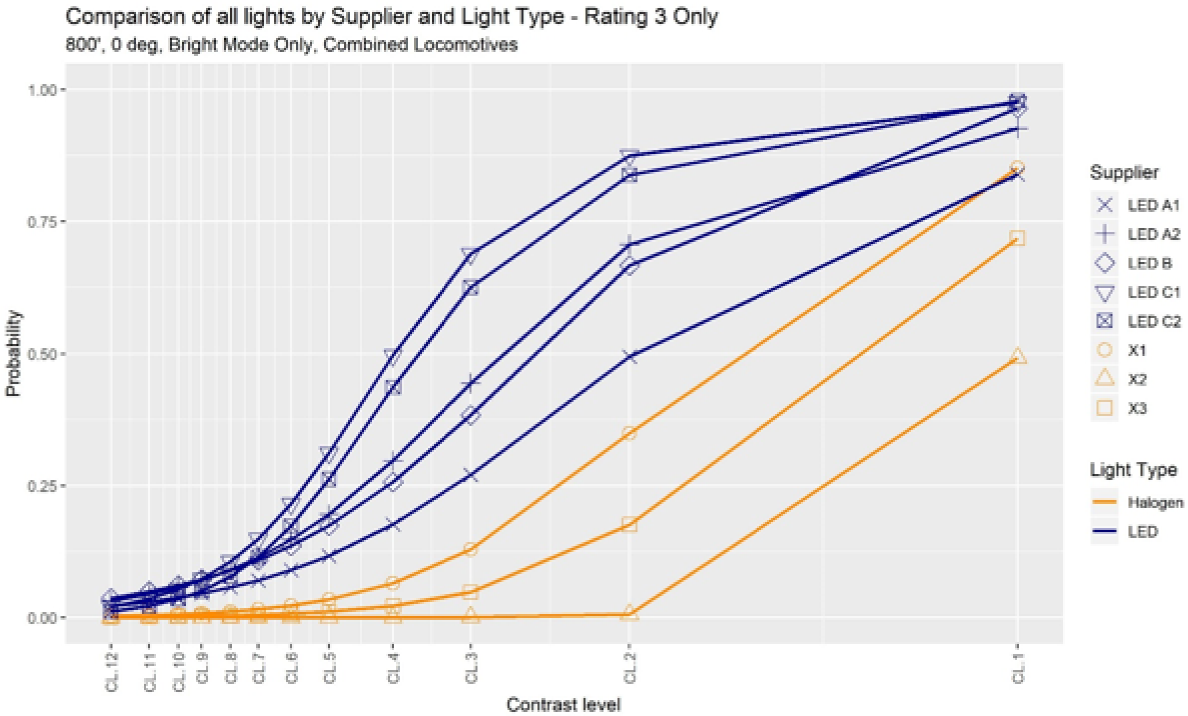
Probability functions for high-detailed contrast detection applied to all Suppliers at 300 ft.



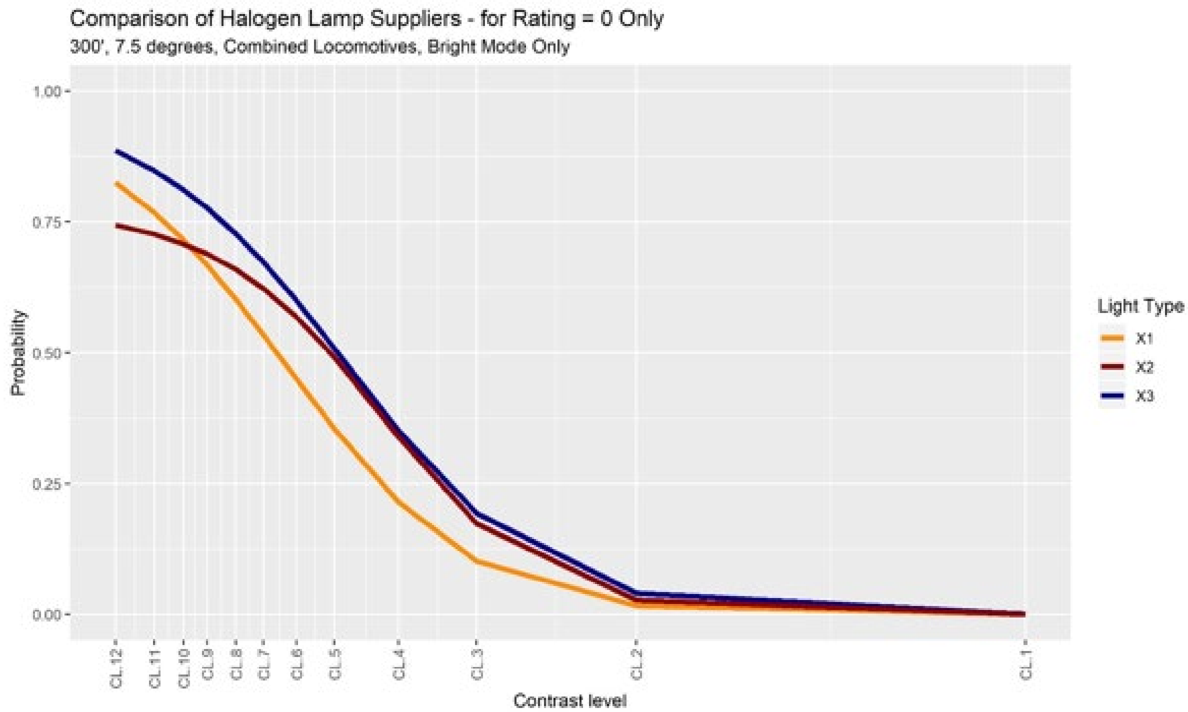
Probability function for null contrast detection applied to all Suppliers at 800 ft.



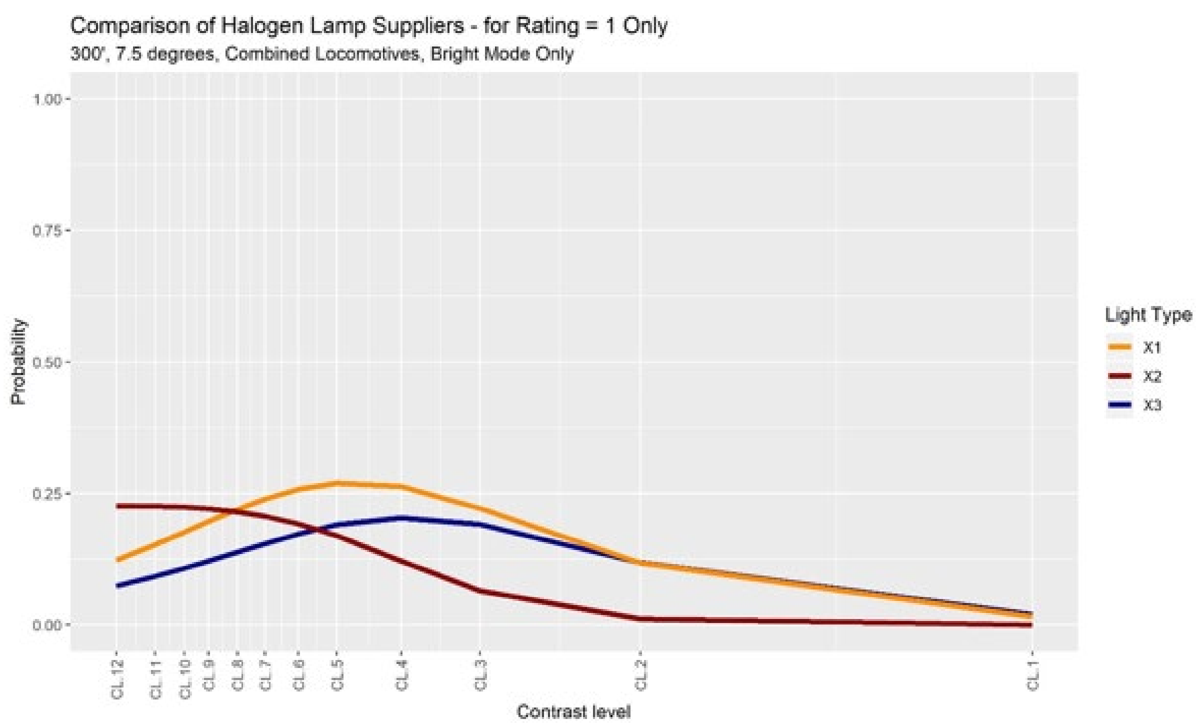
Probability function for contrast detection only applied to all Suppliers at 800 ft.



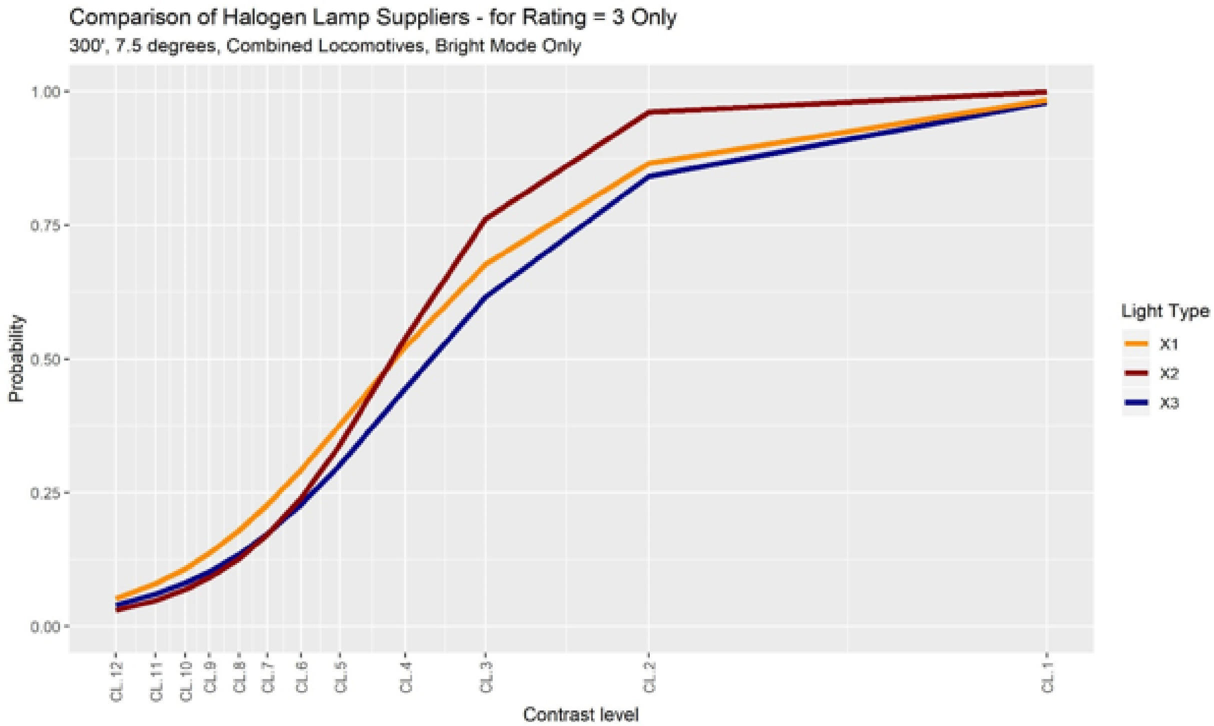
Probability functions for high-detailed contrast detection applied to all Suppliers at 800 ft.



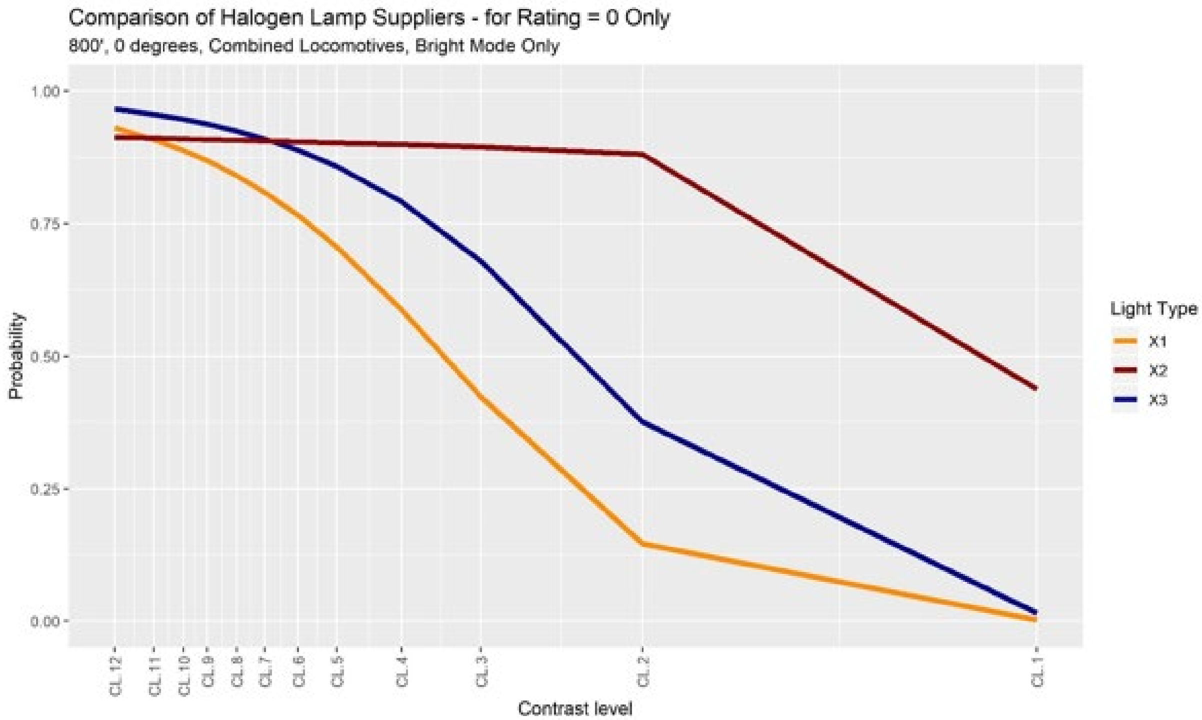
Probability function for null contrast detection applied to halogen lamps at 300 ft.



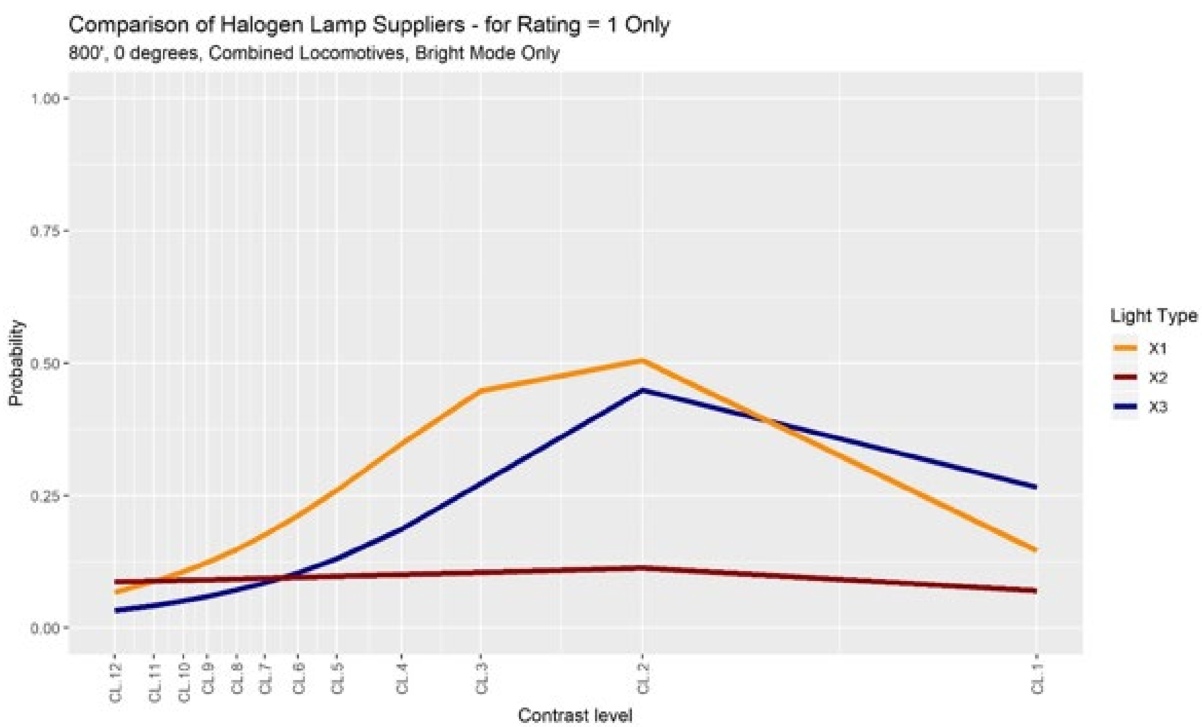
Probability function for contrast detection only applied to halogen lamps at 300 ft.



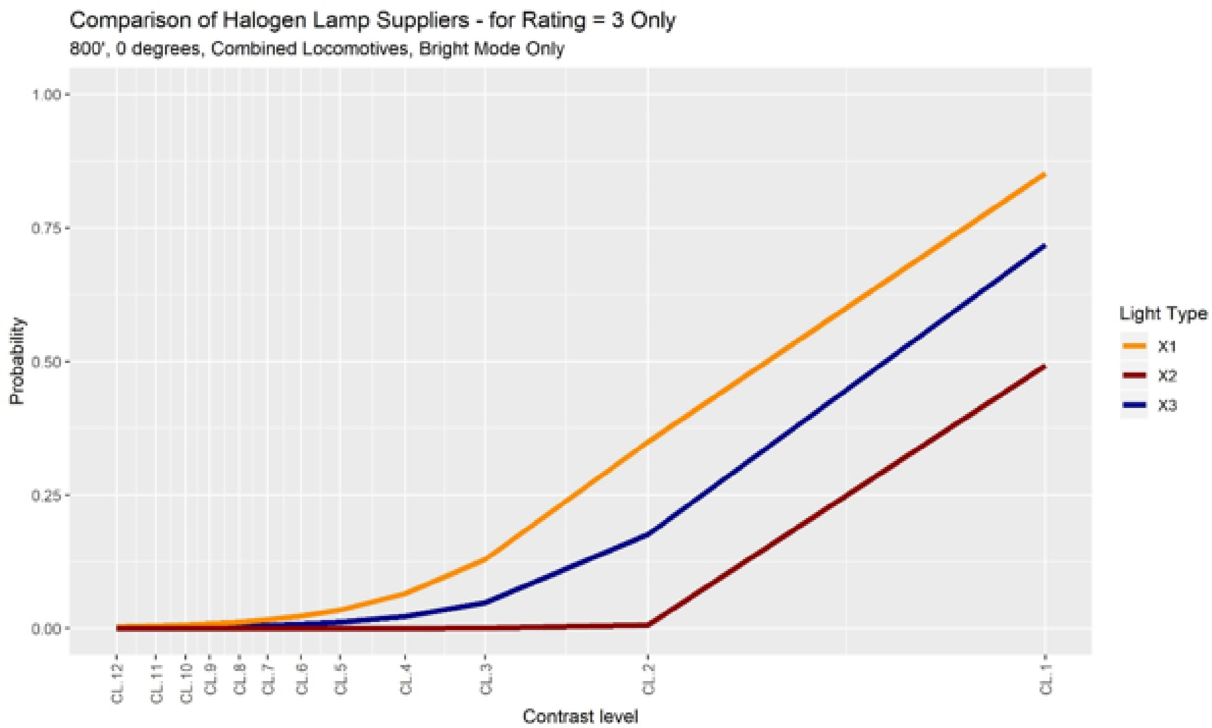
Probability functions for high-detailed contrast detection applied to halogen lamps at 300 ft.



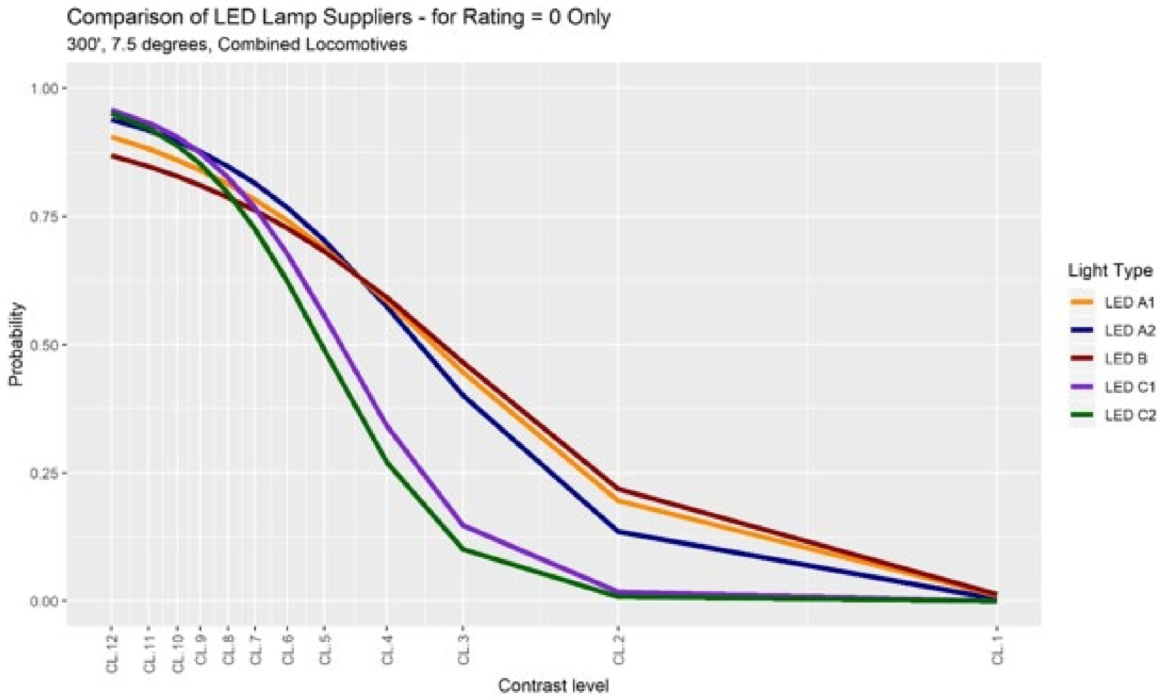
Probability function for null contrast detection applied to halogen lamps at 800 ft.



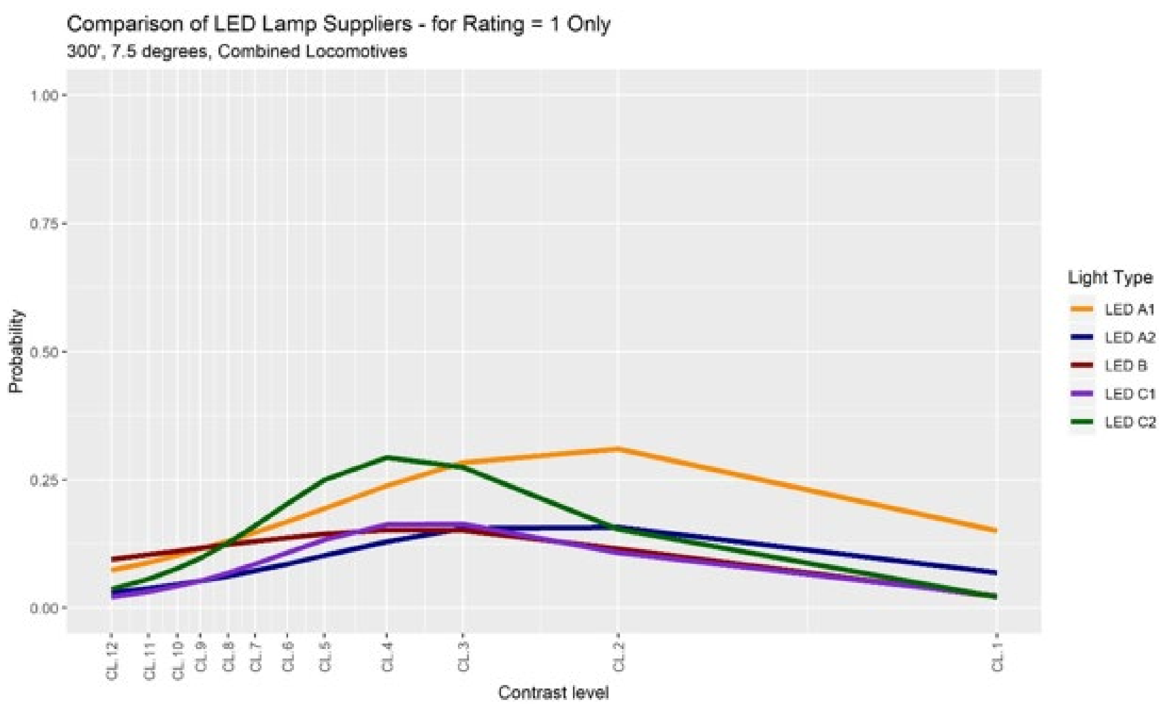
Probability function for contrast detection only applied to halogen lamps at 800 ft.



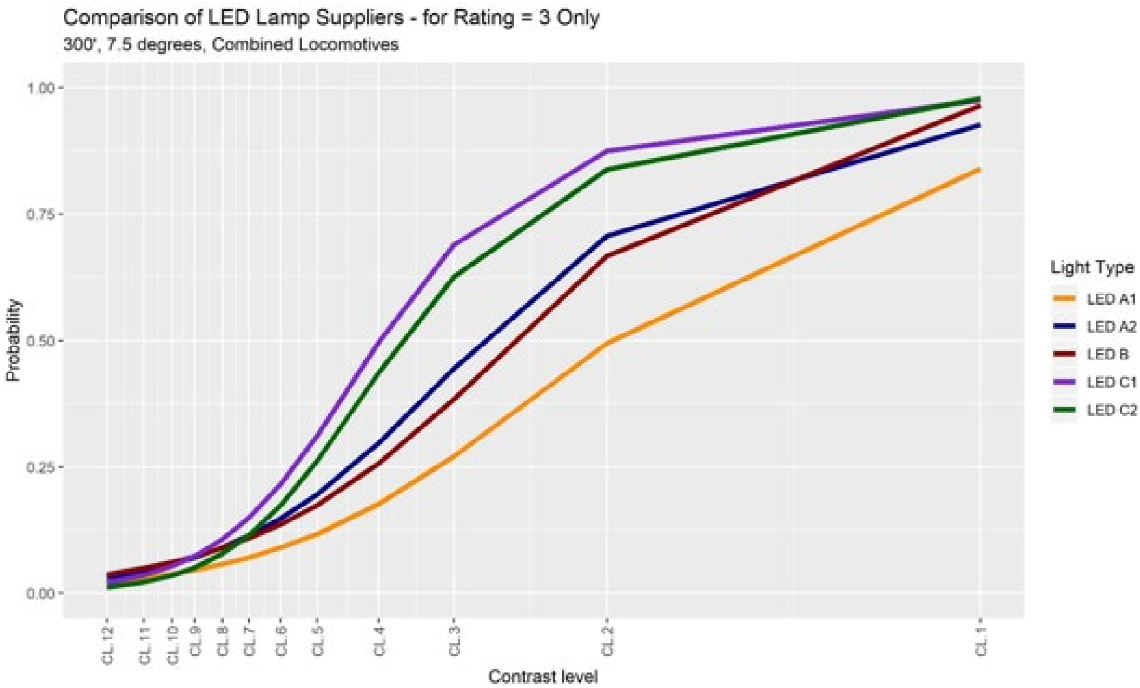
Probability functions for high-detailed contrast detection applied to halogen lamps at 800 ft.



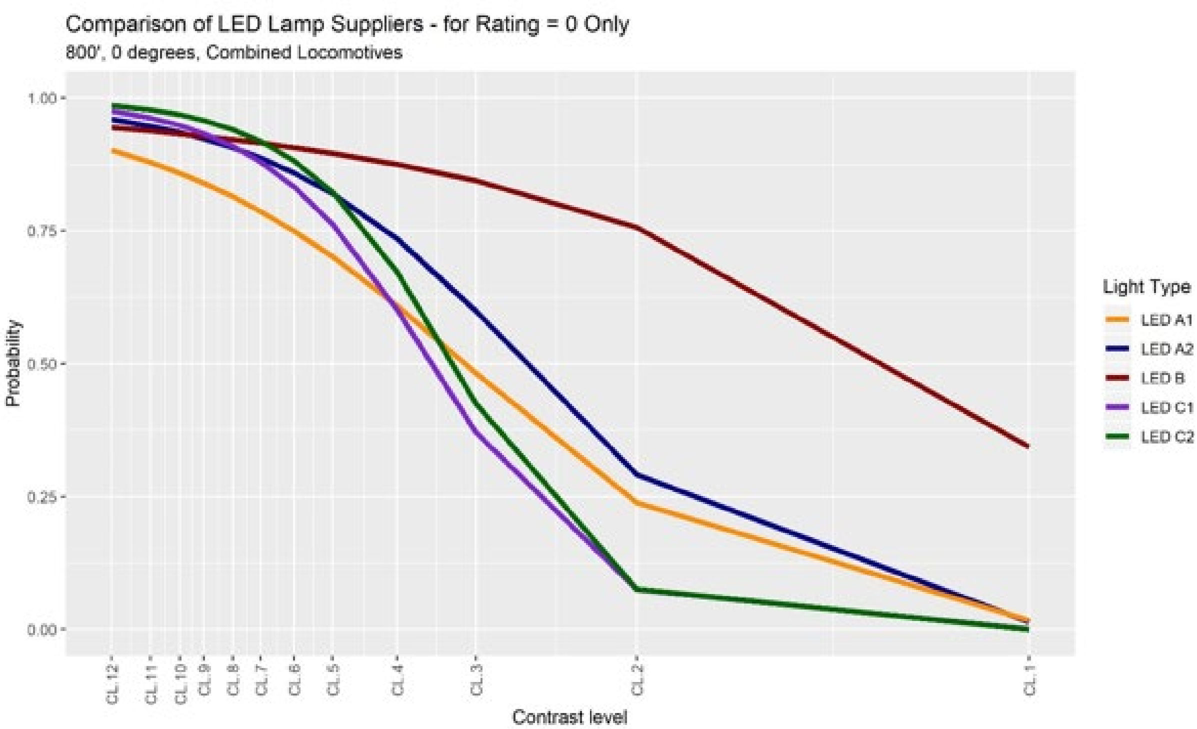
Probability function for null contrast detection applied to LED lamps at 300 ft.



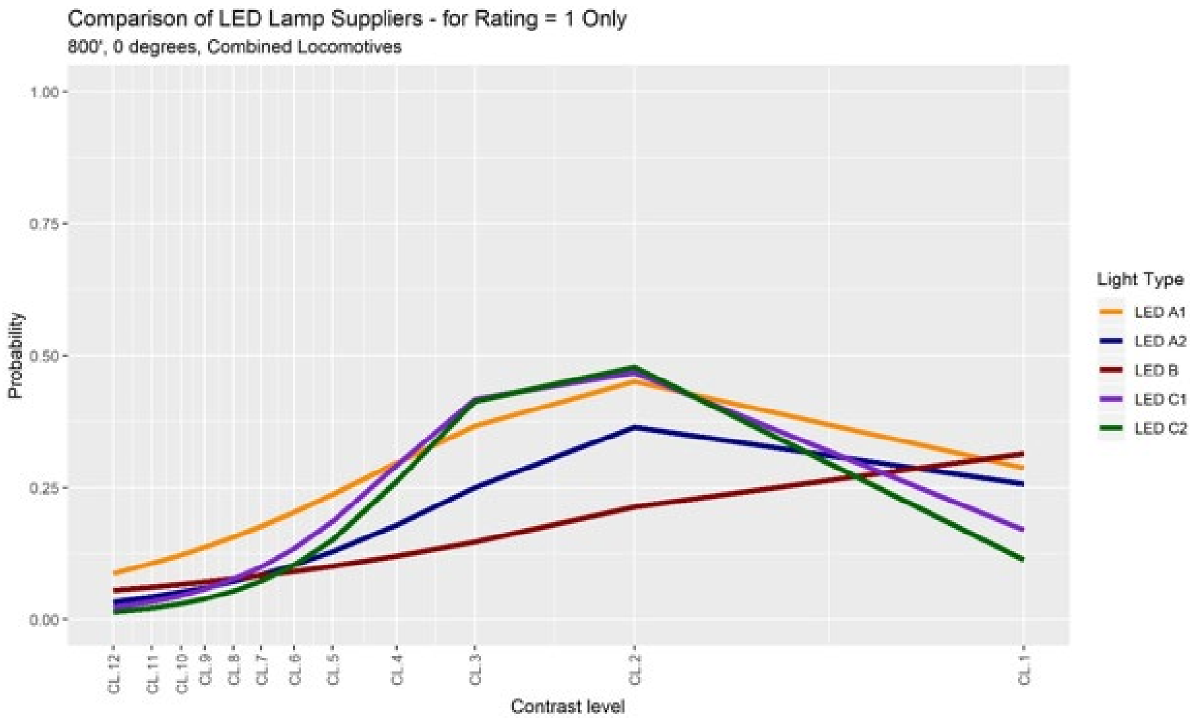
Probability function for contrast detection only applied to LED lamps at 300 ft.



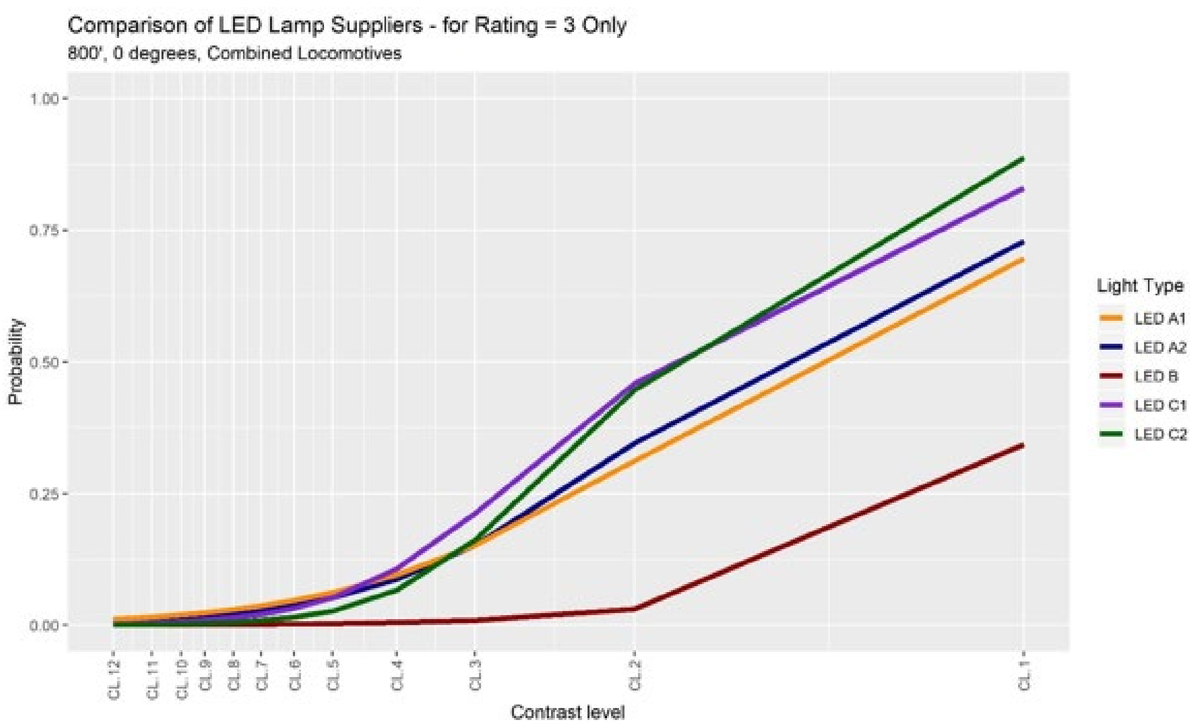
Probability functions for high-detailed contrast detection applied to LED lamps at 300 ft.



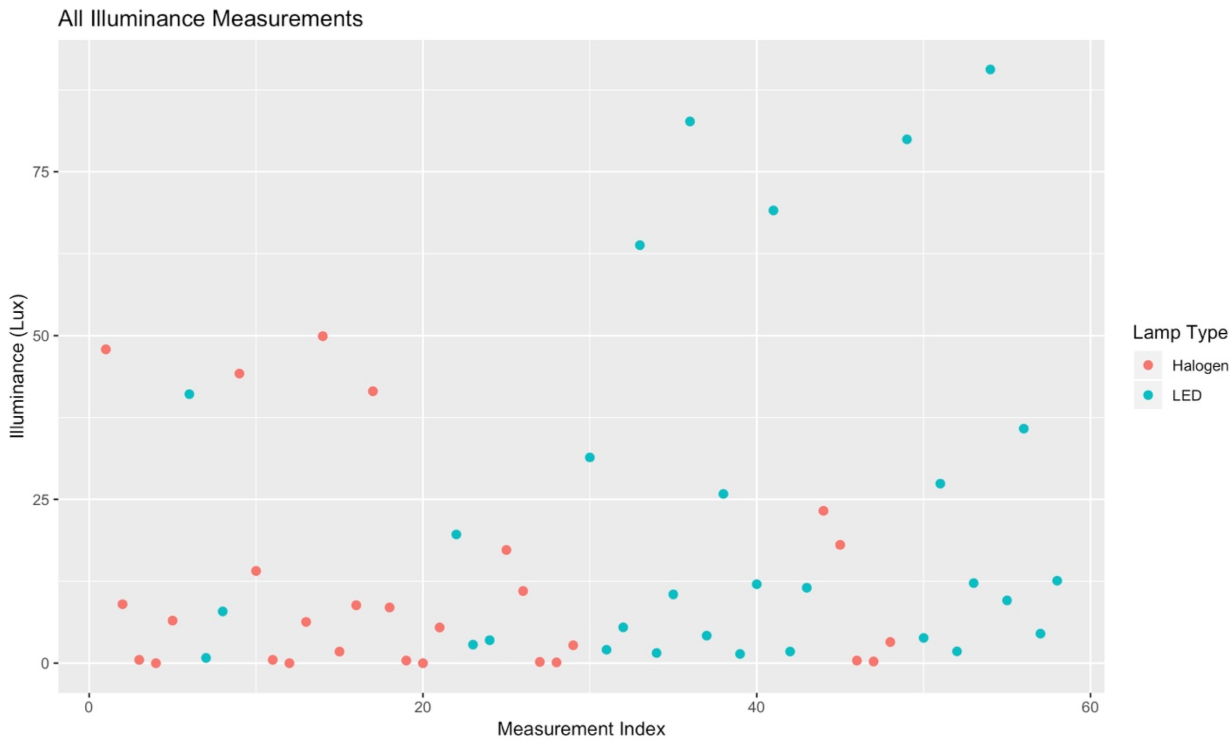
Probability function for null contrast detection applied to LED lamps at 800 ft.



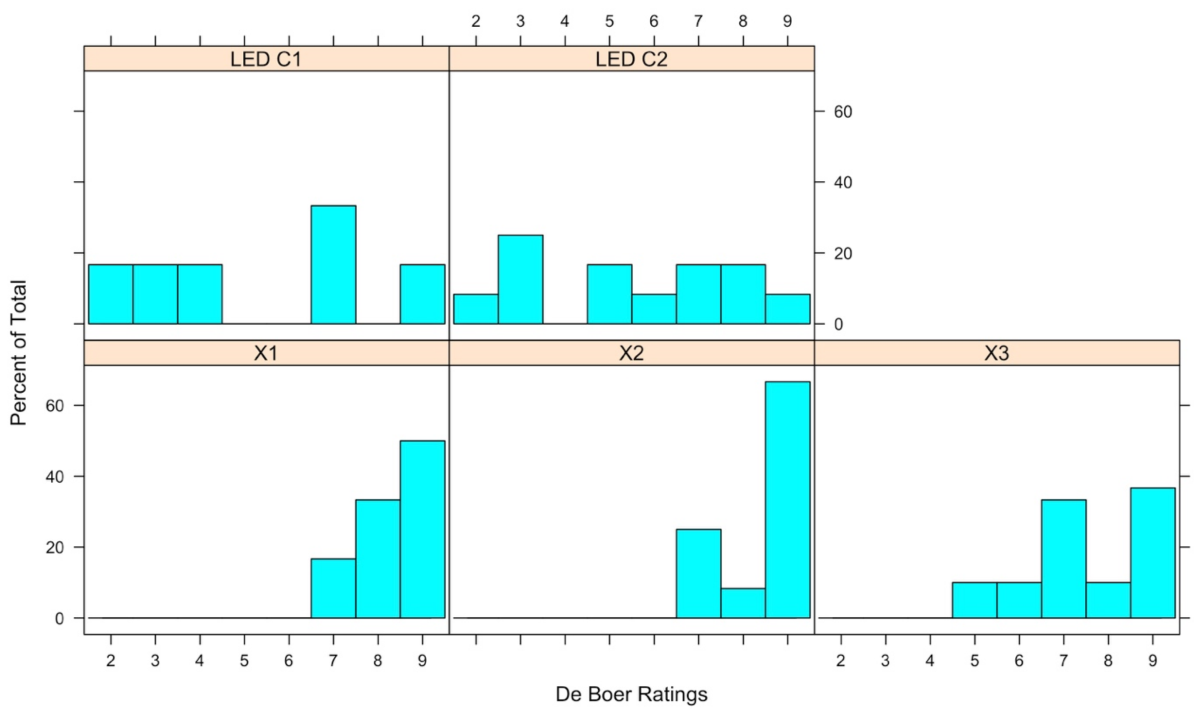
Probability function for contrast detection only applied to LED lamps at 800 ft.



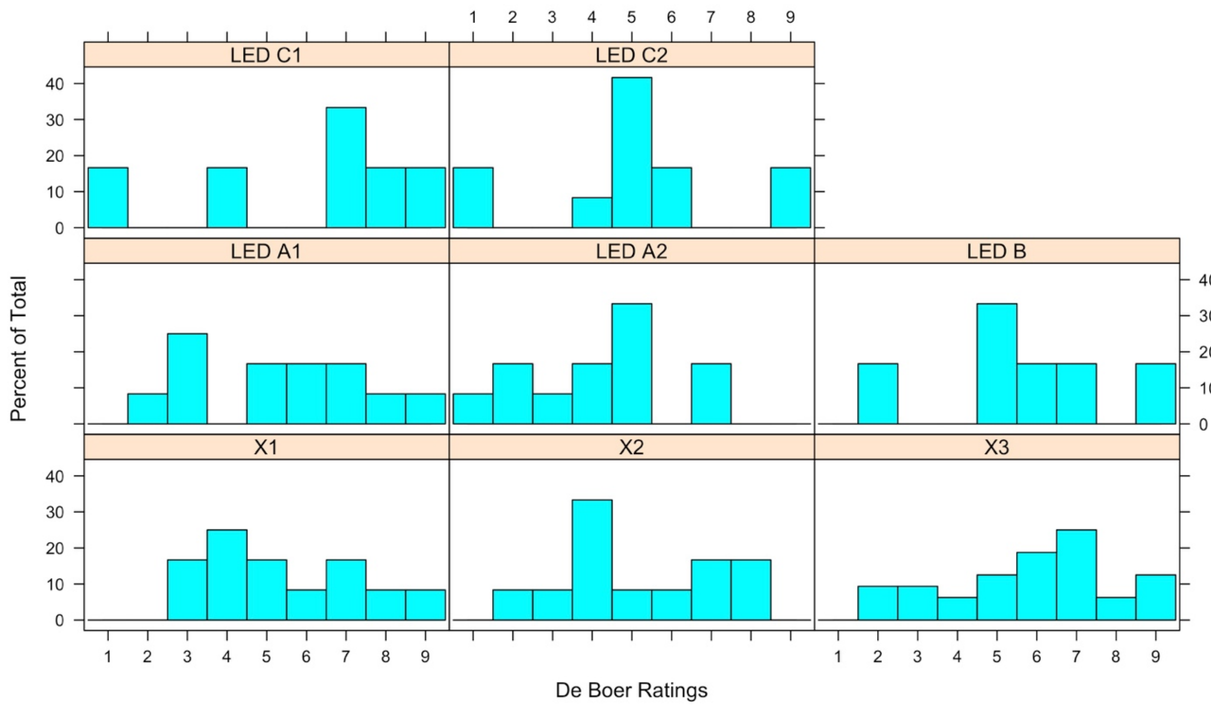
Probability functions for high-detailed contrast detection applied to LED lamps at 800 ft.



All illuminance measurements including all distances and orientations



Histogram of glare ratings in dim mode



Histogram of glare ratings in bright mode

Abbreviations and Acronyms

CFR	Code of Federal Regulations
FMVSS	Federal Motor Vehicle Safety Standards
UTU	United Transportation Union
AAR	Association of American Railroads
TAG	Technical Advisory Group
UP	Union Pacific
NS	Norfolk Southern