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

DOT/FRA/ORD-21/15

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13. ABSTRACT (Maximum 200 words)

This report describes the compliance testing of light-emitting diode fixtures used as locomotive headlights and auxiliary lights. The purpose of Phase III testing was to study the ability of observers to identify inconspicuous visual targets along the track, the pattern formed by the locomotive lights, and the flashing light emitted from an end-of-train device. Observations were made from inside the locomotive cabin as well as on the track wayside and the tests conducted quantified the distance at which observers were able to identify the various visual targets presented.

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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

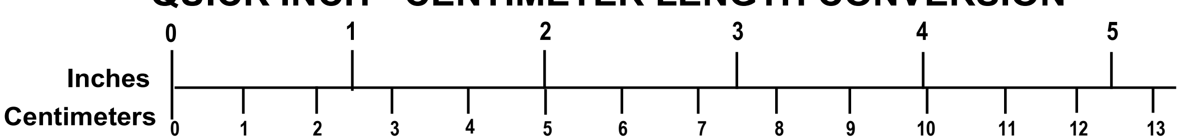
VOLUME (APPROXIMATE)

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



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

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

Updated 6/17/98

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Executive Summary

This report describes the work performed through the Phase III compliance testing to characterize light-emitting diode (LED) fixtures as locomotive headlights and auxiliary lights. The testing described in this report was conducted by a team of engineers from Engineering Systems, Inc. (ESi) and ENSCO, Inc. between August 2019 and April 2020. The research team utilized a locomotive provided by the Union Pacific Railroad for all dynamic testing.

Phase III compliance testing focused on characterizing potentially critical visibility aspects related to the use of LED technology in locomotive headlights and auxiliary lights. The performance of the LED lamps in the locomotive application must be quantified for two reasons: to assess compliance with existing regulations and to determine how LED lamp performance compares to the performance of historically ubiquitous halogen lamps.

The purpose of this particular phase of study focused on the lighting conditions produced by LED and halogen lamps while a locomotive was in motion. The research team evaluated visibility aspects from the viewpoint of an occupant inside the locomotive cabin and that of an observer outside and away from an approaching locomotive. Specifically, the team studied the ability of cabin occupants to detect objects ahead of them on the track and along the wayside, and to detect an end-of-train (EOT) device located on the track ahead. Another objective of this study was to investigate the ability of outside observers to identify the typical triangular pattern formed by the lamps installed on the front of a locomotive, and to recognize the forward motion of an approaching locomotive.

Researchers addressed the objectives of this study by designing multiple experiments and conducting full-scale nighttime testing with human subjects and a dynamic locomotive. Participating manufacturers provided both LED and halogen lamp samples and both were used independently during the study to establish their comparative performance. Six lamp models (four LED and two halogen) were evaluated. Researchers positioned the five test participants in locations inside and outside the locomotive cabin and guided them to give responses according to their perceptions under the various lighting conditions. These responses formed the basis for quantifying distances needed to detect objects on or adjacent to the track, to identify the EOT device or the shape formed by the headlights, and to establish whether a distant locomotive was moving.

The results of this study revealed that the average distance at which participants could detect objects on the track and on the wayside showed no statistically significant difference between lamp models. However, two of the LED lamp models exhibited response distributions that were significantly different than the remaining lamps tested. The variance of the object detection distance along the track did demonstrate statistically significant differences. The two LED lamps with greater variability exhibited the potential for greater detection distances. When grouping all lamp models together, the mean object detection distance was 716 ft. The maximum detection distance was measured under lighting conditions produced by the LED lamp with the greatest variance and was 1,635 ft.

None of the lamps included in this study, LED or halogen, exhibited a “washout” effect, meaning that the EOT device was equally observable by cabin occupants at close range. In addition, none of the lamps were found to impede the detection and identification of an EOT device. Observers could detect the EOT device at significant distances, with a mean detection distance of approximately 10,290 ft.

Average lamp pattern detection distances for an approaching locomotive revealed no statistically significant differences between lamp models. The triangular pattern formed by the locomotive lamps was detected by observers on average at a distance of 468 ft. away. The maximum detection distance for the triangular pattern was 891 ft. When presented with shapes other than the typical triangular pattern, observers were able to detect and correctly identify the pattern at an average distance of 471 ft. The maximum detection distance to correctly identify any lamp pattern was found to be 1,164 ft. away from the approaching locomotive.

The mean detection distance required for external observers to detect whether a locomotive was moving was 13,096 ft. This distance, while based on the responses from the study participants, represents a highly unlikely perceptual ability. After further review of the experimental design and the video of each test run, researchers determined that observers likely predicted when the locomotive would start moving rather than relying only upon visual cues.

The primary outcome of this study was that while there may be subtle differences in the light output, distribution, and color temperature of various LED and halogen lamp models, there were no statistically significant differences found in the ability of observers to detect objects illuminated with either light source. Overall, there were no detrimental effects to the use of LED technology for locomotive headlights and auxiliary lights under dynamic conditions. Observers inside the cabin of the locomotive and positioned outside of and away from the moving locomotive could similarly detect objects on and along the track, detect an EOT device, identify the shape pattern formed by the locomotive lamps, and establish whether the locomotive was moving.

1. Introduction

This report summarizes Phase III of the ongoing efforts to update standards and recommendations related to the use of LED technology for locomotive headlights and auxiliary lights. As part of the Phase III compliance testing for using LED lamps in locomotive headlights, a research team designed an experiment to examine visibility aspects of LED headlights during the dynamic operation of a locomotive. The designed experiment evaluated specific aspects of track visibility from the viewpoint of a moving locomotive and the ability to perceive different lamp patterns while using LED and halogen samples on a locomotive in motion.

1.1 Background

In the initial effort of this process (Phase I) LED samples' photometric characteristics (i.e., luminous intensity and color temperature) were tested and validated for compliance with applicable regulatory requirements and standards. Also, LED samples were compared to halogen counterparts in laboratory conditions. Phase II of this process entailed static field testing to assess visibility and glare aspects of the LED and halogen lamps when installed in two stationary locomotives.

1.2 Objectives

Per the scope of work established by the Association of American Railroads (AAR) Locomotive Committee LED Headlight-Auxiliary Light Standard Technical Advisory Group (TAG), three main objectives were established for Phase III of the LED compliance testing. These objectives pertain to visibility and perception aspects of LED lamps and depend on the illumination provided solely by the locomotive lamps when the locomotive is in motion. The objectives are:

1. To determine the ability of cab occupants to distinguish the track and wayside ahead of the locomotive.
2. To determine the ability of cab occupants to distinguish an end-of-train (EOT) device on the rear of a train ahead.
3. To determine the ability of individuals outside the locomotive cab to distinguish the motion and identify the triangular light pattern of an approaching locomotive.

1.3 Overall Approach

To achieve the goals of this study, researchers conducted two concurrent experiments at the Precision Test Track of the Technological Transportation Center (TTC). Experiment 1 was conducted from inside the cabin of a moving locomotive and was designed to acquire data to achieve Objectives 1 and 2. Perception-response judgments of cab occupants related to targets positioned on the track and wayside were recorded. Simultaneously, Experiment 2 was conducted from test stations along the track approximately 2 miles from where the locomotive started its motion. Perception-response judgments of individuals at the test stations related to the geometric shapes formed by the approaching locomotive lamps were recorded. Experiment 2 was designed to acquire data to achieve Objective 3.

The position of the locomotive, the on-track and wayside targets, and the human observers were recorded via GPS (Global Positioning System). The GPS coordinates were then used to calculate the distance between an observer and the corresponding stimulus (e.g., targets on the track or the lamp patterns from an approaching locomotive) that prompted a response. This data was analyzed to compare the visibility aspects produced by LED and halogen lamps.

1.4 Scope

The controlled environment of this study facilitated the comparison of the performance of a variety of LED and halogen lamps under the specific conditions of the testing. Researchers expected that some variation in performance may have existed for both the LED and halogen lamps when utilized in real-life scenarios different than those present during the testing. However, the dynamic nature of the testing enabled the LED and halogen lamp performance to be directly compared and conclusions on the anticipated real-world performance of the lamps to be drawn.

1.5 Organization of the Report

Section 2 provides an overview of the relevant regulatory framework related to locomotive lighting. 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. Background

Title 49 of the Code of Federal Regulations (CFR) part §229.125 prescribes the Federal safety standards for locomotive headlights and auxiliary lights. Relevant to the present study, this section of the CFR outlines the minimum requirements for the luminous intensity and the level of illumination at given distances and angles relative to the locomotive. A more in-depth discussion of the regulation can be found in the Phase I and Phase II reports.

The CFR part §229.125 prescribes minimum illumination and visibility distances for headlamps and auxiliary lights in road service (a) and yard service (b) conditions (Federal Railroad Administration, DOT, 2018):

(a) …Each headlight shall be aimed to illuminate a person at least 800 ft ahead and in front of the headlight…

(b) …Each headlight… and shall be aimed to illuminate a person at least 300 ft ahead and in front of the headlight.

The Phase II testing investigated the visibility of human-sized objects along and the track and on the wayside using contrast-sensitivity targets positioned 300 and 800 feet away from a stationary locomotive. To summarize the results of Phase II, the research team found that the LED lamps provided better contrast discrimination than halogen lamps along the tracks, but worse contrast discrimination than halogen lamps at an angle offset of 7.5º from the track centerline. An objective of Phase III was to better understand such conditions with respect to a cab occupant in a moving locomotive. Experiment 1 of Phase III incorporated visibility measurements of various-sized objects that would blend in with dark nighttime surroundings rather than using only human-sized contrast-sensitivity charts as in Phase II. The purpose of including dark and low-reflectance objects was to maximize the likelihood that the perception of a given target would be due to the illuminance provided by the locomotive lamps and not due to a characteristic of the object that would make it stand out against its background (e.g., high-reflectance color).

A second focus of Phase III testing was related to the ability of a cab occupant to distinguish the EOT device on a train ahead. Current EOT devices have several functions and capabilities. One of their primary functions is to provide a warning to any following trains that the track ahead is occupied. 49 CFR part §221 prescribes the minimum requirements for marking devices on the trailing end of all passenger, commuter, and freight trains. Part §221.13 states:

(a) During the periods prescribed in paragraph (b) of this section, each train to which this part applies that occupies or operates on main track shall (1) be equipped with, (2) display on the trailing end of the rear car of that train, and (3) continuously illuminate or flash a marking device prescribed in this subpart.

(b) …the marking devices prescribed by this subpart shall be illuminated continuously or flash during the period between one hour before sunset and one hour after sunrise…

The implementation of new technology such as LED lamps can introduce uncertainty regarding the performance of established safety devices in the railroad environment. With respect to an EOT device, there was concern regarding the effects that the luminous intensity and cooler color temperature of some LED headlights and auxiliary lights may have on the conspicuity and apparent color of an EOT device. Color appearance depends on a set of complex interactions within the visual system (DiLaura, Houser, Mistrick, & Steffy, 2011). One of many examples of the result of these interactions is the change in color appearance of a stimulus due to its surrounding background and the level of chromatic adaptation of the observer. For instance, the same red stimulus surrounded by a yellow background will appear different when surrounded by a blue background. In Figure 1, the circle on the right appears darker than the circle on the left only due to its background.

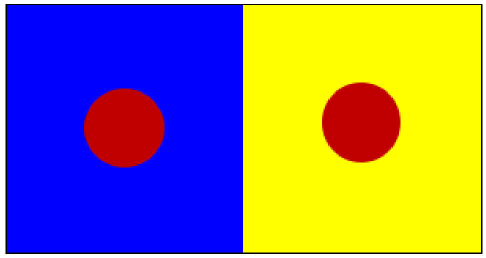

Figure 1. Example of change in color appearance

Similarly, a given visual stimuli such as a white wall can appear significantly different when viewed under light sources of different color temperatures. The main concern regarding the interaction between an EOT device and an LED lamp was a potential "wash out" effect or lessening of its conspicuity due to the differences in color temperature.

A third focus of Phase III testing was to determine if individuals outside of the locomotive could distinguish the typical triangular light pattern of oncoming locomotives when LED samples were used in the headlight and auxiliary lamp housings. The ability of the locomotive lighting system to create a distinctive light pattern is important for enhancing motorist recognition of the approaching hazard as a train. In 1995, FRA published research (Carroll, Multer, & Markos, 1995) that studied the detectability and the detection distance of various alerting devices in the vicinity of a road crossing. The visual alerting devices studied included light systems, paint schemes, and reflective material, with a single headlight being considered the control. Researchers determined that the combination of headlight and dual ditch lights (triangular light pattern) increased the detectability of the locomotive compared to the single headlight and resulted in a smaller overestimation of train arrival, providing a greater safety margin. Under nighttime lighting conditions, the mean detection distance for the triangular arrangement of headlights and ditch lights was equal to 1,568 feet. The triangular light pattern created by the incorporation of dual auxiliary ditch lights was made a requirement in 1997 (see Locomotive Safety Standards, 1997, 49 CFR 229).

After the triangular light arrangement had been a requirement for several years, an examination of factors that aided in the reduction of crossing incidents, published in 2013, revealed that the auxiliary light system significantly improved the safety of grade crossings by *"making locomotives more conspicuous aids drivers not only in seeing an oncoming train, but in judging its distance and speed"* (Horton & daSilva, 2013). The current Phase III testing is essential for evaluating the ability of external observers to distinguish the triangular light pattern of an oncoming locomotive and for maintaining grade crossing safety when LED headlights are used.

3. Methodology

This section describes the methodology, experimental apparatus and infrastructure, and analytical tools used to perform Experiments 1 and 2, as described in Section 1.3.

3.1 Lamp Samples

New and revised LED samples were used for Phase III testing. A total of four different LED lamp models (provided by J.W. Speaker, Hydra-Tech, Railhead/Divvali, and SMART Light Source) and two different halogen lamp models (AMGLO and ePowerRail) were submitted to ESi for testing. Eight samples per lamp model were provided to ESi. Further details about each of the provided lamp models can be found in Appendix A.

3.2 Testing Grounds

TTC facilities in Pueblo, Colorado, were used as testing grounds for these experiments. An approximately 2-mile tangent section of the Precision Test Track at TTC was used for forward and backward movements of the locomotive. Testing took place on November 11–14, 2019. In addition, Transportation Technology Center, Inc. (TTCI) provided staff to coordinate safety, testing logistics, locomotive operation, and ensure the safe completion of these experiments.

Figure 2. Aerial views of the Precision Test Track at TTC

3.3 Testing Participants

Five human subjects were recruited from a pool of TTCI employees. These participants were kept naïve as to the specific objectives of the experiments. Each participant completed and signed a consent form and biographical information sheet. A unique, randomized subject number was assigned to each participant. The age of the participants ranged from 43 to 67 years, and all had normal or corrected-to-normal vision.

3.4 Testing Setup

The logistics of testing was complex, as the testing protocol was designed such that two experiments were conducted concurrently. For these experiments to occur simultaneously, three testing stations were needed – two along the wayside of the test track and one inside the test locomotive. Each station was equipped with a GPS receiver and an inertial measurement unit sensor developed by DEWESoft. Each station was operated by an ESi experimenter who guided participants through the experiments and recorded their verbal responses.

ESi experimenters were assisted by a team from TTCI who filled three key roles to coordinate the required logistics for the completion of Experiments 1 and 2:

1. Cabin Experimenter (Cabin Station):
    - Acted as main testing operator and coordinated with the other experimenters before starting each test iteration
    - Guided participants during Experiment 1 tasks and recorded verbal responses
    - Coordinated the rotation of participants between testing stations
2. Track Operators:
    - Placed specific visual targets on track and along the wayside as established by the planned sequence of experiments
    - Coordinated with other operators along the track and all other experimenters to ensure all testing and safety procedures were adhered to.
3. End-track Experimenters (North and South Stations):
    - Coordinated with cabin experimenter for Experiments 1 and 2 to run simultaneously
    - Guided participants through Experiment 2 tasks and recorded verbal responses

In addition to these roles, there were multiple other individuals involved in the testing. TAG members and other railroad individuals coordinated with the TTCI, ESi, and ENSCO teams for additional tasks that were needed for the proper function of the locomotive and the installation of lamp samples.

3.4.1 Track Setup

Prior to testing, the track was surveyed and all relevant locations included in the testing were documented via GPS coordinates for later reference. One portion of the track surveyed was the length of track required for the locomotive to reach a steady speed of 30 mph (see Figure 4, "Acceleration Section"). In addition, the testing site was documented using a DJI Phantom 4 Pro drone, which captured photographs and HD video.

Figure 3. Sample of visual targets along the test track

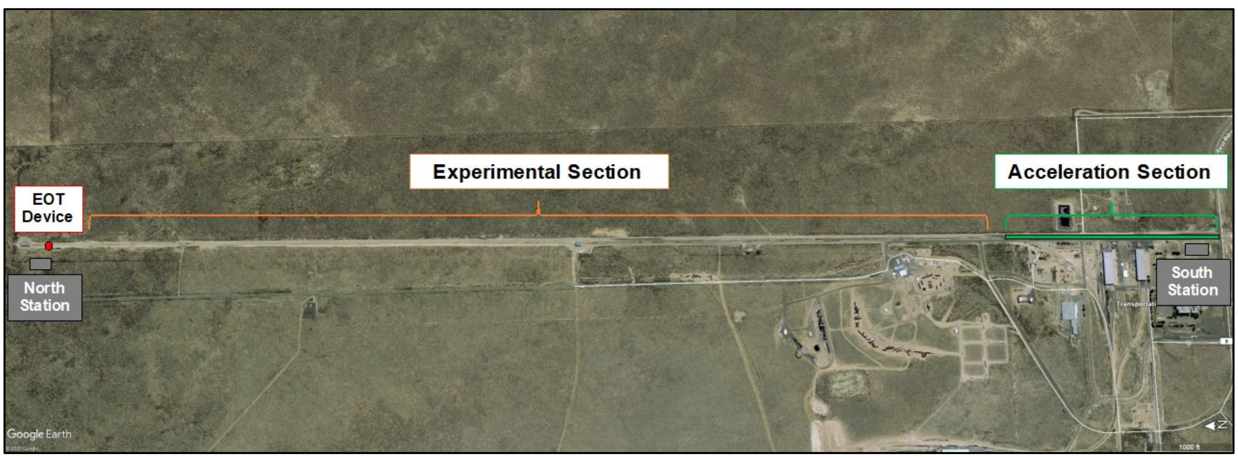

Figure 4. Aerial view of the Precision Test Track at TTC

3.4.2 Locomotive Setup

The locomotive used for testing was an EMD SD70M series provided by Union Pacific (Road Number 5062). The front of the locomotive was equipped with a dual-lamp headlight above the cabin and two auxiliary lights on the front walkway, while the rear of the locomotive was equipped with a dual-lamp housing. Prior to testing, the rear of this locomotive was modified with the addition of a wooden frame configured to hold five additional lamp fixtures. Including the original headlamp, the rear of the locomotive was fitted with a total of six lamps (see Figure 5).

The cabin of the locomotive was equipped with two video cameras – one facing the participant and another facing the experimenter. A computer station was installed to capture GPS data and verbal responses provided by the participants. Two video cameras were installed outside the cabin, facing forward. Two additional, low-frequency GPS receivers were placed on the locomotive to provide redundant positioning data.

Figure 5. Front and rear of the test locomotive

3.5 Experiment 1 – Track, Wayside, and EOT Visibility Evaluations

Track, wayside, and EOT visibility were evaluated through perceptual observations made by participants from inside the cabin during the forward motion of the locomotive. As stated previously, Experiment 1 addressed Objectives 1 and 2 – i.e., track visibility and EOT detection (see Section 1.2).

This experiment was designed to provide answers to the following general questions:

1. How well can cab occupants see down a section of track with the headlight set to “bright”?
2. How well can cab occupants see the track wayside with the headlight set to “bright”?
3. At what distance is it possible to see an EOT device on the train ahead?
4. Does the LED headlight reduce the conspicuity of the EOT device?

3.5.1 Visual Stimuli

A total of 12 visual targets (5 track targets, 6 wayside targets, and 1 EOT device) were used for testing in Experiment 1. The targets were placed along the track in two different configurations. The specific location of each target was marked using reflective survey stakes. In addition, the coordinates of each of these locations were recorded using a GPS receiver (Adafruit Ultimate GPS logger shield module).

The track and wayside visual targets were made from 55-gallon polypropylene barrels. Wayside targets consisted of complete barrels, while track targets consisted of barrels cut in half along their long axis. All barrel targets were covered with low-reflectance fabric (i.e., Duvetyn) to reduce their conspicuity.

The targets used for track visibility testing consisted of a set of five half-barrels placed on the center of the track. For each test iteration, one of the five barrel targets was inclined, presenting a larger visual surface to the approaching locomotive (see Figure 6). The targets used for visibility testing along the track wayside consisted of six full-size barrels placed at two different distances perpendicularly away from the track centerline (three targets at 15 feet and three targets at 30 feet). Two of these targets (one at 15 feet and one at 30 feet) were placed such that there was partial occlusion due to features of the surrounding area (e.g., vegetation or a nearby structure). The distance between successive targets was approximately 1,000 feet.

Finally, to test for EOT detectability, an EOT device was modified to illuminate continuously in stand-alone operation and placed on the center of the track approximately 2 miles away from the initial position of the locomotive (see center picture in Figure 3).

Figure 6. On-track targets at different visual angles placed on the test track

3.5.2 Testing Procedure

Data collection for all experiments was conducted after the end of civil twilight, during nighttime conditions. Experiment 1 began with the locomotive positioned at the south end of the test track. A participant was seated in the conductor's seat of the locomotive cabin. Participants were instructed to visually scan the track and its periphery for dark objects and a red blinking light. Subjects were asked to verbally respond immediately after detecting the presence of such targets (see Appendix B for the specific instructions provided to the participants).

After coordination between all testing stations and track operators, the locomotive started its forward motion (i.e., north). The goal of the locomotive engineer was to reach 30 mph before reaching a predefined marker on the test track. For all trials, the locomotive achieved 30 mph well before the predefined marker. After reaching 30 mph, a test operator activated the EOT device and the cabin experimenter recorded the verbal responses that corresponded to each of the visual targets. The cabin experimenter entered the participants' responses in the DEWESoft GPS system by pressing a button that corresponded to the response given. The GPS system then recorded the time and coordinates at which the participant identified a visual target. All recorded responses occurred while the locomotive was in motion and traveling at a relatively steady speed of 30 mph. Participants occasionally identified milepost markers, signage, and other pieces of track infrastructure which were not deliberately installed as visual targets. Responses that did not correspond to any of the experimental visual targets were not flagged with the GPS system. Following each test iteration, participants were not provided feedback regarding their answers to avoid development of an expectation bias. In addition, the verbal responses of the participants and the button actuation of the experimenter were video recorded.

There were four forward-facing lamps on the locomotive, a high-mounted dual-lamp headlight and two ditch lights, all set to bright mode. This was the sole light source illuminating the track and the visual targets that participants were asked to identify. Before starting a trial, the track and wayside targets were positioned in one of two possible configurations (see Table 1 and Table 2). In summary, participants inside the locomotive cabin attempted to identify the following targets:

1. Five track targets – one at a greater visual angle and four of equal and lesser visual angles.
2. Three wayside targets 15 ft. away from the center of the track. One of these was partially occluded.
3. Three wayside targets 30 ft. away from the center of the track. One of these was partially occluded.
4. One functional EOT device located at the north end of the track.

Table 1. Configuration 1 for visual target placement

Target Order	Target Location	Track Side	Lateral Distance (ft.)	Marker Code	Latitude (deg)	Longitude (deg)
1	Wayside	West	30	P-30	38.4407100	-104.2818367
2	On track	-	-	T	38.4435267	-104.2816733
3	Wayside	East	30	P-30	38.4448900	-104.2815600
4	On track	-	-	T	38.4463300	-104.2816250
5	Wayside	East	15	P-15	38.4491450	-104.2815433
6	On track	-	-	T	38.4517867	-104.2815433
7	Wayside	West	15	P-15	38.4545900	-104.2815433
8	On track	-	-	T	38.4587767	-104.2814450
9	Wayside	East	30	oP-30	38.4615067	-104.2812833
10	On track	-	-	eT	38.4642670	-104.2813483
11	Wayside	West	15	oP-15	38.4697670	-104.2812833
12	On Track	-	-	EOT	38.4711330	-104.2812111

Table 2. Configuration 2 for visual target placement

Target Order	Target Location	Track Side	Lateral Distance (ft.)	Marker Code	Latitude (deg)	Longitude (deg)
1	On track	-	-	T	38.4406900	-104.2817550
2	Wayside	East	15	P-15	38.4435300	-104.2816400
3	Wayside	West	15	P-15	38.44488167	-104.2817217
4	On track	-	-	T	38.44633000	-104.2816250
5	Wayside	East	30	P-30	38.44914167	-104.2815100
6	On track	-	-	T	38.45178670	-104.2815430
7	Wayside	East	30	oP-30	38.45459333	-104.2814130
8	On track	-	-	eT	38.45877667	-104.2812111
9	Wayside	West	30	P-30	38.46152833	-104.2814933
10	On track	-	-	T	38.46426700	-104.2813483
11	Wayside	West	15	oP-15	38.46976700	-104.2812833
12	On track	-	-	EOT	38.47113300	-104.2812111

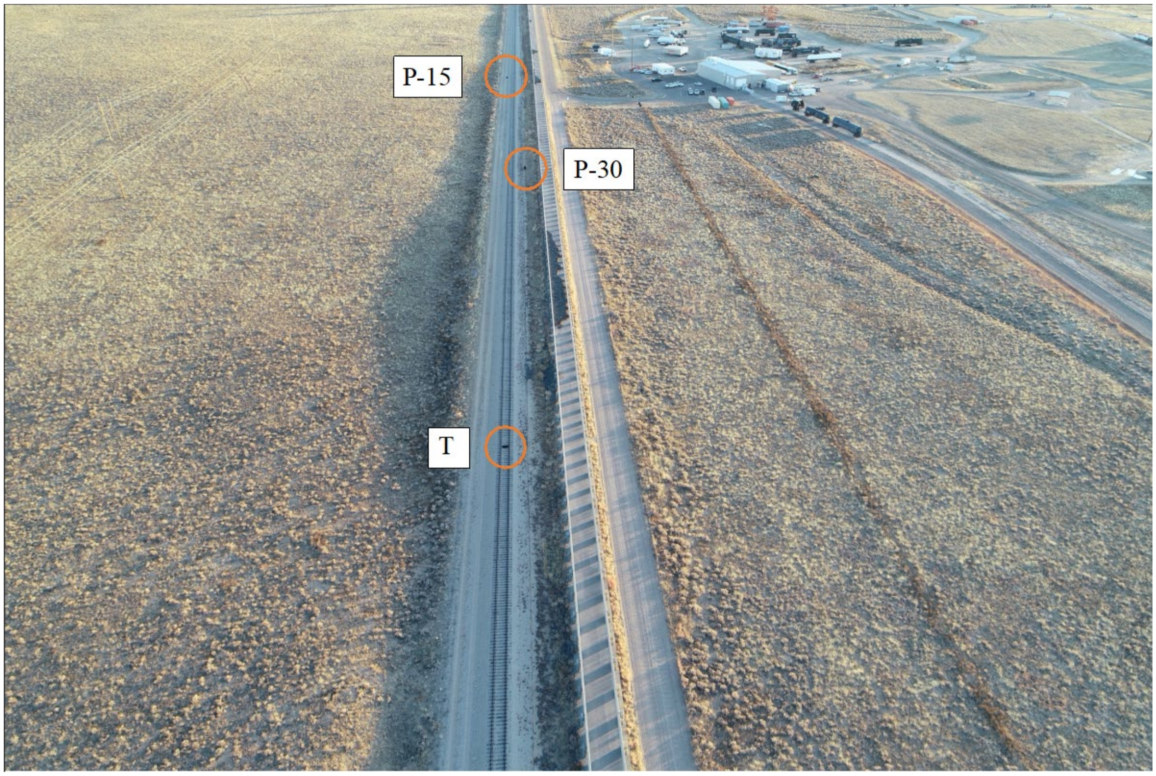

Figure 7. Daytime aerial view of visual targets placed on the test track

3.6 Experiment 2 – Identification of Lamp Patterns and Locomotive Motion

The ability of participants to distinguish the triangular lamp pattern typically formed by the combination of headlight(s) and auxiliary lights on a locomotive was assessed through perceptual observations made by participants positioned approximately 2 miles down the track from the starting point of the locomotive. Figure 9 and Figure 10 show a schematic representation of the simultaneous occurrence of Experiments 1 and 2.

The test design for Experiment 2 included perceptual evaluations made by participants located along the track wayside. These evaluations were designed to address Objective 3 (see Section 1.2). Specifically, participants were instructed to provide verbal responses regarding two specific aspects of the approaching locomotive:

1. Is the locomotive moving?
2. What shape is created by the lights of the approaching locomotive (e.g., single point of light, three lights in a triangular shape, etc.)?

3.6.1 Testing Procedure

To test participants' ability to distinguish both the pattern formed by the lamp arrangement on the locomotive and discern the longitudinal motion of a locomotive, the test locomotive was fitted with lamps on the front and rear. The front was equipped with the typical lamp arrangement of a locomotive, while the back was equipped with a grid of lamps capable of presenting different geometric patterns (e.g., a square pattern, a single light point, or a horizontal line). The right picture in Figure 5 shows the rear of the test locomotive with the configurable lamp arrangement.

While the locomotive was in motion, a stationary participant was alternately located at either the north or south test station and attempted to determine two aspects related to the locomotive, the geometric pattern presented by the illuminated lamps, and whether the locomotive was in motion (see Appendix B for the specific instructions provided to the participants). Participants were asked to verbally respond as soon as they were able to answer these questions. Similar to Experiment 1, the test operators at the north and south test stations entered the verbal response provided by the participants into the GPS system. Verbal responses and button actuations were also video recorded.

This experiment was intended to answer the following questions:

1. At what distance can a human subject discern the geometric shape presented by the locomotive lamps?
2. At what distance can an observer discern that the locomotive is moving closer?

In summary, Experiment 2 required the following conditions for each test run:

1. One participant located at the north test station. During the forward motion of the locomotive, this participant provided verbal responses regarding the lamp pattern at the front of the locomotive and the time at which the longitudinal motion of the locomotive began. The lamp arrangement presented to the participant during this test was always the typical triangular lamp pattern on the front of the locomotive.
2. One participant located at the south test station. During the backward motion of the locomotive, this participant provided verbal responses regarding the lamp pattern at the rear of the locomotive and the time at which the longitudinal motion of the locomotive began. The lamp arrangement presented to the participant during this test varied with each test iteration (see Table 3).

3.6.2 Visual Stimuli

Repeatedly presenting participants with only one type of visual stimulus, the triangular pattern formed by locomotive lamps, would make it challenging to determine whether the observer's ability to detect such a pattern has been affected by an expectation or learning bias. After a single test run of Experiment 2, a participant could assume that, given the observed geometry and features of the locomotive, the lamp pattern would be the same for the second test run of the experiment. After a few runs, the observer would then become convinced that the next lamp arrangement would again be a triangular pattern without fully resolving the actual pattern being presented. Therefore, the purpose of showing multiple shapes was to minimize potential observer learning bias or expectation-driven responses.

Five different shapes were selected as the visual stimuli for Experiment 2. For each test iteration, the rear of the locomotive depicted one of the five geometric patterns (see Figure 8 for depiction of these lamp patterns): (1) triangle, (2) square, (3) 3-lamp horizontal line, (4) 2-lamp horizontal line, and (5) single-lamp point.

Figure 8. Rear of the locomotive depicting all lamp patterns tested

3.7 Concurrency of Experiments 1 and 2

As previously stated, Experiments 1 and 2 were conducted simultaneously. The forward motion (northbound) of the locomotive was used to collect observations from inside the locomotive cabin (Cabin Station, Experiment 1) and from the north end of the test track (North Station, Experiment 2). The rearward motion (southbound) of the locomotive was used to collect observations from participants located at the south end of the test track (South Station, Experiment 2). When the locomotive was moving southbound, the participants in the Cabin and North Station remained idle, while the participant in the South Station was actively performing tasks related to Experiment 2. Similarly, when the locomotive was moving northbound, the participant in the South Station remained idle while the participants in the Cabin and North Station were actively performing tasks related to Experiments 1 and 2, respectively. (See Figure 9 and Figure 10 for a schematic depiction of Experiments 1 and 2.)

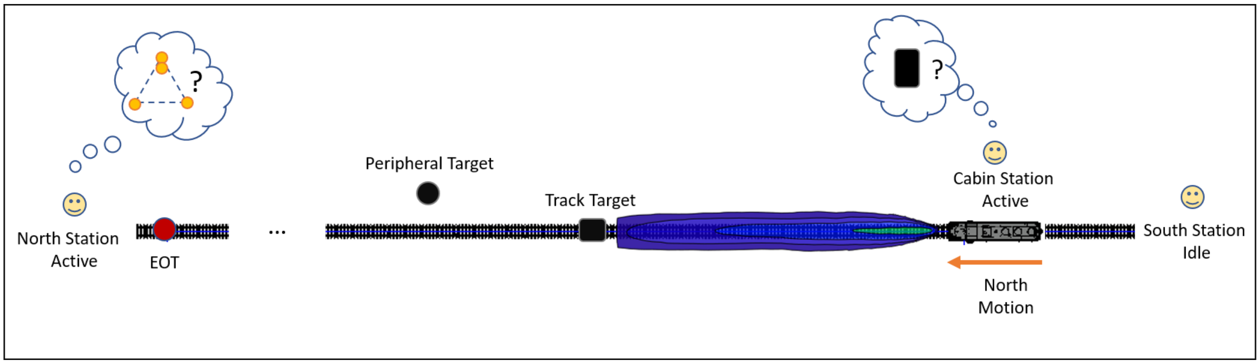

Figure 9. Schematic depiction of Experiment 1

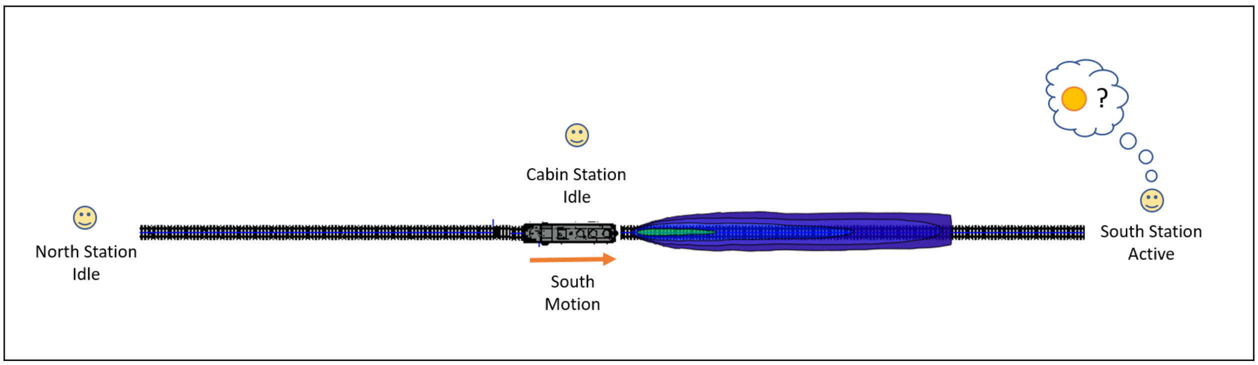

Figure 10. Schematic depiction of Experiment 2

Testing Sequence

A total of 60 test iterations were planned to collect data for both experiments. This number of trials ensured that every lamp model was installed in the front and rear of the locomotive to complete Experiments 1 and 2. Each participant made observations for both experiments and made evaluations of all lamp models.

Table 3 is a sample of the sequence for data collection during Experiments 1 and 2. The testing sequence was designed to allow all models of lamps to be tested in both the forward- and rear-facing positions. Figure 11 shows the view from 3 different cameras. The bottom frame shows the external view facing forward from a camera affixed to the "nose" of the locomotive. The top-left frame shows the view of the test participant located inside the locomotive cabin. Due to the low-illumination conditions required for the experiment, only a silhouette is perceptible in this view. The top-right frame shows the view from a camera located adjacent to the North Station, in which the triangular pattern formed by the locomotive lamps can be seen. Figure 12 includes two camera views taken from the South Station during two separate test runs of Experiment 2.

Each test run lasted between 5 and 6 minutes. Before each test run, instructions were provided to the participants as needed. At the end of each test run, the locomotive was moved to a shop for the installation of a different set of front and rear lamps. The data collection process lasted 3 days.

Table 3. Sample of the testing sequence accounting for the rotation of participants, lamp models, rear lamp patterns, and track target configurations during Experiments 1 and 2

Trial	Run	Direction	Cabin Station	North Station	South Station	Subject Queue	Front Lamps	Target Config.	Rear Lamps	Rear-Lamp Config.
1	1	North	S1	S2	-	S4, S5	LED 1	1	LED 2	Triangle
1	2	South	-	-	S3	S2, S5	LED 1	1	LED 2	Single-Lamp
1	3	North	S2	S4	-	S3, S1	LED 1	1	LED 2	Triangle
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
6	58	South	-	-	S2	S5, S4	X1	2	LED 1	2-Lamp Array
6	59	North	S5	S1	-	S2, S4	X1	2	LED 1	Triangle
6	60	South	-	-	S4	-	X1	2	LED 1	Square

Figure 11. Triple-camera view showing Experiment 1 operations

Figure 12. Sample views during two different Experiment 2 test iterations

4. Analysis and Discussion

This section describes the data analyses performed, the results obtained, and the implications of such results on the differences in visibility aspects between halogen and LED lamps.

4.1 Experiment 1

The purpose of Experiment 1 was to determine the ability of locomotive cab occupants to identify objects on the track and the wayside, while illuminated by different lamp models. As described in Section 3.5.1, the GPS coordinates of each visual target presented to participants during Experiment 1 was recorded a-priori. The time and GPS coordinates corresponding to the participants' detection of visual targets during Experiment 1 were also recorded.

The GPS coordinates (i.e., latitude and longitude) were transformed to decimal degrees to calculate the distance at which participants could identify the visual targets presented during Experiment 1. The distance between two coordinates was calculated using the spherical law of cosines, as shown in Equation 1.

$$D = cos^{-1}\big(sin(\alpha_1)sin(\alpha_2) + cos(\alpha_1)cos(\alpha_2)cos(\Delta\lambda)\big) \cdot R$$ **Equation 1**

where α corresponds to latitude coordinates, λ corresponds to longitude coordinates, *R* corresponds to the radius of the Earth in miles, and *D* corresponds to the distance between coordinates in miles. The spherical law of cosines assumes a perfect sphere; however, the Earth is not a perfect sphere and its radius varies depending on where it is measured (e.g., at the equator or at the pole). For the purposes of this study, the radius of the earth, *R*, was assumed to be 3,437.747 miles, which corresponds to the spherical-Earth approximation (Phillips, 2004). The percentage error of the distances calculated using GPS coordinates averaged 1.7 percent, based on the comparison of calculated distances and those measured using a measuring wheel at the site.

The calculated distances were compared with the video recordings of each participant to ensure that the responses recorded by the experimenter matched the responses given by the participant during each test iteration.

4.1.1 Track Visibility

As described in Section 3.5.1, the visual targets that participants were asked to identify were constructed from polypropylene barrels covered in a low-reflectance fabric. There were five half-barrel targets located on the track, one of which was presented to the participants at an elevated visual angle (Target codes: T and eT, respectively; see Figure 6 and Figure 13). Researchers expected this target would be easier to resolve by participants than the other four track targets, which presented a less prominent profile. Additionally, there were six full-barrel targets located on the wayside at distances of 15 feet and 30 feet from the track centerline.

Thirty test runs (five participants × six lamp models) were planned for data collection pertaining to Experiment 1. For each test run, 12 responses (5 track targets, 6 wayside targets, and 1 EOT device) were expected to be collected from each participant. However, only 26 runs were captured in their entirety. During three test runs, GPS dropouts resulted in a partial loss of data, resulting in those test runs providing only a portion of the expected data points. In addition, one of the test runs could not be completed due to a non-critical medical condition effecting of one of the participants. The data collected was sufficient to complete the required analyses. The data was analyzed using the R programming language.

The first step of the data analysis effort was to graphically plot the distances at which participants detected both elevated and low-profile, on-track targets (eT and T respectively; see Figure 6 and Figure 13). Figure 14 shows a boxplot of the detection distances by type of on-track target and lamp model. The horizontal line through each box corresponds to the median of the sample; the lower bound of each colored box represents the 25th percentile cut-off, and the upper bound represents the 75th percentile cut-off. As expected, the boxplot shows a difference in detection-distance for the two types of on-track targets. The elevated on-track target was detected from a greater distance than the low-profile target. The mean detection distance and standard error for elevated targets were 959.22 ft. and 48.51 ft., while the mean detection distance for low-profile targets was 666.48 ft. (*SE* = 30.48 ft.).

Figure 13. On-Track targets presented during Experiment 1 testing

The greatest mean detection distance for elevated on-track targets was 1,062.28 ft. (*SE* = 140.08 ft.), produced by lamp model LED 4. Similarly, the maximum detection distance for elevated on-track targets was also produced by lamp LED 4 at 1,590.84 ft. The detection distance results for low-profile track targets were also greatest with LED 4 trials, with the mean detection distance at 731.69 ft. (*SE* = 91.95 ft.), and the maximum detection distance was 1,634.75 ft. These metrics served as an inspection step for ensuring that the experimental results were in-line with expectations. As mentioned previously, researchers expected the elevated on-track targets to yield greater detection distances than the low-profile on-track targets.

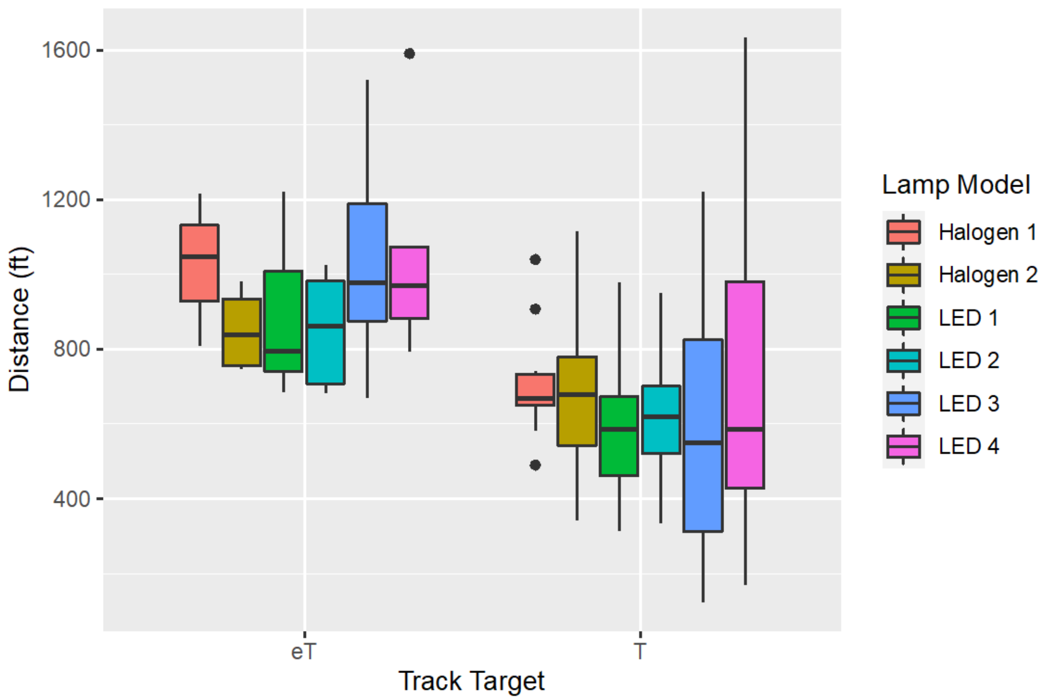

Figure 14. Boxplot of detection distances by type of track target ("eT" refers to the elevated target) and lamp model

Considering both elevated and low-profile on-track targets as a single group revealed specific distribution characteristics between lamp models. As shown in Figure 15, the estimated distributions appeared to peak near the same detection distance. Table 4 shows that the mean detection distances between lamp models were close in magnitude. An ANOVA test (see Appendix C Normality Tests – On-Track Targets) confirmed there was no statistically significant difference in average detection distance between lamp models ($p > 0.507$). However, the distribution of detection distances for lamp models LED 3 and LED 4 showed extended tails, indicating a wider spread of data along the distance axis (see Figure 15). This distribution characteristic of both lamp models is associated with the longer detection distances observed for both track targets (elevated and low-profile). The standard deviation for both lamp models (LED 3 and LED 4) was at least two times greater than the standard deviation for the other lamps. A Levene test showed a significant difference in variance between lamp models ($p < 0.001$), indicating a statistically significant difference between the variances. The difference in variances suggest the potential for lamps LED 3 and LED 4 to provide greater track visibility for occupants of the locomotive cabin.

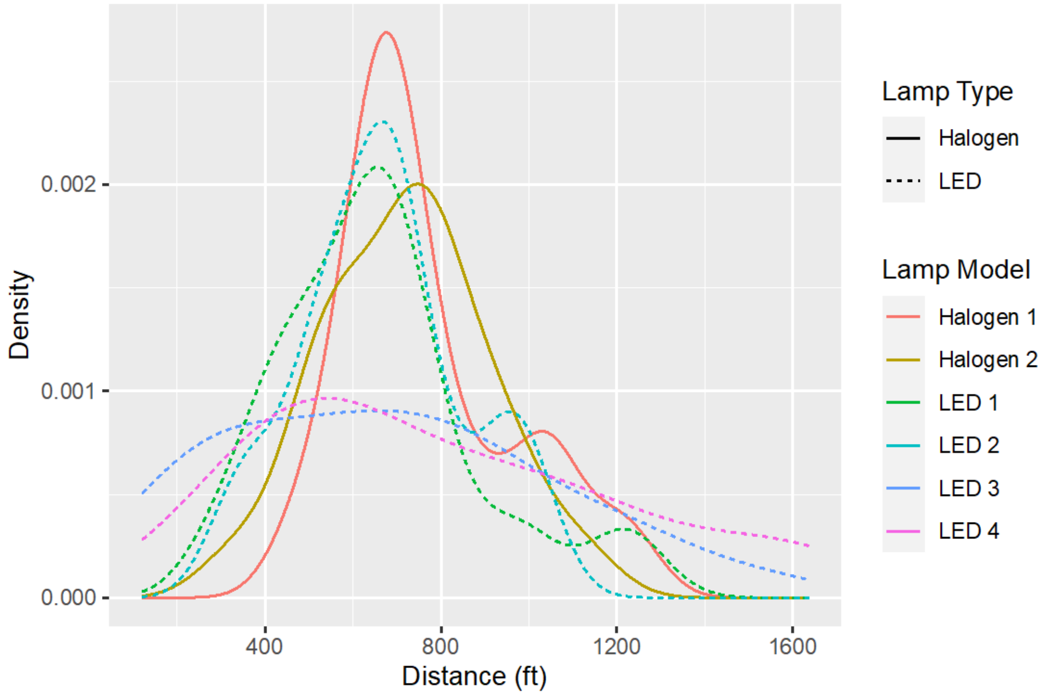

Figure 15. Density plot of all on-track targets by lamp model

Table 4. Mean detection distance, standard deviation, maximum detection distance, and standard error for all on-track targets by lamp model

Lamp Model	Mean (ft.)	*SD* (ft.)	Max (ft.)	*SE* (ft.)
Halogen 1	769.03	199.64	1215.13	51.55
Halogen 2	720.93	187.03	1115.17	41.82
LED 1	659.90	232.93	1220.13	62.25
LED 2	668.08	188.17	1025.84	37.63
LED 3	677.67	370.30	1520.83	74.06
LED 4	797.81	410.41	1634.75	82.08

4.1.2 Track Wayside Visibility

Data related to the visibility of wayside targets being illuminated by the various lamp samples was collected via the same number of test iterations and a similar protocol as was used for on-track targets (see Section 4.1.1).

A total of six full-size-barrel targets were located on the track wayside, three positioned 15 ft. away (Target code: P-15) from the track centerline and three positioned 30 ft. away (Target code: P-30) from the track centerline. Two of these wayside targets, one 15 ft. away (Target code: oP-15) and one 30 ft. away (Target code: oP-30), were partially obscured by either the surrounding vegetation or existing structures along the Precision Test Track (see Figure 16). Researchers expected that these two targets would be more difficult for participants to resolve than those not obscured, resulting in shorter detection distances. The participant responses collected supported this expectation, with the mean detection distance for partially obscured targets at 459.17 ft. (*SE* = 27.24 ft.) and the mean detection distance for non-obscured targets at 623.72 ft. (*SE* = 36.48 ft.).

Figure 16. Wayside targets presented during Experiment 1 testing

Results from the prior Phase I research demonstrated that the luminous intensity of both halogen and LED lamps decreased as the distance from the track centerline increased. Results from Phase II established that the probability of detecting a range of contrast levels decreased significantly when targets were positioned at an angle of 7.5° from the track centerline. Based on these results, researchers expected that in the present experiment, the wayside targets located at a greater lateral distance from the track would result in shorter detection distances. Figure 17 shows a boxplot of the detection distances grouped by lateral distance from the track centerline. The plot shows a downward trend for the mean detection distance moving from 15 ft. to 30 ft. away from the track centerline. Accordingly, the overall mean detection distance for peripheral targets 15 ft. away was 655.63 ft. (*SE* = 39.17 ft.). The greatest mean detection distance for the wayside targets was produced by Halogen 2 at 791.43 ft. (*SE* = 75.91 ft.), while the maximum detection distance was produced by LED 4 at 1,315.45 ft. The overall mean detection distance for wayside targets 30 ft. away from the track centerline was 475.95 ft. (*SE* = 32.42 ft.). Halogen 1 produced the largest mean detection distance of 546.53 ft. (*SE* = 120.23 ft.), and LED 4 produced the maximum detection distance at 1,264.93 ft. The comparison between partially obscured targets and non-obscured targets provided the expected results, with partially obscured targets showing shorter detection distances. In general terms, these exploratory results helped to confirm that the designed experiment produced results as expected.

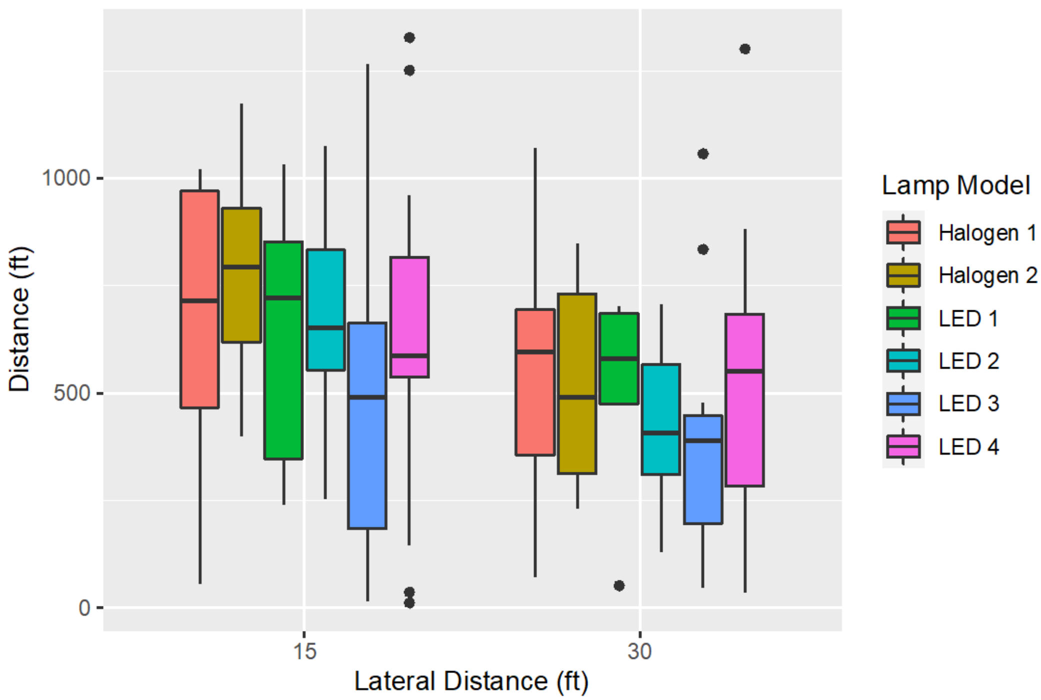

Figure 17. Boxplot of detection distance grouped by lateral distance from the track centerline and lamp model

Grouping all wayside targets together did not reveal definitive differences between lamp models. The density plot in Figure 18 is an estimation of the distribution of detection distances for wayside targets illuminated by each lamp model. The distribution of detection distances did not show a distinctive pattern characteristic to either halogen or LED lamps. The plot shows all lamp model distributions, other than LED 3, peaking at similar detection distances. Table 5 summarizes descriptive statistics for all lamp models. The largest mean detection distance of 660.73 ft. (*SE* = 55.70 ft.) was produced by Halogen 2. However, the two greatest detection distances recorded were produced by LED 3 and LED 4, with a detection distance of 1,266.70 ft. and 1,327.66 ft., respectively. A Kruskal-Wallis test (see Appendix D Normality Tests – Wayside Targets) showed no statistically significant differences in the mean detection distances between lamp models ($p > 0.16$). Unlike the results for on-track targets, a Levene test used to analyze wayside target detection distances showed no statistically significant difference in the variances between lamp models ($p > 0.606$).

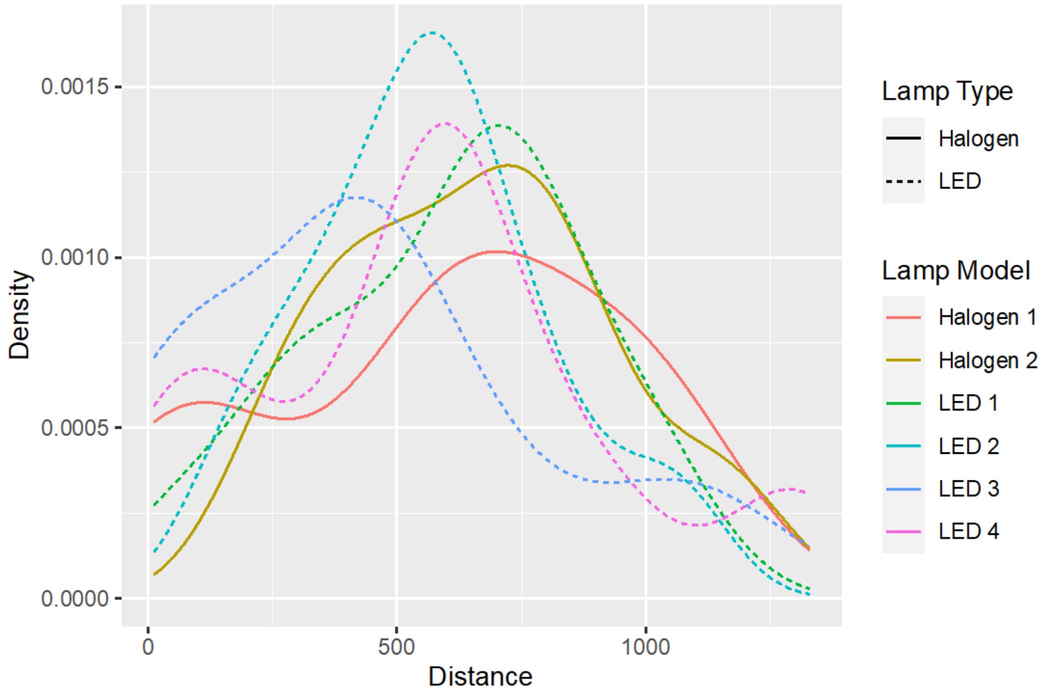

Figure 18. Density plot of wayside target detection distance by lamp model

Table 5. Mean detection distance, standard deviation, maximum detection distance, and standard error for wayside targets by lamp model

Lamp Model	Mean (ft.)	SD (ft.)	Max (ft.)	*SE* (ft.)
Halogen 1	595.24	356.84	1070.42	89.21
Halogen 2	660.73	272.86	1174.07	55.70
LED 1	601.68	280.18	1032.26	74.88
LED 2	565.53	244.27	1075.57	44.60
LED 3	457.08	349.35	1266.70	66.02
LED 4	568.18	361.90	1327.66	67.20

4.1.3 Overall Analysis of Track and Wayside Visibility

A total of 11 non-reflective targets were presented to participants during each run, five on-track and six wayside targets. The physical characteristics of these targets were essentially the same – all were made from polypropylene barrels and covered in black fabric. Analyzing the distribution of detection distances with on-track and wayside targets combined as a single group accentuates the patterns observed in Section 4.1.1 (see Figure 19). The mean detection distances between all lamp models showed comparable magnitude (see Table 6), and the tails of the distributions for LED 3 and LED 4 exhibited a greater probability of detection near the upper bound of the detection distance variable. Similar to the results of Section 4.1.1 (see Appendix E Normality

Tests – Track and Wayside Targets), no statistically significant difference in the mean detection distance was observed ($p > 0.136$), and a statistically significant difference in the distribution variance between lamp models was observed ($p < 0.002$). As shown in Table 6, the largest standard deviations and the maximum detection distances were produced by LED 3 and LED 4 lamps.

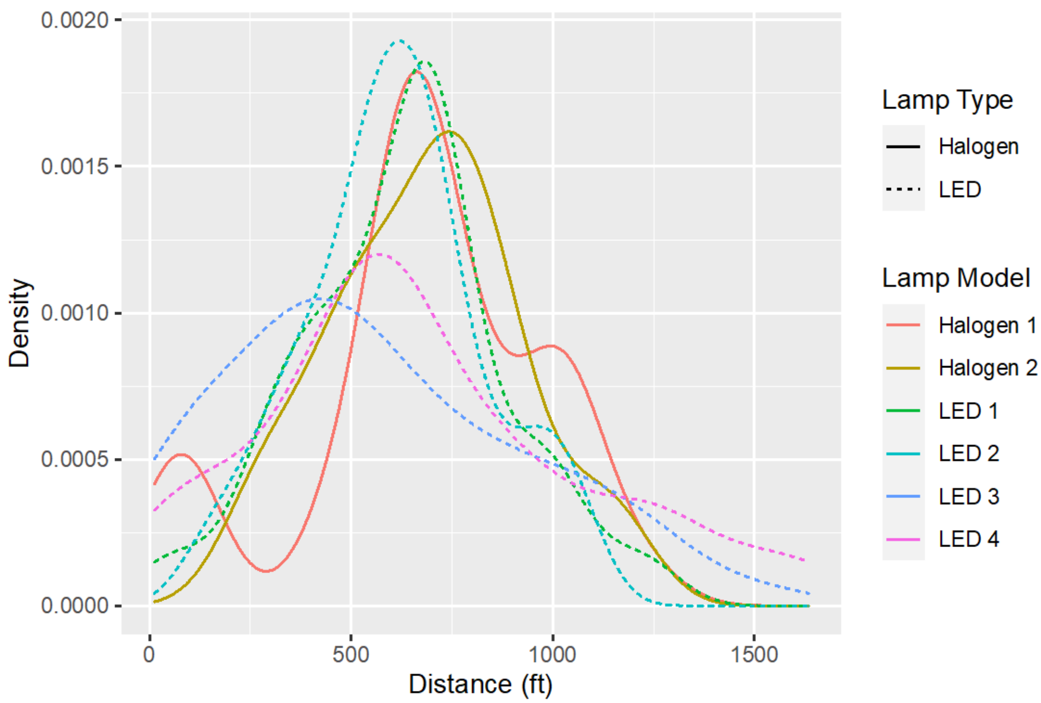

Figure 19. Density plot of on-track and wayside target detection distance by lamp model

Table 6. Mean detection distance, standard deviation, maximum detection distance, and standard error for on-track and wayside targets by lamp model

Lamp Model	Mean (ft.)	SD (ft.)	Max (ft.)	*SE* (ft.)
Halogen 1	679.33	300.10	1215.13	53.90
Halogen 2	688.09	237.06	1174.07	35.74
LED 1	630.79	254.55	1220.13	48.11
LED 2	612.14	224.58	1075.57	30.28
LED 3	561.13	372.85	1520.83	51.22
LED 4	674.49	398.52	1634.75	54.23

This analysis revealed that the most significant differences between lamp models was primarily driven by the detection distances of the on-track targets rather than the wayside targets. This result was likely due to two factors. First, the track in front of the locomotive was the primary focal point for the participant riding inside the cabin. The track dictated the direction and path of movement; therefore, it would be a natural area of focus for the individual riding in the locomotive. Second, the locomotive headlamps were aimed such that the track ahead of the locomotive receives the highest intensity illumination, making observation of the relatively dim wayside more difficult.

Based on these findings, the most likely area to be visible at a significant distance away from the locomotive would naturally be on the track or in the immediate vicinity. Whether an area becomes illuminated depends on the photometric characteristics of the lamps – i.e., the luminous intensity and photometric distribution of the lamp.

Researchers expected that the lamps' visibility aspects exhibited during Phase III would correlate with the luminous intensity and photometric distribution results obtained during Phase I. To expand on this relationship, data from Phase I was analyzed to determine if the photometric distribution of the lamps were correlated with the measured detection distances of visual targets studied in Phase III. Figure 20 shows a bird's eye view of illuminance maps projected at ground level (see Appendix H for a full-resolution version of the figure).

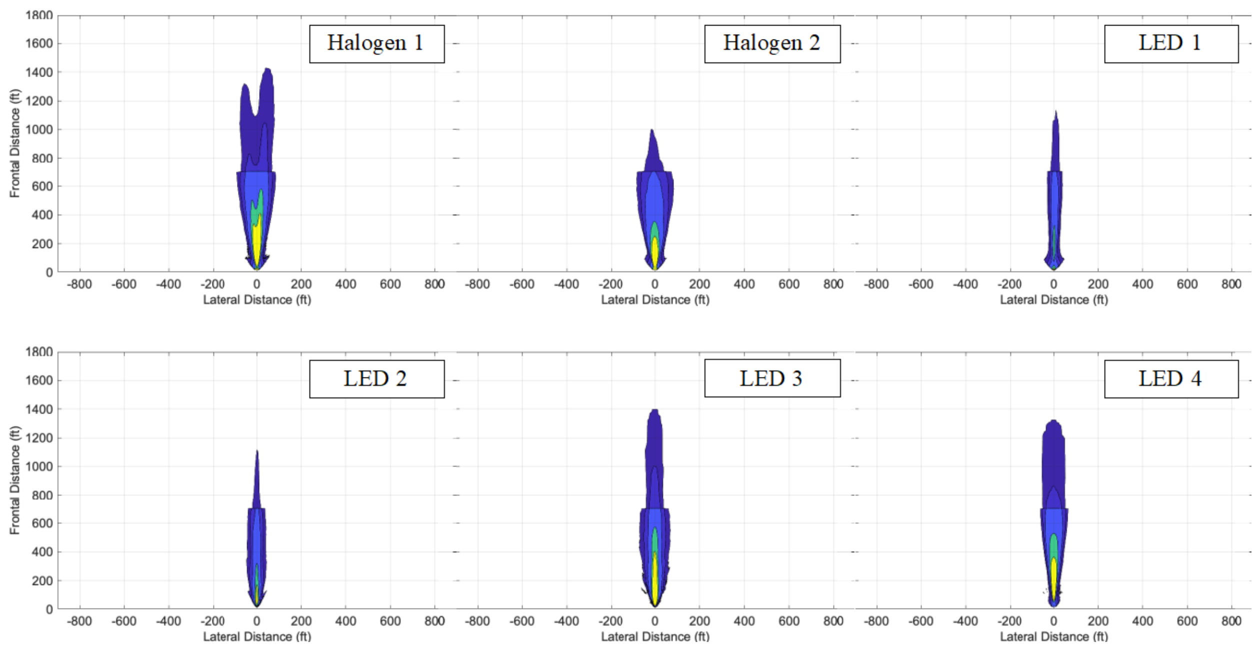

Figure 20. Illuminance maps of lamp samples

These illuminance maps represent the amount of light falling on the ground from a set of lamps (a dual-lamp headlight and two auxiliary lights) installed on a locomotive of similar characteristics as the one used during Phase III testing. In these graphs, the front of the locomotive was assumed to be at the origin of the lateral and frontal distance axes. The outer-most edge of the contour lines in each illuminance map represents a cut-off threshold of 0.3 lux. The comparison of these illuminance maps shows that Halogen 1, LED 3, and LED 4 produced the greatest amount of forward illuminance, reaching 1,400 ft. ahead of the locomotive lamps. Similarly, Figure 19 shows that these three lamp models produced greater densities (or frequencies) at the upper bound of detection distance, consistent with the greater illuminance produced by these lamps.

It is important to reiterate that the design of Experiment 1 included some level of uncertainty related to the participant. During Experiment 1, the participant was asked to constantly scan the track and surrounding areas for dark objects without any expectation regarding their location. Therefore, it is likely that an experiment with non-naïve participants would result in greater detection distances for similar types of visual targets.

4.1.4 Detection of End-of-Train Device

All experimental testing conducted under Phase III revealed that the EOT device was detectable at distances greater than those corresponding to on-track and wayside targets. However, there were seven responses that corresponded to a detection distance of less than 5,000 ft. Based on a video review of all participants' EOT detection, the responses that corresponded to these lower distances were due to the inattention of the participant (i.e., the participant forgot to look for the red-blinking light) rather than a condition created by the locomotive lamps. After removing these outliers, the mean detection distance of the EOT device was 10,289.83 ft. (*SE* = 558.63 ft.), while the maximum detection distance was 12,749.77 ft. Figure 21 shows a density plot of the EOT detection distance based on participant responses. The dashed line corresponds to the mean detection distance. The distribution shows a bimodal behavior (two peaks). This is likely due to the variability between participants and the manner in which they approached the experiment. Some participants tended to look for targets around the track and momentarily forget about the red blinking light on the far horizon.

At the end of each Experiment 1 test run, participants were asked if they could still perceive the blinking red light on the EOT device. In all instances, the participants could distinguish the EOT device at close range, demonstrating the lack of a "washout" effect due to any difference in the illumination produced by LED and halogen lamps.

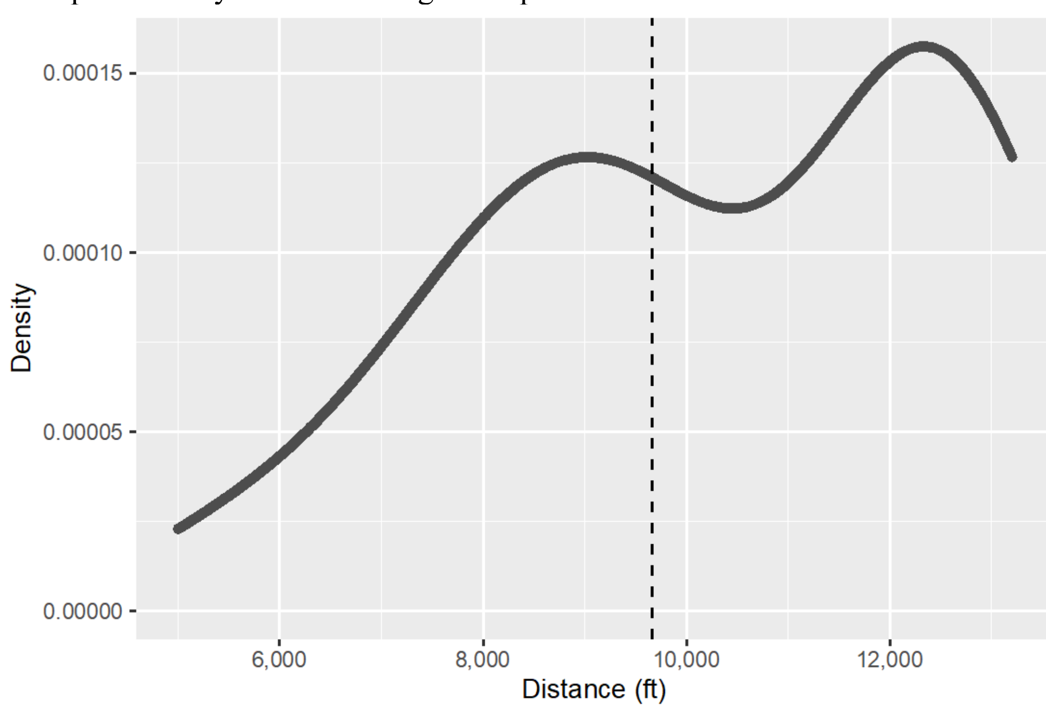

Figure 21. Density plot of detection distance of the EOT device with mean value denoted by the dashed line

4.2 Experiment 2

Experiment 2 was designed to address two objectives. The first was to determine the participants' ability to identify the pattern, or shape, formed by the locomotive lamps, especially the triangular pattern formed by headlights and auxiliary lights on the front of a locomotive. The secondary goal of Experiment 2 was to examine the participants' ability to determine whether the test locomotive was moving.

4.2.1 Locomotive Lamp Pattern

As described in Section 3.6, experimenters at the North and South Stations recorded the verbal responses provided by participants on a GPS system (DEWESoft). This GPS system was identical to the one installed inside the locomotive cabin. All three systems shared the same clock and sampling rate. For each test run, the GPS time and coordinates of the moving locomotive were matched to the GPS time and static coordinates of the corresponding station (i.e., the North or South Station).

For Experiment 2, a total of 58 test runs were completed. During seven of those test runs, GPS dropouts occurred leaving the experimenter with no means of documenting the position associated with participants' responses. A preliminary analysis of the detection distance data revealed several notable outliers. A video review of all documented responses revealed that in six of the test runs, participants correctly guessed the shape of the lamp pattern at an early stage of the test run. These guesses yielded detection distances of greater than 10,000 ft., a highly unlikely human ability. Contrary to these six test runs, a clear behavior pattern exhibited by participants was the constant guessing of the shape of the lamp pattern as the locomotive drew near. For all but six test runs, participants constantly guessed the shape of locomotive lamps until the visual cues were obvious enough such that the shape could be recognized unambiguously. This was an expected outcome for this experiment, namely that a participant would change their response from a single point of light with the locomotive far away to a set of distinct points of light moving apart from each other as the locomotive approached.

Figure 22 shows a sample of four randomly selected test runs where participants exhibited this type of behavior. This figure shows that participants changed their responses as the locomotive approached and would then settle on a consistent response when the locomotive was sufficiently close to provide them with the necessary visual information to determine the correct lamp pattern. The green rectangles in these graphs highlight the correct and final response given by the participants. For these reasons, outliers were removed from the analysis, leaving a total of 45 data points (see Table 7).

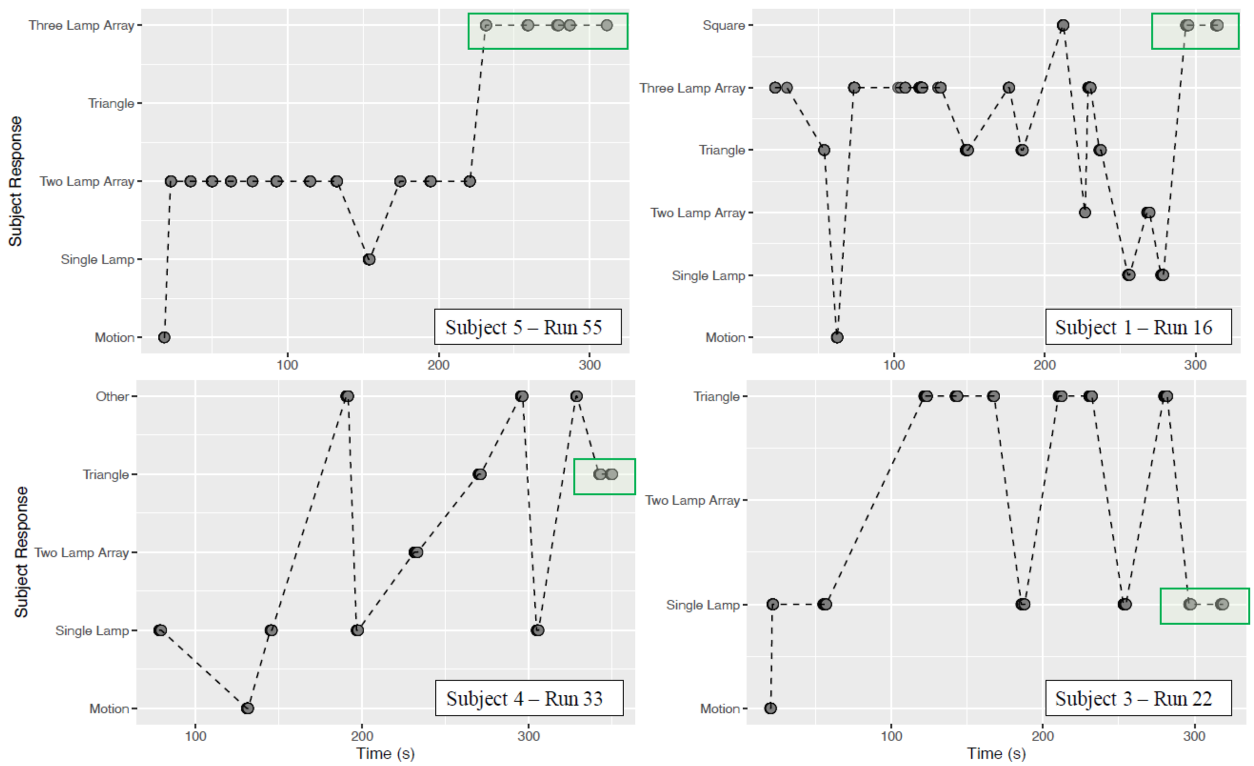

Figure 22. Random sampling of responses given by participants during Experiment 2

Table 7. Mean detection distance by lamp pattern

Lamp Pattern	Mean (ft.)	SD (ft.)	Max (ft.)	*SE* (ft.)
2-lamp line	471.20	202.08	852.69	76.38
3-lamp line	471.21	307.03	1164.10	102.34
Single lamp	376.09	244.99	681.17	109.56
Square	556.42	296.79	794.12	121.16
Triangle	467.63	242.27	890.90	57.10

To calculate detection distances for each lamp pattern, only the final and correct response was used. This was done to remove the effect of participants correctly guessing the lamp pattern early in the test run. As shown in Table 7, the magnitude of the mean detection distances was relatively similar for all lamp patterns. A Kruskal-Wallis test revealed that the lamp pattern presented did not have a significant effect on detection distances ($p > 0.76$; see Appendix G Normality Tests – Lamp Patterns by Shape).

Considering all lamp patterns as a single group, the difference in detection distance between lamp models was examined. Figure 23 shows a boxplot of the detection distance of lamp patterns grouped by lamp model. No distinctive pattern was observed in the differences between lamp models. A slight increase in mean detection distance was observed for LED 2 and LED 3, with LED 3 producing the greatest maximum detection distance of 1,164 ft. (see Table 8). Application of a Kruskal-Wallis test did not reveal any statistically significant differences in detection distances between lamp models ($p > 0.78$). Additionally, a Shapiro-Wilk test revealed there was no significant difference in variance between lamp models ($p > 0.78$; see Appendix F. Normality Tests – Lamp Patterns by Lamp Model).

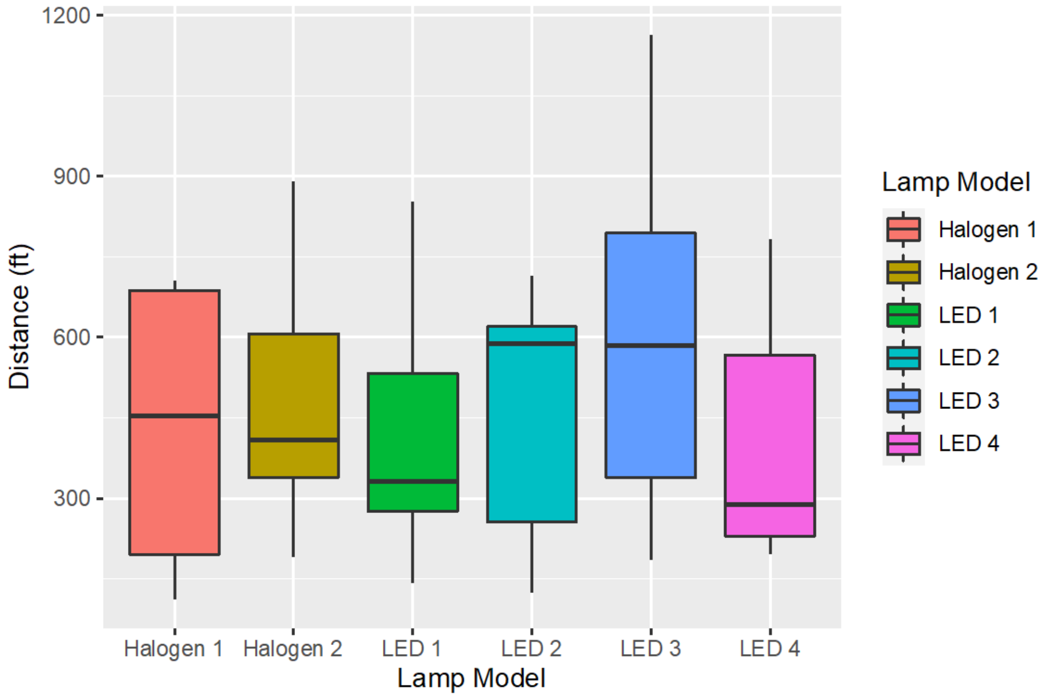

Figure 23. Boxplot of detection distance by lamp model

Considering all lamp models as a single group showed that participants could distinguish any lamp pattern at an average distance of 470.57 ft. (*SE* = 37.38 ft.). This analysis also showed that participants could distinguish any lamp pattern at an average maximum distance of 851.50 ft. However, a density plot of all responses captured during Experiment 2 revealed a bimodal distribution for detection distances. With lamp patterns and lamp models not having a significant effect on detection distances, the remaining factor driving this bimodal distribution was the variability among participants. Figure 25 shows the density distribution of detection distance by Test Subject, with the combined distribution for all subjects depicted by the solid black line. As shown in this figure, the density distributions obtained from Test Subjects 1, 3, and 4 demonstrated a similar peak in likelihood of detection and account for the first and highest peak in the overall density distribution. The density distributions of Test Subjects 2 and 5 peaked at longer detection distances, accounting for the second peak of the overall density distribution.

Table 8. Descriptive statistics for detection distance of lamp pattern by lamp model

Lamp Model	Mean (ft.)	SD (ft.)	Max (ft.)	*SE* (ft.)
Halogen 1	430.27	307.23	705.18	153.62
Halogen 2	473.15	230.87	890.90	81.62
LED 1	426.91	276.31	852.69	123.57
LED 2	462.73	211.96	713.85	70.65
LED 3	588.28	320.95	1164.09	106.98
LED 4	407.57	221.19	782.26	69.95

Although all participants had normal or corrected-to-normal vision, this result suggests that the sample of participants included two groups of distinct visual abilities, one represented by Test Subjects 1, 3, and 4; and a second group represented by Test Subjects 2 and 5. One possible explanation for this bimodal behavior could be the test subjects' age. The group represented by subjects 1, 3, and 4 had an average age of 58.7 years, while the group represented by subjects 2 and 5 had an average age of 47.5 years. Another likely contributor to the bimodal behavior may be the small sample size of participants. It is possible that an increase in the sample size of participants could modify the density distribution of responses to a single mode – i.e., a bell-shape curve. Based on this bimodal distribution, one group of subjects (1, 3, 4) had a mean detection distance of 259.68 ft., which represents the higher detection density mode in the distribution. The second group of subjects (2, 5) had a mean detection distance of 635.76 ft, representing the second, lower mode of the detection density distribution.

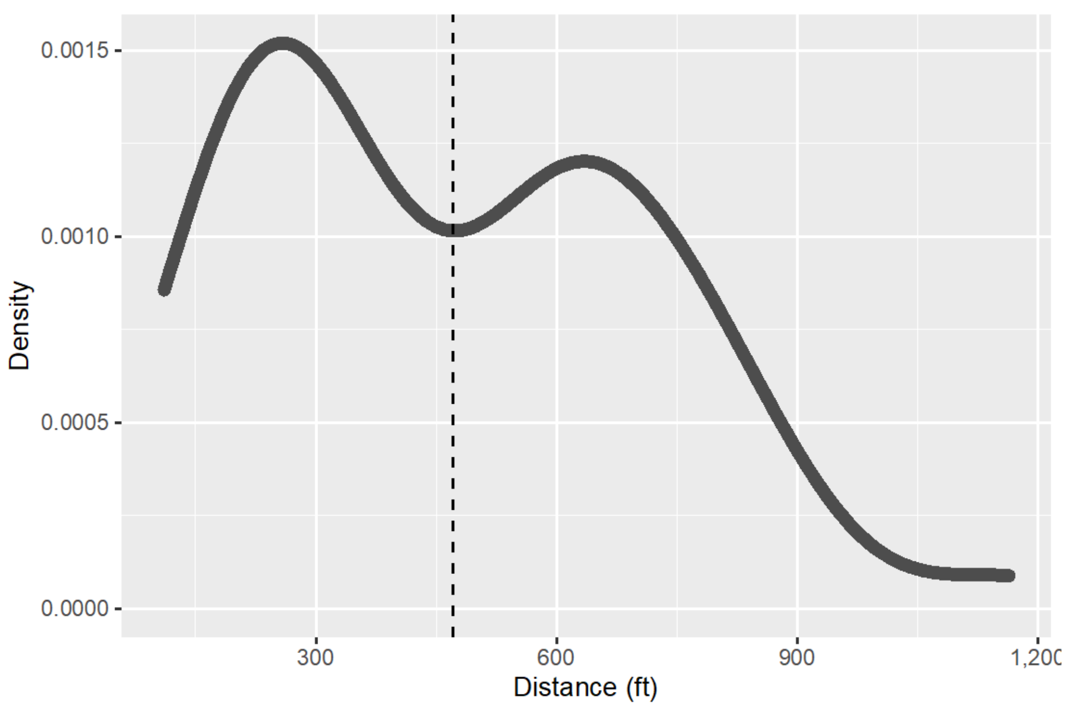

Figure 24. Density plot of detection distance for all lamp patterns

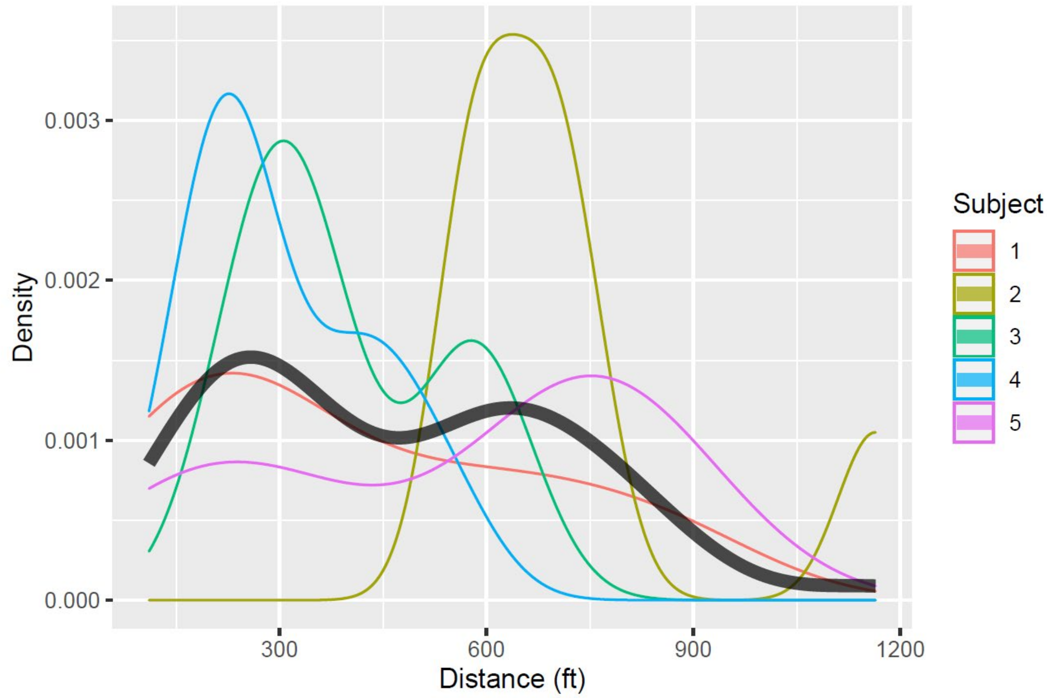

Figure 25. Density plot of detection distance of lamp pattern by test subject

4.2.2 Locomotive Motion

The mean distance at which participants responded they could detect the motion of the locomotive was 13,096.13 ft. (*SE* = 178.37 ft.), a highly unlikely perceptual ability for a person. Figure 26 shows the distribution of detection distances for identification of locomotive movement. A review of the data showed that for eight test runs participants responded that they could detect the movement of the locomotive before the locomotive had started moving. For another 14 test runs, researchers found that participants provided their responses within 1 to 5 seconds after the locomotive had started moving. A review of the video recordings for this experiment revealed that participants' responses were likely influenced by a set of actions that experimenters had to follow before starting Experiment 2, providing unintentional cues to participants regarding the status of the test run, and therefore, the moment when the locomotive started moving. The experimenters' actions included radio communications, triggering data collection equipment, and providing instructions to participants. In addition, the response-guessing behavior identified during analysis of the lamp pattern responses further supports the notion that participants were asserting that the locomotive was in motion at an early stage of the experiment without any explicit visual information. This suggests that participants guessed based on indirect cues rather than waiting for explicit visual cues that would provide them with a definite and unambiguous response.

Based on observations made by the experimenters during Experiment 2, it is likely that the ability to recognize the movement of the locomotive was correlated with the ability to recognize lamp patterns. Based on this correlation, researchers expected that the detection distance for identifying locomotive motion would be similar to the detection distance for recognition of lamp patterns.

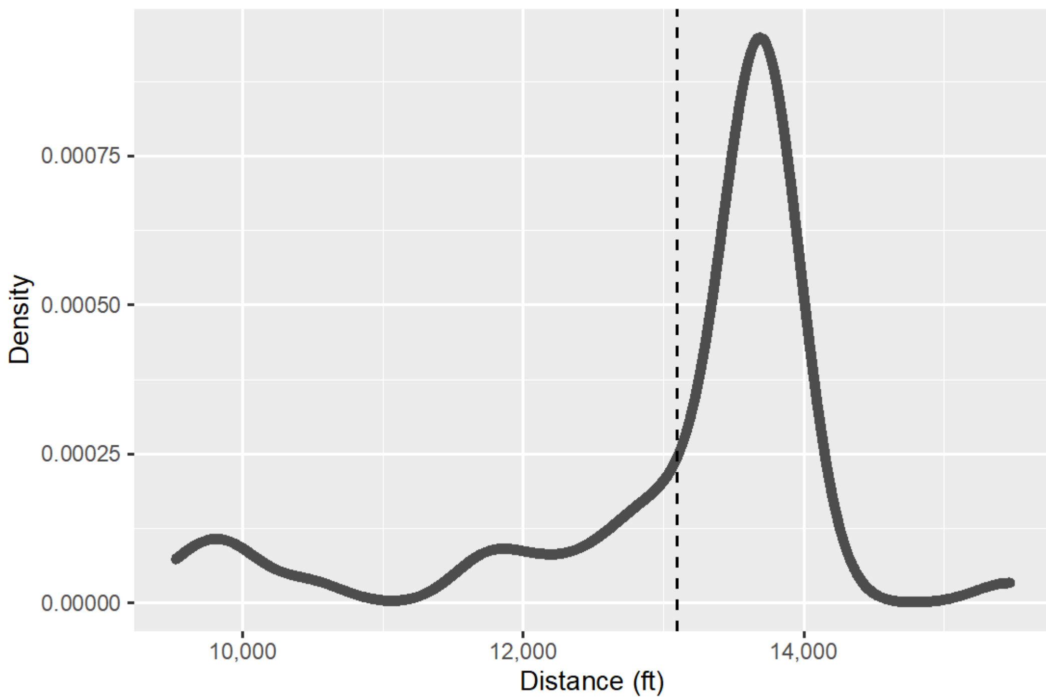

Figure 26. Density plot of calculated detection distance for locomotive motion

5. Conclusion

The purpose of this research was to evaluate visibility aspects related to the lighting conditions produced by LED and halogen lamps when used as headlights and auxiliary lights in a moving locomotive. The visibility aspects were examined from the viewpoint of observers inside the locomotive cabin as well as from the viewpoint of observers outside of and away from an approaching locomotive. Specifically, the present study investigated the ability of observers inside a locomotive cabin to detect objects on the track and along the wayside, and also to detect a flashing EOT device. In addition, this research evaluated the ability of observers to identify the typical triangular pattern formed by the lamps installed on the front of a locomotive and to recognize the motion of an approaching locomotive.

The results of this experiment revealed no statistically significant differences in the cabin occupants' visibility of the track and wayside when illuminated by any of the lamp models tested. However, two of the LED lamp models demonstrated similar response distributions that were distinct from the remaining samples. These two LED lamp models exhibited significantly greater variances in the detection distance of objects located along the track and produced the maximum detection distances recorded during the testing. These results indicate the potential for improved visibility and greater detection distances compared with the other samples that were evaluated.

This study also showed no statistically significant differences among the models tested in terms of detecting the lamp pattern displayed on an approaching locomotive. On average, observers were able to detect any lamp pattern presented at a distance of 470.57 ft. The maximum detection distance for any of the available lamp patterns was measured at 1,164.09 ft. away from the approaching locomotive. Although this study could not produce reliable results for the detection of locomotive motion, the research team expected that a participant's ability to unambiguously identify the motion of an approaching locomotive would be strongly correlated with the distances recorded for the detection of lamp patterns.

The detection distances for track visibility measured in this study resulted from a dynamic visual trial in which observers were required to scan their field of view for various objects ahead of the locomotive. By design, the test protocol included a certain level of uncertainty as to the nature, location, and sequence in which the objects would be presented. An experiment including non-naïve human subjects with full knowledge of the appearance of objects to be detected may result in greater detection distances.

None of the individual experiments included in this study revealed significant differences when comparing the measured detection distances for LED and halogen lamps. Therefore, the team concludes that for the particular tasks examined here, the lighting conditions produced by LED technology lighting would be comparable to the lighting conditions produced by halogen lamps when used in a locomotive application. This supports the conclusion that there is no detectable degradation in visibility if LED lamps are utilized as locomotive headlights and auxiliary lights.

6. References

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Appendix A.
Lamp Samples

Figure 27. LED lamp sample manufactured by J.W. Speaker

Supplier: J.W. Speaker

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

Figure 28. LED lamp sample manufactured by Hydra-Tech International

Supplier: Hydra-Tech International

Model: HYD-LOC001.28K (Hydra-Tech 2800 °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 temperature: 2800 °K

Figure 29. LED lamp sample manufactured by Railhead/Divvali

Supplier: Railhead/Divvali

Model: KE-PAR56 75V LED

Specifications summary:

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

Figure 30. LED lamp sample manufactured by Smart Light Source Co.

Supplier: Smart Light Source Co.

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

Specifications summary:

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

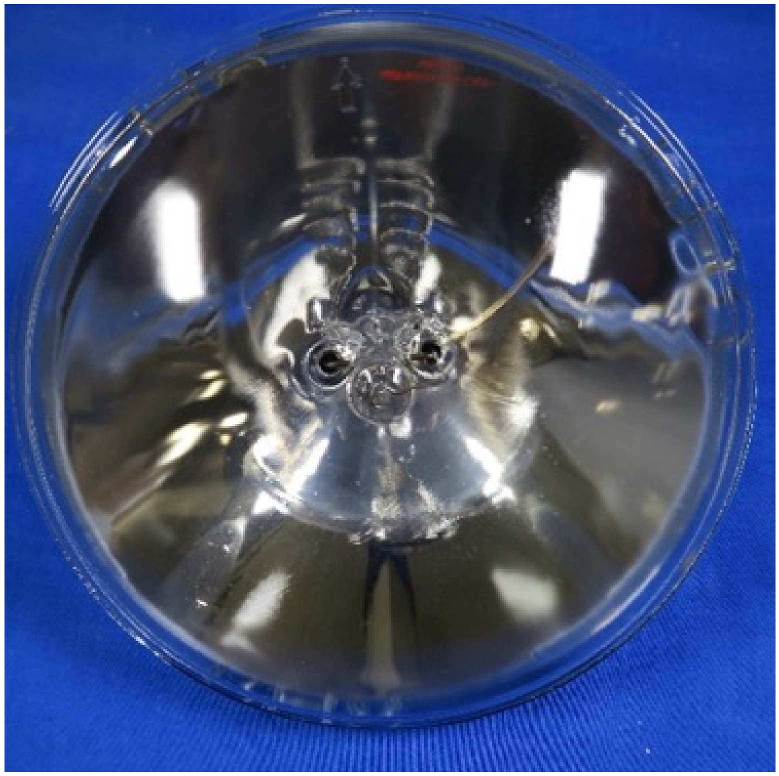

Figure 31. Halogen lamp sample manufactured by AMGLO

Supplier: AMGLO – Halogen Sample

Model: AHQV56-75V350WCS

Specifications summary:

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

Figure 32. Halogen lamp sample manufactured by ePowerRail

Supplier: ePowerRail (SMART Light Source, Co.)

Model: FRA350PAR56-SP

Specifications summary:

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

Appendix B.
Testing Scripts

Testing Script – Experiment 1: Visibility, Evaluations inside the Locomotive

Greet the subject (i.e., thank you for taking part in the study, thank you for volunteering, etc.). Read the instructions to the first subject for his/her very first trial. For subsequent trials, the subject may not need complete instructions, but specific reminders about the task in the experiment can be repeated from the script.

In this part of the testing, you will be riding inside the locomotive cabin. The ride will last for about 5 minutes. Your task during this ride will be to identify three different types of objects. The first type will be located on the train tracks, will be dark and approximately the size of a man. The second type will be of similar size and appearance but will be located to the side of the tracks on either the left or the right; and the third type will be a red blinking light that will appear along the tracks at some point during the ride. I would like for you to verbally announce these objects to me right at the moment that you see them. If you see an object on the track, I would like you to say: **"*Object on the track.*"** If you see an object to the side of the tracks, I would like you to tell me where it is. For instance, if you see it to the left of the track, please say: **"*Object to the left,*"** and vice versa for an object located on the right (i.e., **"*Object to the right*"**). Similarly, please say: **"*blinking light,*"** the very moment that you see the red blinking light.

Any questions? Ready?

Testing Script – Experiment 2: Light Patterns, Evaluations Outside the Locomotive.

For this part of the testing, I will ask you to pay attention to the locomotive that is about 2 miles down the track. At some point, the locomotive's lights will turn on and it will eventually start moving, I will then instruct you to begin the experiment. Your will have two tasks during this experiment. Your first task is to identify the shape or pattern formed by the lights on the locomotive. Your perception of the shape may change while the locomotive is in motion. For instance, with the locomotive far away, you may only see a single point of light. As the experiment progresses and the locomotive gets closer, you may see that what you first identified as a single point of light may be multiple lights describing a different shape. The different shapes or patterns that the points of light may be in, include a triangle, a square, a line, a single point, or other. I would like you to tell me how your perception of the number of lights and their shape changes throughout the experiment. For instance, if you first see a single light point say: **"One light or single point"**; if the shape changes as the locomotive gets closer, inform me of the number of lights and shape that you recognize, For instance, you may say: **"Three lights in a triangle shape."** Please tell me each time your perception of the light or lights changes throughout the entire test, and I will continue to ask questions about your perception of the points of light.

As you pay attention to these lights, your second task will be to identify the moment at which you can clearly recognize that the locomotive is in motion. To report your answer simply tell me when you can see it moving, you may say something like: ***"Locomotive is moving."***

Any questions? Ready?
(Check that all is set with team over radio, and get ready for the experiment…)

Appendix C.
Normality Tests – On-Track Targets

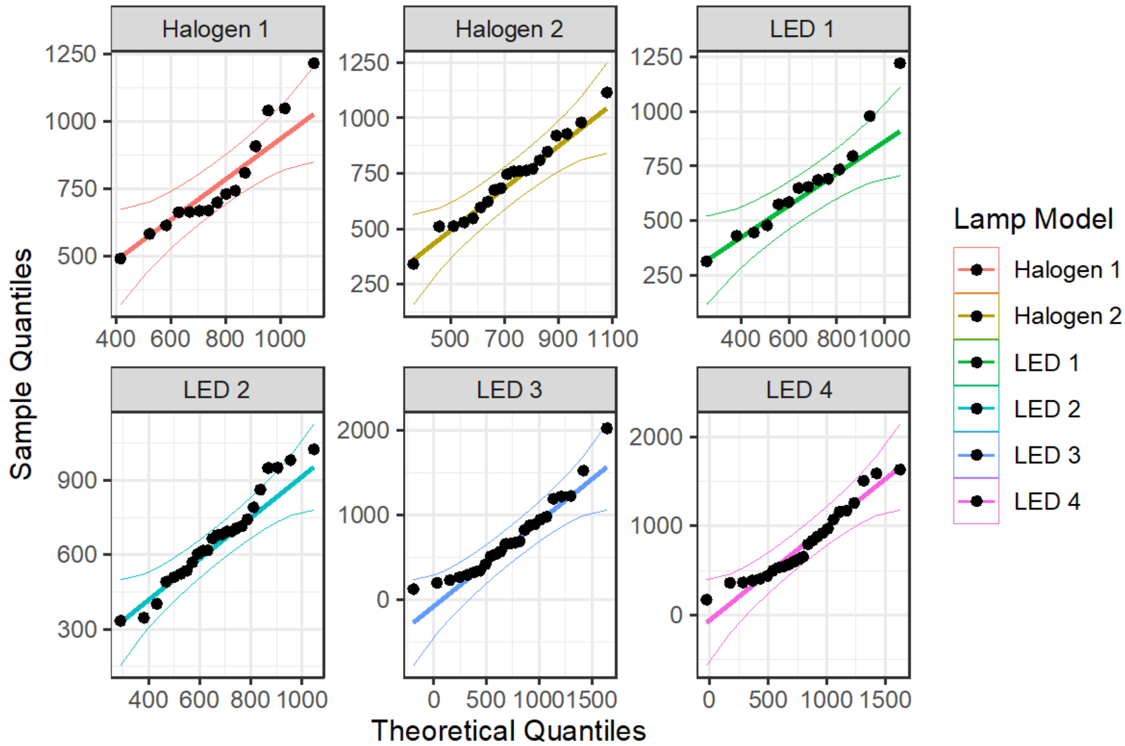

Figure 33. Q-Q plots for on-track targets by lamp model

Table 9. Table of *p*-values for the Shapiro-Wilk test for normality of on-track targets

Lamp Model	W	p-value
Halogen 1	0.900	0.095
Halogen 2	0.985	0.981
LED 1	0.934	0.352
LED 2	0.966	0.542
LED 3	0.961	0.445
LED 4	0.934	0.109

Appendix D.
Normality Tests – Wayside Targets

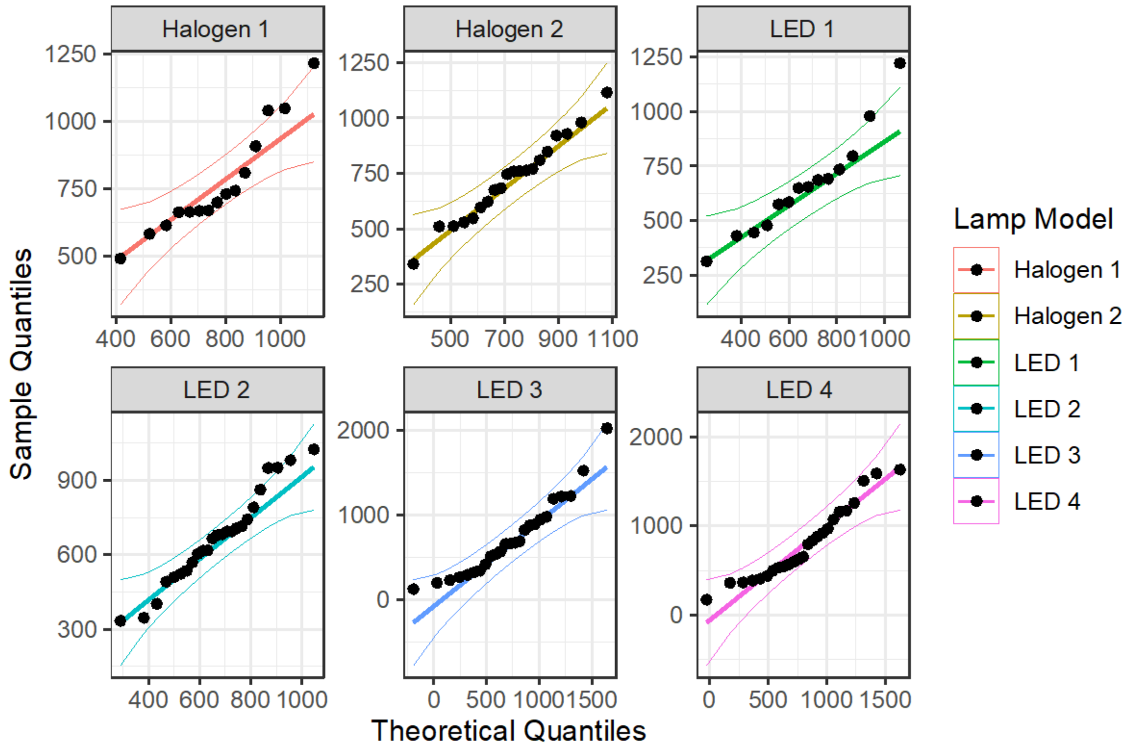

Figure 34. Q-Q plots for wayside targets by lamp model

Table 10. Table of *p*-values for the Shapiro-Wilk test for normality of wayside targets

Lamp Model	W	p-value
Halogen 1	0.898	0.0746
Halogen 2	0.960	0.433
LED 1	0.961	0.742
LED 2	0.975	0.668
LED 3	0.912	0.023
LED 4	0.940	0.103

Appendix E.
Normality Tests – Track and Wayside Targets

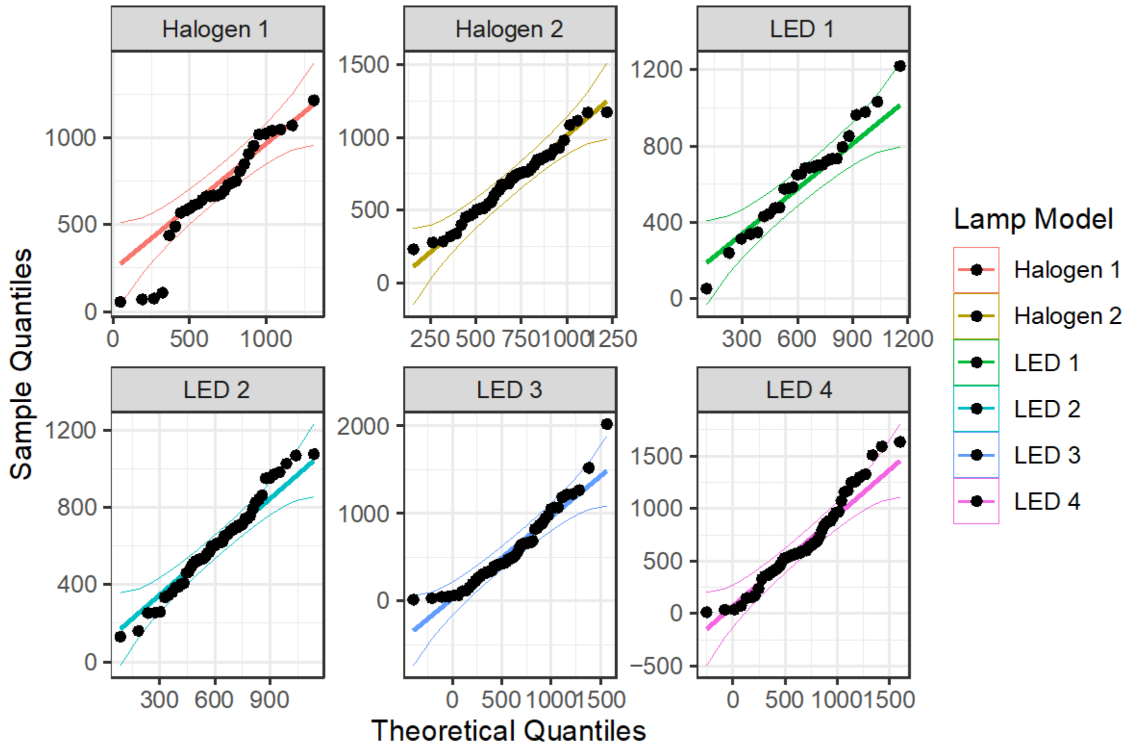

Figure 35. Q-Q plots for on-track and wayside targets by lamp model

Table 11. Table of *p*-values for the Shapiro-Wilk test for normality of on-track and wayside targets

Lamp Model	W	p-value
Halogen 1	0.923	0.028
Halogen 2	0.980	0.650
LED 1	0.983	0.917
LED 2	0.984	0.649
LED 3	0.929	0.004
LED 4	0.958	0.054

Appendix F.
Normality Tests – Lamp Patterns by Lamp Model

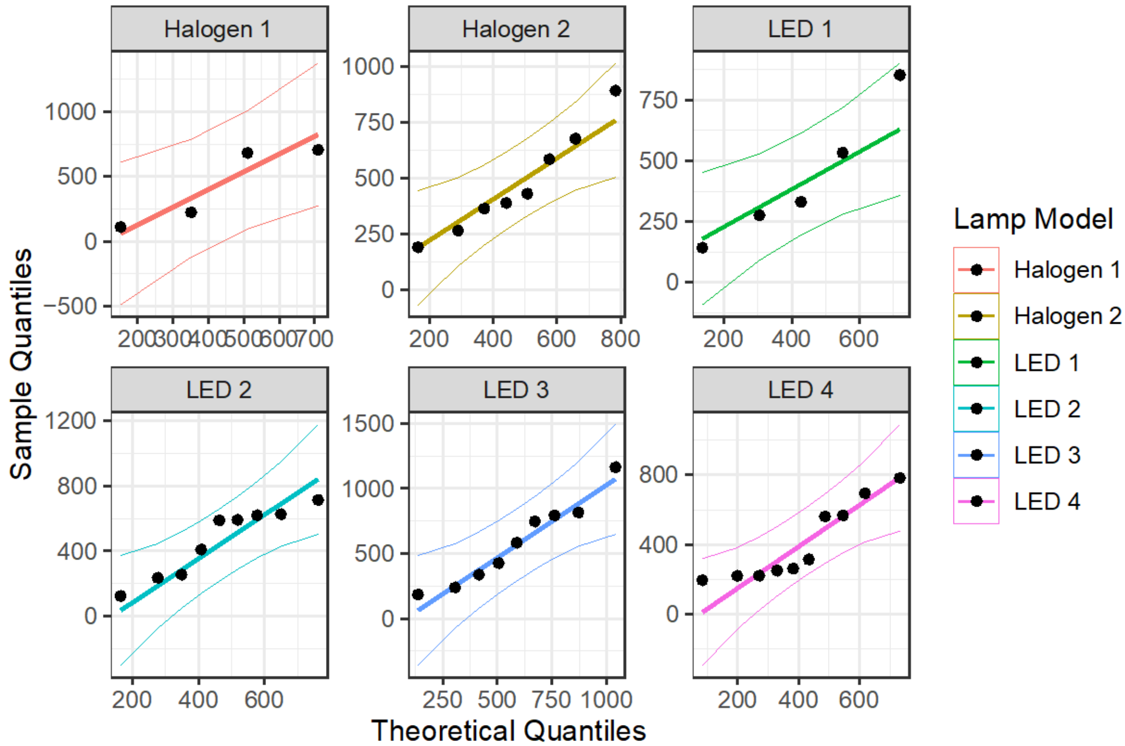

Figure 36. Q-Q plots for lamp patterns by lamp model

Table 12. Table of *p*-values for the Shapiro-Wilk test for normality of lamp patterns by lamp model

Lamp Model	W	p-value
Halogen 1	0.829	0.166
Halogen 2	0.950	0.714
LED 1	0.933	0.620
LED 2	0.884	0.173
LED 3	0.948	0.673
LED 4	0.836	0.0391

Appendix G.
Normality Tests – Lamp Patterns by Shape

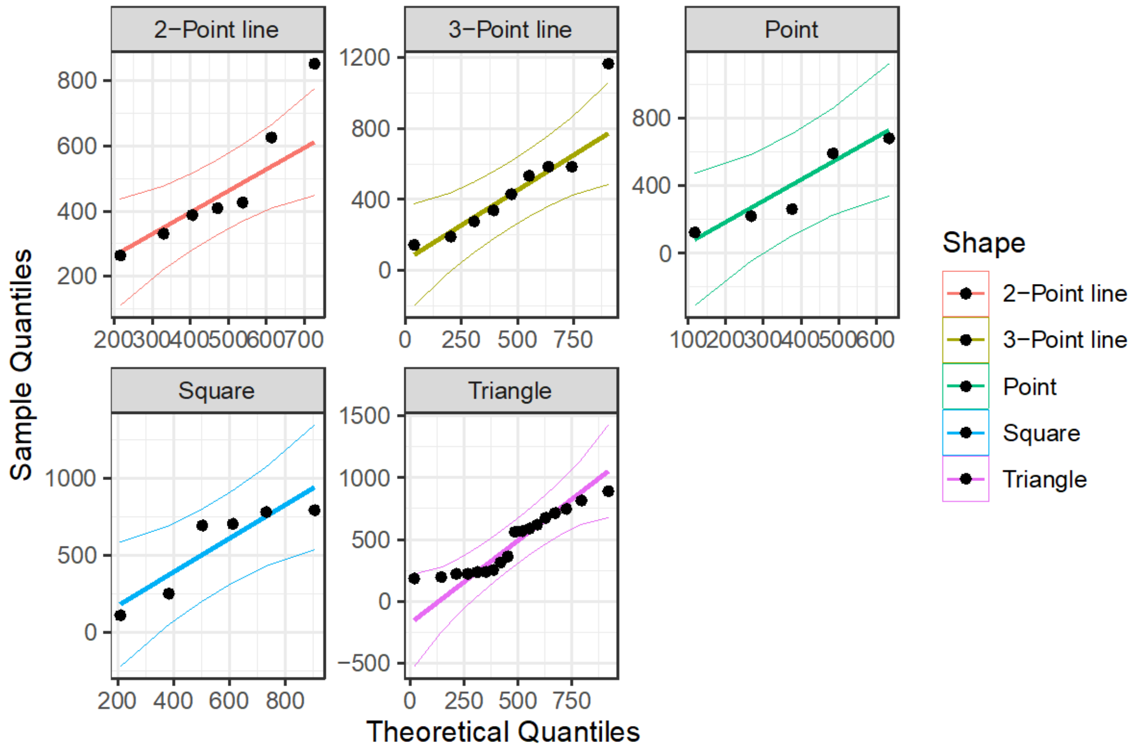

Figure 37. Q-Q plots for lamp patterns by shape

Table 13. Table of *p*-values for the Shapiro-Wilk test for normality of lamp patterns by shape

Lamp Model	W	p-value
2-lamp array	0.871	0.188
3-lamp array	0.867	0.115
Single lamp	0.881	0.314
Square	0.789	0.0463
Triangle	0.883	0.0299

Appendix H.
Illuminance Maps of Lamp Samples

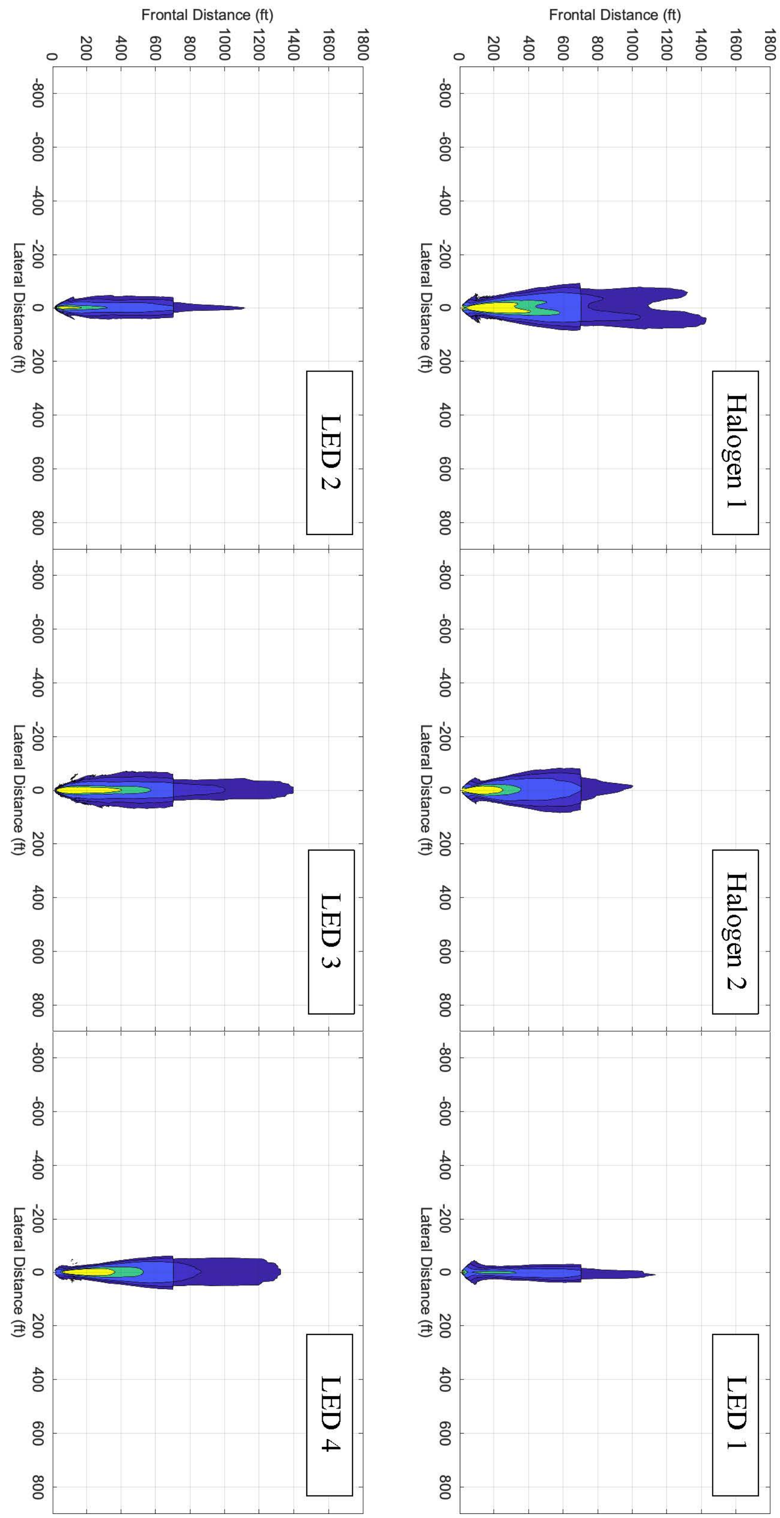

Figure 38. A bird's eye view of lamp illuminance projected at ground level

Abbreviations and Acronyms

Abbreviation	Explanation
AC	Alternating Current
CFR	Code of Federal Regulations
DC	Direct Current
EOT	End-of-Train
ESi	Engineering Systems, Inc.
FRA	Federal Railroad Administration
GPS	Global Positioning System
IMU	Inertial Measurement Unit
LED	Light-Emitting Diode
Q-Q	Quantile-Quantile
SD	Standard Deviation
SE	Standard Error
TAG	Technical Advisory Committee
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc.