



# **EVALUATION OF GUARDRAIL EMBEDDED LIGHTING SYSTEM IN TRINIDAD, COLORADO**

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**COLORADO DEPARTMENT OF TRANSPORTATION**  
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16. Abstract This report provides information on the design considerations of the embedded highway lighting design on Interstate-25 in Trinidad, Colorado, in terms of visibility. The information is based on visibility characterizations of small targets using luminance, illuminance, and contrast calculations as well as participant input on the detectability of small targets. Experimental conditions included two different aim angles of the lighting design (forward and cross) as well as two small target colors (red and blue). When compared to the small target detection distances produced by conventional overhead lighting systems in previous studies, the research determined that the small target visibility distances of the embedded lighting design to be shorter by approximately 50%. Adjustments to the spacing, aim, and breadth of the lighting design are recommended for future research considerations.  Implementation The results of this research indicate the lighting design is an alternative; however, additional considerations to the beam angle, beam width, beam height, and spacing may improve the implementation of the system.			
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# **EVALUATION OF GUARDRAIL EMBEDDED LIGHTING SYSTEM IN TRINIDAD, COLORADO**

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## **EXECUTIVE SUMMARY**

The City of Trinidad in southeast Colorado is located alongside an overpass for Interstate-25 that contains multiple on- and off-ramps in need of sufficient illumination. City planners wanted to avoid light spilling from the overpass onto the town and opted for a unique lighting design that involved embedding light-emitting diode (LED) lighting into the concrete barriers of the overpass. This design limited the amount of light spilling from the overpass by keeping the light concentrated to the roadway. This unique design is the only one of its kind known and no analysis of visibility had ever been conducted prior to this research.

### **Project Description**

The primary intent of this project was to determine how well the lighting system on the Trinidad overpass lent itself to visibility. The project used a specially equipped vehicle for performing tests of Small Target Visibility (STV), which capture data on the ability of participants to detect small colored objects. This method is common for determining the amount of visibility produced by a lighting system and can be directly correlated with safety for both drivers and pedestrians. The lighting system was also characterized in terms of luminance and illuminance to better understand the areas of the roadway that the system might favor or neglect. A vehicle outfitted with an in-house light measurement system was used to collect information about the lighting system and how it interacted with passing vehicles and stationary targets.

The project consisted of two areas of interest. The southbound portion of I-25 contained embedded lights aimed down the forward roadway, and the northbound lanes contained embedded lights aimed directly across the roadway.

### **Subjective Survey**

A questionnaire was administered to the participants by the research team. After participants traveled through the test area and detected the targets, they were asked questions about the impact of glare and if they noticed a difference between either travel lane in terms of comfort and visibility.

## **Objective Testing**

Thirty-six people participated in the target detection portion of the study. As the research vehicle traveled through the test area, participants inside the vehicle responded to the detection of a target on the shoulder of the roadway by pressing a button. These instances were flagged in the data for later analysis to accurately calculate the detection distance.

## **Research Results**

The results of this assessment indicate that the embedded lighting design does not perform comparably to conventional overhead roadway lighting systems. Previous research conducted by this same team has found overhead LED roadway lighting systems to promote detection distances of small targets from as far as 233 feet. The embedded lighting system in Trinidad achieved average detection distances of 95 and 86 feet for cross- and forward-aimed lights respectively.

In addition, there was no statistically significant difference found between the two aims of the embedded system (95 and 86 feet). These short distances suggest vehicle headlamps, not the lighting system, were mostly responsible for the detection of the small targets. Because of the narrow focal point of the lighting system, the probability that an object or potential hazard is being illuminated sufficiently by the lighting system to be seen from further away is limited.

The survey results showed that in general participants are neutral in regard to the lighting system. They did not indicate a preference for the aim of the system and did not find it overwhelmingly glaring. Comments made by participants in the questionnaires did illuminate issues such as the lighting system causing confusion when merging onto the highway and the existence of a strobe effect taking place inside the vehicle as their vehicles passed.

The research team also noticed that snow becomes compacted around the fixtures inside the barrier, which could result in limited light reaching the roadway during snowfall.

The research team encourages further investigations of the lighting system. Namely, spacing and aiming adjustments to the light system could vastly improve upon the system and improve visibility while decreasing the strobe effect and other distracting characteristics. The following bullet points highlight key adjustments that could potentially improve the lighting system in terms of visibility.

- Adjust the color temperature.
  - Could mitigate confusion with headlamps for merging traffic
  - May alter the contrast of potential hazards, thus increasing visibility on the concrete overpass
- Adjust the spacing.
  - Could also mitigate confusion with headlamps for merging traffic
- Adjust aiming and orientation.
  - Other angles could relieve distraction and discomfort experienced by some
  - Vertical adjustments may mitigate strobe effects
- Increase beam width.
  - Current system has narrow focal point
  - Could increase uniformity of roadway lighting

## **Implementation Statement**

The results of this research indicate the lighting design is an alternative; however, additional considerations of the beam angle, beam width, beam height, and spacing may improve the implementation of the system.



# TABLE OF CONTENTS

INTRODUCTION .....	1
BACKGROUND .....	2
Lighting System .....	2
Vision .....	3
Prior Work .....	3
Lighting Impact.....	3
EXPERIMENTAL METHODOLOGY .....	6
Equipment .....	6
Participants.....	7
Experimental Design.....	8
Route .....	8
Experimental Tasks.....	11
Greeting Participants.....	11
Vehicle Familiarization.....	11
Data Collection .....	12
Experimental Procedure.....	12
Questionnaire .....	14
Limitations .....	14
Data Analysis .....	15
RESULTS .....	16
Lighting Characterization and Evaluation .....	16
Vehicle Side Characterization – Mean Illuminance .....	16
Glare.....	19
Vehicle Side Characterization – Vertical Assessment.....	21

Luminance and Contrast Characterization.....	22
Illuminance Characterization.....	32
Target Detection.....	33
Subjective Assessment.....	38
DISCUSSION.....	41
CONCLUSION.....	45
REFERENCES .....	47

## LIST OF FIGURES

Figure 1: Embedded lighting system light orientation .....	2
Figure 2: Overview of lighted route portion. ....	10
Figure 3: Individual input button. ....	12
Figure 4: Detection targets used within test area. ....	13
Figure 5: Target placement. ....	14
Figure 6: Light meter orientation, vehicle side. ....	16
Figure 7: Northbound, driver’s side illuminance. ....	17
Figure 8: Southbound, driver’s side illuminance. ....	18
Figure 9: Northbound, passenger’s side illuminance. ....	18
Figure 10: Southbound, passenger’s side illuminance. ....	19
Figure 11: Glare meter inside front windshield. ....	19
Figure 12: Vertical assessment, northbound, left lane, driver’s side. ....	21
Figure 13: Vertical illuminance of vehicle side. ....	22
Figure 14: Target placement (southbound example). ....	23
Figure 15: Mean luminance by direction and lane. ....	24
Figure 16: Mean luminance by direction and position. ....	25
Figure 17: Positive (left) and negative (right) contrast. ....	26
Figure 18: Mean Weber Contrast by direction and lane. ....	26
Figure 19: Mean Weber Contrast by direction and position. ....	28
Figure 20: Mean Weber Contrast by lane and position. ....	29
Figure 21: Box plot of left lane, northbound contrast by target position. ....	30
Figure 22: Box Plot of left lane, southbound contrast by target position. ....	30
Figure 23: Box plot of right lane, northbound contrast by target position. ....	31
Figure 24: Box plot of right lane, southbound contrast by target position. ....	31
Figure 25: Mean detection distance by target. ....	35
Figure 26: Color detection distance and Weber Contrast. ....	36
Figure 27: Mean detection distance by direction. ....	37
Figure 28: Mean Weber Contrast by target. ....	38
Figure 29: XY chromatic diagram (source: CIE). <sup>(6)</sup> .....	43
Figure 30: Embedded lighting system and snow. ....	44

## LIST OF TABLES

Table A: Distance Between Targets .....	11
Table B: Glare (Lux).....	20
Table C: Target Illuminance Facing Travel Lane (Lux).....	32
Table D: Target Illuminance Facing Embedded Luminaire (Lux) .....	32
Table E: Target Descriptions for the Participant Testing .....	33
Table F: Questionnaire Responses.....	39
Table G: Detection Distances of Luminaires from Similar Evaluations .....	41

## INTRODUCTION

Trinidad is a rural town in southeast Colorado with the unique predicament of being centered beneath an interstate overpass, or viaduct. With light trespass in mind, civic leaders and residents preferred to not have overhead luminaires placed along the overpass. Instead, a solution was offered to place a light-emitting diode (LED) lighting system inside concrete barriers along the overpass that would predominantly light the roadway and not spill to the town below.

The lighting system uses vertically mounted LED strips. The strips were initially intended to project light in the direction of travel of the driver; however, complaints from passers-by influenced a change. The Colorado Department of Transportation (CDOT) tweaked the angle of the lights in the northbound lanes to project directly across the roadway. Each of these light orientations was available for comparison in the study.

This implementation of roadway lighting is unique, and its effectiveness compared with traditional overhead lighting systems is unknown. This test involved an experiment conducted with participants from the Trinidad general public and a local college. These experiments will be compared with similar experiments performed using traditional lighting systems.

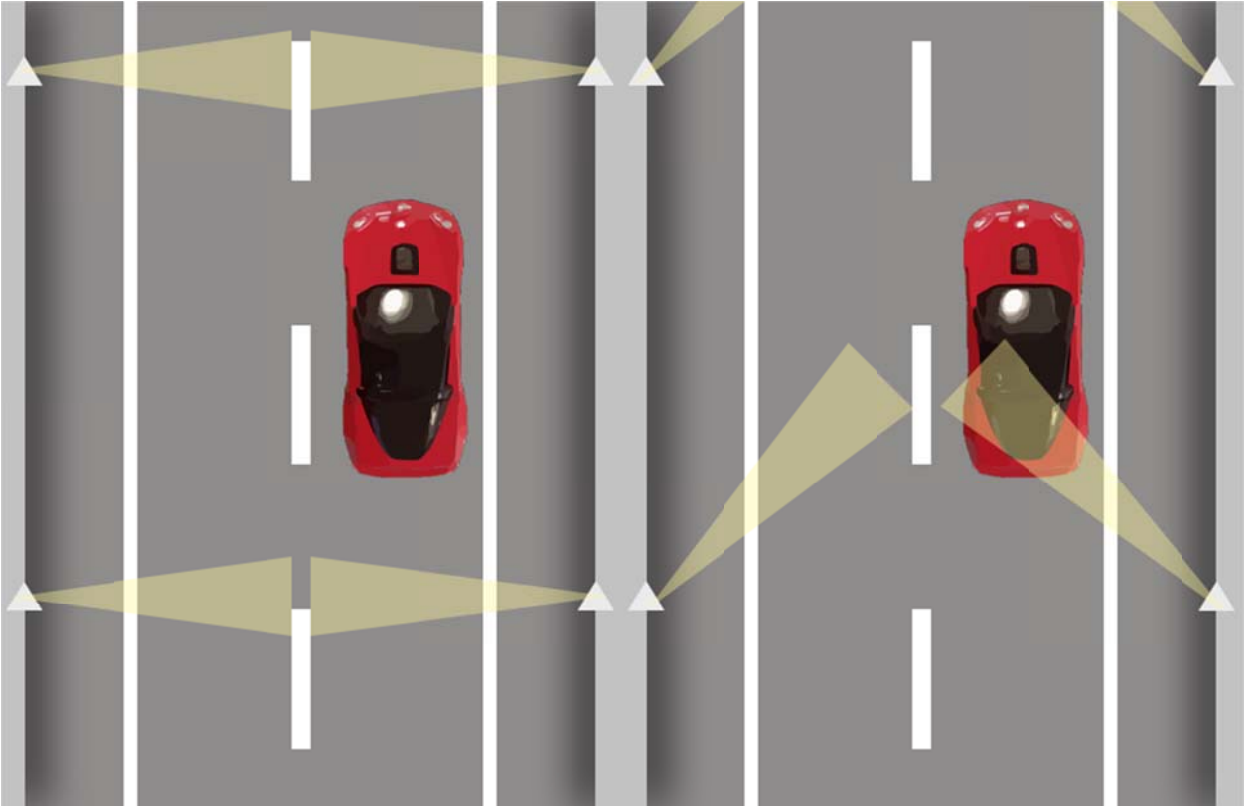
The objectives of the project are:

1. Compare the visibility of small targets on the Trinidad viaduct with conventional lighting systems evaluated in previous studies.
2. Compare the visibility of small targets for each lighting orientation (north- versus southbound lanes).
3. Gain feedback from participants about each lighting orientation.
4. Identify critical characteristics of the novel lighting design and evaluate efficiency.

# BACKGROUND

## Lighting System

The lighting system in Trinidad, Colorado, was originally designed to have the embedded luminaires project light forward in the direction of travel. Due to complaints from citizens about distraction and discomfort when traversing the overpass, CDOT experimentally altered one direction of the lights to project directly across the roadway. Figure 1 illustrates the two different orientations. These images are not to scale and do not represent an accurate lighting projection but serve to represent the concept of the lighting installation. The left image shows the concept of the cross-road lighting orientation and the right image shows the forward, approximately 45 degree, orientation.



**Figure 1: Embedded lighting system light orientation (left: cross-road orientation, right: forward facing).**

## **Vision**

During daylight hours, the human visual system operates on a photopic level, thus allowing for color perception using the cone receptors of the eye. When light conditions are extremely low, the visual system operates on a scotopic level that utilizes the rod receptors.

Mesopic vision is a combination of both photopic and scotopic systems. A mixture of both rods and cones are utilized. When driving at night under roadway lighting, or even with just vehicle headlamps, the mesopic visual system is operating. Models for photopic and scotopic vision exist; however, mesopic vision has been difficult to predict, perhaps partially due to the multiple variations in artificial lighting.

## **Prior Work**

The Virginia Tech Transportation Institute (VTTI) has performed similar analyses of LED roadway lighting recently. The locations include Anchorage, San Diego, San Jose, Seattle, and Honolulu. In these studies, various forms of conventional roadway lighting, such as high-pressure sodium (HPS) or low-pressure sodium (LPS), were evaluated alongside LED lighting. Various LED luminaires included different cut-off types as well as varying color temperatures. The evaluations included subjective analyses by Clanton & Associates and objective analyses coordinated by VTTI. Both objective and subjective analyses in Trinidad, Colorado, were performed by VTTI.

## **Lighting Impact**

A previous experiment conducted on the Virginia Smart Road found that small target detection occurred predominantly within the reach of vehicle headlamps. The vehicle headlamps in the study illuminated a small vertical target from as far as 300 feet. Detections of the small target with only vehicle headlamps and no overhead lighting resulted in a detection average of 170 feet and a maximum of 272 feet (*standard deviation [sd] = 40.9, standard error [se] = 8.7*). Detections of the same small target with headlamps and fully powered overhead LED lighting resulted in an average detection distance of 208 feet and a maximum of 476 feet (*SD = 143.3, SE = 31.3*). The variance in detection distance for the latter scenario could be due in part to the use

of a gray colored target. The contrast of the target fluctuated as the vehicle neared, causing it to occasionally blend in with the pavement background. The report for the Virginia Smart Road experiment is currently under review.

An assessment of street lighting in San Diego found that an LED luminaire with an average illuminance of less than 2 lux outperformed other luminaire types, including HPS and induction, as well as other LED luminaires of greater illuminance in terms of detection distance. The detection distance for this LED luminaire was approximately 134 feet. Another LED luminaire with an average illuminance of approximately 6 lux provided an average detection distance of only 105 feet. These findings suggest two things: 1) a dimmed LED luminaire can provide comparable or even further detections than brighter alternatives; and 2) because a bulk of the detections occurred within 300 feet, headlamps are still a critical force in small target detection. The detection distances between the best performing LED and a conventional HPS system used in the San Diego study were nearly even; however, the HPS luminaire consumed more energy.<sup>(1)</sup> It should be noted that the purpose of the study performed and discussed in this report was to evaluate only the safety of the use of LEDs in Trinidad and costs were not a part of the study.

A second assessment in Anchorage, Alaska, found similarities in the performances of overhead LEDs with different color temperatures. The three LEDs compared provided detection distances between 147 and 170 feet and consisted of 4300K, 4100K, and 3500K color temperatures. On their highest settings, the LED luminaires achieved an average vertical illuminance range between 4 and 8 lux. Compared with a conventional 400 watt HPS luminaire in the study (~18 lux average illuminance, 2500K on the Correlated Color Temperature [CCT] scale), the LEDs provided a detection distance approximately 50 feet shorter than the HPS but used far less energy. Again, these findings fall within the 300-foot range of headlamps. The findings also indicate a cost in visibility associated with dimming luminaires and potential loss in detection distance compared with conventional lighting systems.<sup>(2)</sup>

A third assessment in San Jose, California, also compared detection distances of LEDs to conventional HPS luminaires. Here, the mean detection distances of the three different types of LEDs compared ranged from 160 feet to 232 feet. The mean detection distance for the lone HPS



lighting system tested was approximately 196 feet. In terms of vertical target illuminance, the three LEDs ranged between 8 and 10 lux while the HPS luminaire was 11 lux.<sup>(3)</sup>

Using these evaluations as a backdrop for comparison with the unique lighting system in Trinidad, it is important to note that while these systems are vastly different in design they aim to achieve the same purpose of adequately lighting the roadway. Other objectives of these three cases include seeking opportunities for reduced energy consumption and increased efficiency; however, the assessment in Trinidad is strictly meant to characterize the lighting system and gain feedback on its acceptance.

## **EXPERIMENTAL METHODOLOGY**

This project consists of a subjective survey and an objective analysis. The subjective survey portion was meant to determine community acceptance of the embedded guardrail light system. The objective portion was meant to determine visibility performance through the use of Small Target Visibility (STV). Both portions of this project were completed with the intent of evaluating the functional visibility and public preference for this lighting technology.

### **Equipment**

The data collection equipment used during the experiment contained a variety of elements for collecting illuminance, luminance, and participant response data. The Roadway Lighting Mobile Measurement System (RLMMS) is a device created by the Center for Infrastructure-based Safety Systems (CIBSS) at VTTI as a method for collecting roadway lighting data in addition to participant response data while the vehicle is being driven.

A specially designed “Spider” apparatus containing four waterproof Minolta illuminance detector heads was mounted onto the vehicle via magnets. The configurations of the illuminance detector heads are detailed in a later section. An additional vertically mounted illuminance meter was positioned in the vehicle windshield as a method to measure glare from the lighting installations. The waterproof detector heads and windshield-mounted Minolta head were connected to separate Minolta T10 bodies that sent data to the data collection PC positioned inside the vehicle.

A NovaTel Global Positioning Device (GPS) was positioned on the roof of the vehicle. The GPS device was connected to the data collection box and the vehicle’s latitude and longitude position data were incorporated into the overall data file.

Two separate video cameras were mounted on the vehicle’s windshield. One camera collected color images of the forward driving luminous scene and the other camera collected luminance information of the forward driving scene. Each camera was connected to a stand-alone computer that was then connected to the data collection computer. The data collection computer was

responsible for collecting illuminance, human response (reaction times), and GPS data, and synchronizing the camera computer images with a common time stamp. Additional equipment inside the vehicle consisted of individual input buttons for participant responses.

A specialized software program created in LabVIEW™ controls each component of the RLMMS. The software synchronizes the entire hardware suite, and data collection rates are set at 20 Hz. Video image capture rate was set at 3.75 frames per second (fps). The final output file used during the analysis contained a synchronization stamp, GPS information (e.g., latitude, longitude), input box button presses, individual images from each of the cameras inside the vehicle, vehicle speed, vehicle distance, and the illuminance meter data from each of the Minolta T-10s (four total).

## **Participants**

Participants were recruited through advertisements placed in newspapers local to Trinidad, as well as through Trinidad Junior State College (TJSC). A psychology professor at the institution granted our research team access to openly recruit members of her class in exchange for a guest lecture on the topic of VTTI's research. A number of participants were acquired via the newspaper ads; however, a majority of the participants were students, faculty, or staff at TJSC.

The recruitment goal of forty participants was met; however, the study only allotted time for 38 to participate. The remaining two who were not able to participate were paid for their time and dismissed. One of the 38 participants' data was deemed unusable and removed from analysis.

The final data consisted of 20 males and 17 females. The average age of the participants was 33.9 years, ranging from 18 to 76 years. Aside from being at least 18 years of age and providing a valid driver's license, there were no other restrictions. Five participants did not include their age on their questionnaire and are not accounted for in the average.

## **Experimental Design**

### *Route*

The study route circulated through a small portion of Trinidad's town center, just beneath the Interstate 25 overpass, before entering the highway. The meeting place for participants was a small, lit park-and-ride lot near the overpass. Once participants were loaded into the vehicle and after the experimental instructions were given, the in-vehicle experimenter drove the vehicle to the northbound Interstate 25 entry ramp toward Exit 15, US-160 E, Kit Carson Trail. One target was placed in the overhead lighting section of this on-ramp.

The vehicle exited at Exit 15 and then re-entered the highway heading southbound. The reason for this upper loop was to capture the entirety of the embedded lighting section traveling north to south. The vehicle drove to where the embedded lighting began and entered a left lane closure provided by CDOT. The vehicle's speed was adjusted from the posted 65 mile per hour (mph) speed limit to 45 mph. A CDOT vehicle outfitted with proper reflectors and beacons followed at a safe distance behind the experimental vehicle while it was entering and exiting the lane closure as a safety buffer. While in the mile-long southbound embedded lighting section, the vehicle passed three targets placed on the left shoulder of the roadway.

Once out of the lane closure, the experimental vehicle changed lanes to the right lane. Shortly after the embedded lighting ends, HPS overhead lighting begins on the right side of the roadway. Just beyond the last of the HPS luminaires, another target was placed on the right shoulder of the roadway.

The vehicle then took Exit 12 toward Starkville and re-entered I-25 heading northbound. Once again, the vehicle entered a CDOT lane closure in the left lane just before entering the embedded lighting section followed by a CDOT buffer vehicle. Three more targets were placed on the left shoulder in the embedded lighting section. Once the vehicle exited the lane closure at the end of the northbound embedded lighting section, the experiment was finished and there were no more targets for participants to identify.

The vehicle exited the highway at Exit 15 again and re-entered the highway toward the Colorado Avenue exit. After taking the Colorado Avenue exit, the experimental vehicle returned to the queuing area below the I-25 overpass to collect the next set of participants. In total, the route took approximately twenty minutes to complete.

The focus of the assessment was the LED lights embedded into the concrete barriers on the overpass. The I-25 overpass is nearly a mile in length, with the lighting system embedded into barriers on both sides of the roadway in each direction of travel.

Figure 2 illustrates the locations of the queuing area and the targets in the lighted location. Green-labeled target locations are in the southbound lanes and blue-labeled target locations are in the northbound lanes.



1) Participant Queuing Area

2) Target #2

3) Target #3

4) Target #4

5) Target #6

6) Target #7

7) Target #8

Figure 2: Overview of lighted route portion.

Targets were strategically placed on the highway so there would be no overlap in visibility. The distances between the targets are shown in Table A. Note that Target 1 was placed on a northbound on-ramp and was not in the same travel lane as other targets.

**Table A: Distance Between Targets**

Targets	Distance Between Targets (ft)	Direction
Target 2 and Target 3	1,584	Southbound
Target 3 and Target 4	792	Southbound
Target 4 and Target 5	2,270	Southbound
Target 6 and Target 7	1,003	Northbound
Target 7 and Target 8	739	Northbound

## **Experimental Tasks**

### *Greeting Participants*

Participants were assigned a time to arrive at the park-and-ride facility beneath the overpass to begin the assessment. Approximately five participants arrived every half-hour, and up to three participants could partake in the study at a time. Upon arrival, members of the research team administered informed consent forms. Participants were queued until the experimental vehicle returned to pick them up.

### *Vehicle Familiarization*

Once participants entered the vehicle, the in-vehicle experimenter noted their assigned participant numbers and started the data-recording software. A file was named on the basis of the participant numbers in coordination with where they were seated in the vehicle. This was to ensure that participants, participant numbers, and data entry were kept in sync. The in-vehicle experimenter drove while participants sat in the front passenger seat, the rear passenger seat, and the rear middle seat. The rear driver's side seat was reserved for recording equipment. Participants were required to wear seatbelts and sit in a position that allowed them to see out the front windshield.

The in-vehicle experimenter explained to participants how to operate their individual input buttons. A practice target was placed in the park-and-ride lot to demonstrate to the participants what size and shape to expect once the assessment began.

### *Data Collection*

For the participant portion of the study, no lighting data were collected. Because the lighting system was embedded in the guardrail, the light measurement system needed to be attached to the sides of the vehicle, prohibiting efficient exit and entry of the vehicle by participants. Because of this, the lighting was assessed separately. For the participant portion, only the GPS and individual input buttons were in use.



**Figure 3: Individual input button.**

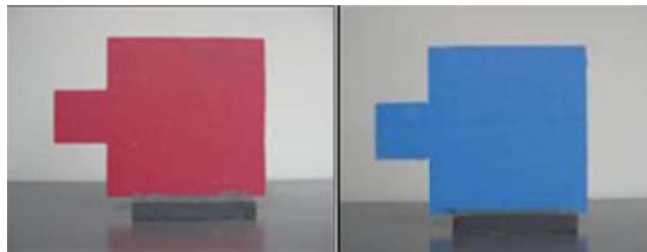
The individual input buttons are handheld sticks with buttons on the top (Figure 3). Participants held the buttons in their hands and pressed down with their thumbs as soon as they detected a target. The button press was synced with the GPS data so that upon analysis the exact location and distance from the target could be determined.

### *Experimental Procedure*

As the in-vehicle experimenter drove the route, participants pressed individual input buttons as soon as they could identify the presence of a target on either shoulder of the roadway. The participants were asked not to speak throughout the test portions of the route in order to not tip off other passengers of a target's presence.

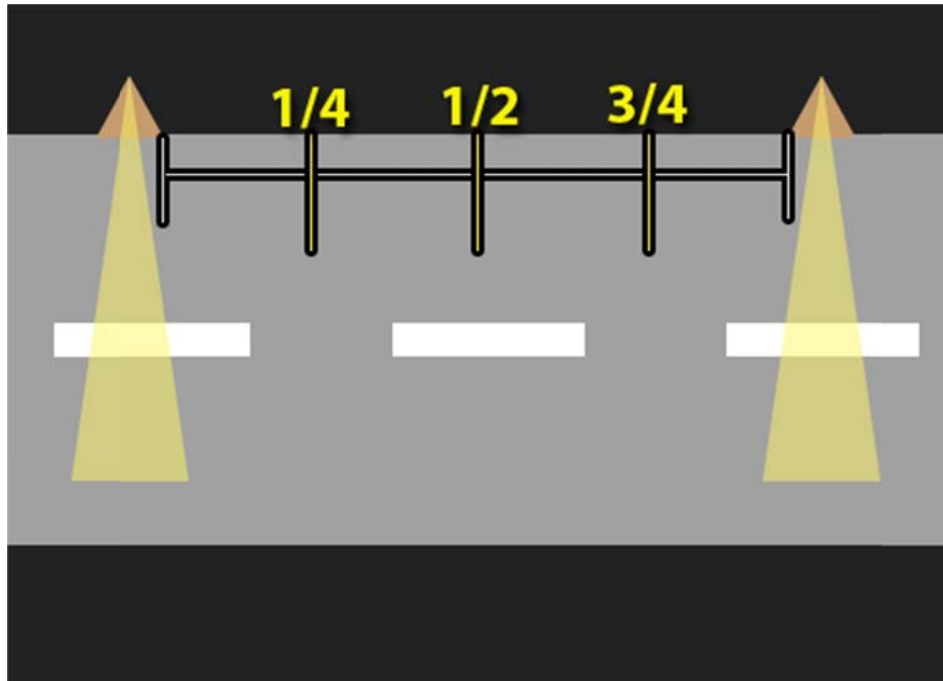


There were eight total targets placed along the route, and six were in the embedded guardrail lighting section. These six were on the left shoulder of the roadway as CDOT closed the left lane to make it exclusive to the experimental vehicle. The other two targets were placed on the right shoulder of the roadway and not in the embedded guardrail lighting section. One was placed on an on-ramp to I-25 and another just beyond a segment of overhead HPS luminaires outside the embedded guardrail lighting section. The targets were painted either red or blue (Figure 4).



**Figure 4: Detection targets used within test area.**

Targets placed in the lighting section were spaced at one quarter and half distances between two fixtures. For example, in Figure 5, assuming traffic is moving left to right in this diagram, targets are placed at either the  $1/4$  or  $1/2$  positions. Specific details about target placement are discussed in a later section.



**Figure 5: Target placement.**

### *Questionnaire*

Once the vehicle completed the route and returned to the park-and-ride facility, participants exited the vehicle and returned to the initial research team members who had greeted them. They were administered a ten-question questionnaire with a comments section meant to gain insight on their acceptance of the embedded guardrail lighting technology.

### *Limitations*

The research team was limited to using only the left lane of the I-25 viaduct through Trinidad. Because there were multiple right exits in each direction, CDOT opted only to close the left lane to preserve safety for participants as well as the naturally flowing traffic through the area. Orange cones were placed on the centerline of the highway to indicate the lane closure; these cones may have caused shadows across the road from the embedded lighting in the guardrail of the right lane and may have affected the contrast of the targets on the left shoulder.

For the lighting and characterization evaluation, the cones had already been removed by CDOT, so luminance and illuminance data are not exactly representative of how the participants

experienced the route. However, it is thought that the effect of the lane closure will have minimal impact when comparing lighting metrics to the participant responses.

The characterization was completed using a large sport utility vehicle. The height of the vehicle and placement of mirrors are likely not the dimensions of an average vehicle traveling on that particular stretch of highway.

### *Data Analysis*

The participant input is part of the data stream collected via the RLMMS. The format of the data can be imported into Microsoft Excel, where the data can be reduced. The exact moments at which participants pressed their buttons upon detection of the targets were extracted and GPS distances were calculated to the next target to quantify distance. After the distances of each detection point to the target were calculated, Statistical Analysis Software (SAS) was used to analyze the data.

The characterization data acquired were analyzed using a similar method. The filename for each luminance image recorded is placed into a data stream synced by GPS and time recorded by the RLMMS. These images were ported to an in-house-developed MatLab® program used to calculate the luminance and background luminance of traced images. Trained reductionists “cut-out,” or traced, the outlines of targets in the images, then built-in algorithms calculated the luminance and contrast. These results were then ported to a format compatible with SAS for statistical analyses.

## RESULTS

### Lighting Characterization and Evaluation

The participant portion of the study was complete once all participants completed their questionnaires, were paid for their time, and left the premises. The lighting evaluation portion began shortly thereafter. Once the RLMMS equipment was set up, the in-vehicle experimenter redrove the test route. The route was driven three more times, once for each light meter orientation described below.

#### *Vehicle Side Characterization – Mean Illuminance*

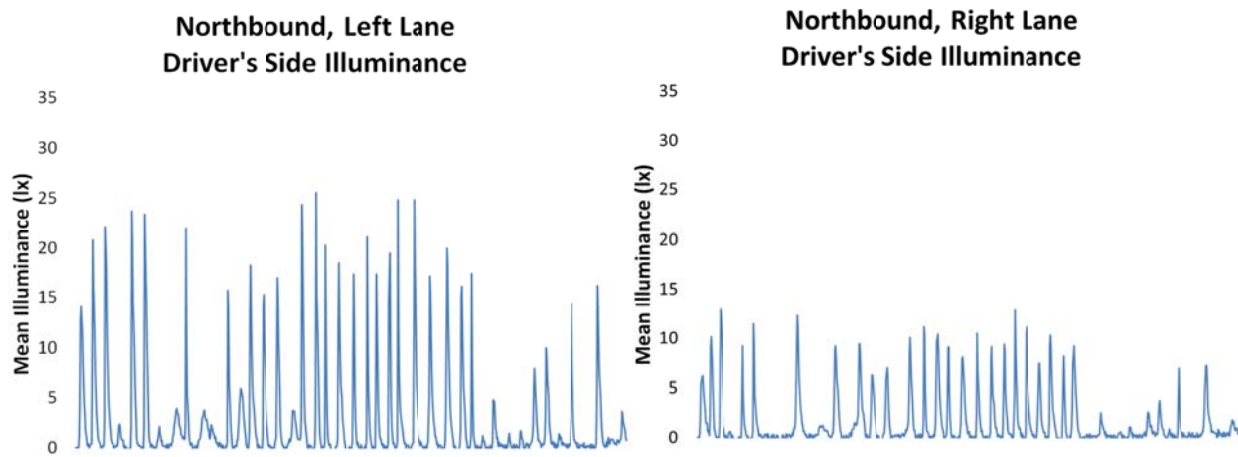
The illuminance meters were placed onto the vehicle and held in place by magnets. Figure 6 illustrates where the illuminance meters were placed on the vehicle. The research team wanted to investigate how the light interacted with a passing vehicle. Illuminance meters were placed almost evenly along the sides of the vehicle, starting at 2 feet from the ground up to 6 feet high. The ability of magnets to stick to the metal sides of the vehicle was more trusted than that of suction cups, even though suction cups could also utilize the passenger windows. Because of this, the contours of the vehicle, the placement of door handles, and the location of side windows limited how evenly spread on the vehicle the meters could be placed.



**Figure 6: Light meter orientation, vehicle side.**

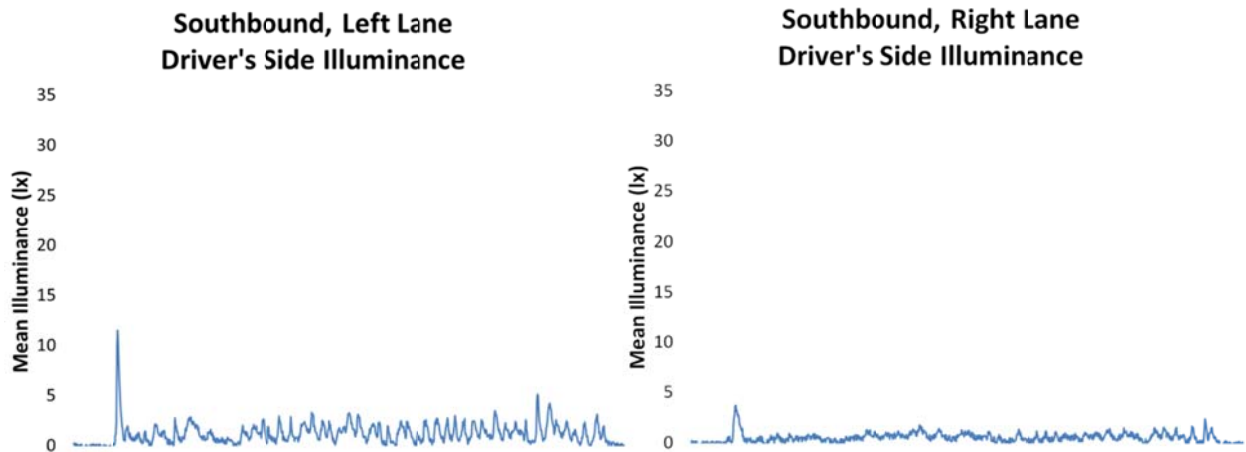
Figure 7 and Figure 8 show the average illuminance results of all four light meters for the embedded lighting system when light meters were attached to the driver's side of the vehicle.

Each spike along the line represents a single light fixture from the embedded lighting system projecting light onto the side of the traveling research vehicle. The vehicle is traveling in the northbound lane; therefore the embedded lighting is aimed directly at the side of the vehicle. The left shoulder of the highway is narrower than the right shoulder, meaning the embedded lighting system in the left lane would be closer and cause the light meters mounted on the driver's side to measure greater illuminance versus the right lane. Considering the aim of the lighting system and the narrow shoulder, it is expected that the "Northbound, Left Lane, Left Side Illuminance" would record the highest illuminance measure of any side-vehicle mounted scenario in either direction.



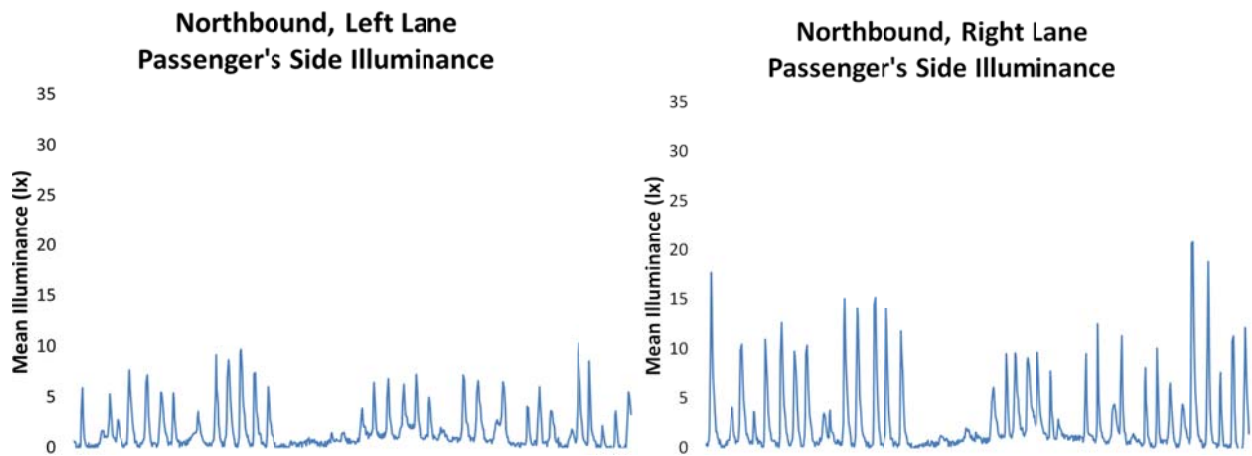
**Figure 7: Northbound, driver's side illuminance.**

The results shown in Figure 8 are the average illuminance results of illuminance meters placed on the driver's side of the vehicle in the southbound lanes. The southbound embedded lighting system is aimed up the forward roadway and projected less light onto the side of the vehicle, as modeled in Figure 1. The spike at the beginning of the line may be a result of a misaligned aim of one of the fixtures.



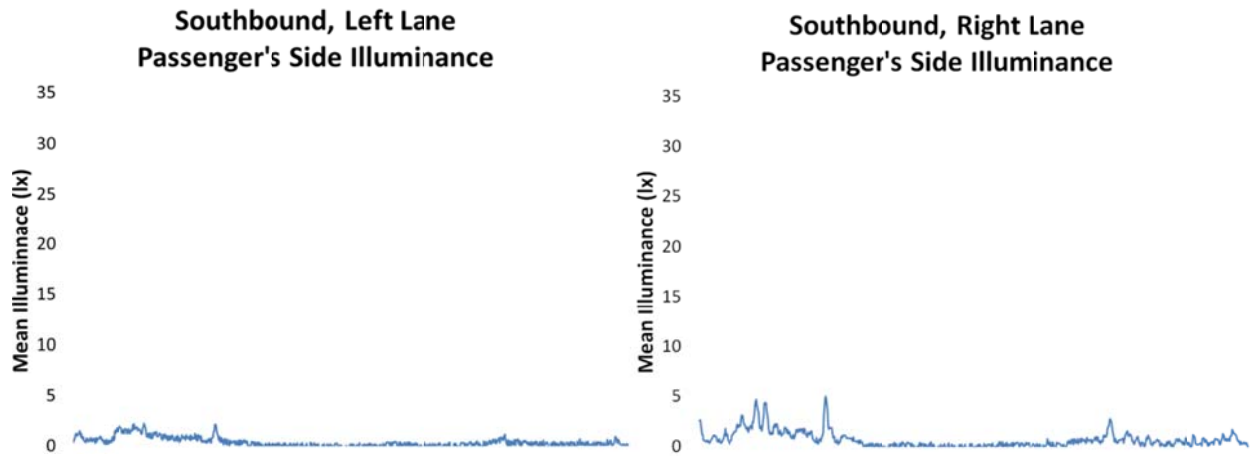
**Figure 8: Southbound, driver's side illuminance.**

The average illuminance measurements on the passenger's side of the vehicle in the northbound direction exhibited expected results as the right lane yielded higher lux readings versus the left lane (Figure 9). The peak illuminances of the right lane are slightly, though noticeably less, than the peak illuminances of the left lane for the illuminance meters mounted on the driver's side due to the difference in the size of the shoulders. The gap in the middle of the peaks may represent a break in the barrier where an on-ramp merged with the highway.



**Figure 9: Northbound, passenger's side illuminance.**

Figure 10 illustrates the average illuminance of the embedded lighting system on the right lane of the southbound direction with measurements taken on the passenger's side of the vehicle. Taking into account the wide right shoulder and the forward-aiming lighting system, this scenario is expected to have the lowest illuminance measurement.



**Figure 10: Southbound, passenger's side illuminance.**

### *Glare*

Glare was assessed using a forward-facing light meter mounted to the inside of the windshield (Figure 11). The average glare from each lane in each direction is represented in Table B. The illuminance measurements, including this glare measurement, were recorded with no traffic in the same direction. However, oncoming traffic could not be avoided and may have had an impact on the glare readings despite the existence of a separation barrier.



**Figure 11: Glare meter inside front windshield.**

The northbound lanes produced more glare, particularly in the left lane, than the southbound. One possible explanation is that the southbound lighting was aimed forward. At one point in the route as the road curves, the embedded lighting system in the southbound lane appears brighter to northbound drivers. Also, the northbound lighting system orients more light toward the car than the forward-aimed southbound lighting system. While driving through the northbound section, lighting can be observed inside the car, nearly creating a strobe effect. This strobe-like effect is not observed in the southbound lanes.

**Table B: Glare (Lux)**

<b>SOUTHBOUND</b>		<b>NORTHBOUND</b>	
<b>LEFT LANE</b>	<b>RIGHT LANE</b>	<b>LEFT LANE</b>	<b>RIGHT LANE</b>
<b>0.456</b>	<b>0.486</b>	<b>0.597</b>	<b>0.502</b>

Figure 12 illustrates the amount of light reaching each illuminance meter on the side of the vehicle. Per the figure, the projection of light from the embedded system is concentrated on the lower half of the vehicle (24 to 39 inches). At 54 inches and above, illuminance is reduced to a factor of around 10% of the lower half.



## Vertical Assessment Northbound, Left Lane Driver's Side

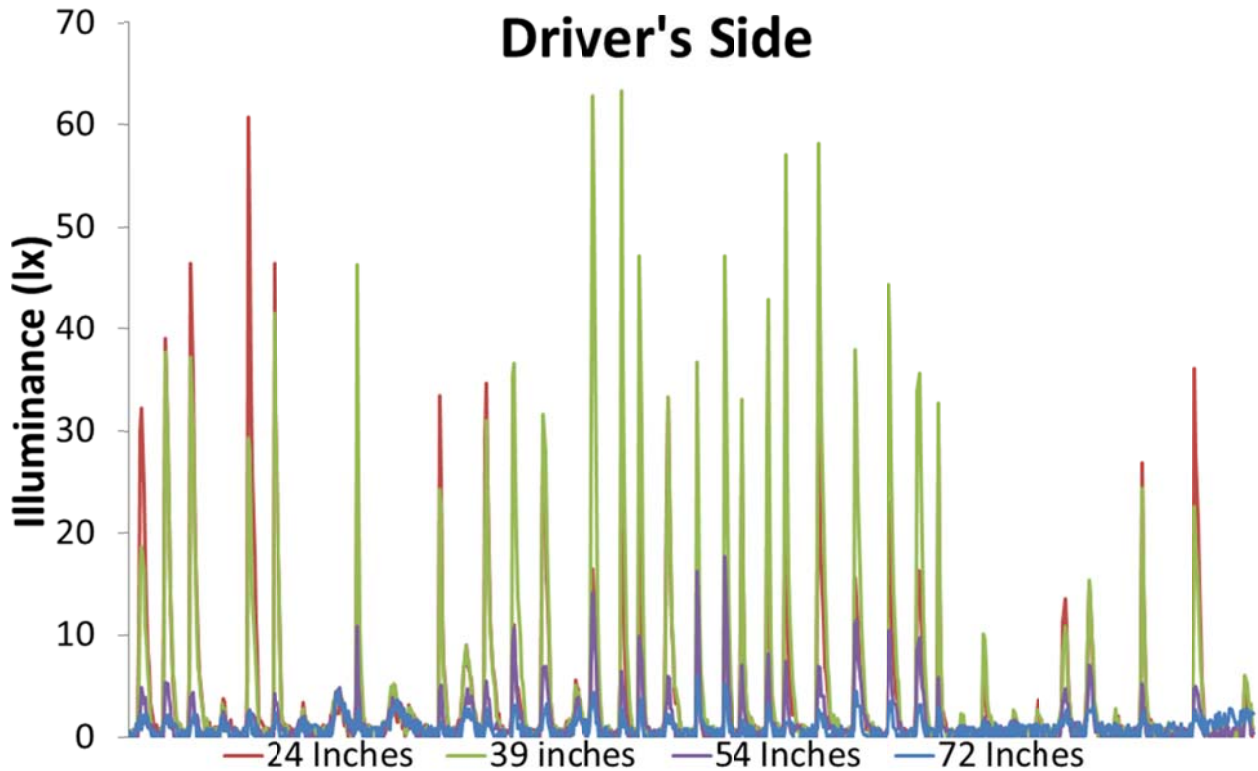
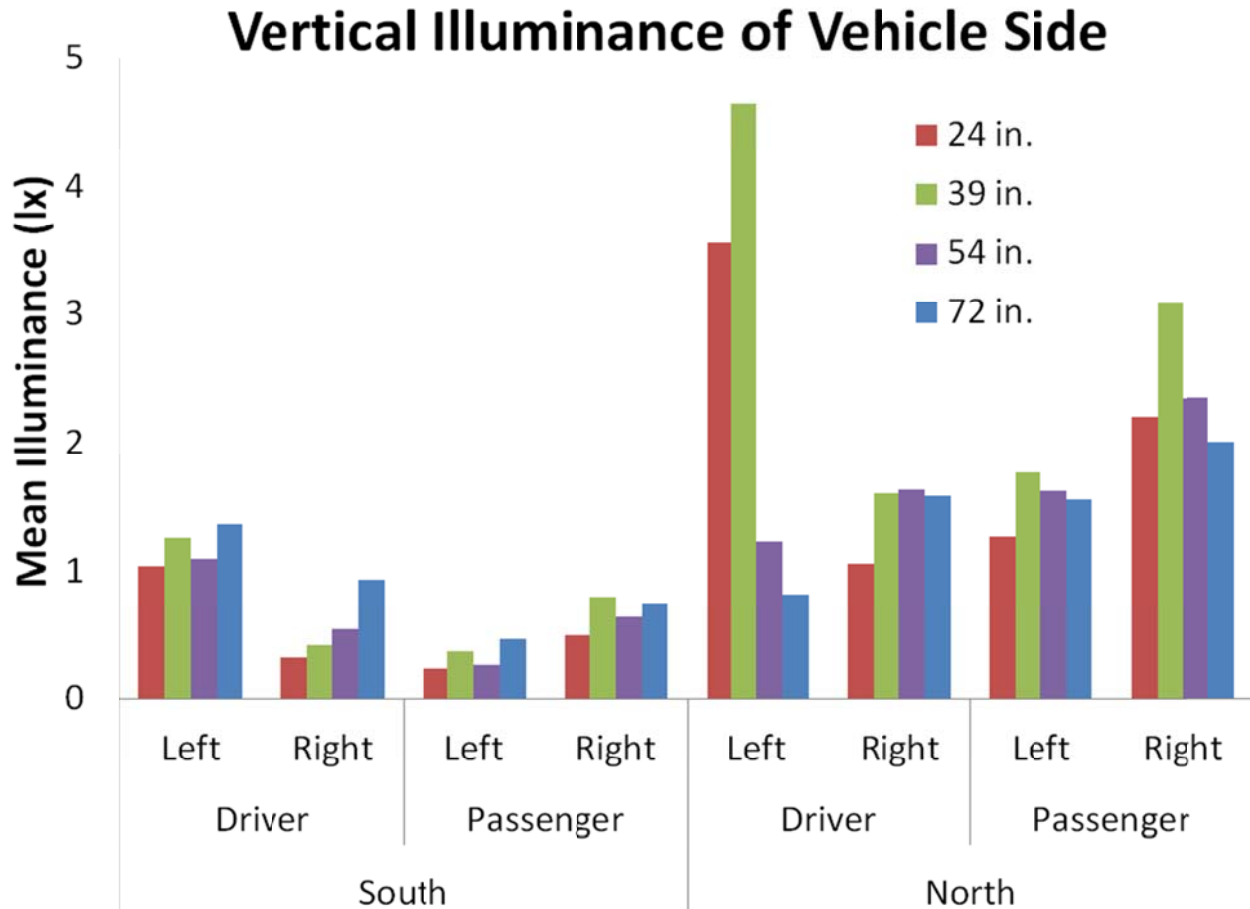


Figure 12: Vertical assessment, northbound, left lane, driver's side.

### *Vehicle Side Characterization – Vertical Assessment*

The amount of vertical illuminance for each side of the vehicle in both directions and both lanes is detailed in Figure 13. The lighting system in the northbound lanes projects more light at a height of 39 inches, or at about half the vehicle's height. In the southbound lanes, the lighting system projected nearer to the top of the vehicle, with the 72-inch-high meter recording the most illuminance, though altogether vertical illuminance in the southbound lanes was less than in the northbound lanes.

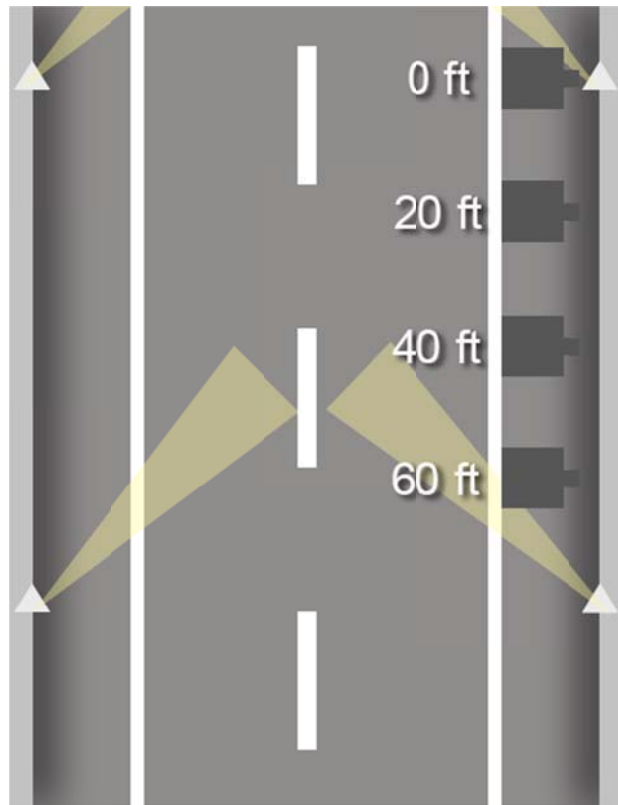
It is important to note that the inward-aimed northbound lighting systems had a higher incident illuminance on the side of the vehicle than the forward-aimed southbound system. This may indicate that drivers perceive a higher discomfort or flash level as they drive past the luminaires.



**Figure 13: Vertical illuminance of vehicle side.**

#### *Luminance and Contrast Characterization*

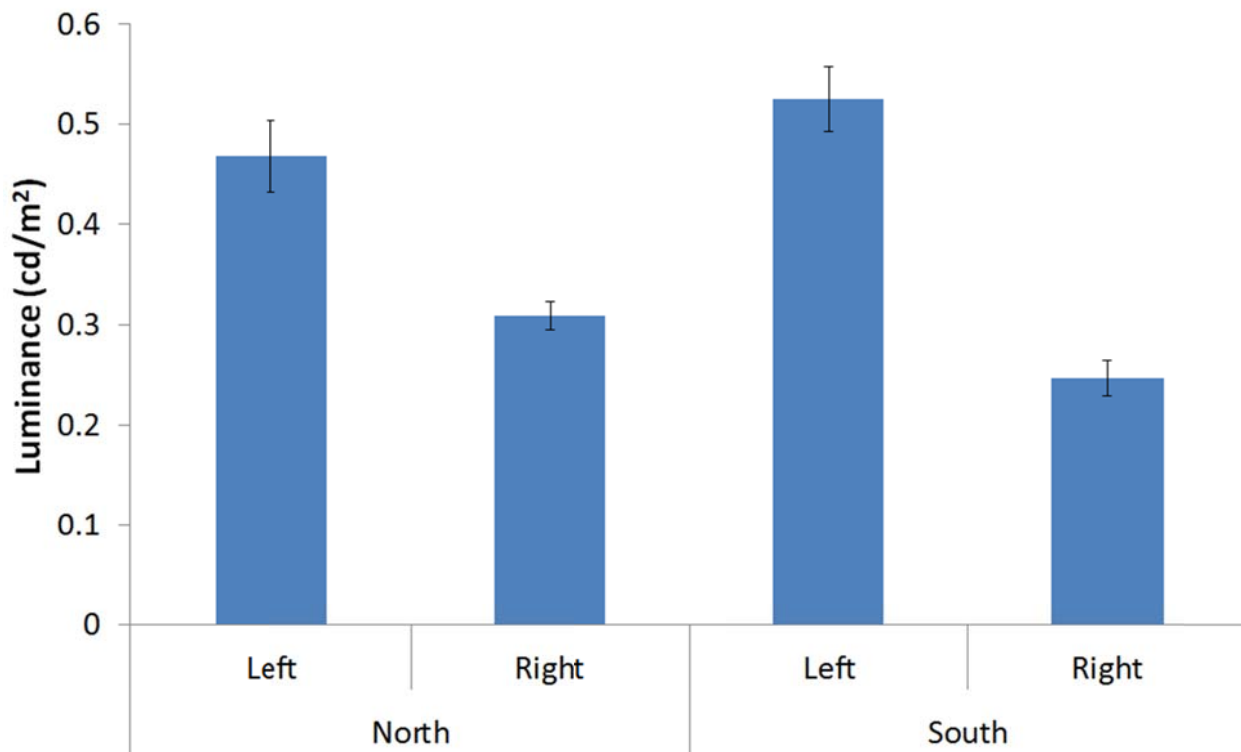
A return trip to the test site was made approximately three months after the initial evaluation to better characterize target luminance. This characterization included the use of two gray targets of the same size and features of the original red and blue targets used in the participant evaluation. Targets were placed every twenty feet between two of the embedded guardrail lights, which were spaced evenly 80 feet apart on the highway. The layout of the targets is shown in Figure 14. Here, each target distance is labeled; however, while measurements were taken only two targets were present (at 0 and 40 feet or 20 and 60 feet) to prevent overlap in the luminance images. Also, this image shows the forward-oriented lighting design; note that both orientations, forward- and cross-aimed, were used for target luminance characterization.



**Figure 14: Target placement (southbound example).**

Figure 15 shows the recorded luminance of the targets placed in either the left or right lanes for each direction. There is not a significant impact on luminance between the directions of travel, indicating that the luminance of the target was likely a result of vehicle headlights dominating the light contribution on the target surface. The right lane in the southbound direction did yield less luminance, perhaps due to its being further from the roadway and aimed forward instead of across, allowing less light from the barrier to directly reach the target. There is an obvious difference between left and right lanes due to the width of the right shoulder being much larger than the left lane shoulder.

## Mean Luminance by Direction and Lane

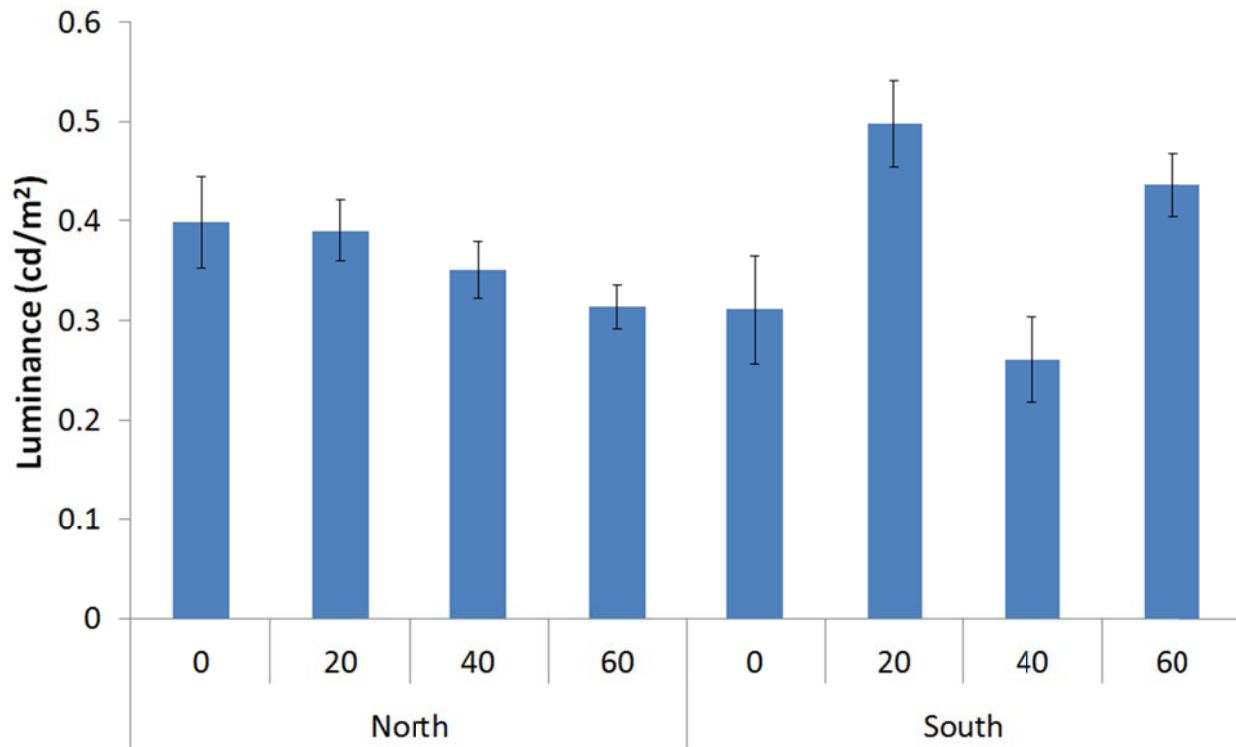


**Figure 15: Mean luminance by direction and lane.**

Figure 16 illustrates the amount of luminance at each target position per direction of travel. A significant difference between directions of travel was the result that targets in the southbound direction placed at 20 and 60 feet from the luminaire were “hot-spots” in terms of luminance. Referring back to Figure 14, it is interesting that the targets at 20 and 60 feet would result in higher luminance values. It is not believed that luminaires in the opposite barrier impacted the target’s vertical luminance.

In the northbound travel lanes with the cross-aimed lighting system, luminance results were nearly even among the targets. It is important to note that the target at 60 feet is still 20 feet from the next luminaire, and its slight decrease in luminance compared to targets at 0, 20, and 40 feet indicates that the cross-aimed lighting system may be aimed slightly forward, perhaps due to the design of the barrier.

## Mean Luminance by Direction and Position



**Figure 16: Mean luminance by direction and position.**

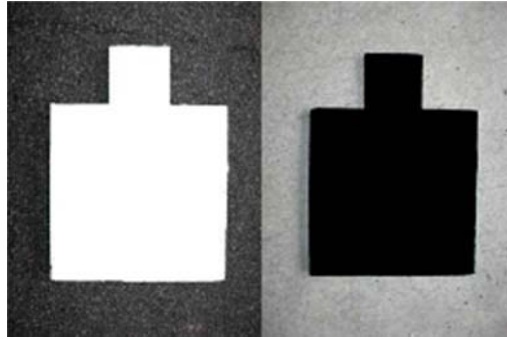
Figure 18 shows the calculated Weber Contrast by direction and lane (Equation 1). The positions of the targets in relation to the luminaires are not included here. Also, note that the images recorded of the targets were of varying distances and the interaction with vehicle headlamps is not accounted for.

### Equation 1: Weber Contrast

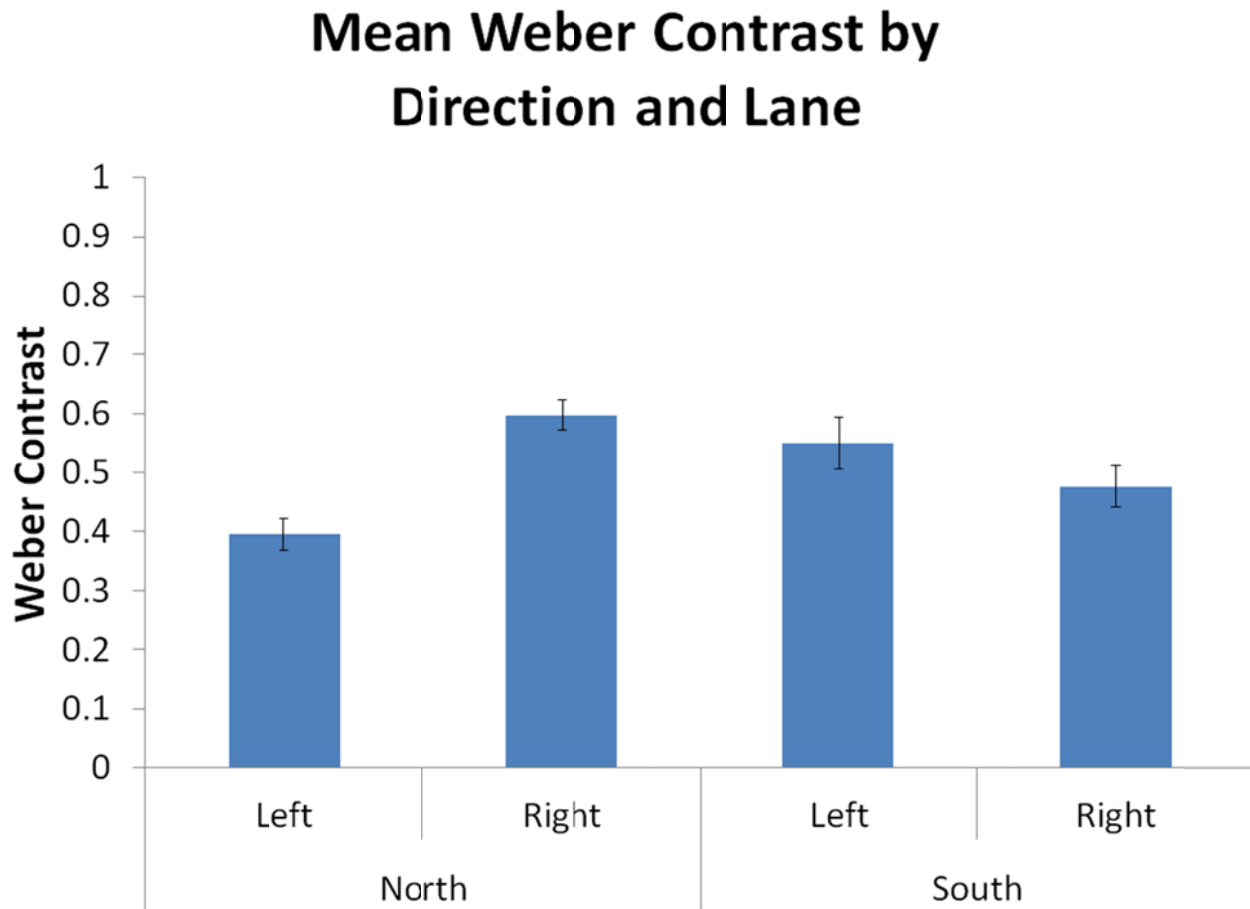
$$C = \frac{L - L_b}{L_b},$$

where  $L$  and  $L_b$  are luminance and luminance background, respectively.

The target with the greatest contrast, Target 2, was the last detected of all targets. Furthermore, the target with the furthest detection, Target 6, had the least contrast and was the only target to have a negative contrast average. An example of positive and negative contrast is featured in Figure 17.



**Figure 17: Positive (left) and negative (right) contrast.**

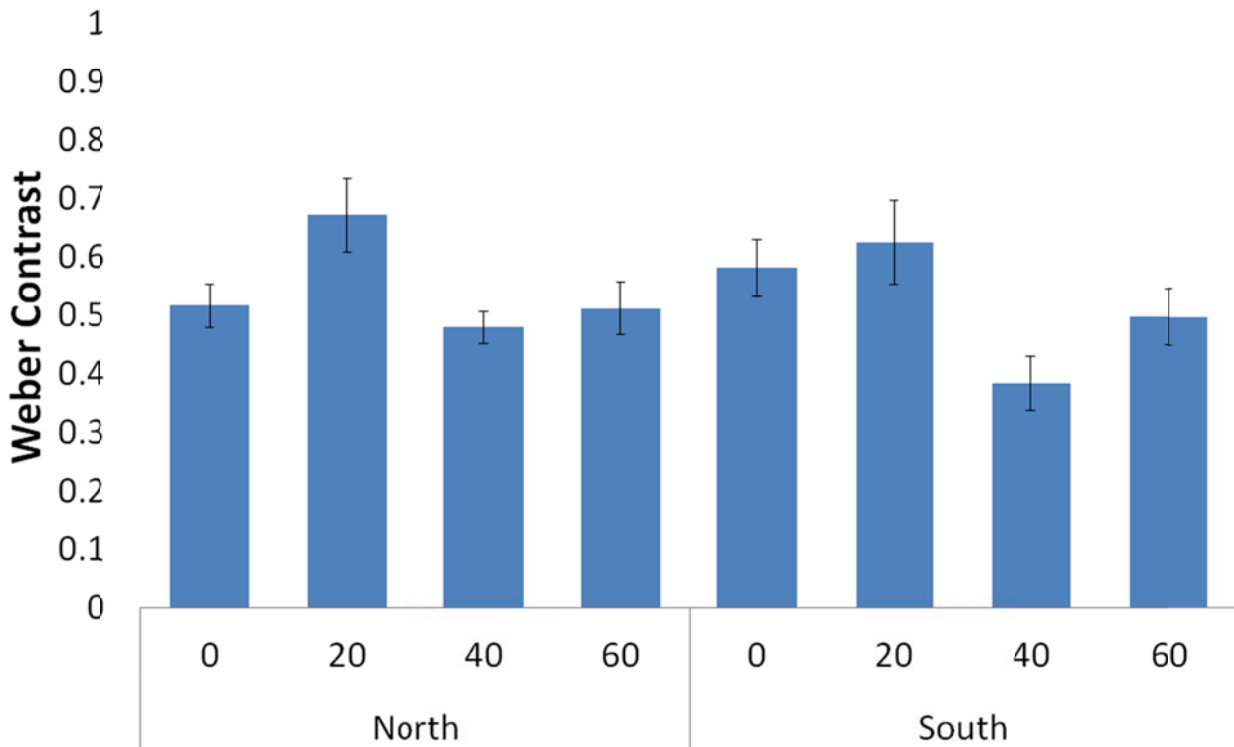


**Figure 18: Mean Weber Contrast by direction and lane.**

Mean Weber Contrast by direction and position is shown in Figure 19. As expected, targets placed further from the luminaire (40 is in the middle) are not as contrasted, or visible, as the targets placed closer to the light source. There is little difference between the north and south directions despite the aiming difference of the lighting system. Luminance, shown in Figure 15, indicates that the targets in the left lanes were more lit; however, with respect to contrast, left-lane targets were no more visible than right-lane targets. This may be a result of beam width and the beam's relationship to the road surface not allowing a shadow to form behind the object to increase contrast.

One of the items for consideration is that the light sources had a fairly narrow beam angle and had a definite "hot spot" (area of noticeably brighter light). The visibility is not equivalent throughout the space between the luminaires, with those at 20 feet being more visible than others. This impact of the hot spot was even more evidenced in the southbound lanes with a higher degree of variability in the contrast. These measurement results indicate that a light source with less of a hot spot and a wider beam pattern might even the visibility level throughout the luminaire spacing.

## Mean Weber Contrast by Direction and Position



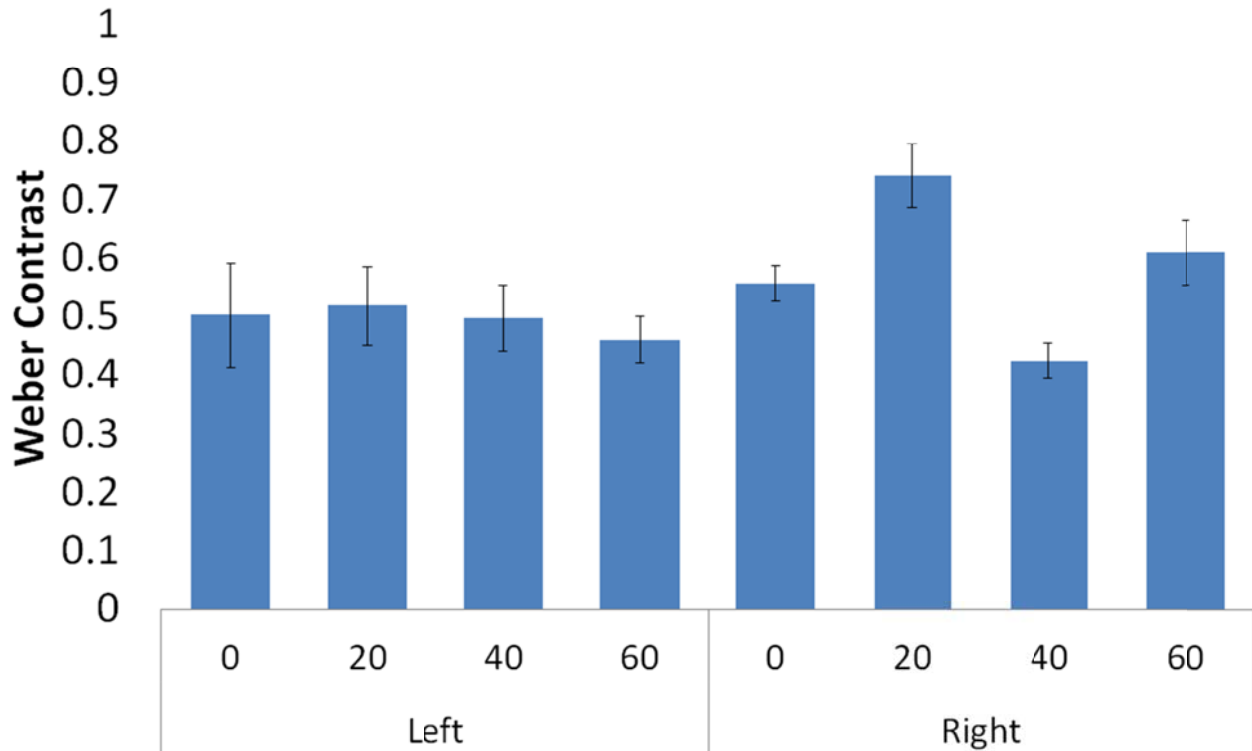
**Figure 19: Mean Weber Contrast by direction and position.**

The difference between the right and left lanes in either direction is the width of the right shoulder. The edge of the left lane is approximately 4 feet from the barricade containing the lighting system, whereas the right shoulder is between 9 and 10 feet wide. Targets were always placed 2 feet from the white edge line on either side; however, the lighting system in the right lanes needed approximately 7 feet to reach the targets but only 2 feet at the most for the left lanes. Figure 20 illustrates the differences in the lanes in terms of Weber Contrast. Unexpectedly, targets on the right shoulders are apparently more visible based on the measured contrast despite being up to three times further away from the lighting system

Compared to contrast, the luminance (Figure 16) difference of targets at 20 and 60 feet compared with 0 and 40 feet in the southbound direction was more drastic. The contrasts between positions in the southbound lane are only mildly different save for the target at 40 feet, which had less luminance.

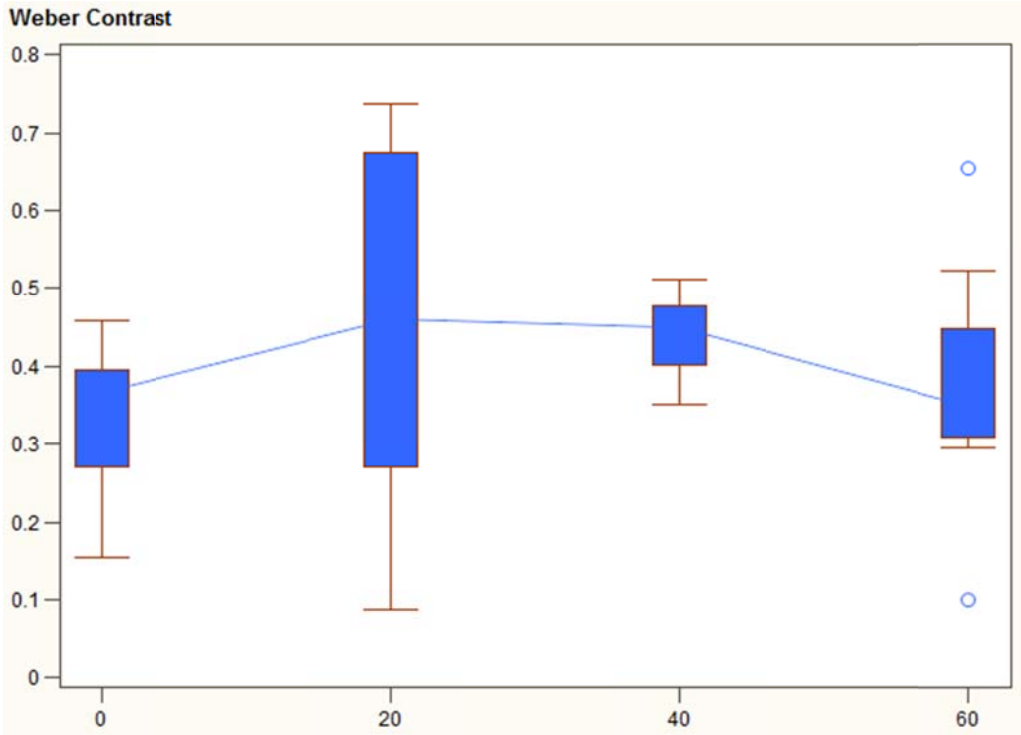


## Mean Weber Contrast by Lane and Position

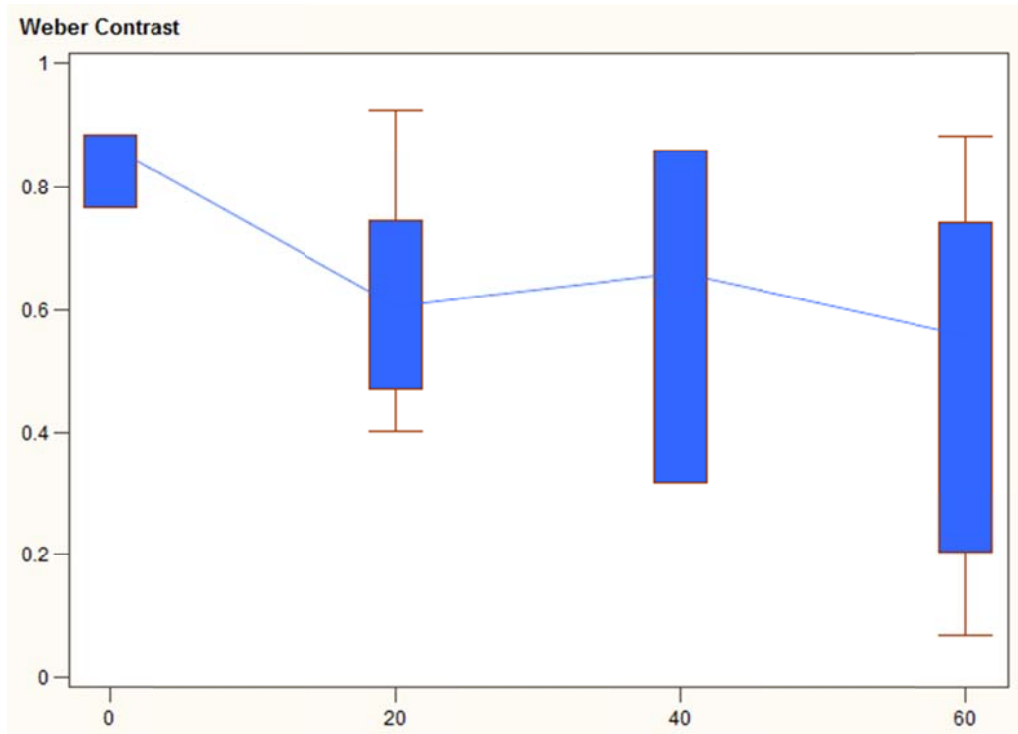


**Figure 20: Mean Weber Contrast by lane and position.**

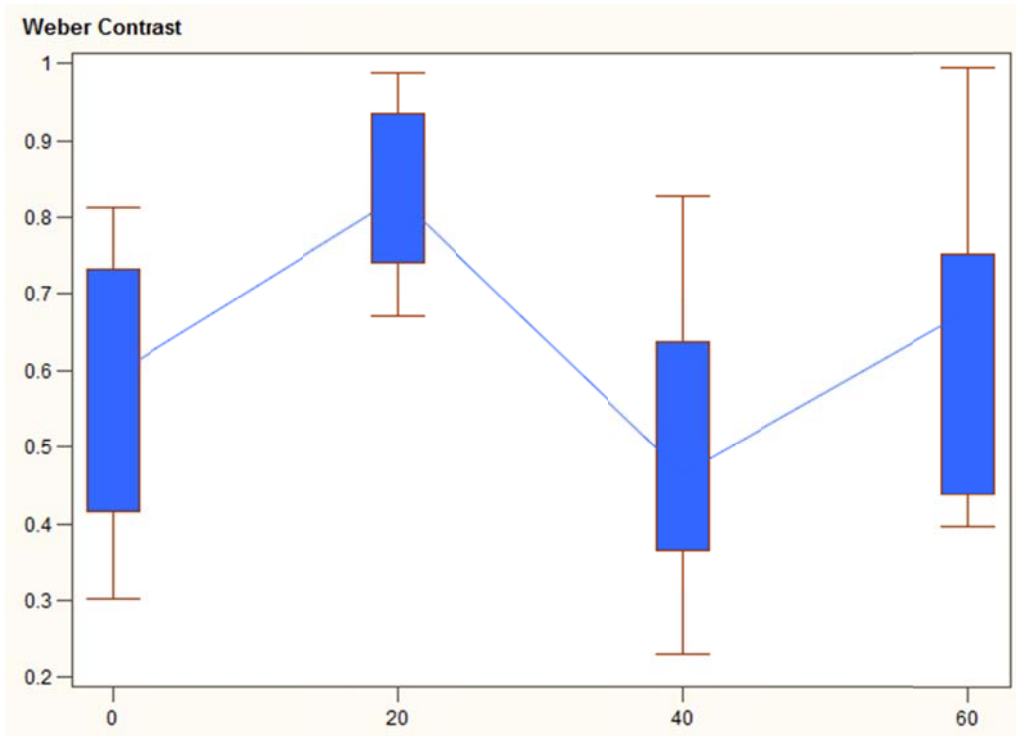
A box plot representation of Weber Contrast in each lane is shown in Figure 21, Figure 22, Figure 23, and Figure 24. Note that these contrast results do not consider the varying distances in which the images were recorded. This, however, is an average of the contrast values calculated for each image taken as the vehicle passed. These results illustrate a range of contrast, or visibility, of the targets. For instance, in Figure 21 it is clear that the target at 20 feet had the largest range of contrast, indicating an interaction between the roadway lighting and the vehicle headlamps. Also of note, the contrast of each target in each lane is positive, meaning that the face of the target is more brightly lit than the roadway itself.



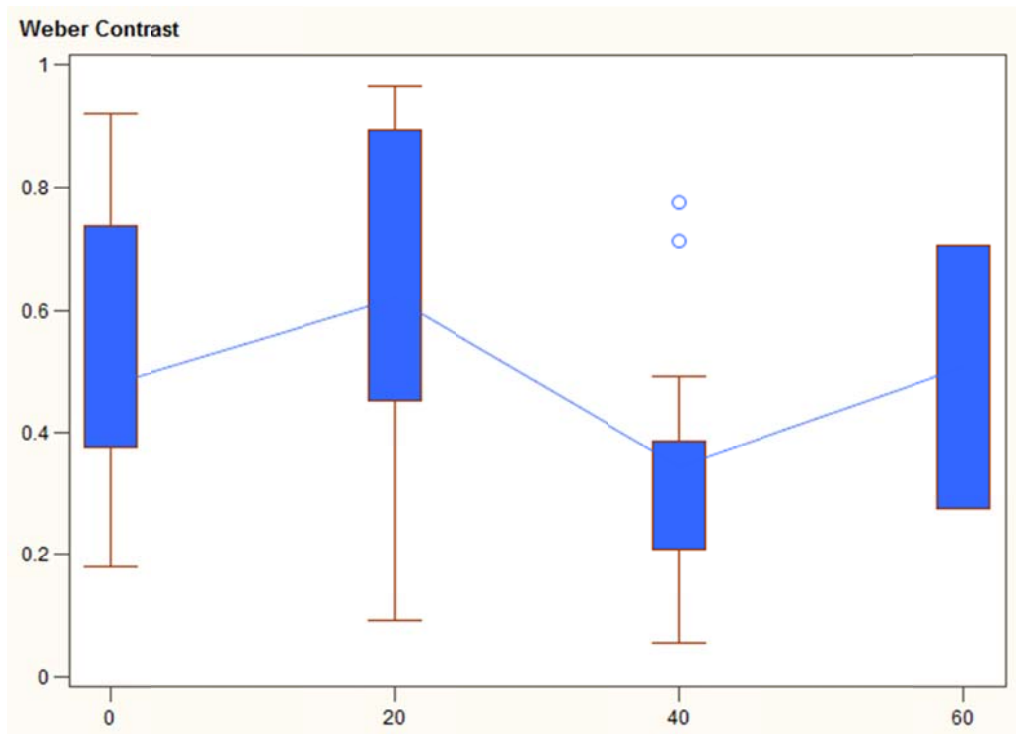
**Figure 21: Box plot of left lane, northbound contrast by target position.**



**Figure 22: Box Plot of left lane, southbound contrast by target position.**



**Figure 23: Box plot of right lane, northbound contrast by target position.**



**Figure 24: Box plot of right lane, southbound contrast by target position.**

### *Illuminance Characterization*

Vertical illuminance measurements were taken of each target placed 20 feet apart in the test area. Two illuminance measurements were taken: 1) facing the travel lane and 2) facing oncoming traffic and thus the previous luminaire in the embedded lighting system. These two measurements were taken to characterize light impact from luminaires on the opposite side of the road and the impact from same-side luminaires, respectively. These results are listed in Table C and Table D.

The left lane southbound targets had the highest illuminance by a substantial margin despite being contrasted less per the luminance calculations. The greater amount of light incident upon the target may explain the higher and more focused contrast found in Figure 22. The least illuminated targets were found in the northbound right lanes.

**Table C: Target Illuminance Facing Travel Lane (Lux)**

FACING TRAVEL LANE	SOUTHBOUND		NORTHBOUND	
	LEFT LANE	RIGHT LANE	LEFT LANE	RIGHT LANE
0 FT	62.7	3.57	0.38	0.66
20 FT	11.2	2.85	2.12	0.88
40 FT	4.25	3.45	1.98	0.71
60 FT	25.24	2.80	0.32	4.59

**Table D: Target Illuminance Facing Embedded Luminaire (Lux)**

FACING PREVIOUS LUMINAIRE	SOUTHBOUND		NORTHBOUND	
	LEFT LANE	RIGHT LANE	LEFT LANE	RIGHT LANE
0 FT	0.52	2.1	0.72	0.15
20 FT	1.4	0.89	5.27	0.09
40 FT	0.42	1.07	2.85	0.05
60 FT	3.56	0.71	0.52	0.10

Table E describes the location and variables associated with each target used in the participant detection portion. Targets are referred to by “Target Number” in the following results. In the

“Location” column, the direction of travel in which the target was placed is detailed here either by “NB” for northbound or “SB” for southbound travel lanes on “I-25,” or Interstate 25. The “Position” column details the side of the road the targets were placed on, either on the left or right shoulder. The targets were one of two colors: red or blue. The “Nearest Light” column describes the light closest to the specific targets. Targets 1 and 5 were not in the embedded guardrail lighting section but had overhead roadway lighting in their vicinity. The southbound directions contained embedded LEDs that projected toward the direction of travel while the northbound lanes contained embedded LEDs that projected directly across the highway.

**Table E: Target Descriptions for the Participant Testing**

Target Number	Location	Position	Color	Nearest Light	Distance to Nearest Light
1	NB I-25 On Ramp	Right Shoulder	Blue	Overhead LED	
2	SB I-25	Left Shoulder	Blue	Forward-facing Embedded LED	40 feet
3	SB I-25	Left Shoulder	Red	Forward-facing Embedded LED	20 feet
4	SB I-25	Left Shoulder	Blue	Forward-facing Embedded LED	40 feet
5	SB I-25	Right Shoulder	Red	None	
6	NB I-25	Left Shoulder	Red	Cross-road Embedded LED	20 feet
7	NB I-25	Left Shoulder	Blue	Cross-road Embedded LED	40 feet
8	NB I-25	Left Shoulder	Red	Cross-road Embedded LED	20 feet

### Target Detection

The following section describes the results of target detection by the on-board participants in the research vehicle.

Mean detection distance by target is shown in Figure 25. Note that Targets 1 and 5 were not in the embedded guardrail lighting section. Target 5 was a red target located out of reach of any

roadway luminaire. It was detected an average of 30 feet sooner than Target 6, which was the furthest detected target in the embedded luminaire section.

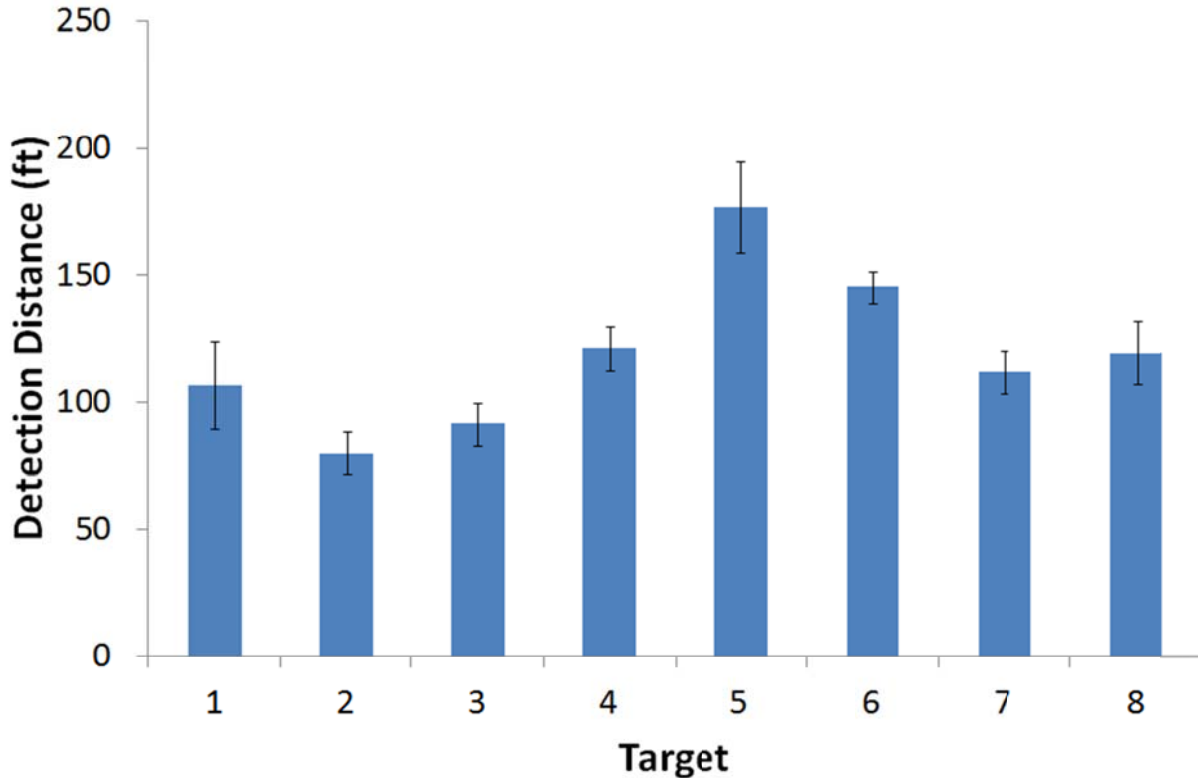
While the southbound orientations faced forward to illuminate targets similar to how vehicle headlamps project forward to illuminate targets, the “cross highway” orientation yielded a much greater detection distance. Participants detected targets approximately 27 feet sooner in the northbound lanes of travel versus the southbound lanes.

Note that Target 1 was located on a highway on-ramp and may have incurred a ceiling effect due to its location. In other words, as the vehicle turned on to the on-ramp, the target on the ramp may have become immediately visible to some participants.

Due to nested variables and limited degrees of freedom, three separate Analysis of Variance (ANOVA) tests were completed. The first ANOVA considered only the targets in the embedded lighting section and did not include direction of travel or color. Despite the differences in detection distances shown in Figure 25, the results were not significant ( $p = 0.089$ ).

There is no statistical relationship between the target’s placement in relation to the nearest embedded light and detection distance.

## Mean Detection Distance by Target

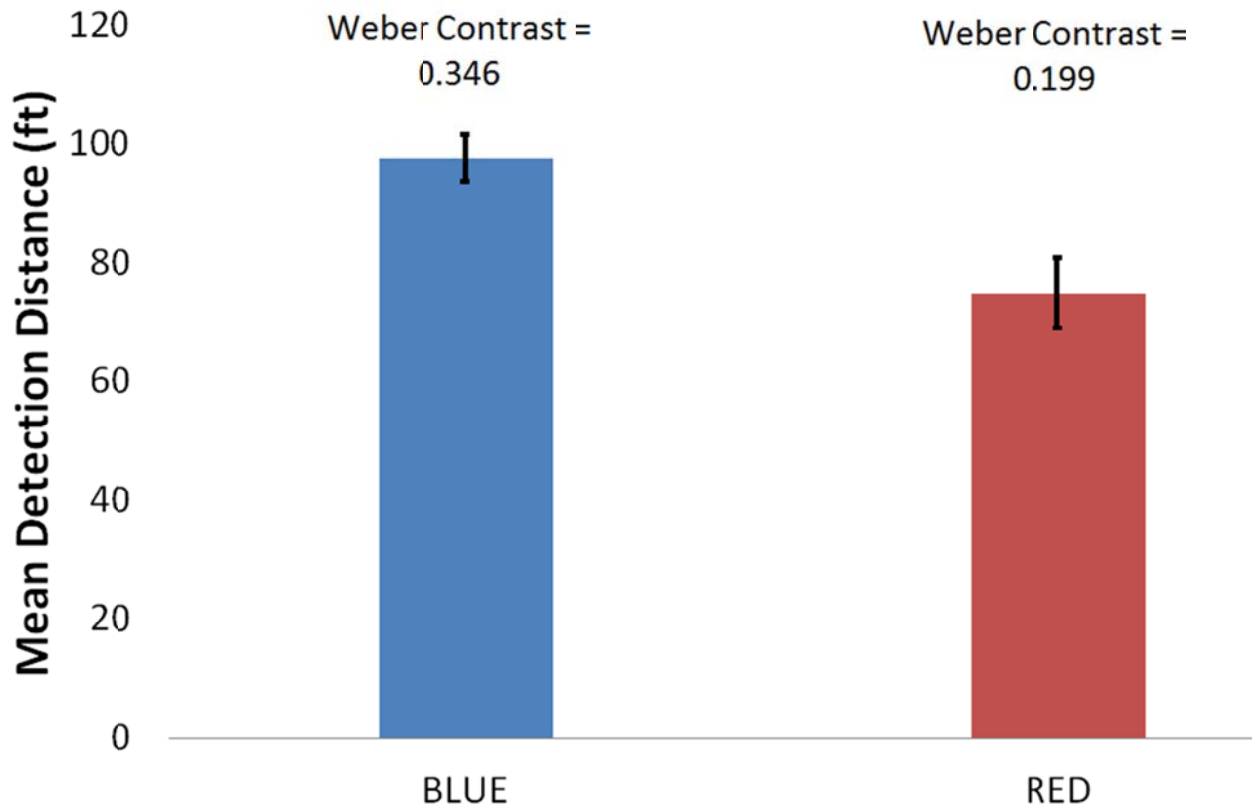


**Figure 25: Mean detection distance by target.**

The second test was an Analysis of Covariance or ANCOVA. This test is used to test the main interaction effects of categorical variables on a continuous dependent variable, such as contrast. The covariate, along with detection distance, was Weber Contrast, as the difference in detection between red and blue targets is the focus. Because the research team was unable to swap the colors of the targets once the targets were in position, color becomes a nested variable within the target locations. Direction of travel was ignored in this analysis. With Weber Contrast as a covariate, the difference in detection between red and blue targets is significantly different ( $p = 0.009$ ).

Note that the ANCOVA only considered targets within the embedded lighting section. By using Weber Contrast as a covariate, only detections where a recorded luminance image of an identifiable target could be considered. This reduced the number of detections considered in the analysis from 188 to 121.

## Color Detection Distance and Weber Contrast



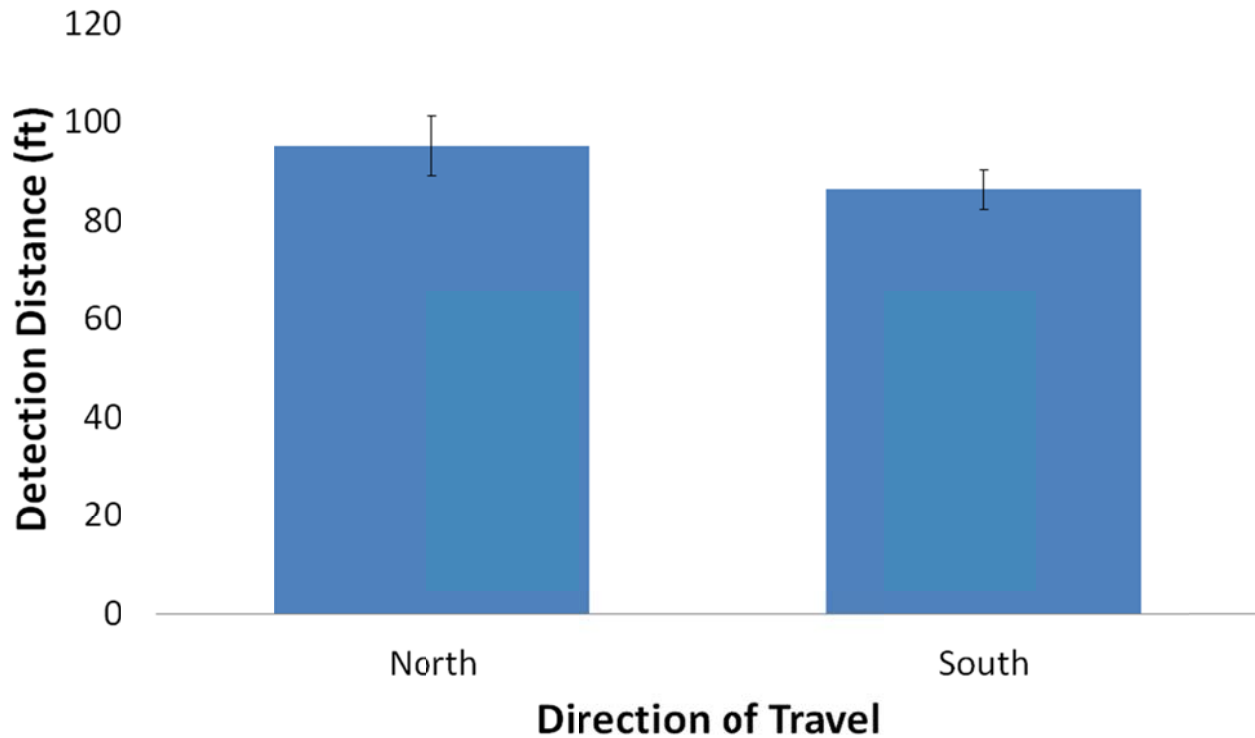
**Figure 26: Color detection distance and Weber Contrast.**

Blue targets were detected approximately 22 feet sooner than red targets and had a greater calculated Weber Contrast (Figure 26). Both red and blue targets had a positive contrast average, indicating the targets were brighter than their backgrounds. The blue targets likely stood out more to participants in the embedded lighting section due to the color temperature of the LEDs being closer to the blue region of the CCT scale. The positive contrasts may be due to the vehicle headlamps shining on the target.

The final of the three analyses focused on direction: north versus south. In this ANOVA, direction was isolated and differences in target color were not considered. The ANOVA did not find the directions to be significantly different (Figure 27).

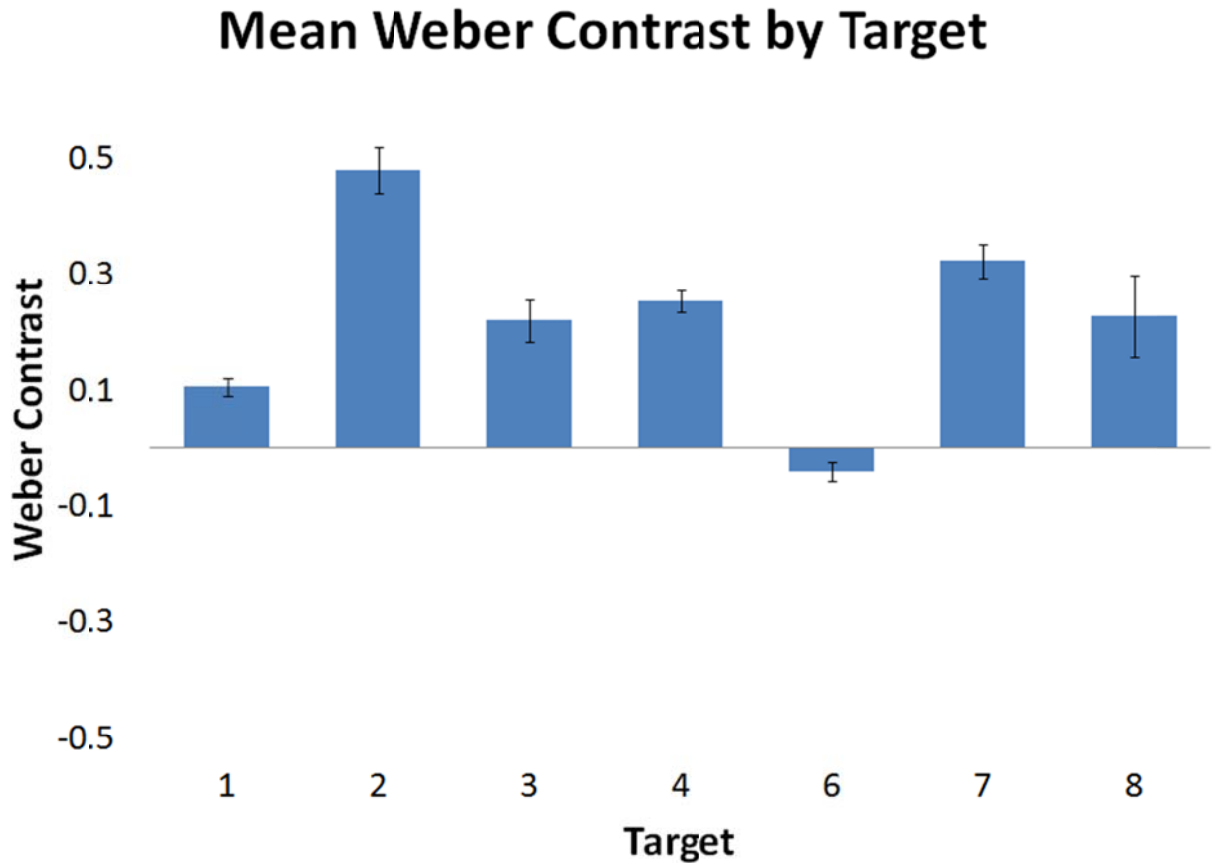


## Mean Detection Distance by Travel Direction



**Figure 27: Mean detection distance by direction.**

Figure 28 shows the results of calculated Weber Contrast by target. Target 5 was not included in this assessment because of its location in a dark area; images taken of the target during the on-site characterization were not adequate for analysis. Much like the luminance measurements taken of the targets placed between two luminaires in the characterization section, these same measurements were conducted of the targets used during the participants' detection portion.



**Figure 28: Mean Weber Contrast by target.**

### Subjective Assessment

The survey questions are listed here:

1. The lighting on the road is very comfortable for the purpose of driving.
2. The lighting on the road is distracting for the driver at night.
3. The lighting on the road is free from glare for drivers at night.
4. The lighting arrangement on the road makes it easy to drive at night.
5. The lighting arrangement on the road makes it easy for drivers to see vehicles in front.
6. The lighting arrangement on the road makes it easy for drivers to see vehicles in rear.
7. The lighting arrangement on the road makes it hard for drivers to see vehicles to the sides.

8. The lighting arrangement on the north bound lanes is better than the one in the south bound lanes.
9. Glare in the south bound lanes is less than the glare in the north bound lanes
10. The lighting arrangement on the north bound lanes is less distracting than the south bound lanes.

Table F contains the answers provided by participants.

**Table F: Questionnaire Responses**

Question	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Average Answer
1	3 (8.1%)	7 (18.9%)	8 (21.6%)	12 (32.4%)	7 (18.9%)	3.35
2	4 (10.8%)	10 (27.0%)	10 (27.0%)	8 (21.6%)	5 (13.5%)	2.94
3	4 (10.8%)	7 (18.9%)	6 (16.2%)	15 (40.5%)	5 (13.5%)	3.33
4	4 (10.8%)	8 (21.6%)	8 (21.6%)	12 (32.4%)	5 (13.5%)	3.22
5	2 (5.4%)	2 (5.4%)	16 (43.2%)	14 (37.8%)	3 (8.1%)	3.44
6	4 (10.8%)	9 (24.3%)	14 (37.8%)	8 (21.6%)	2 (5.4%)	2.92
7	5 (13.5%)	12 (32.4%)	6 (16.2%)	12 (32.4%)	2 (5.4%)	2.78
8	2 (5.5%)	10 (27.7%)	16 (44.4%)	8 (22.2%)	0 (0%)	2.80
9	2 (5.4%)	12 (32.4%)	13 (35.1%)	10 (27.0%)	0 (0%)	2.81
10	4 (10.8%)	10 (27.0%)	13 (35.1%)	10 (27.0%)	0 (0%)	2.83

Though survey results indicated no significant lean toward the lighting either positively or negatively, comments made on the survey do seem to indicate a general lack of acceptance for the technology.

**Comment 1:** *Lighting seems to be at wrong height for “normal” vehicles- better if driver is in higher-sitting vehicles*

**Comment 2:** *The lighting makes it difficult to differentiate oncoming cars when attempting to merge onto the highway. The glare from the lights on the opposite lane of traffic (oncoming) is*

*distracting. Would like the lights put at different angle or perhaps colored in some way to differentiate traffic better.*

**Comment 3:** *The lighting on I-25 is a severe distraction. It seems to have vehicles coming at you in all directions*

**Comment 4:** *I think the overall lighting is uncomfortable to drive against*

**Comment 5:** *I feel the lighting gives off a strobe light effect which is distracting*

However, two commenters did appreciate the lighting system.

**Comment 6:** *I think the light on the highway are cool I didn't see anything wrong*

**Comment 7:** *The lighting is very useful to drivers on the road*

Two other commenters left notes about the study protocol itself.

**Comment 8:** *Saw the targets once the headlights hit them*

**Comment 9:** *Cones felt like they distracted my view of the targets. Perhaps if no cones I could have reacted faster*

## DISCUSSION

Considering the detection distance results for the embedded lighting system section, the furthest average target detection was 145 feet and the closest was 80. In Table G, comparisons are made of the results in Trinidad with the results in San Jose, San Diego, Seattle, and Anchorage. The targets in each direction in Trinidad were combined and averaged so that the orientations of the northbound and southbound lighting systems could be represented separately.

Note that differences in average detection distances in Table G can be attributed to variability in lighting design, wattage, road geometry, environmental background, target color, and participant protocol. The most similar background environment to Trinidad is San Jose.

**Table G: Detection Distances of Luminaires from Similar Evaluations**

Location	Luminaire Type	CCT & System Type	~Avg Target Detection Distance (ft.)
<b>San Jose, CA</b>	LED	5000K Overhead	233
<b>San Jose, CA</b>	LED	4000K Overhead	223
<b>Anchorage, AK</b>	LED	4100K Overhead	213
<b>Anchorage, AK</b>	LED	4300K Overhead	210
<b>San Jose, CA</b>	Induction	4000K Overhead	197
<b>San Jose, CA</b>	HPS	2100K Overhead	193
<b>San Jose, CA</b>	LPS	1700K Overhead	190
<b>Anchorage, AK</b>	Induction	4000K Overhead	174
<b>Anchorage, AK</b>	LED	3500K Overhead	167
<b>San Jose, CA</b>	LED	3500K Overhead	157
<b>Seattle, WA</b>	LED	4100K Overhead	145
<b>Anchorage, AK</b>	HPS	2000K Overhead	141
<b>Seattle, WA</b>	LED	4000K Overhead	138
<b>San Diego, CA</b>	LED	3500K Overhead	135
<b>San Diego, CA</b>	Induction	3000K Overhead	131
<b>San Diego, CA</b>	HPS	2100K Overhead	128
<b>San Diego, CA</b>	Induction	3000K Overhead	125
<b>Seattle, WA</b>	LED	5000K Overhead	122
<b>San Diego, CA</b>	LED	3500K Overhead	105
<b>Seattle, WA</b>	HPS	2000K Overhead	103
<b>Seattle, WA</b>	LED	3500K Overhead	100
<b>Trinidad, CO</b>	LED	Embedded Cross	95
<b>Trinidad, CO</b>	LED	Embedded Forward	86
<b>Seattle, WA</b>	HPS	2000K Overhead	68

As the table shows, the detection distances in Trinidad fall far below the average of this assessment type. This means that the system is not as effective at highlighting targets as other systems. This may impact the public but the relationship of detection of safety is not deterministic. Target 5 was placed in a dark section of the highway and was detected at approximately 175 feet, which is almost double the distance of the average target placed in the embedded lighting section.

The short detection distances suggest that the vehicle's headlamps interacting with the targets may be more responsible for the targets' visibility than the embedded lighting system.

Significant differences between blue and red target detection distances indicate what would be expected from a white light system. One appeal of LED lighting is the absence of the amber hue of conventional HPS lighting. LED can produce a whiter light, which is assumed to be better for color recognition. Per the XY Chromatic Diagram in Figure 29, HPS luminaires typically fall in the CCT range of 2000K to 2500K on the Planckian curve. Most white light LEDs start at 3500K and go as high as 6000K for a pure white ambience. The colors along the Planckian curve are more visible at these color temperatures due to spikes in the wavelengths of the human visual spectrum.

Although the detection distances and lane characterizations suggest that the lighting system is insufficient for detecting small objects at a safe stopping distance, the questionnaires resulted in a neutral reaction to the system. The comments, however, were overall critical of the lighting system. Comment 1, for example, complained that the height of the luminaires was impacting drivers of smaller vehicles whereas larger vehicles and trucks would not encounter the same handicaps. The height characterization completed in this study indicates that the lighting varies by each direction and lane, but more light appears to be focused at approximately 39 inches from the ground. Common sedans, for example a 2013 Chevrolet Malibu or 2014 Ford Fiesta, reach a total height of only about 58 inches.<sup>(4,5)</sup> Where the lighting system may focus on the door of a larger vehicle, the lighting may intrude into the vehicle or reflect from side mirrors of a smaller vehicle and cause distraction.

Commenter 2 complains that the lighting can cause confusion when merging and suggests that a different color LED may mitigate this effect. White light such as that on the I-25 test section is preferred for color recognition and target detection. Adjusting the color temperature of the lighting system would likely decrease its effectiveness to discern color. However, adjustments in the size of the light fixtures, their aim, and their spacing could eliminate this confusion effect. These adjustments may also satisfy the complaints of Commenters 3, 4, and 5.

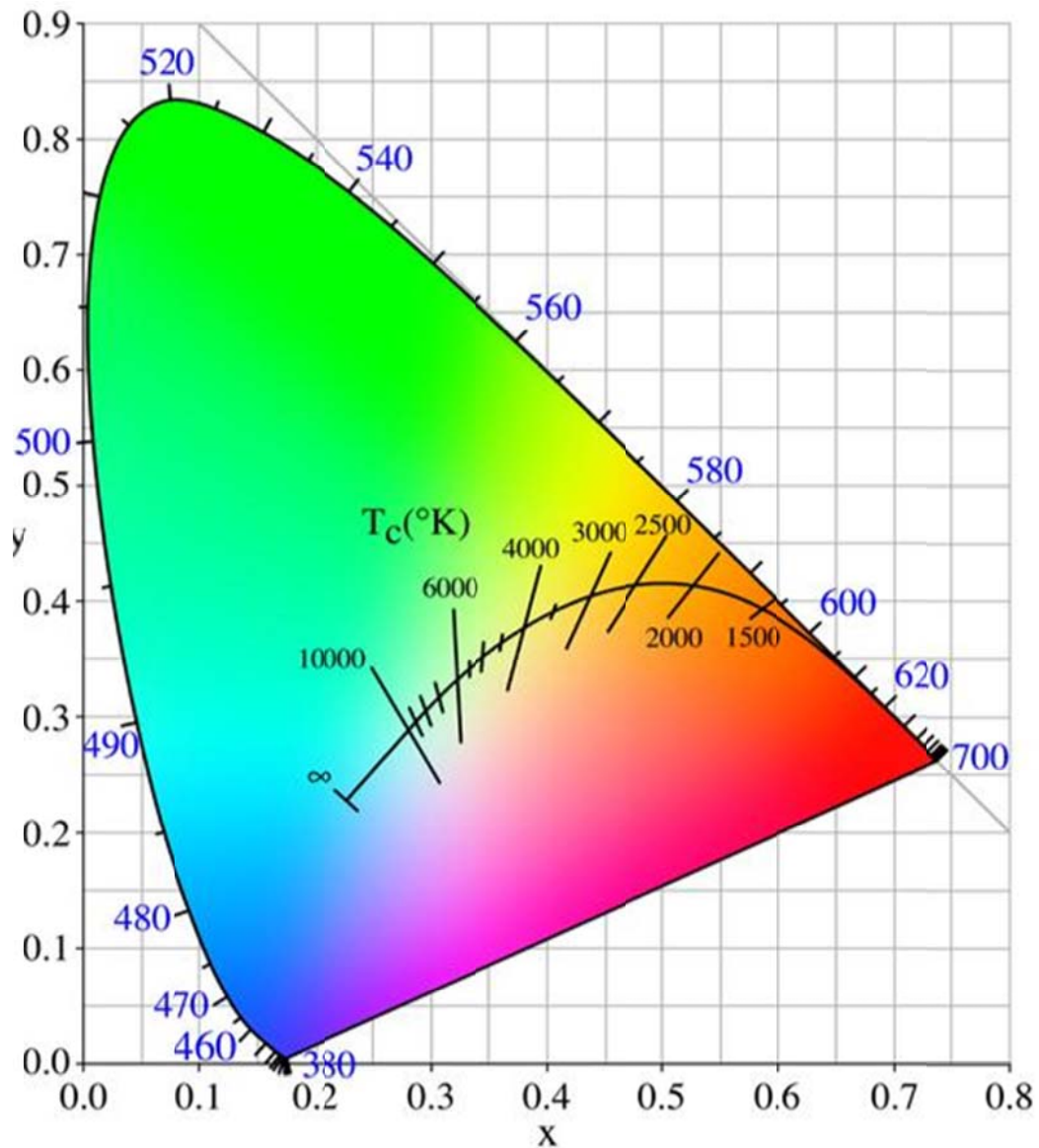


Figure 29: XY chromatic diagram (source: CIE).<sup>(6)</sup>

Another concern about the lighting system was brought to the attention of researchers during a casual observation of the system after a snowstorm. The snow tends to become compacted around the fixture, thus preventing the light from being fully projected outward onto the intended roadway area (Figure 30). The design of the barricade itself appears to be partly responsible for trapping the snow around the fixture. Further study into this effect may be required to determine the impact on the visibility.



**Figure 30: Embedded lighting system and snow.**



## CONCLUSION

The forward-aimed southbound lanes and cross-aimed northbound lanes did not exhibit a significant difference. The system aimed across the road promoted a greater detection distance versus the system aimed at a forward angle, though there was only a 9-foot difference. Due to the beam angle of the forward-aimed system, there is a high likelihood that a specific position between two of the luminaires exists where the light is more focused, thus producing greater contrast and detection distance. However, it is believed that none of the targets placed along the roadway for this experiment were in that position. Referring back to Figure 7 and Figure 8, the spikes in the illuminance measurements are indicative of a beam's focal point. In Figure 9 and Figure 10, these spikes are more obvious as the northbound lighting system is aimed straight across the road and directly at the side of the passing vehicle. Unfortunately, due to the timing of the study and a pending snowstorm, characterizations of the lighting system were not completed until after the completion of the participant portion. The results of characterization of the system might have led to changes in the object positions, and might have found a high point in the data, but it did not impact the average results.

Despite the non-significant differences in the aim of the lighting system, neither produced an average detection distance comparable with that of conventional overhead roadway lighting. The system produces minimal glare to drivers, and prevents light from escaping the roadway and trespassing beyond the roadway barriers and onto the town areas adjacent to the viaduct; however, improvements to the system must be made in regard to the lower detection distances.

The subjective assessment of the participants resulted in overall neutral results. However, criticisms posed in the comments section are worth investigating. Questionnaire comments suggesting that the lighting system is a distraction paired with results that suggest vehicle headlamps are primarily responsible for target detection indicate an opportunity for reconsidering the design of the lighting system. Though not mentioned by participants, a strobe effect was observed by experimenters and may be of concern to those with a history of epilepsy. The possibility of distraction should not pose an increased risk to the public, and the potential for Epileptic response is relatively low.

Future research should address these concerns with adjustments in light color, spacing, and aim.

The recommended activities are:

- Research adjustments in color temperature.
  - Could mitigate confusion with headlamps for merging traffic
  - May alter contrast of potential hazards, increasing visibility on concrete overpass
- Research adjustments in spacing.
  - Could also mitigate confusion with headlamps for merging traffic
- Research adjustments in aiming and orientation.
  - Other angles could relieve distraction and discomfort experienced by some
  - Vertical adjustments may mitigate strobe effects
- Research adjustments in beam width.
  - Current system has narrow focal point
  - Could increase uniformity of roadway

All of these proposed adjustments have the potential to increase visibility.

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