VTRC
Virginia Transportation Research Council

We Bring Innovation to Transportation

Use and Worker Perceptions of Wearable Lighted Apparel

https://vtrc.virginia.gov/media/vtrc/vtrc-pdf/vtrc-pdf/27-R02.pdf

Brian M. Williams, Research Associate
Virginia Tech Transportation Institute

Andrew J. Kassing, Senior Research Specialist
Virginia Tech Transportation Institute

Rugved S. Kore, Ph.D., Senior Research Associate
Virginia Tech Transportation Institute

Sarah E. Robinson, Program Manager
Virginia Tech Transportation Institute

Ronald B. Gibbons, Ph.D., Program Leader
Virginia Tech Transportation Institute

Final Report VTRC 27-R02

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454
vtrc.virginia.gov

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 27-R02	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Use and Worker Perceptions of Wearable Lighted Apparel		5. Report Date: July 2026 6. Performing Organization Code:
7. Author(s): Brian M. Williams, Andrew J. Kassing, Rugved S. Kore, Ph.D., Sarah E. Robinson, Ronald B. Gibbons, Ph.D.		8. Performing Organization Report No.: VTRC 27-R02
9. Performing Organization and Address: Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903		10. Work Unit No. (TRAIS): 11. Contract or Grant No.: 125841
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation 1221 E. Broad Street Richmond, VA 23219	Federal Highway Administration 400 North 8th Street, Room 750 Richmond, VA 23219-4825	13. Type of Report and Period Covered: Final Contract 14. Sponsoring Agency Code:

15. Supplementary Notes:
This is an SPR-B report.

16. Abstract:

In 2023, fatalities that involved workers on foot being struck by a vehicle accounted for 60% of all fatal highway worker injuries (National Work Zone Safety Information Clearinghouse, n.d.). Increasing the visibility of road workers to oncoming drivers may help reduce this crash risk. Wearable lighted apparel has the potential to increase the visibility of road workers, but its impact on visibility and any potential drawbacks are not well understood. Additionally, regulations and codes governing safety apparel and the use of lights within work zones do not specifically address personal lighted apparel, so it is unclear how it fits within current standards. This study sought to fill these gaps in knowledge. First, a market review was conducted to determine the range of lighted apparel options currently available. Second, a review of legal and regulatory barriers was conducted to determine what types of lighted apparel may be allowed under current standards. Third, a closed-course human factors study was conducted to gather both objective and subjective measures of worker visibility using a variety of lighted apparel options. Fourth, a field study was conducted to gather user feedback from road workers who used various lighted apparel devices.

Fourteen different lighted apparel ensembles (including one no-lighting baseline ensemble) were selected for inclusion in the closed-course testing. The ensembles utilized three distinct lighted apparel devices (a lighted vest, a helmet light, and a shoulder-mounted light) in various configurations so that the impact of various aspects of lighted apparel could be tested. These included the lighting design (where the light was located on the worker), the light color (amber, green, red, or white), the flash pattern (flashing or steady-on), and intensity (high or low). Closed-course testing was conducted on the Virginia Smart Roads Highway test track. Three simulated work zones of varying complexity were set up. Within each work zone, an experimenter acting as a worker wore one of the selected ensembles. Participants drove an experimental vehicle along the test track and verbally indicated when they could first detect a worker in a work zone. The detection distance was measured using the differential GPS coordinates of the vehicle at the time of detection. Participants drove 15 laps to ensure that they saw each ensemble within each work zone. Results indicated that a combination of lights on the torso and lights on the head significantly improved detection distance in medium- and high-complexity work zones when compared to the standard retroreflective safety apparel. Green lights significantly improved detection distance across all conditions. Steady-on lights performed significantly better than flashing lights in the high-complexity work zone, but no difference was found in low- and medium-complexity work zones. No consistent effect of intensity was found.

The field study equipped Virginia Department of Transportation and contractor personnel with a subset of five ensembles for use in their daily activities. Feedback was gathered through surveys and a focus group discussion. Users agreed that green was the most effective color. Users also tended to prefer the helmet-mounted lights over torso or shoulder-mounted lights. Users indicated a desire for more flashing options. Based on the results of this study, the research team recommends using a green, steady-on, helmet-mounted light to increase the visibility of road workers.

17 Key Words:	18. Distribution Statement:
Personal protective equipment, work zone safety, work zones, occupational safety, visibility	No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.

19. Security Classif. (of this report):	20. Security Classif. (of this page):	21. No. of Pages:	22. Price:
Unclassified	Unclassified	71	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL REPORT

USE AND WORKER PERCEPTIONS OF WEARABLE LIGHTED APPAREL

Brian M. Williams
Research Associate
Division of Technology Implementation
Virginia Tech Transportation Institute

Andrew J. Kassing
Senior Research Specialist
Division of Technology Implementation
Virginia Tech Transportation Institute

Rugved S. Kore, PhD.
Senior Research Associate
Division of Technology Implementation
Virginia Tech Transportation Institute

Sarah E. Robinson
Program Manager
Division of Technology Implementation
Virginia Tech Transportation Institute

Ronald B. Gibbons, PhD.
Program Leader
Division of Technology Implementation
Virginia Tech Transportation Institute

VTRC Project Manager
Benjamin Cottrell, P.E., Virginia Transportation Research Council

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

July 2026

VTRC 27-R02

DISCLAIMER

The project that is the subject of this report was done under contract for the Virginia Department of Transportation, Virginia Transportation Research Council. The contents of this report reflect the views of the author(s), who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

Each contract report is peer reviewed and accepted for publication by staff of the Virginia Transportation Research Council with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

ABSTRACT

In 2023, fatalities that involved workers on foot being struck by a vehicle accounted for 60% of all fatal highway worker injuries (National Work Zone Safety Information Clearinghouse, n.d.). Increasing the visibility of road workers to oncoming drivers may help reduce this crash risk. Wearable lighted apparel has the potential to increase the visibility of road workers, but its impact on visibility and any potential drawbacks are not well understood. Additionally, regulations and codes governing safety apparel and the use of lights within work zones do not specifically address personal lighted apparel, so it is unclear how it fits within current standards. This study sought to fill these gaps in knowledge.

First, a market review was conducted to determine the range of lighted apparel options currently available. Second, a review of legal and regulatory barriers was conducted to determine what types of lighted apparel may be allowed under current standards. Third, a closed-course human factors study was conducted to gather both objective and subjective measures of worker visibility using a variety of lighted apparel options. Fourth, a field study was conducted to gather user feedback from road workers who used various lighted apparel devices.

Fourteen different lighted apparel ensembles (including one no-lighting baseline ensemble) were selected for inclusion in the closed-course testing. The ensembles utilized three distinct lighted apparel devices (a lighted vest, a helmet light, and a shoulder-mounted light) in various configurations so that the impact of various aspects of lighted apparel could be tested. These included the lighting design (where the light was located on the worker), the light color (amber, green, red, or white), the flash pattern (flashing or steady-on), and intensity (high or low).

Closed-course testing was conducted on the Virginia Smart Roads Highway test track. Three simulated work zones of varying complexity were set up. Within each work zone, an experimenter acting as a worker wore one of the selected ensembles. Participants drove an experimental vehicle along the test track and verbally indicated when they could first detect a worker in a work zone. The detection distance was measured using the differential GPS coordinates of the vehicle at the time of detection. Participants drove 15 laps to ensure that they saw each ensemble within each work zone. Results indicated that a combination of lights on the torso and lights on the head significantly improved detection distance in medium- and high-complexity work zones when compared to the standard retroreflective safety apparel. Green lights significantly improved detection distance across all conditions. Steady-on lights performed significantly better than flashing lights in the high-complexity work zone, but no difference was found in low- and medium-complexity work zones. No consistent effect of intensity was found.

The field study equipped Virginia Department of Transportation and contractor personnel with a subset of five ensembles for use in their daily activities. Feedback was gathered through surveys and a focus group discussion. Users agreed that green was the most effective color. Users also tended to prefer the helmet-mounted lights over torso or shoulder-mounted lights. Users indicated a desire for more flashing options. Based on the results of this study, the research team recommends using a green, steady-on, helmet-mounted light to increase the visibility of road workers.

FINAL REPORT

USE AND WORKER PERCEPTIONS OF WEARABLE LIGHTED APPAREL

Brian M. Williams
Research Associate
Division of Technology Implementation
Virginia Tech Transportation Institute

Andrew J. Kassing
Senior Research Specialist
Division of Technology Implementation
Virginia Tech Transportation Institute

Rugved S. Kore, PhD.
Senior Research Associate
Division of Technology Implementation
Virginia Tech Transportation Institute

Sarah E. Robinson
Program Manager
Division of Technology Implementation
Virginia Tech Transportation Institute

Ronald B. Gibbons, PhD.
Program Leader
Division of Technology Implementation
Virginia Tech Transportation Institute

INTRODUCTION

While the number of fatal highway worker injuries has decreased each year since 2019, the percentage of these fatalities involving workers on foot being struck by a vehicle has been increasing, accounting for nearly 60% (40 fatalities) in 2023 (National Work Zone Safety Information Clearinghouse, n.d.). Increasing the visibility of road workers to oncoming traffic may reduce the risk of crashes. The Federal Highway Administration (FHWA), via the Manual of Uniform Traffic Control Devices (MUTCD), and the Occupational Safety and Health Administration (OSHA) mandate the use of high-visibility safety apparel for road workers. High-visibility safety apparel typically consists of conspicuous colors and passive retroreflective treatments attached to vests, jackets, and other apparel. With the advent and advancement of LED technology, high-visibility safety apparel with integrated LEDs is now also widely accessible. Lighted apparel has the potential to increase worker visibility beyond standard high-visibility apparel, but the effects and regulations around their use remain in question.

PURPOSE AND SCOPE

This project sought to provide recommendations to the Virginia Department of Transportation (VDOT) for the use of lighted apparel. This was accomplished by understanding the types of lighted apparel currently commercially available, reviewing the various standards and regulations which may govern their use, determining their impact on worker visibility through human factors testing on a closed-course test track, and gathering feedback from workers through a field study.

METHODS

Literature, Market, and Regulatory Review

As part of this project, three separate reviews were conducted:

1. A literature review focusing on human visibility and previous lighted apparel research;
2. A review of the current state of commercially available lighted apparel, including availability, functionality, and cost; and
3. A review of regulations and standards that apply to worker apparel.

Literature Review

To understand how wearable lighted apparel might increase the detection of workers in a work zone, the literature review focused on the visual detection of the human form in biomotion.

Market Review

The project team conducted a thorough review of all wearable lighting technologies, including vests, jackets, pants, and helmet-mounted lighting, among others. The project team found that several vendors offered similar products and therefore categorized the products by their specifications. The team categorized all elements of the wearable lighted apparel, including color, shape, material, weight, and clothing type (vest, hat, straps, etc.), as well as whether the lighting elements hinder or obstruct breakaway features. These factors were compiled in spreadsheet format. During this task, the project team gave special consideration to the lighted portions of each piece of apparel, considering whether the lighting was visible, enhanced the apparel, and did not detract from the retroreflective aspects of the clothing.

Regulatory Review

The project team conducted a thorough review of the existing regulations, guidelines, and industry-accepted standards to understand any legal barriers or hurdles that might influence the adoption of wearable lighted safety apparel in Virginia. During the review, team members identified areas of focus within the Manual on Uniform Traffic Control Devices (MUTCD) (Federal Highway Administration, 2023) and the Virginia Work Area Protection Manual (VWAPM) (Virginia Department of Transportation, 2026a) that discussed, either directly or tangentially, wearable lighted apparel. The VWAPM is Virginia's version of the MUTCD Part 6; FHWA has determined that the VWAPM is in "substantial conformance" with the Federal requirements.

Closed-course Testing

A human factors study was conducted on the Smart Road's Highway test track to gather objective and subjective measures of performance of various lighted apparel. The following section describes the experimental design variables, the equipment and facilities that were utilized, the experimental procedures, and the data reduction and analysis methods.

Experimental Design Variables

Independent Variables

Several independent variables were manipulated or controlled within the experimental design to determine their impact on the performance of lighted apparel. Table 1 lists each factor and factor level, which are discussed in further detail below.

Table 1. Independent Variables

Factor	Type	Levels
Work Zone Complexity	Within Subject	Low
		Medium
		High
Worker Task	Within Subject	Worker
		Flagger
Lighting Design	Within Subject	No lighting (retro-only)
		Torso
		Head
		Shoulder
		Shoulder × 2
		Head + Torso
		Shoulder + Torso
Lighting Color	Within Subjects	Amber
		Green
		Red
		White
Light Intensity	Within Subject	High
		Low
Flash Pattern	Within Subject	Flashing
		Steady-on
Observer Age	Between Subjects	Younger
		Older

- **Work Zone Complexity** – Three levels (Low, Medium, High). Three simulated work zones of different complexities were set up on the Smart Roads so that the impact of the lighted apparel could be established in scenarios of varying visual complexity. Detailed descriptions of the work zones are found in the Equipment and Facilities section of this report.

- **Worker Task** – Two levels (Worker, Flagger). Workers wearing lighted apparel were divided into two groups based on the task they were performing to determine if the lighting needs varied based on how exposed the worker was.

- **Lighting Design** – Seven levels (No Lighting, Torso, Head, Shoulder, Shoulder × 2, Head + Torso, Shoulder + Torso). Lighting design referred to the location of the light on the worker. This was included to determine how light placement or combinations of lights affected worker visibility.

- **Lighting Color** – Four levels (Amber, Green, Red, White). Four lighting colors were included to determine the effect of color on worker conspicuity.

- **Lighting Intensity** – Two levels (High, Low). Two levels of intensity were included to determine the impact of intensity on worker conspicuity. The high intensity (58 candelas) represented the maximum intensity of one device, while the low intensity (14 candelas) represented a lower intensity option on the same device.

- **Flash Pattern** – Two levels (Flashing, Steady-on). Two types of flash pattern were included to determine the impact on worker conspicuity.

- **Observer Age** – Two levels (Younger, Older). Participants were divided into two age groups: younger participants (18–34 years old) and older participants (65+ years old). These groups were selected because they represent the extreme ends of the driving public. Younger drivers tend to have better vision but less driving experience, while older drivers tend to have worse vision but extensive driving experience.

Dependent Variables

The primary dependent variable was an objective measure of performance called detection distance. Detection distance was defined as the distance between the participant vehicle and the worker at the moment a participant first detected them. Precise details of how detection distance was measured are included in the Experimental Procedures section of this report. Secondary assessments of the lighted apparel included subjective evaluations of visibility and selecting the most effective ensemble for a given scenario.

Equipment and Facilities

Lighted Apparel

During Task 1, the research team performed an extensive review of available lighted apparel that informed the selection of ensembles for closed-course testing. Table 2 outlines the market-available materials (both lighted and non-lighted) that were selected for use in this study. These items were selected for their compliance with VDOT standards, their features, and cost. These products were used to create the 14 specific ensembles, which were tested. Photometric characterizations were performed for each of the devices. The procedures for these tests are discussed later in this section, and the outcomes are discussed in the Results section.

Table 2. Worker Apparel

Apparel Location	Photo	Product Name	Price
Head		Kask Zenith X2 Type II Class E Non-Vented Yellow Safety Helmet w/ Reflective Stickers (not pictured)	$178
		Coast LHS500R Headlamp	$60
Shoulder		Guardian Angel Elite Series Safety Light	$115
Torso		Stop-Lite ANSI Class 3 Vest w/ 16 white LEDs	$55
Legs		701CSLM Lightweight Poly Mesh Hi-Vis Pants	$17

Ensembles

Figure 1 shows each of the 14 unique ensembles. All ensembles used the helmet with reflective stickers, the ANSI Class 3 vest (with lights turned off), and the hi-vis pants as the baseline ensemble, consistent with the VWAPM's personal protective equipment (PPE) requirements for workers in temporary traffic control zones (which are more stringent than the requirements of the Federal MUTCD). These ensembles were strategically selected to allow for examination of the four factors of interest, which included lighting design, lighting color, lighting intensity, and light behavior, while also maintaining a relatively manageable number of ensembles. Table 3 shows how subsets of ensembles were grouped to isolate the factors of interest.

Figure 1. Photos of the 14 Tested Ensembles

Table 3. Ensembles and Factor Groupings

Ensemble	Factor			
	Lighting Design	Lighting Color	Lighting Intensity	Light Behavior
Retro	Control	NA	NA	NA
Vest	Torso	NA	NA	NA
White Helmet	Head	NA	NA	NA
White Shoulder	Shoulder	White	Low	NA
White Shoulder × 2	Two Shoulder	NA	NA	NA
White Shoulder Vest	Shoulder + Torso	NA	NA	NA
White Helmet Vest	Head + Torso	NA	NA	NA
White Shoulder MAX	NA	NA	High	NA
Green Shoulder	NA	Green	NA	NA
Green Shoulder × 2	NA	NA	NA	NA
Amber Shoulder	NA	Amber	NA	NA
Red Shoulder	NA	Red	NA	NA
Red Helmet	NA	NA	NA	Steady
Red Helmet Flashing	NA	NA	NA	Flashing

NA= not applicable

Test Vehicles

Participants drove a 2017 Ford Explorer (Figure 2) equipped with a data acquisition system (DAS). The DAS recorded vehicle information such as speed, throttle and brake status, multiple camera views inside and outside the vehicle, and differential GPS (DGPS) data. In-vehicle experimenters also had the ability to flag the data stream with a button press. During the study, the headlamps of the vehicle were controlled and kept on low beams to ensure conditions among participants remained the same.

Figure 2. VTTI Experimental Test Vehicle

Virginia Smart Roads Test Track

The closed-course test was conducted on the Virginia Smart Roads Highway test track (Figure 3). The highway is a 2.2-mile-long, two-lane roadway built to Virginia highway standards that offered ample sight distance for approaching drivers to evaluate lighted apparel visibility. Figure 3 shows a diagram of the test track with the locations of the simulated work zones. For each lap of the test track, participants drove the full length from Turn 1 to Turn 4 and back (4.4 miles), passing each work zone in both directions.

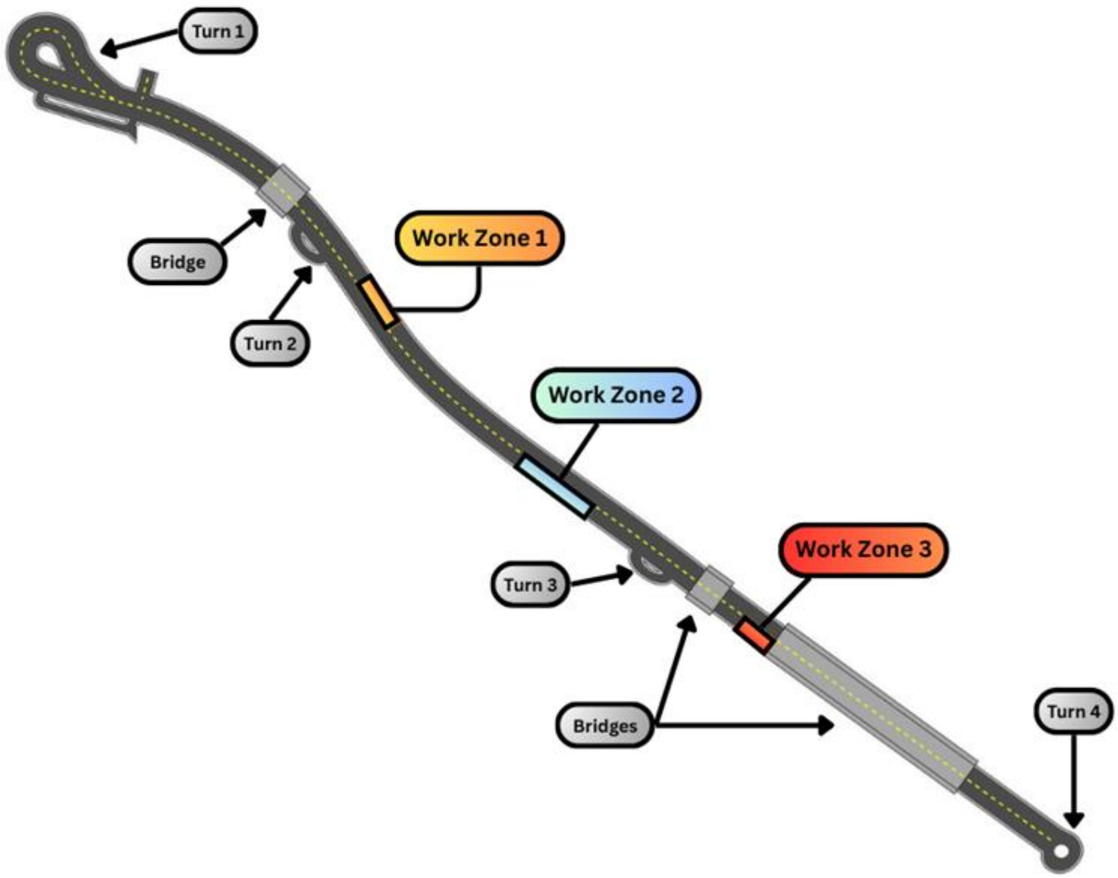

Figure 3. Virginia Smart Roads Highway Diagram with Simulated Work Zone Locations

Simulated Work Zone #1 (Medium Complexity)

The medium-complexity work zone (Figure 4) simulated a work zone of medium visual complexity such as the operation pictured in Figure TTC-4.0 of the VWAPM. This work zone simulated a shoulder closure using reflective traffic cones to demarcate the work area. The total length of the work area was approximately 125 ft (25 ft taper and 100 ft work area). A white work truck with a flashing amber beacon was positioned inside the cones at the end of the cone taper with its headlamps and taillamps on. A single worker was positioned approximately 80 ft downstream of the truck, approximately 2 ft inside the cones.

Figure 4. Medium-complexity Work Zone Diagram (top) and Photo (bottom)

Simulated Work Zone #2 (High Complexity)

The high-complexity work zone (Figure 5) simulated a work zone of high visual complexity such as the operation shown in Figure TTC-23.0 of the VWAPM. This work zone simulated a lane closure on a two-way roadway requiring flaggers at each end. Reflective traffic cones were used to demarcate the work area, which was 300-ft long (100-ft tapers on each end and 100-ft work area in the middle). The flaggers, lit by balloon lights, were positioned on the shoulder of the road at the beginning of each taper. For the safety of research staff, mannequins were used for the flagger positions. To add visual complexity to the scene, two vehicles were placed within the work area straddling the white edge line. The first vehicle, positioned at the end of the first taper, was an orange pickup truck with a large amber and black retroreflective panel attached to the back to simulate the appearance of a truck-mounted attenuator. The second vehicle, positioned at the end of the second taper, was a white pickup truck. Both vehicles had aftermarket flashing amber beacons mounted to the roof (36-W, 2 Source 12-inch by 3-inch rectangular LED lighting system) and had their headlamps and taillamps on. The worker was positioned approximately 80 ft downstream of the first vehicle in the middle of the closed lane.

Figure 5. High-Complexity Work Zone Diagram (top) and Photo (bottom)

Simulated Work Zone #3 (Low Complexity)

The low-complexity work zone (Figure 6) simulated a work zone of low visual complexity such as a surveying or asset inspection operation in the shoulder. This work zone simulated a simple work area consisting of one vehicle and one worker on the shoulder of the road. The vehicle was a gold SUV equipped with an amber lightbar above the rear windshield, which flashed in a sequencing pattern flowing from the right to the left. The vehicle's headlamps and taillamps were also on. The worker was positioned approximately 80 ft downstream of the vehicle and just outside the white shoulder line.

Figure 6. Low-complexity Work Zone Diagram (top) and Photo (bottom)

Experimental Procedures

Participants

Participants were recruited via the Virginia Tech Transportation Institute's (VTTI's) private internal participant database, as well as through ads, email, and word of mouth. To qualify to participate, participants had to be between 18 and 34 or 65+ years old. They also had to have a minimum visual acuity of 20/40 and not have any medical conditions that would preclude them from participating. Participants also had to pass a simple hearing assessment to ensure they would be able to hear instructions from the experimenter during the experiment. The participant pool was gender and age balanced, with a total of 48 participants completing the study (12 older females, 12 older males, 12 younger females, and 12 younger males).

Orientation

Two participants were scheduled to participate simultaneously for each data collection session. When participants arrived at VTTI, they completed consent forms and then performed a Snellen visual acuity assessment and a simple hearing assessment in which they repeated sentences back to the experimenter. An experimenter then oriented the participants to the study procedures via a slide presentation and script, so that all participants received the same instructions.

Participants were then escorted to the two experimental vehicles parked on the test track, and oriented to the vehicle's seat and steering controls. They were then asked to make adjustments as needed to get into a comfortable driving position and to buckle their safety belt. An in-vehicle experimenter rode in the back seat of each vehicle to provide participants with instructions and to run the data collection equipment.

Practice Lap

Once both participants were ready, they were instructed to drive to the Highway portion of the test track, where they then completed a practice lap. The practice lap served several purposes: it gave participants an opportunity get accustomed to operating the vehicle prior to any study trials; it allowed the participants to see the three work zones and observe a worker within each so they had a clear understanding of what they would be looking for during the study; and it allowed the experimenter to identify key locations such as where the participant would need to change lanes or turn around. Participants were also encouraged to ask questions if anything was unclear.

Vehicle Movements

During data collection, the two participant vehicles were referred to as Vehicle 1 and Vehicle 2. For each lap of the test track, Vehicle 1 began its lap first while Vehicle 2 waited. After waiting approximately 30 s, Vehicle 2 began its lap. Each time Vehicle 1 reached the end of the test track, it would stop and wait for Vehicle 2, and then the process would repeat. This allowed the two vehicles to drive simultaneously while never passing each other and maintaining space between them so that the headlamps or taillamps of one participant vehicle did not interfere with the detection tasks of the other participant.

The speed limit for the study was 45 mph; however, for safety, participants were required to slow to 35 mph when driving through the lane closure at Work Zone 2. Additionally, for Work Zones 1 and 3, whenever a participant was traveling in the lane closest to the work zone, they were required to change lanes away from the work zone when passing it. A small green cone was placed on the shoulder of the road approximately 120 ft upstream of the work zone. Participants were instructed to change lanes after detecting the worker or at the green cone, whichever occurred first.

Worker Detection and Visibility Rating

While driving laps, participants were instructed to say "person" as soon as they could detect the presence of a worker within a work zone. "Person" was used as the identifying word because it was easier to say than "worker," and because it starts with a sharp sound, which aided data reduction. Participants were instructed to say "flagger" whenever they detected the presence of a flagger. Participants were only asked to detect the first flagger upstream of the work zone. Whenever a participant verbally identified a worker or flagger, the in-vehicle experimenter flagged the data with a button press. During data reduction, these button presses were used to identify the location of detection events in the data stream, and then reductionists reviewed the video/audio to find the precise moment of detection. The DGPS position of the vehicle at this moment was then compared to the known location of the worker/flagger to determine the detection distance for that scenario.

After detecting a worker, participants were also instructed to provide a subjective rating of how visible the worker was on a scale from 1 to 5 (Figure 7). The in-vehicle experimenter wrote down the answer on a note sheet. A copy of this rating scale was taped to the dashboard of the vehicle for participants to reference.

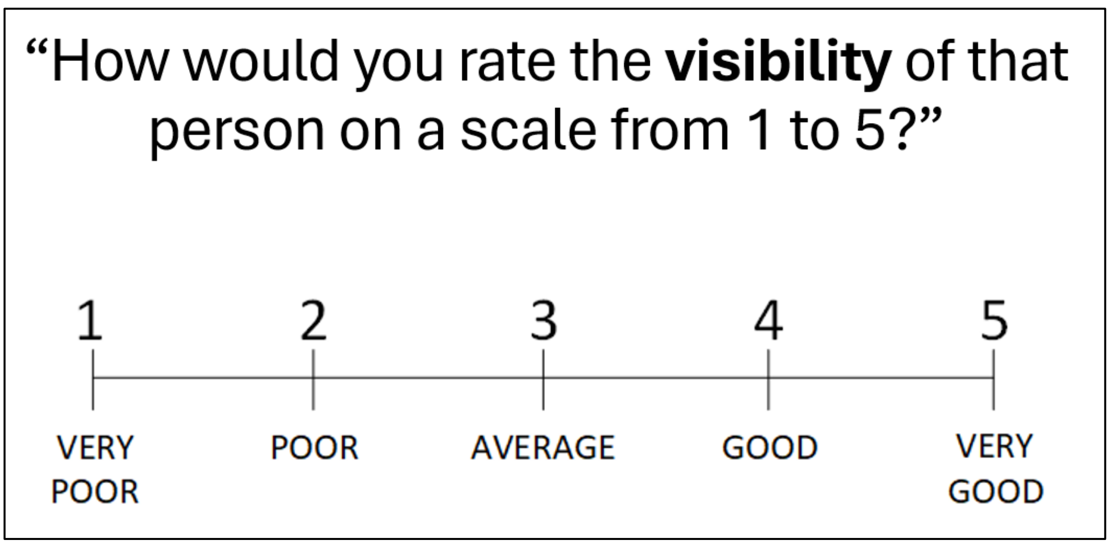

Figure 7. Visibility Rating Scale

Ensemble Presentations and Worker Movement

On-road experimenters acted as the workers within each work zone. Each lap, they donned a specific ensemble according to an order sheet. Each work zone utilized two semi-randomized order sheets to ensure that ensembles were seen in different orders across and within work zones, and between participants. Orders included "blank" trials during which no worker was present at the work zone so that participants could not always anticipate the presence of the worker. Table 4 shows an example of one order sheet.

On-road experimenters at Work Zone 2 (high complexity) were also responsible for changing the lighted apparel on the flagger mannequins according to their order sheets. Blank trials for the flaggers were achieved by covering the mannequins in a black curtain.

Table 4. Example Ensemble Presentation Order

Lap	Order 1
Pr	Retro
1	White Shoulder MAX
2	Red Helmet Flash
3	White Helmet
4	Vest
5	Red Shoulder
6	Amber Shoulder
7	Green Shoulder × 2
8	Red Helmet
9	White Shoulder Vest
10	White Helmet Vest
11	Retro
12	Blank
13	Green Shoulder
14	White Shoulder × 2
15	White Shoulder

At each work zone, on-road experimenters acting as workers paced back and forth within a 20-ft area parallel to the roadway. This pacing area was centered on the worker location, which was 80 ft downstream of the vehicle in the work zone (±10 ft). Figure 8 shows an example of the pacing area. When turning around, on-road experimenters alternated between turning clockwise and counterclockwise, ensuring that they were viewed from all possible angles as participants approached.

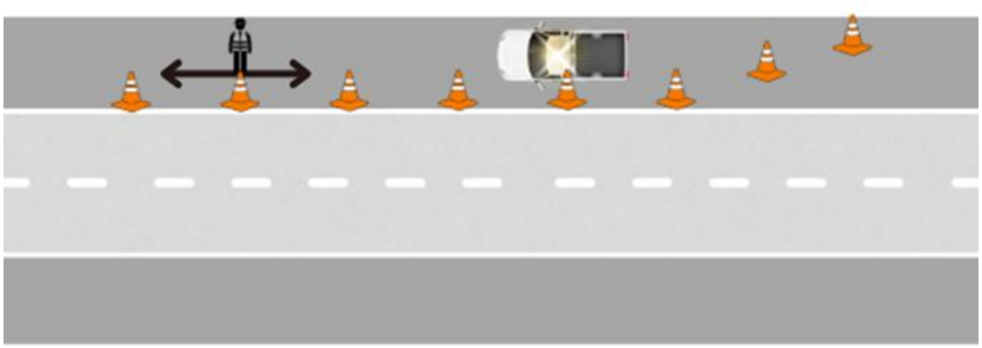

Figure 8. Example Worker Pacing Area

Driver Survey

Once participants had completed all laps, they were instructed to exit the highway test track and drive back to the VTTI building. Once the vehicle was parked, the in-vehicle experimenter handed the participant a series of photos that pictured a subset of the ensembles and asked them to pick the most effective one among the options shown (see the Supplemental Materials that accompany this document). Questions were designed to assess participants' preferences regarding the:

- Most effective lighting design
- Most effective lighting color
- Most effective lighting behavior
- Most effective ensemble for flaggers
- Most effective ensemble for workers inside or outside traffic cones
- Most effective ensemble overall

Data Reduction and Analysis

Participant data from each driving session was accessible only to specially trained reductionists through the proprietary data management software. Due to the confidential nature of participant information, the reductionists accessed and worked with the study data from a secure data reduction enclave. Reductionists used the data management software to view the video feeds inside and outside of the vehicle, audio from inside the vehicle, the vehicle's speed, and the button press indicator. Reductionists also referenced physical note sheets recorded by the in-vehicle experimenters when reviewing data files.

Reductionists used the button press indicators to locate each instance of a participant detecting a worker or flagger. They then played back the video and listened for the participant's verbal response and recorded the time stamp when the detection occurred. Detection was determined to occur at the moment the participant began to say the word "person" or "flagger." Each detection was logged in an Excel sheet, which tracked the time of detection, the corresponding visibility rating, and the lighted apparel conditions under which it was seen. Using MATLAB, the research team retrieved the DGPS coordinates of the vehicle at the moment of detection and calculated the distance of the vehicle to the worker or flagger (i.e., the detection distance). A reductionist familiar with the study reviewed the driver survey and transcribed the responses into Excel. The detection distance and survey datasets were then formatted for variable consistency and prepared for statistical modeling.

Statistical modeling sought to understand the relationship between lighted apparel and worker (or flagger) detection distance while also considering the driver preference and the user experience. The results from the closed course testing and driver survey tasks were modeled and analyzed separately. This research project utilized an experimental design containing fixed effects, random effects, and repeated measurements, which required multivariate mixed-effect models to fit the data. Therefore, linear mixed modeling (LMM) procedures were used. LMMs related the observed means (Y) against the fixed effect (X) and random effect (Z) design matrices by fitting a linear combination of random and fixed effects, which took the form shown in Figure 9, where $\boldsymbol{\beta}$ was a vector of fixed effect parameters, $\boldsymbol{\gamma}$ was a vector of random effects, and $\boldsymbol{\varepsilon}$ was a vector of random errors. For this analysis a separate model was developed for the evaluation of lighting design approach, color, flashing, intensity, and visibility rating. All models contained a subset of the following fixed effects: lighting design approach, color, flashing, intensity, and age in addition to participant-to-participant variation as a random effect.

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\boldsymbol{\gamma} + \boldsymbol{\epsilon}$$

Figure 9. Equation. Traditional Mixed Effects Linear Regression Equation

Post hoc testing was conducted using pairwise comparisons between least squares estimates of the treatment means. To ensure the study's significance level was preserved (0.05), all familywise comparisons were adjusted using Tukey's Honestly Significant Difference (HSD) methodology (Abdi & Williams, 2010). Some visualizations contain error bars, which represent the standard error obtained during least squares means estimation. Significant difference observed during pairwise comparisons is indicated on each visualization using uppercase letters above the model estimate bars, using a technique called compact letter display (Piepho, 2018). Model estimates sharing a letter of the same case are statistically similar. Difference in case or lettering indicates that the post hoc comparisons resulted in statistical significance with a *p*-value of $\alpha = 0.05$ or lower.

Photometric Characterization

Photometric characterizations were performed for each of the lighted apparel devices and are presented in the Results section. All characterization testing, except retroreflectivity measurements, was conducted in the dark laboratory at VTTI. The laboratory consisted of a dark tunnel with black walls and a length of approximately 20 ft and width of 5 ft to minimize stray reflections and ambient light. A mannequin was positioned at one end of the tunnel and was used to mount each lighted wearable apparel item in a consistent manner during testing.

Three wearable lighted apparel devices were evaluated: (1) the helmet light, (2) the lighted vest, and (3) the shoulder beacon. The helmet light was tested in white and red output modes. The lighted vest was tested in white mode. The shoulder beacon was tested in amber, white, green, and red, and at four light output settings (Levels 1–4), where Level 1 was the brightest and Level 4 was the dimmest.

Optical measurements in the dark lab were collected using a Konica Minolta CL- 500A spectrophotometer. It was used for spectral power distribution (SPD) measurement, profile comparison, intensity comparison, and battery life measurements.

Retroreflectivity-related measurements were conducted separately using an Ocean Optics HR2000+ ES measurement system. This system used Illuminant A as the reference light source and a fiber-optic-based collection system to measure light reflected back to the integrating sphere. These measurements were used to characterize the retroreflective tape and the green PPE material on the lighted vest.

Procedures

For dark laboratory testing, each wearable device was mounted on the mannequin in its intended wearing position. The spectrophotometer was fixed at a height of 3.5 ft and aligned toward the device under test. The same general setup was maintained across all measurements to support consistent comparisons among devices, colors, and intensity settings.

Prior to testing, each device was fully charged. For SPD, profile comparison, and intensity comparison, measurements were collected during a single test instance immediately after charging. For battery life testing, each device was again fully charged before the start of the test, after which the spectrophotometer was operated in logging mode to record measurements automatically at 5-min intervals over time.

For retroreflectivity measurements, the Ocean Optics system was used to evaluate the retroreflective tape and the green PPE material on the lighted vest. These measurements were conducted outside the dark lab optical characterization setup because they required a dedicated retroreflectivity measurement configuration and reference source. These measurements complemented the active light characterization by documenting the passive visibility-related properties of the vest materials.

Field Study and User Feedback

In addition to the closed-course testing, which evaluated the performance of the lighted apparel in terms of worker visibility, the research team sought to gain feedback from those who would be wearing the devices. Based on the results of the closed-course testing, 5 of the 14 ensembles were selected for inclusion in a field study. These included the lighted vest, the red helmet light (both flashing and steady-on options), the white shoulder beacon, and the green shoulder beacon (Figure 10). Ten of each device were provided to VDOT and contractor personnel, who were asked to use a particular ensemble during their daily work activities. After approximately 2 weeks, personnel were encouraged to fill out a survey regarding their experience. The devices were then rotated among the different work crews, and the process was repeated until everyone had used each ensemble.

Additionally, an in-person focus group was conducted at VDOT's Salem Traffic Operations Center offices, during which VDOT and contractor personnel discussed their experiences with the devices with the research team.

For the field study user survey, due to the low number of responses ($N = 12$) and incompleteness of the responses, formal statistical analyses could not be performed. Instead, responses from the survey were combined with feedback gathered during the focus group discussion, and the results of the user feedback are presented as general sentiments and thoughts provided by the users.

Figure 10. Ensembles Selected for the Field Study

RESULTS

Literature, Market, and Regulatory Review Results

Literature Review

Visual Detection of the Human Form

Research studies have identified the neural mechanisms involved in the perception of motion. The magnocellular (M) pathway in human eyes, responsible for detecting motion, mainly receives input from the peripheral retina where rods are predominant (Grossman & Blake, 2002). Rods are highly sensitive to light and function primarily in low-light environments (scotopic vision). Therefore, the distribution of rods and motion-detecting pathways in the peripheral retina contributes to faster detection of small proximal human motion in the dark compared to bright conditions (Cavanagh & Mather, 1989). Other factors contributing to the detection of motion in the dark include human attention and expectations, as well as the speed and direction of motion.

Attention significantly influences how we perceive motion. Our brains naturally prioritize information that is relevant or interesting, a phenomenon known as selective attention. Similarly, our expectations about how objects typically move, shaped by prior experiences, can also significantly impact our perception of motion. Humans are remarkably adept at recognizing and interpreting these patterns, even from little visual information like point-light displays where only the joints of a moving person are visible (Johansson, 1973; Barlow, 1978). Multiple research studies have confirmed that patterns of human motion, also known as biomotion, are a rich source of information to which the human visual system is particularly attuned (Bowden, 2000; Pollick et al., 2002; Pitcher & Ungerleider, 2021).

Thus, the form factor (reflective pattern) of a wearable lighting treatment or combination of treatments that are visible under low light conditions are critical to ensure the conspicuity of road workers or pedestrians to oncoming traffic. Retroreflective treatments placed along the extremities and the torso provide proximal motion patterns, such as the pendulum-like motion of wrist or ankle with respect to torso, which are essential information needed for immediate visual identification of human motion (Johansson, 1973; Balk et al., 2008).

Many studies using a variety of experimental designs have compared the use of retroreflective treatments for the extremities. These studies used various combinations of extremity treatments alongside the standard ANSI/ISEA 107-2020–recommended torso garments. Results showed that high-visibility safety apparel containing retroreflective treatments on the users' extremities provided 3 times more visibility of road workers in motion when compared to high-visibility safety apparel that had retroreflective markings only on the torso. These studies controlled for the surface area of retroreflective markings to better compare results across location of markings (Sayer & Mefford, 2004; Balk et al., 2008; Tyrrell et al., 2009 & Wood et al., 2011; Wood, 2023). Researchers also found that the ankles only and ankles plus wrist combination treatments were as effective as the full biomotion (torso plus wrist plus ankles) treatment. All treatments providing some retroreflective material to the extremities performed far better than no vest or vest (torso) only treatments (Balk et al., 2008; Tyrrell et al., 2009).

Studies have also found that the presence of visual clutter does not mask the influence of pedestrians wearing retroreflective material in biological motion configurations (Balk et al., 2008; Tyrrell et al., 2009; Wood et al., 2011). Even in the presence of glare from the headlights of oncoming traffic or emergency vehicle lighting, biomotion configurations were shown to maximize conspicuity (Wood et al., 2014). In contrast, the conspicuity of pedestrians wearing only a retroreflective vest was found to be as poor as for those wearing no reflective vest at all (Borzendowski et al., 2015).

Existing research indicated that humans are generally better at detecting motion in the horizontal and vertical directions compared to oblique directions (Ball & Sekuler, 1980). Road workers may move at varying speeds depending on their age, physical ability, and job function. Pedestrians might also change direction suddenly, especially if they are distracted or trying to avoid an obstacle. A study that used an eye-tracking system found that adding biomotion reflectors to the vest facilitated earlier recognition of pedestrians and faster identification of the direction that the pedestrian faced (Wood et al., 2017). It was found that stationary pedestrians could be at relatively more risk than moving pedestrians. A few studies compared visibility of a pedestrian wearing full biomotion in static versus moving conditions. Although some studies did not find a significant difference (Tyrrell et al., 2009), the consensus was that moving pedestrians with full biomotion were more visible to the oncoming traffic (Owens et al., 1994; Balk et al., 2008; Wood et al., 2011). The findings of the latter studies are also supported by clinical evidence that suggests that primary information channels in the visual system are more strongly activated by dynamic stimuli, leading to faster and more accurate recognition (Mauss et al., 2015).

Going beyond retroreflective striping, Fekety et al. (2016) examined nighttime conspicuity using electroluminescent patches on pedestrian extremities (wrist, knee, and ankle). Retroreflective materials require a beam of light to produce increased visibility, but electroluminescent materials do not. The research found that when electroluminescent materials were added to retroreflective apparel, pedestrians outside the headlights were visible from farther distances. This effect was particularly weak when the test pedestrian was positioned near an area illuminated by headlamps (Fekety et al., 2016).

Literature Review Summary

- Adding light sources to traditional retroreflective garments has been shown to increase worker conspicuity. The extent of this benefit is less understood, especially in low-light or visually cluttered environments.
- Studies have also found that the presence of visual clutter does not mask the influence of pedestrians wearing retroreflective material in biological motion configurations. This conclusion has not been tested for lighted apparel, and the influence of glare must be taken into consideration.
- The form factor of a wearable lighting treatment or combination of treatments is critical to ensure the conspicuity of road workers in low-light conditions. The optimal combinations of lighted treatments to increase worker conspicuity are significantly less understood. Furthermore, there are no use case recommendations for road workers to consider when selecting wearable lighted apparel.
- Current research has suggested that highlighting the human form with retroreflective material is the most effective way of making road users conspicuous. Research has shown that high-visibility retroreflective safety apparel with torso and head-only treatments provided significantly less benefit for road users in motion when compared to treatments containing biomotion configurations. Apparel with retroreflective treatments affixed to the extremities (wrist, elbow, knees, ankles, or shoes) increased the visibility of road workers in motion by 3 times (Wood et al., 2014).

This literature review indicated several gaps in research. The project team has formalized these gaps into the following list. Conclusions and insights gained during the research are also presented alongside the gaps.

Gaps in Existing Research

- There is minimal research investigating the extent to which lighted apparel improves the conspicuity of road workers in low-light conditions when compared to traditional retroreflective apparel.
- Existing research typically used lighted apparel torso or helmet treatments, but there appeared to be a gap in research utilizing any extremity treatments (wrist, elbow, thigh, or ankle) and how lighting specific body areas influences driver perception.
- There is also limited research on the effectiveness of full-biomotion lighted apparel configurations for enhancing the visibility and recognition of road workers in low-light environments.
- The project team did not identify any research that looked at variation in flash rate or pattern of lighted apparel. Additionally, there was a gap in investigating if the addition of lighted apparel increases disability glare among drivers.
- There were gaps in looking at full-biomotion lighted apparel compared to torso-only lighted apparel or full-biomotion retroreflective apparel.
- There was a lack of research into comparing the lighting method of illuminating the road worker. The project team did not find any research comparing the use of wearable lighted apparel against electroluminescent safety apparel.
- There was a lack of research investigating the use of personal mounted lighting devices in low-light work environments. The project team did not identify any studies investigating the use of multiple personal lighting devices to perform several functions simultaneously (i.e., task lighting and hazard lighting).
- In general, there was very little published research considering the wearability and user acceptance aspects of lighted apparel. More specifically, existing research has not established if there are types of lights that the road worker perceives as more comfortable, effective, or even a hindrance to their job function.

Market Review

An overview of commercially available wearable lighted apparel appears in Table 5. Products were found to be available for users to wear on their head, torso, legs, and extremities. Table 5 provides the ranges of product cost, weight, and lighting factors. The project team also provided an assessment of product availability and a subjective evaluation of the viability of including wearable lighted apparel products of each type in Task 3, based on current market availability.

Overall, the market review identified 14 torso products, seven head products, one leg-specific product, and 13 extremities products as potential lighted apparel treatments for the closed-course testing. The treatment candidates encompassed a wide range of testable factors such as light method, light color, and flashing function, which could be explored for their comparative performance benefit. For the full list of the candidate treatments, see the Supplemental Materials that accompany this document.

Table 5. Wearable Lighted Apparel Material Availability Overview

Wearable Apparel Type	Availability	Cost Range	Weight Range	Light Types	Light Colors	Lighting Mode
Head	Widely available	\$14.99 - \$139.99	1 oz – 12 oz	Standard LED, Fiber Optic LED	White, Red, Amber	Solid, Flashing, Task, and Flood
Torso	Widely available	\$19.99 - \$302.07	2.4 oz – 3.0 lbs.	Standard LED, Fiber Optic LED	White, Red, Green	Solid, Slow Flash, Fast Flash
Legs	Very limited availability	\$99.00	18 oz estimate	Standard LED	White	Solid, Flashing
Extremities	Widely available	\$3.59 - \$109.99	0.9 oz – 6 oz	Standard LED, Fiber Optic LED	White, Red, Amber, Green, Blue	Solid, Flashing

Regulatory Review

The full list of relevant regulations can be found in the Supplemental Materials that accompany this document. In general, the MUTCD and supplemental sources laid forth the expectations for high-visibility apparel in detail and specified the industry standards that employers must adhere to. A great deal of guidance was provided for how an employee should be dressed and under what circumstances it was required.

Most of this detail, however, was focused on garments without any lighted elements. The only mention of wearable lighted apparel was section 6C.05 of the VWAPM, which states, "Lights internal and external to the high visibility apparel shall be steady burn yellow, white, or yellow green" (Virginia Department of Transportation, 2026a). There is no comparable statement in FHWA's MUTCD.

Outside of these few details, there was no guidance provided relating to wearable lighted apparel. Similarly, the Code of Virginia did not offer direct guidance on the use of wearable lighted apparel. Employers in Virginia are expected to provide PPE for their employees in conjunction with a number of Federal and State-adopted standards. Current statutes offer guidance for when the use of high-visibility apparel is needed and direct the user to industry standards for specifications. The Code of Virginia mandates specific light colors to specific vehicle types, such as blue to law enforcement, but these codes make no mention of personal lighting devices. There was no guidance available on the legality of lighting a pedestrian or road worker with personal lighting devices. The research team did find that standard practice is to not introduce disability glare to any member of the roadway or work zone. Garments that introduce disability glare to drivers or flaggers would not be permitted.

Because employers in Virginia are held responsible for outfitting their employees in the correct PPE, they have a distinct need for guidance on when wearable lighted apparel is needed. In the absence of guidance, contractors and agencies may have concerns when considering the adoption of lighted worker apparel. The project team identified the four following broad categories as barriers to widespread adoption of wearable lighted apparel:

- **Lack of Clear Guidelines**: There is an absence of clear regulatory guidelines specifically addressing wearable lighting technologies. There is a lack of guidance concerning both personal lighting devices and those embedded into commercially available garments. Lack of clear guidance may contribute to confusion among decision-makers. Overcoming this barrier will speed up the adoption process, as stakeholders will have a clearer picture about the legality of wearable lighted safety apparel. Future guidance should provide the same level of detail for lighting elements as they do for the composition and selection of high-visibility garments.

- **Current Safety Standards**: Apparel designed for safety must meet specific industry standards, such as those set by the Virginia Occupational Safety & Health Program and ANSI. These standards currently do not specifically address the use of electronic components, which can create uncertainty for manufacturers regarding compliance.

- **State-specific Regulations**: Variability from State to State may pose additional complications for manufacturers designing wearable lighted safety apparel. State-specific regulations can vary significantly from Federal standards (or lack thereof), presenting challenges for manufacturers trying to develop products for nationwide use. This may also pose a barrier to the certification process, as certifying new garments for use can be costly and time-consuming.

- **Liability Concerns**: Practitioners may be hesitant to adopt new technology due to potential liability issues. If a wearable lighted safety garment fails to perform as expected, it could lead to accidents or injuries, prompting companies to stick with traditional gear that meets established standards.

VDOT's internal safety policies currently generally limit VDOT employees to specifically approved VDOT headlamps and helmet-mounted illumination devices. However, many VDOT contractors, who frequently work adjacent to or shoulder-to-shoulder with VDOT employees in work zones, utilize various types of wearable lighting devices.

Summary of Relevant Regulations

Relevant findings within the VWAPM (Virginia Department of Transportation, 2026a) include the following:

- Lighting-related guidance typically suggests the practitioner avoid introducing light sources that increase the influence of glare. They should instead opt for low-glare light sources or place light sources in a way that they do not obstruct the visibility of flaggers, workers, or the view of approaching road users.
- The VWAPM stipulates that employers are responsible for identifying and providing the appropriate high-visibility garment class.
- Lighting is restricted by color.
- Lighting is restricted by flash type.
- Garment color is restricted.
- Garment retroreflective material color is restricted.
- Garment standards refer to ANSI/ISEA 107/207.

- All torso PPE shall meet ANSI/ISEA 107 Class 3 requirements (with limited exceptions for law enforcement and fire workers).
- The VWAPM seems to imply that the use of personal lighting devices would fall under special devices, but the manual offers that practitioners need to be careful about misuse or overuse.
- Visibility elements on the garment must provide 360 degrees of visibility coverage. Workers must zip up vests to ensure they provide that 360-degree visibility.
- Flagger-specific direction seems to deviate from other workers.

ANSI/ISEA standards for worker apparel (American National Standards Institute, 2020b) include the following:

- **Colors**: fluorescent yellow-green, fluorescent orange-red, and fluorescent red.
- **Garment Type and Class**: Class 2 or Class 3 vest (based on user). Class E for pants. Class E pants can be combined with a Class 2 or Class 3 vest to create a Class 3 ensemble.
- **Retroreflective Material**: Should provide 360-degree visibility coverage.
- **Testing:** Garments must be tested to meet brightness, fabric strength, and moisture resistance requirements after exposure tests.
- **Visibility:** Vests must meet initial photometric and physical performance standards. Performance typically degrades with use and washing so each vest must have its wash cycles tracked.
- **Usage:** Vests must be labeled with specific markings to track information such as the manufacturer's name, item number, style, size, ANSI/ISEA standard name, flame resistance compliance, and the maximum number of washes.
- **Helmets:** Helmets are available in two function types and three classes per ANSI Z89.1-2014. They can be purchased in high-visibility treatments and must be maintained and labeled in a manner similar to safety vests.
- **ANSI/ISEA 107 Type R vs Type P**: ANSI/ISEA 107 provides different criteria for Type P (Public Safety) and Type R (Roadway) apparel. Type P apparel is tailored for the unique needs of first responders. It allows smaller minimum areas of background and retroreflective materials and shorter lengths to provide access to duty belts, sidearms, and other equipment.

Current Virginia worker apparel guidelines require the following:

- ANSI Class 3 torso treatment.
- ANSI Class E leg treatment for exposed workers such as flaggers.
- Hard hat to be worn all times when out of the vehicle.

Closed-course Testing Results

The detection distance and visibility rating results are presented for each level of work zone complexity, followed by the results of the driver survey.

Low-complexity Work Zone

The analysis results concerning the low-complexity work zone are detailed in the following section. The low-complexity work zone contained one worker and one work truck with a flashing beacon and was a simulation of activities performed by a safety patrol worker or someone setting up signage for a work zone.

Lighting Design Approach

Modeling results for the analysis of lighting design approach at the low-complexity work zone are given in Table 6. The lighting design approach analysis only considered the white light source color. For both approaches, the main effect of lighting design was significant. The interaction terms were not significant, suggesting that the influence of lighting design approach did not vary across age.

Table 6. Type 3 Tests of Fixed Effects for Lighting Design Approach Modeling – Low Complexity

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Uphill Against Work Vehicle Headlamps	Lighting Design Approach	6	271	4.87	**<.0001**
	Age	1	45.7	19.07	**<.0001**
	Lighting Design Approach*Age	6	271	0.61	0.7201
Downhill Against Work Vehicle Taillamps	Lighting Design Approach	6	272	4.83	**0.0001**
	Age	1	45.8	12.65	**0.0009**
	Lighting Design Approach*Age	6	272	1.66	0.1313

Bold font indicates statistical significance.

Post hoc testing results for lighting design approach are shown in Figure 11 and reflect detections when the participant vehicle was approaching uphill against the work vehicle's headlamps. The letters above each bar indicate pairwise comparison results. Estimates which do not share a letter are statistically significantly different. All treatments performed statistically similar except for the condition using two shoulder-mounted light sources. The two-shoulder condition (764 ft) was seen from 19% to 25% farther away than retro (572 ft), head (601 ft), one shoulder (569 ft), and torso (618 ft) lighting design approaches. The two-shoulder condition was the only treatment that performed significantly better than the retro vest.

The post hoc testing results for lighting design approach shown in Figure 12 represent detections as the participant vehicle was approaching downhill against the work vehicle's taillamps. All treatment comparisons were statistically similar except for two. The head plus torso (1,070 ft) and shoulder plus torso (1,073 ft) conditions were seen from 23% farther than the two-shoulder condition (824 ft). Although there was some variation in detection distance, all treatments were statistically similar to the retro vest, which did not use any lighting.

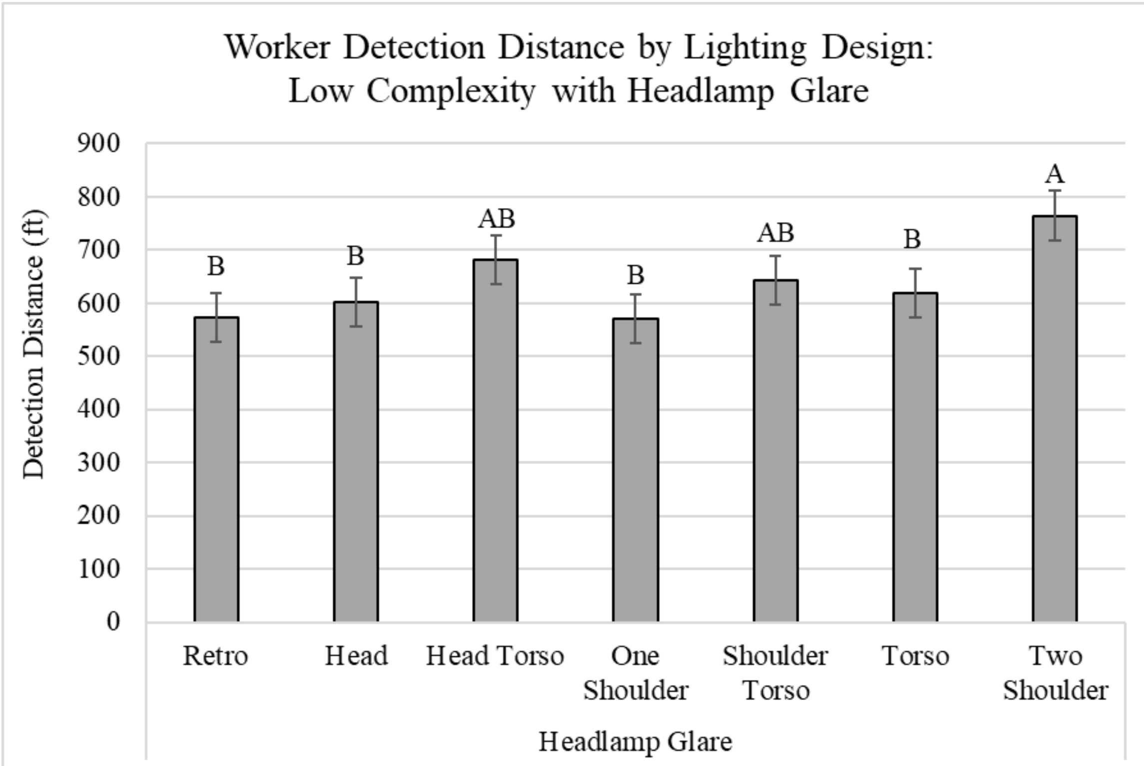

Figure 11. Worker Detection Distance by Lighting Design with Headlamp Glare – Low Complexity

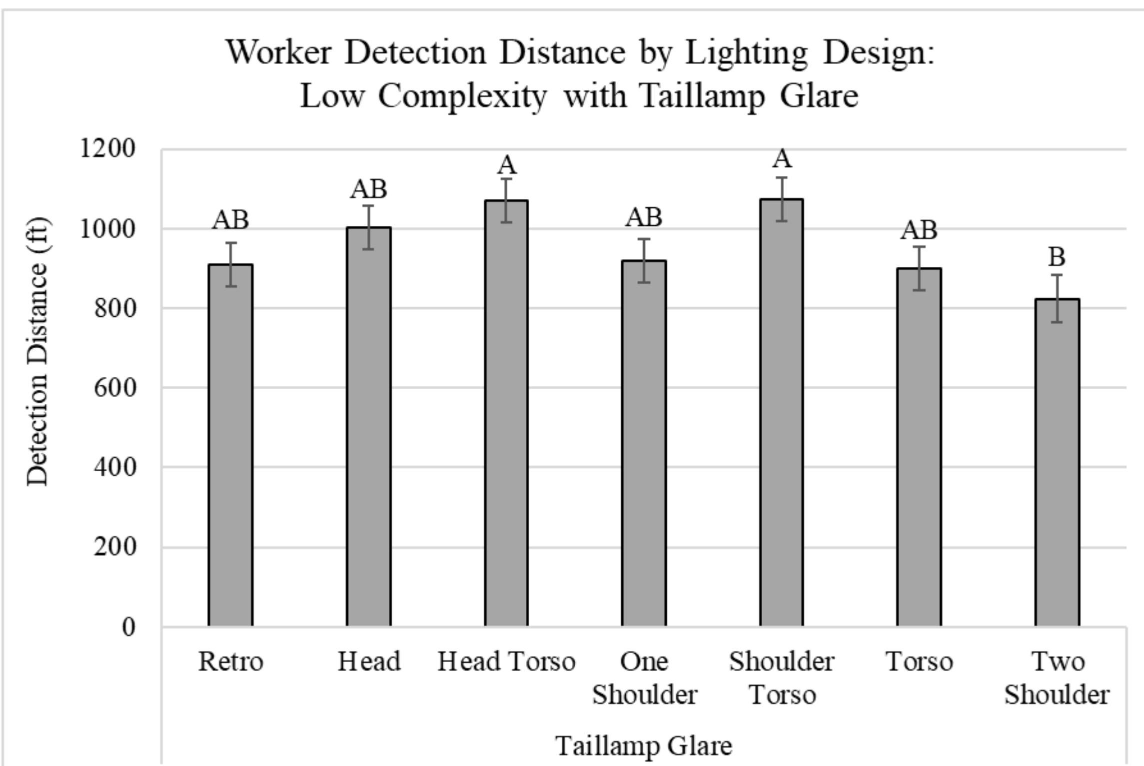

Figure 12. Worker Detection Distance by Lighting Design with Taillamp Glare – Low Complexity

The cumulative detection probability for the worker at the low-complexity work zone is shown in Figure 13 for each lighting design. The cumulative detection probability indicates the proportion of workers that were detected at a given distance for each lighting design. For example, at 1,000 ft, approximately 20% of workers wearing retro only would be detected. Results are summarized across the direction of travel and reflect the proportion of all detections at a given distance. Overall, the head, head plus torso, and shoulder plus torso lighting design approaches were consistently associated with the largest proportion of detections. The influence of lighting design approach was larger at distances at least 400 ft from the work zone.

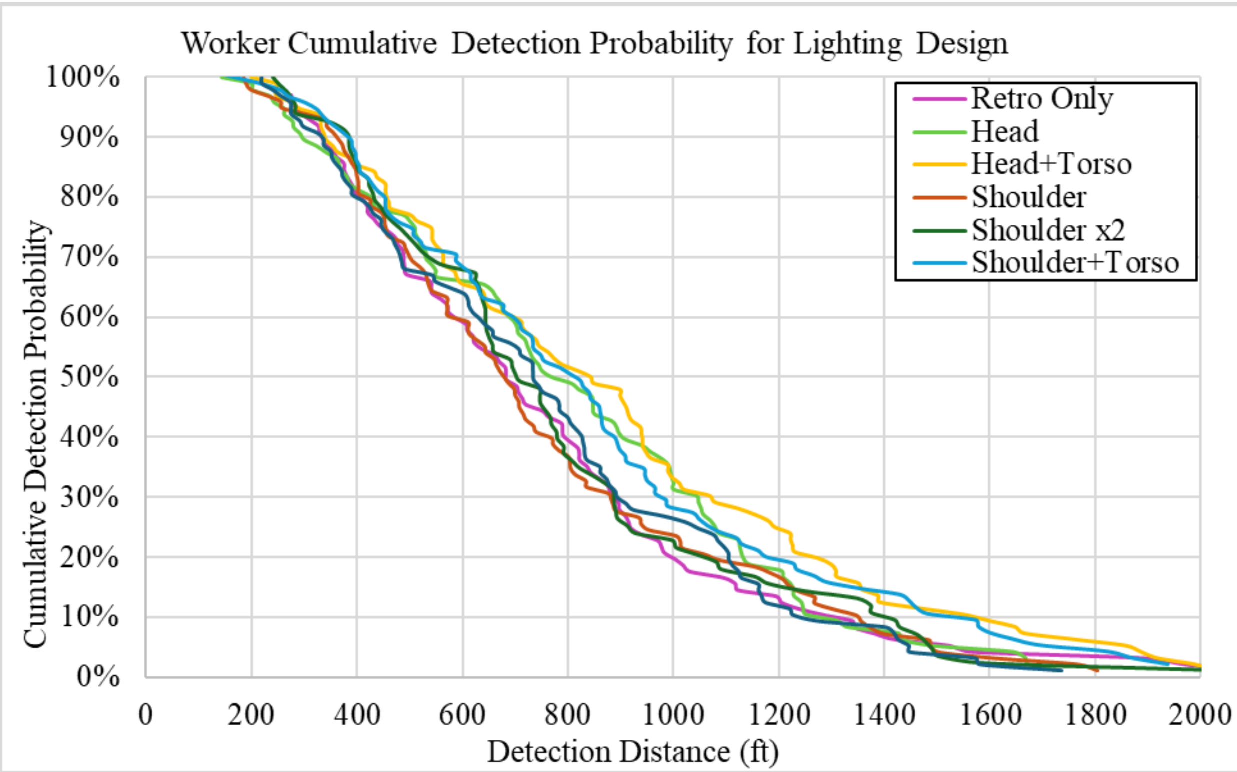

Figure 13. Cumulative Detection Probability of Worker by Lighting Design – Low Complexity

Color

Statistical modeling results for the analysis of color at the low-complexity work zone are given in Table 7. Color was tested using a single light source located on the shoulder of the worker. The main effect of color was significant for each approach. The interaction terms were not significant, suggesting that the influence of color did not vary across age.

Table 7. Type 3 Tests of Fixed Effects for Color Modeling – Low Complexity

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Uphill Approach with Headlamp Glare	Color	3	136	9.45	**<.0001**
	Age	1	46	13.23	**0.0007**
	Color*Age	3	136	0.4	0.7504
Downhill Approach with Taillamp Glare	Color	3	134	6.69	**0.0003**
	Age	1	46.1	11.23	**0.0016**
	Color*Age	3	134	1.78	0.1536

Bold font indicates statistical significance.

Post hoc testing results for color are shown in Figure 14 and reflect detections when the participant vehicle was approaching uphill against the work vehicle's headlamps. The green light source (818 ft) was detected from 17% farther than red (700 ft), 36% farther than amber (601 ft), and 43% farther than white (571 ft). The presence of amber and white light on the work vehicle negatively influenced detections of workers wearing those colors.

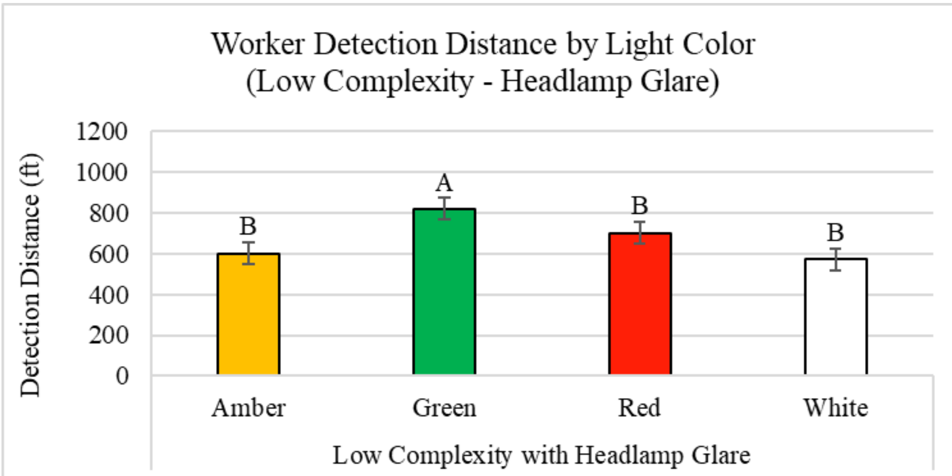

Figure 14. Worker Detection Distance by Light Color with Headlamp Glare – Low Complexity

Pairwise comparison results for color are shown in Figure 15 and reflect detections when the participant vehicle was approaching downhill against the work vehicle's taillamps. Similar to the uphill directions, the green light source (1,096 ft) was detected from 17% farther than white (919 ft), 36% farther than red (908 ft), and 43% farther than amber (831 ft). The presence of red, amber, and white light on the work vehicle negatively influenced detections of workers wearing those colors.

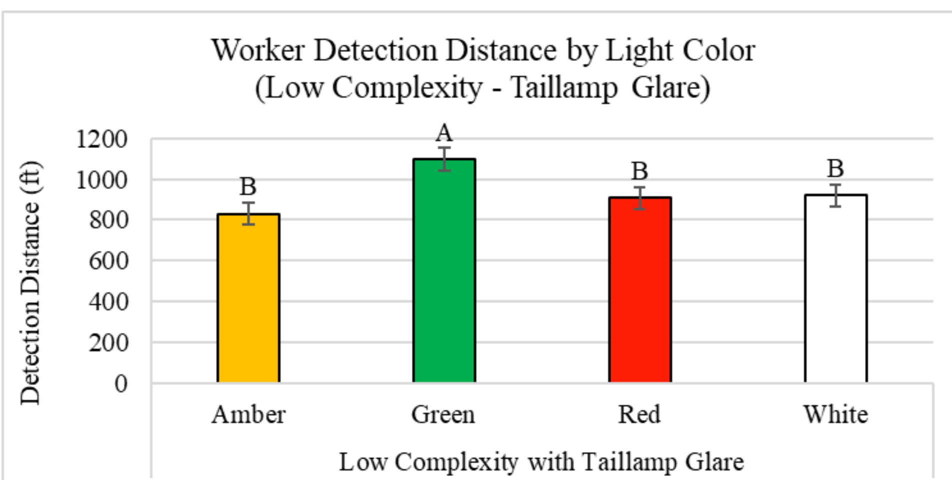

Figure 15. Worker Detection Distance by Light Color with Taillamp Glare – Low Complexity

The relationship between worker detection and light source color, at the low-complexity work zone, is shown in Figure 16. Results are summarized across the direction of travel and reflect the proportion of all detections at a given distance. The green treatment was associated with a significantly larger proportion of detections at all distances from the work zone. Among the other colors, red was the only one consistently associated with a larger proportion of detections than the retro only condition.

The influence of color was most pronounced at distances between 800 and 1,200 ft from the work zone. However, when the participant vehicle was 400 ft from the worker, there was still a substantial gap in performance. At 400 ft away, participants had detected 92% of workers wearing green and 88% wearing red, while, in contrast, participants had only detected approximately 80% of workers wearing amber, white, or retro only. Overall, using a red or green light source resulted in improved detection of workers compared to just a retroreflective vest.

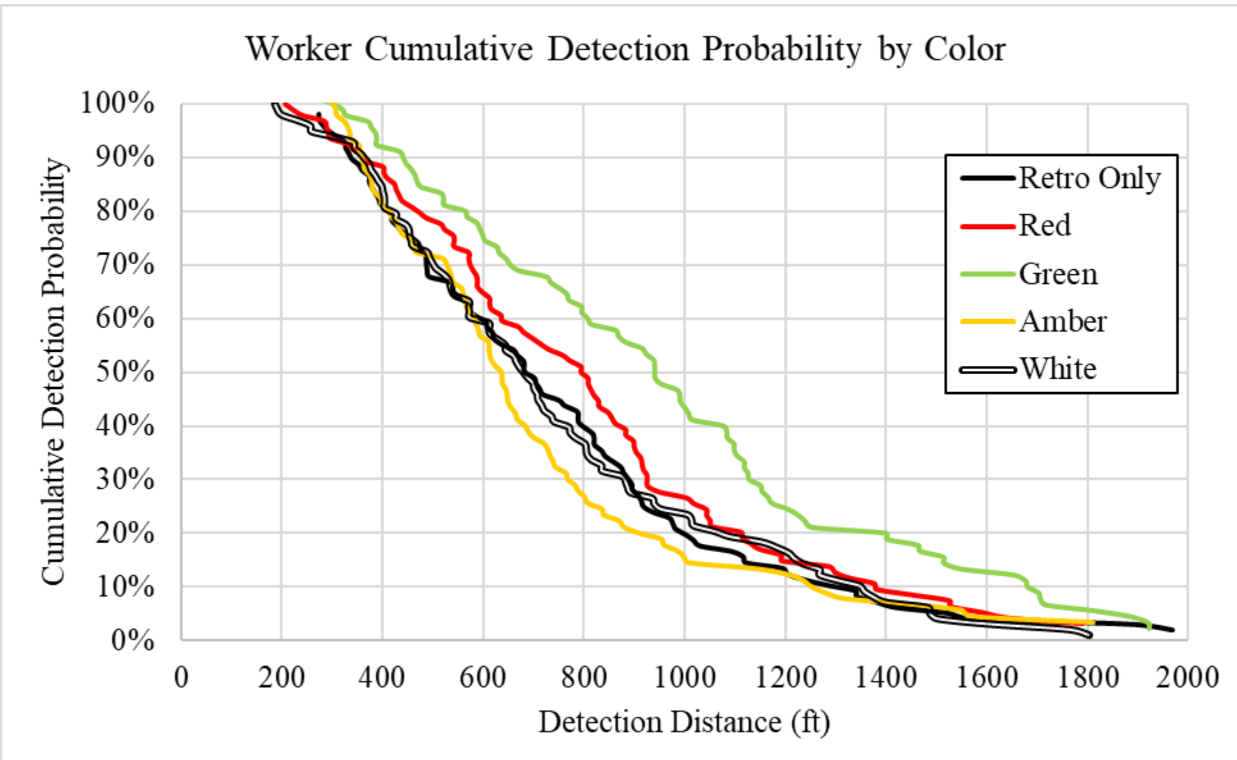

Figure 16. Cumulative Detection Probability of Worker by Color – Low Complexity

Flashing

Modeling found no statistical significance between flash conditions at the low-complexity work zone for both approach directions (Table 8). Results indicated participants detected workers using the red halo at similar distances, in the presence of headlamp glare from the work vehicle, with the device set to flash (622 ft) and steady-on (681 ft). The same trend was true for the taillamp glare approach; however, the magnitude of detection distance was larger for flashing (965 ft) and steady-on (964 ft). Although the steady-on condition was seen from 9% farther, in the presence of headlamp glare, the variability in detections was relatively large (SE = 44 ft), resulting in no significant difference.

Table 8. Type 3 Tests of Fixed Effects for Flashing Modeling – Low Complexity

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Uphill Approach with Headlamp Glare	Flashing	1	46	2.75	0.1039
	Age	1	46	19.65	**<.0001**
	Flashing*Age	1	46	0.71	0.4045
Downhill Approach with Taillamp Glare	Flashing	1	47	0	0.9626
	Age	1	46	14.71	**0.0004**
	Flashing*Age	1	47	0.01	0.9378

Bold font indicates statistical significance.

Intensity

Table 9 provides statistical modeling results for the analysis of intensity at the low-complexity work zone. Intensity was tested using a single white light source located on the shoulder of the worker. The main effect of intensity was significant for each effect on the uphill approach, where glare from the work vehicles headlamps was present. The interaction terms were not significant, suggesting the influence of intensity did not vary across age.

Pairwise comparison results for intensity found that the higher intensity setting for the white light source (713 ft) was detected from 25% farther than low (568 ft). The high setting may have helped to set the worker apart from the work vehicle's headlamps while the lower setting could not outcompete them.

Table 9. Type 3 Tests of Fixed Effects for Intensity Modeling – Low Complexity

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Uphill Approach with Headlamp Glare	Intensity	1	46.9	15.98	**0.0002**
	Age	1	45.9	10.66	**0.0021**
	Intensity*Age	1	46.9	0.75	0.3916
Downhill Approach with Taillamp Glare	Intensity	1	46.4	0.25	0.6221
	Age	1	46.1	13.15	**0.0007**
	Intensity*Age	1	46.4	0.2	0.6593

Bold font indicates statistical significance.

Worker Visibility Assessment

Participant subjective ratings of how visible the worker was for the low-complexity work zone were averaged and are reported in Table 10. Cell shading represents the range of values with low ratings trending toward red and high ratings trending toward green. Overall, participants felt that workers were most visible when wearing the white helmet plus vest treatment or two of the white shoulder light sources, and that the worker was least visible wearing just the standard Class 3 vest. Participants indicated that the green color made the worker most visible and that the worker had below average visibility when wearing amber. Participants felt the steady-on setting made the worker more visible, compared to flashing, and that the worker was equally visible using the high and low intensity settings.

Table 10. Worker Visibility Assessment by Analysis – Low Complexity

Analysis	Ensemble	Average Rating
Lighting Design Approach	Retro Only	2.83
	White Vest	3.11
	White Helmet	3.13
	White Helmet plus Vest	3.43
	White Shoulder	3.23
	White Shoulder plus Vest	3.04
	White Shoulder × 2	3.33
Color	Amber Shoulder	2.73
	White Shoulder	3.23
	Green Shoulder	3.60
	Red Shoulder	2.95
Flashing	Red Helmet	3.33
	Red Helmet Flash	3.07
Intensity	White Shoulder	3.23
	White Shoulder Low	3.23

Medium-complexity Work Zone

The analysis results concerning the medium-complexity work zone are detailed in the following section. The medium-complexity work zone contained one worker and one work truck with a flashing beacon. The work zone also contained reflectorized cones marking a portion of the shoulder as a work area. The medium-complexity work zone simulated a short-term shoulder work zone operation.

Due to the geometric properties of the roadway when approaching the medium-complexity work zone, there was an artificial cap on the detection distance as drivers were limited by the curve that preceded the work zone. As such the data were clustered around a single value and determined to not be representative. Therefore, the medium-complexity uphill approach against the work vehicle taillamps was excluded.

Lighting Design Approach

Modeling results for the analysis of lighting design approach at the medium-complexity work zone are given in Table 11. The lighting design approach analysis only considered the white light source color. For both approaches the main effect of lighting design was significant. The interaction terms were not significant, suggesting that the influence of lighting design approach did not vary across age.

Table 11. Type 3 Tests of Fixed Effects for Lighting Design Approach Modeling – Medium Complexity

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Downhill Approach with Headlamp Glare	Lighting Design Approach	6	271	4.87	**<.0001**
	Age	1	45.7	19.07	**<.0001**
	Lighting Design Approach*Age	6	271	0.61	0.7201

Bold font indicates statistical significance.

Post hoc testing results for lighting design approach are shown in Figure 17 and reflect detections when the participant vehicle was approaching downhill against the work vehicle’s headlamps. Significant difference was found between the head plus torso condition and the retro only condition. The head plus torso condition (582 ft) was seen from 20% farther away than retro (484 ft) and head (501 ft). Notably, the head plus torso condition was the only treatment that performed significantly better than the retro vest.

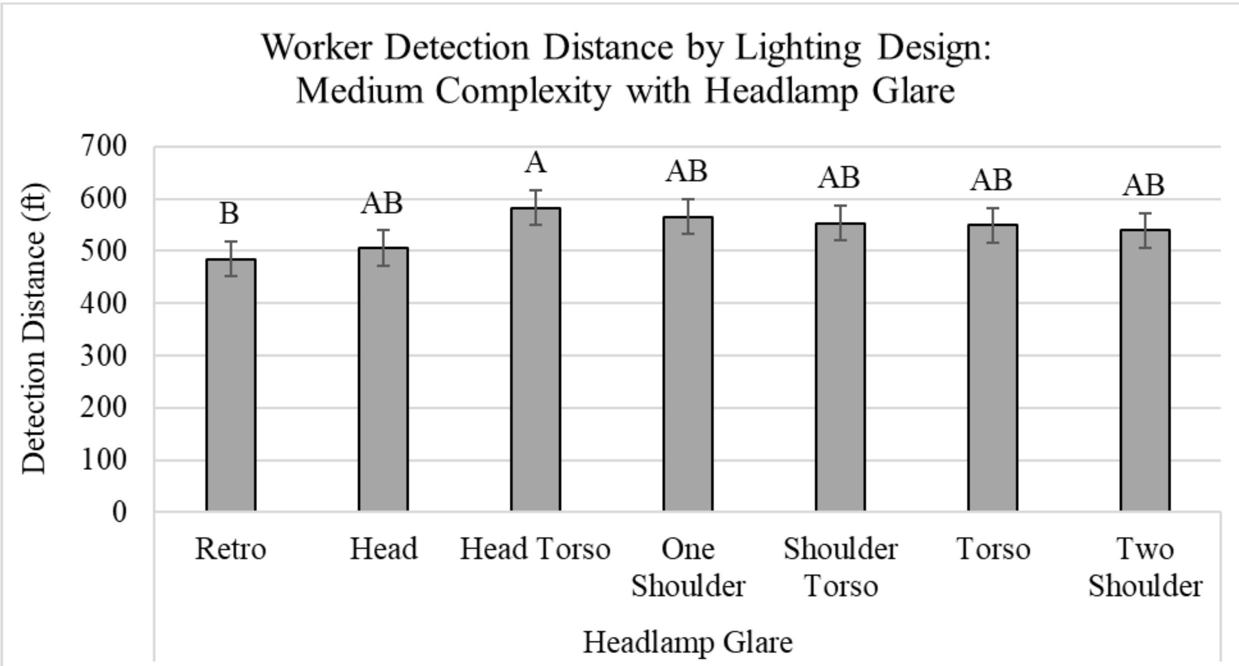

Figure 17. Worker Detection Distance by Lighting Design with Headlamp Glare – Medium Complexity

The relationship between worker detection and lighting design approach at the medium-complexity work zone is shown in Figure 18. In general, the head plus torso lighting design was consistently associated with the largest proportion of detections. Beyond 800 ft from the work zone, all of the lighting design approaches had higher proportion detections than the standard Class 3 vest; however, the difference diminished as the vehicle approached the work zone. Compared to the low-complexity work zone, the proportion of detections was lower at all distances for the medium-complexity work zone, suggesting participants had more difficulty identifying the worker.

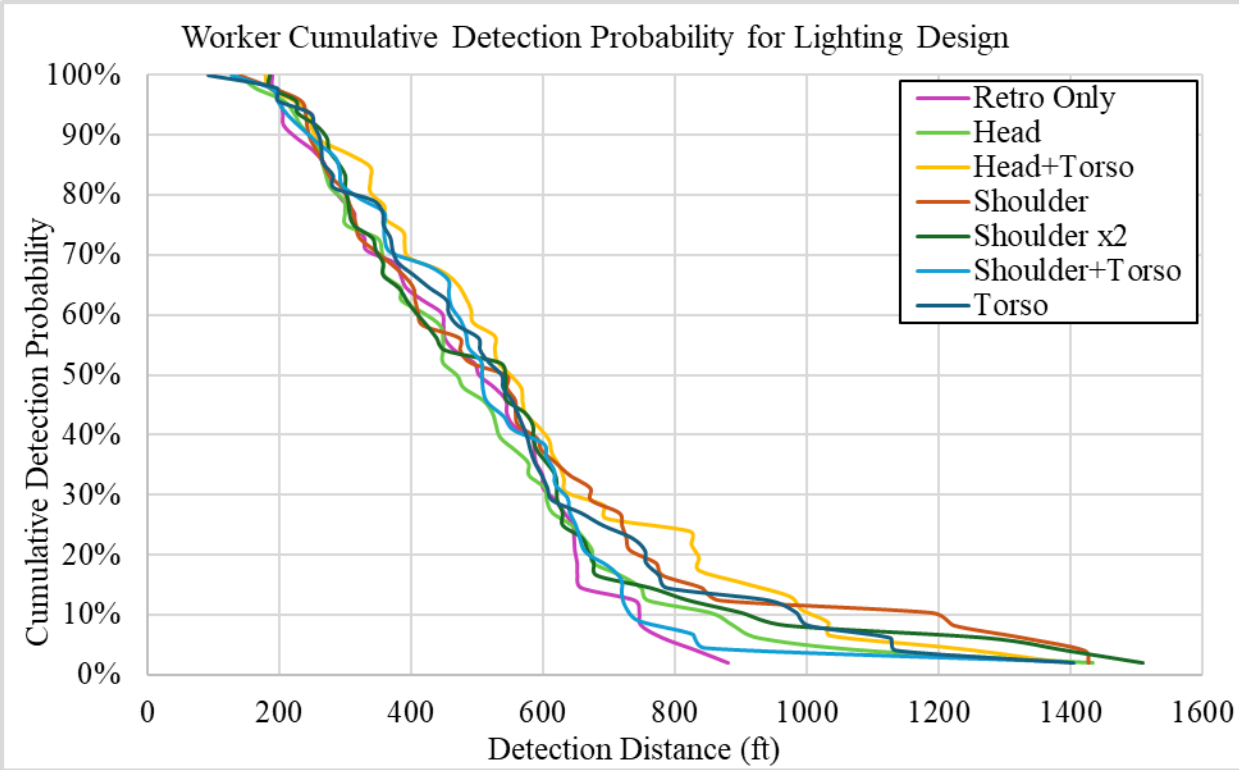

Figure 18. Cumulative Detection Probability of Worker by Lighting Design – Medium Complexity

Color

Modeling results for the analysis of color at the medium-complexity work zone are given in Table 12. Color was tested using a single light source located on the shoulder of the worker. The main effect of color was significant. The interaction term was not significant, suggesting the influence of color did not vary across age.

Table 12. Type 3 Tests of Fixed Effects for Color Modeling – Medium Complexity

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Downhill Approach with Headlamp Glare	Color	3	136	17.27	**<.0001**
	Age	1	46.1	24.66	**<.0001**
	Color*Age	3	136	0.53	0.6596

Bold font indicates statistical significance.

Post hoc testing results for color are shown in Figure 19 and reflect detections when the participant vehicle was approaching downhill against the work vehicle's headlamps. The green light source (774 ft) was detected from 36% farther than white (567 ft), 53% farther than amber (506 ft ft), and 56% farther than red (496 ft). The presence of amber and white light on the work vehicle may have negatively influenced detections when the worker was wearing those colors. However, red and green were both only present when the worker wore them, suggesting green was the more effective choice of color.

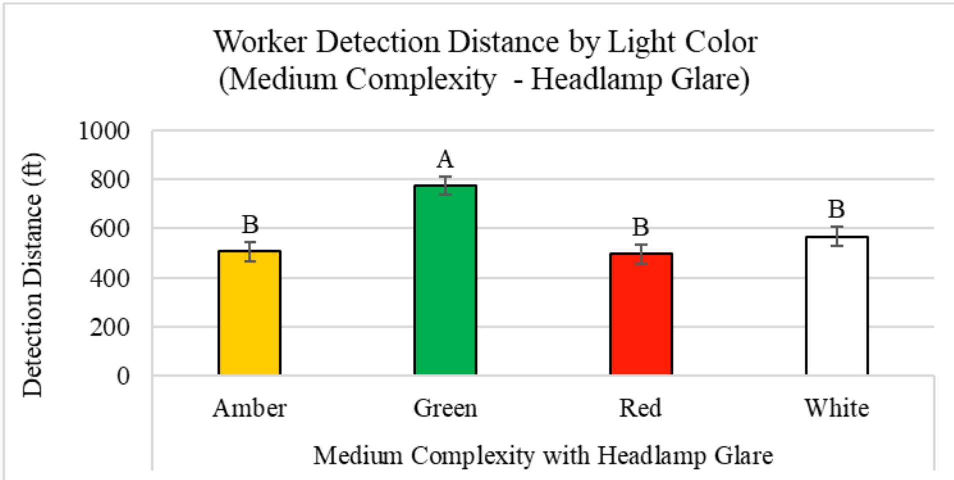

Figure 19. Worker Detection Distance by Color with Headlamp Glare – Medium Complexity

The relationship between worker detection and light source color, at the medium-complexity work zone, is shown in Figure 20. Results are summarized across the direction of travel and reflect the proportion of all detections at a given distance. The green treatment was associated with a significantly larger proportion of detections at all distances from the work zone. Among the other colors, white was the only one consistently associated with a larger proportion of detections than the retro only condition.

The influence of color was most pronounced at distances between 600 and 1,000 ft from the work zone. However, when the participant vehicle was 400 ft from the worker, there was still a substantial gap in performance. At 400 ft away, participants had detected 82% of workers wearing green and 70% wearing red, while participants had only detected approximately 65% of workers wearing amber, white, or retro only. Overall, the green light source resulted in significantly increased proportion of workers detected, and green was the only color that resulted in improved detection of workers compared to just a retroreflective vest.

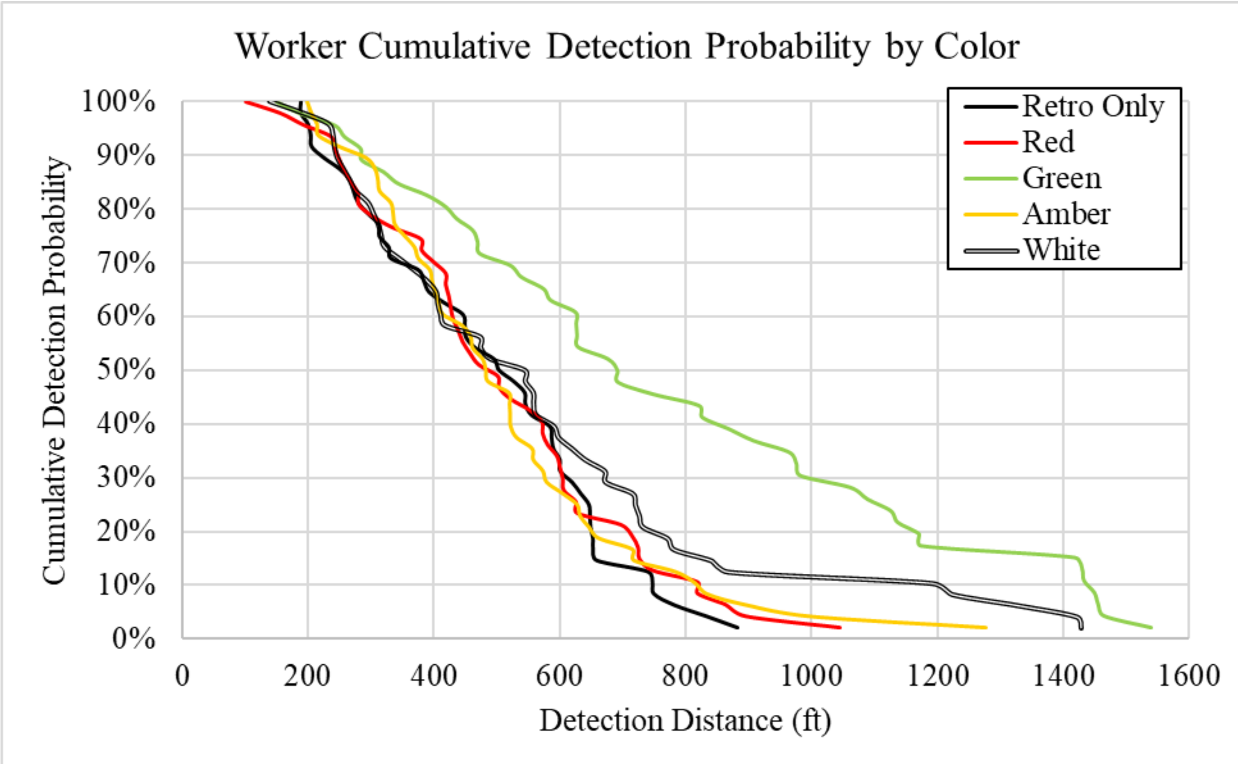

Figure 20. Cumulative Detection Probability of Worker by Color – Medium Complexity

Flashing

Modeling found no statistical significance between flash conditions at the medium-complexity work zone (Table 13). Results indicated participants detected workers using the red halo at similar distances, when headlamp glare was present, with the device set to flash (590 ft) and steady-on (537 ft). Although the flashing condition was seen from 10% farther, the variability in detections was large (SE = 72 ft), resulting in no significant difference.

Table 13. Type 3 Tests of Fixed Effects for Flashing Modeling – Medium Complexity

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Downhill Approach with Headlamp Glare	Flashing	1	46	0.29	0.5948
	Age	1	46	1.74	0.1935
	Flashing*Age	1	46	0.65	0.4235

Bold font indicates statistical significance.

Intensity

Modeling found no statistical significance between intensity conditions at the medium-complexity work zone (Table 14). Results indicated participants detected workers using a single white shoulder light source at similar distances, when headlamp glare was present, with the device set to low (565 ft) and high (494 ft). Although the low condition was seen from 14% farther, the variability in detections was significant (SE = 35 ft), resulting in no statistical difference.

Table 14. Type 3 Tests of Fixed Effects for Intensity Modeling – Medium Complexity

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Downhill Approach with Headlamp Glare	Intensity	1	48.5	2.73	0.1046
	Age	1	46	26.32	**<.0001**
	Intensity*Age	1	48.5	0.26	0.6131

Bold font indicates statistical significance.

Worker Visibility Assessment

Participant subjective ratings of how visible the worker was at the medium-complexity work zone were averaged and are reported in Table 15. Similar to the low-complexity work zone, participants felt that workers were most visible when wearing the white helmet plus vest treatment or two of the white shoulder light sources, and that the worker was least visible wearing just the standard Class 3 vest. Participants indicated that the green color made the worker most visible and that the worker had below average visibility when wearing red or amber. Participants felt the steady-on setting made the worker more visible, compared to flashing, and that the worker was more visible using the high-intensity setting compared to the low.

Table 15. Worker Visibility Assessment by Analysis – Medium Complexity

Analysis	Ensemble	Average Rating
Lighting Design Approach	Retro Only	2.65
	White Vest	3.11
	White Helmet	3.08
	White Helmet plus Vest	3.35
	White Shoulder	3.24
	White Shoulder plus Vest	3.30
	White Shoulder × 2	3.35
Color	Amber Shoulder	2.81
	White Shoulder	3.24
	Green Shoulder	3.79
	Red Shoulder	2.82
Flashing	Red Helmet	3.26
	Red Helmet Flash	2.92
Intensity	White Shoulder	3.24
	White Shoulder Low	3.08

High-complexity Work Zone

The analysis results relating to the high-complexity work zone are detailed in the following section. The high-complexity work zone contained one worker, two flaggers, and two work trucks, each with a flashing beacon. Each flagger station was illuminated with a portable work zone light. The work zone also contained numerous reflectorized cones used to close one lane of travel. The high-complexity work zone simulated a longer-term lane closure work zone operation.

Lighting Design Approach

Worker detection results for the analysis of lighting design approach at the high-complexity work zone are given in Table 16. The main effect of lighting design approach was significant for both approach directions. The interaction between lighting design approach and age was not significant for either approach, which indicated that the influence of the lighting design approach did not vary across age for worker detections.

Table 16. Type 3 Tests of Fixed Effects for Lighting Design Approach Modeling – Worker Detections – High Complexity

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Uphill Approach with Headlamp Glare	Lighting Design Approach	6	274	6.4	**<.0001**
	Age	1	46	36.03	**<.0001**
	Lighting Design Approach*Age	6	274	1.45	0.1958
Downhill Approach with Taillamp Glare	Lighting Design Approach	6	274	3.35	**0.0034**
	Age	1	46	24.1	**<.0001**
	Lighting Design Approach*Age	6	274	0.69	0.6615

Bold font indicates statistical significance.

The results from pairwise comparisons for lighting design approach are shown in Figure 21 and reflect detections as the participant vehicle was approaching uphill against the work vehicle's headlamps. Significant difference was found between the head plus torso condition and the retro only, torso, one shoulder, and torso plus shoulder conditions. The head plus torso condition (956 ft) was seen from 23% farther away than workers wearing a standard Class 3 retroreflective vest (780 ft). Notably, the head plus torso condition was the only treatment that performed significantly better than the retro vest.

The post hoc testing results for lighting design approach shown in Figure 22 reflect detections as the participant vehicle was approaching downhill against the work vehicle's taillamps. Significant difference was found between the head plus torso condition and the retro only condition, torso, and two shoulder conditions. The head plus torso condition (805 ft) was seen from 22% farther away than retro only (660 ft). Notably, the head plus torso condition was the only treatment significantly different from the standard Class 3 retroreflective vest.

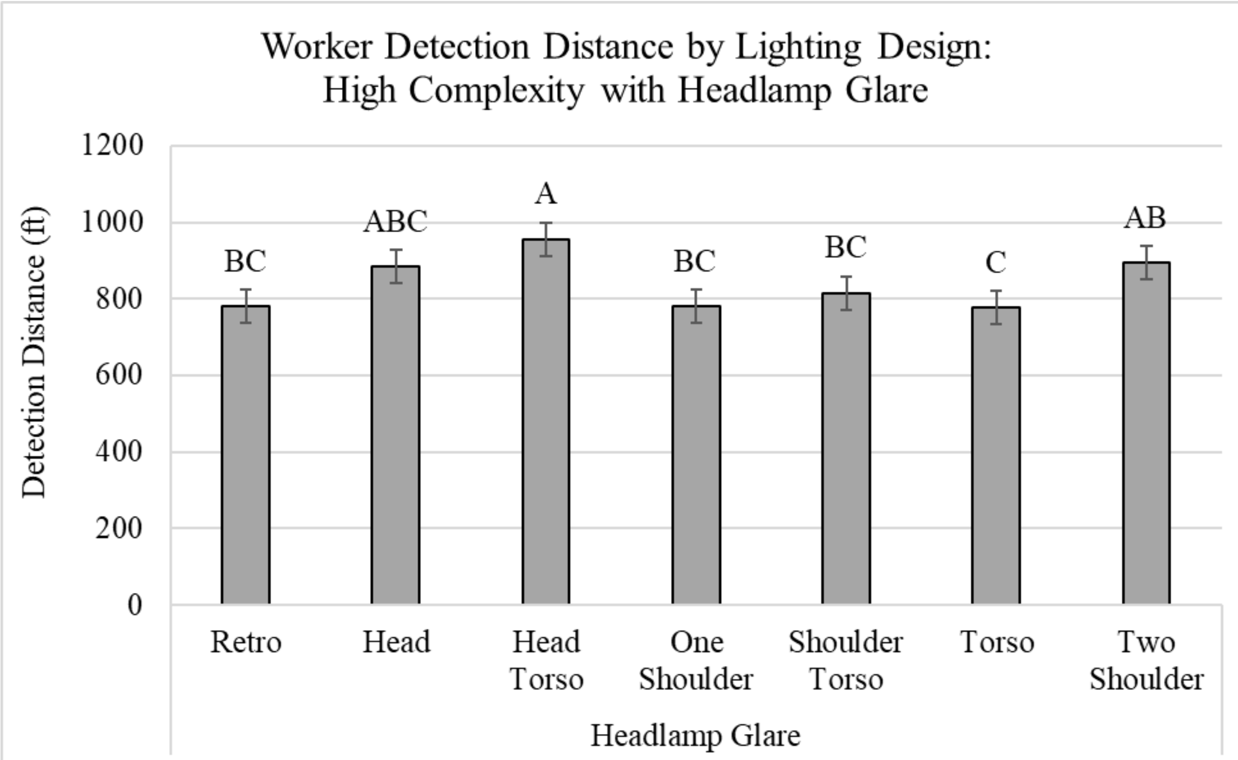

Figure 21. Worker Detection Distance by Lighting Design with Headlamp Glare – High Complexity

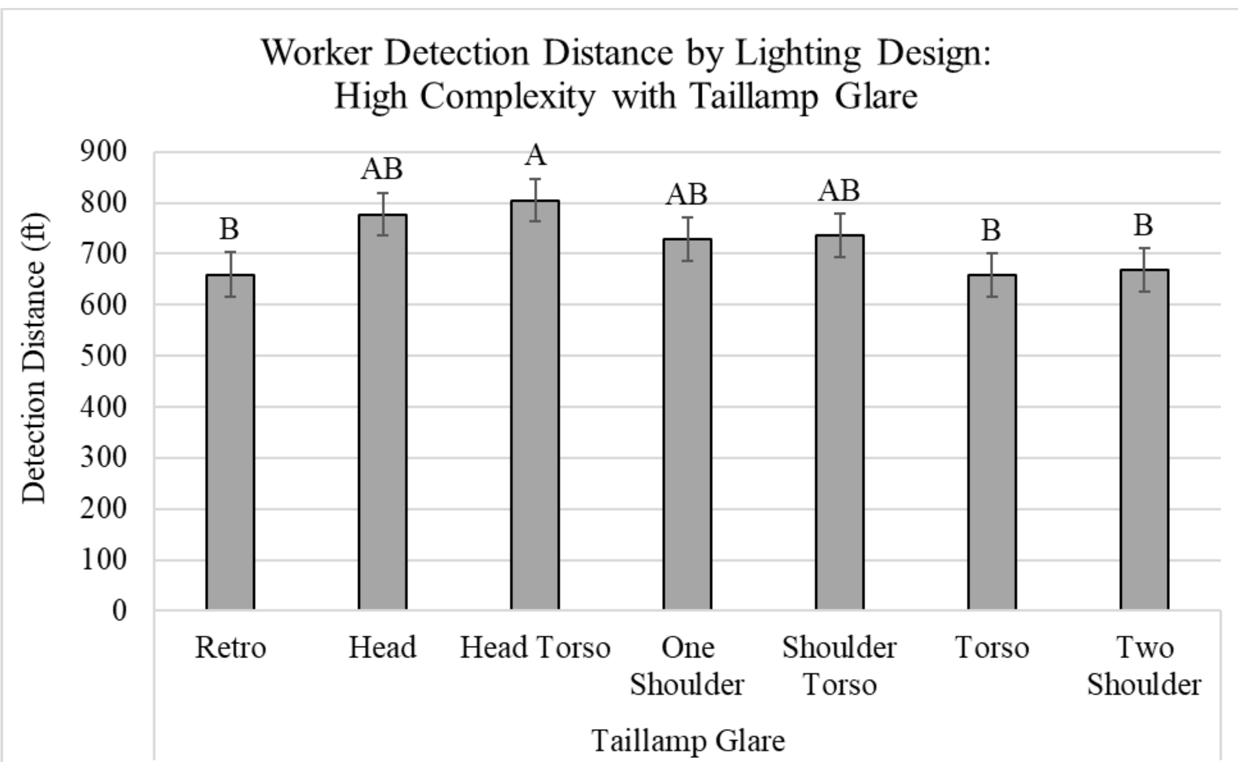

Figure 22. Worker Detection Distance by Lighting Design with Taillamp Glare – High Complexity

The relationship between worker detection and lighting design approach at the high-complexity work zone is shown in Figure 23. The head plus torso lighting design stood out and was associated with the largest proportion of detections. The overall benefit of lighting design approach was largest at approximately 850 ft from the work zone where lighting design approach increased the proportion of workers detected by 10% to 30%. Compared to the low- and medium-complexity work zones, the proportion of detections was high at all distances compared to the medium-complexity and similar to the low-complexity work zone. This result may be due to the low- and high-complexity work zones sharing a very similar stretch of the test track, allowing for a long straight on approach.

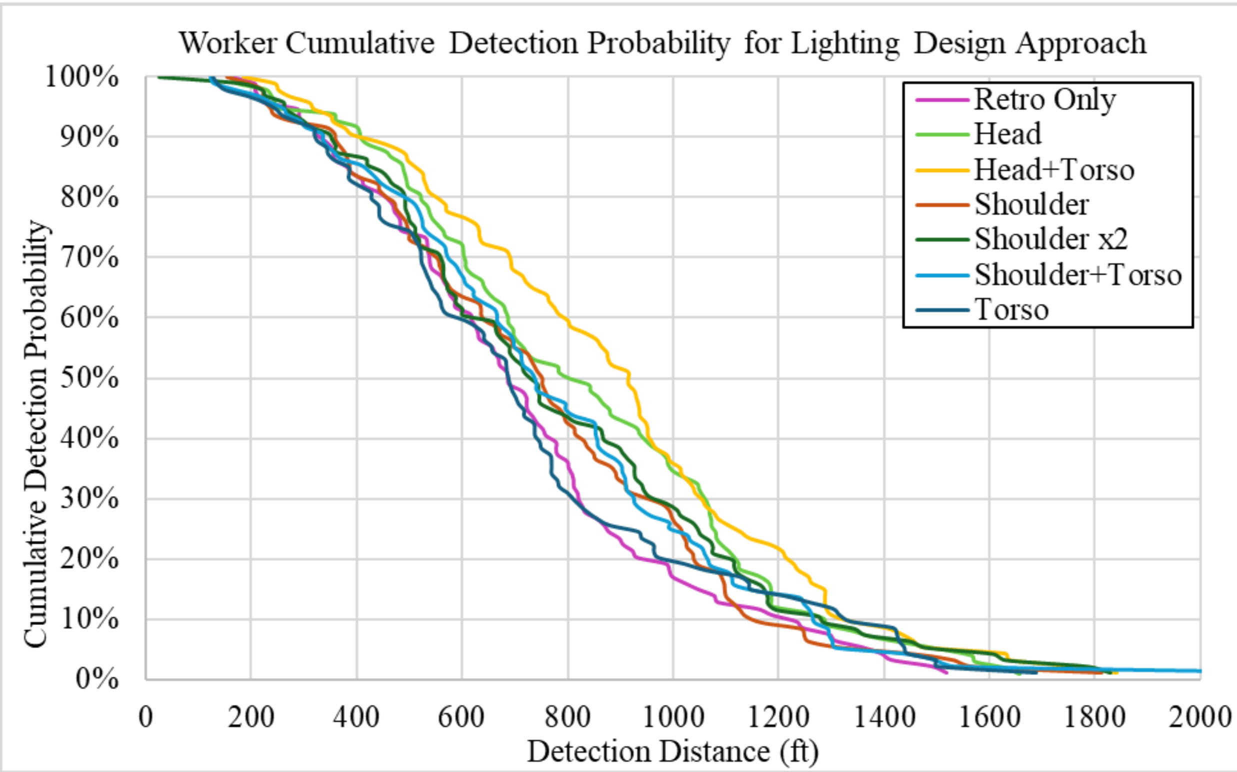

Figure 23. Cumulative Detection Probability of Worker by Lighting Design – High Complexity

Flagger detection results for the analysis of lighting design approach at the high-complexity work zone are given in Table 17. The main effect of lighting design approach was significant for both approach directions. The interaction between lighting design approach and age was not significant for either approach, which indicated that the influence of the lighting design approach did not vary across age for flagger detections.

Table 17. Type 3 Tests of Fixed Effects for Lighting Design Approach Modeling – High Complexity – Flagger Detections

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Uphill Approach with Headlamp Glare	Lighting Design Approach	6	280	2.76	**0.0126**
	Age	1	46	16.75	**0.0002**
	Lighting Design Approach*Age	6	280	2.01	0.0638
Downhill Approach with Taillamp Glare	Lighting Design Approach	6	273	3.86	**0.001**
	Age	1	46.1	13.01	**0.0008**
	Lighting Design Approach*Age	6	273	1.33	0.244

Bold font indicates statistical significance.

The results from pairwise comparisons for lighting design approach shown in Figure 24 reflect flagger detections as the participant vehicle was approaching uphill against the work vehicle's headlamps. Significant difference was found between the head and head plus torso conditions and the should torso condition. Notably, none of the lighting design approaches performed significantly differently from the retro vest for the flagger. Since the flagger was located on the opposite shoulder for this approach and not backdropped by the work zone, the relative reduction in background clutter may have contributed to the lack of significant difference for lighting design approach.

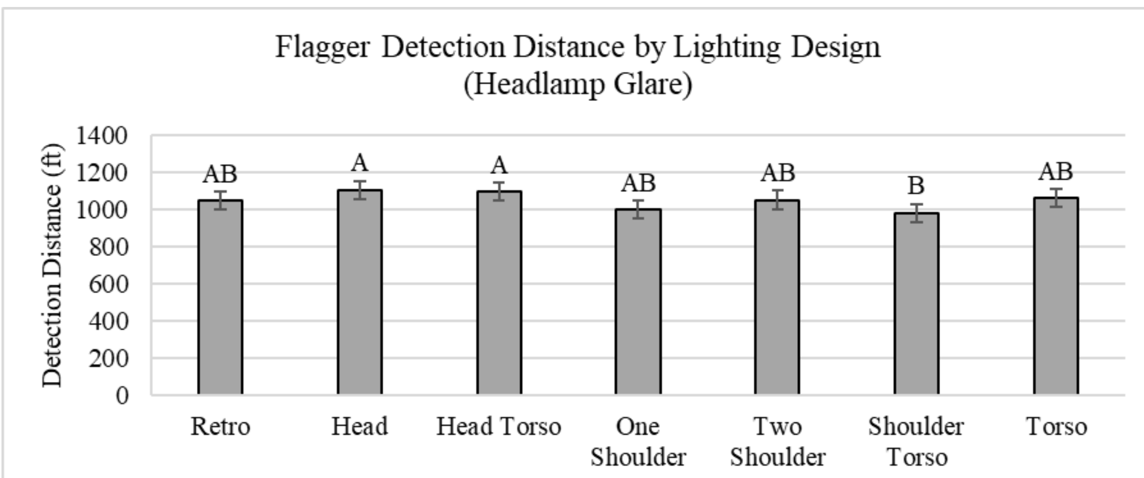

Figure 24. Flagger Detection Distance by Lighting Design with Headlamp Glare – High Complexity

The post hoc comparisons for lighting design approach are shown in Figure 25 and reflect flagger detections when the participant vehicle was approaching uphill against the work vehicle's headlamps. Significant difference was found between the head plus torso condition and the retro only, head, one shoulder, and shoulder plus torso conditions. The head plus torso condition (874 ft) was seen from 14% farther away than retro only (768 ft). Notably, the head plus torso condition was the only treatment that performed significantly better than the retro vest.

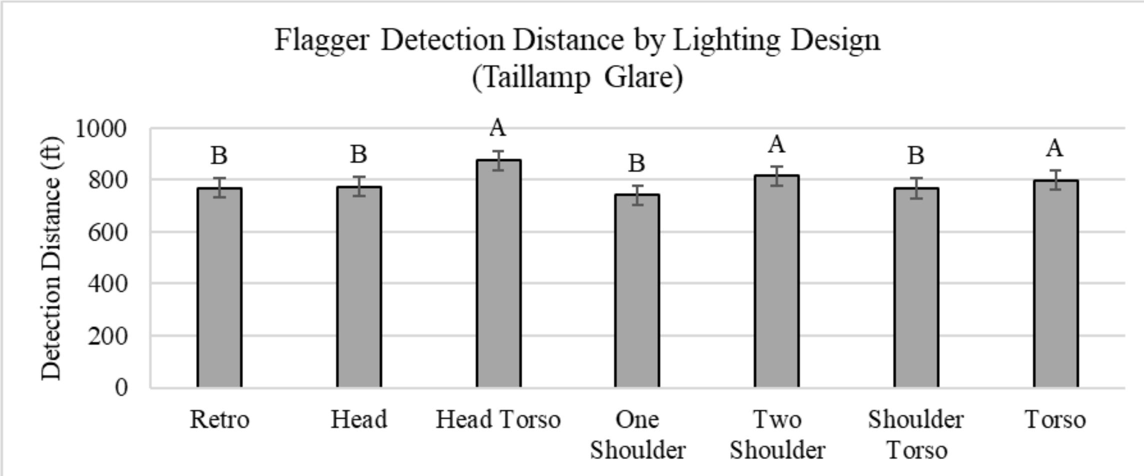

Figure 25. Flagger Detection Distance with Taillamp Glare by Lighting Design – High Complexity

The relationship between flagger detection and lighting design approach at the high-complexity work zone is shown in Figure 26. The head plus torso lighting design was consistently associated with the largest proportion of detections. The influence of lighting design approach on flagger detections was largest 800 to 1,200 ft upstream of the work zone. Compared to the worker detections, the flaggers were detected at a higher proportion at all distances, suggesting that drivers had an easier time locating the flagger compared to the worker.

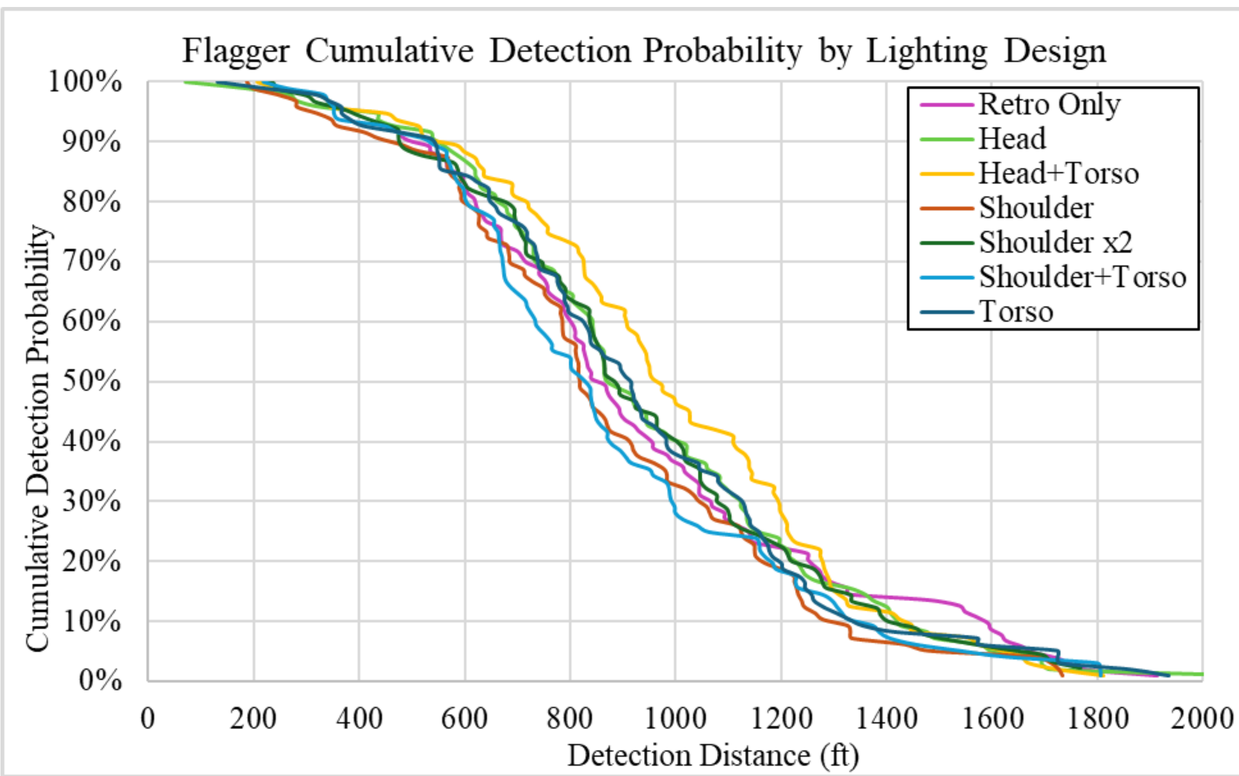

Figure 26. Cumulative Detection Probability of Flagger by Lighting Design – High Complexity

Color

Modeling results for the analysis of worker detection by color at the high-complexity work zone are given in Table 18. Color was tested using a single light source located on the shoulder of the worker. The main effect of color was significant for both approach directions. The interaction term was not significant for either approach, suggesting that the influence of color did not vary across age for the worker.

Table 18. Type 3 Tests of Fixed Effects for Worker Detection Color Modeling – High Complexity

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Uphill Approach with Headlamp Glare	Color	3	135	10.09	**<.0001**
	Age	1	46.1	28.26	**<.0001**
	Color*Age	3	135	0.2	0.8947
Downhill Approach with Taillamp Glare	Color	3	135	9.02	**<.0001**
	Age	1	45.9	11.67	**0.0013**
	Color*Age	3	135	1.12	0.3418

Bold font indicates statistical significance.

Post hoc testing results for worker light color are shown in Figure 27 and reflect detections as the participant vehicle approached uphill against the work vehicle's headlamps. Workers wearing the green light source (949 ft) were detected from 25% farther than amber (757 ft), and 21% farther than white (781 ft). The presence of amber and white light on the work vehicle may have negatively influenced detections when the worker was wearing those colors.

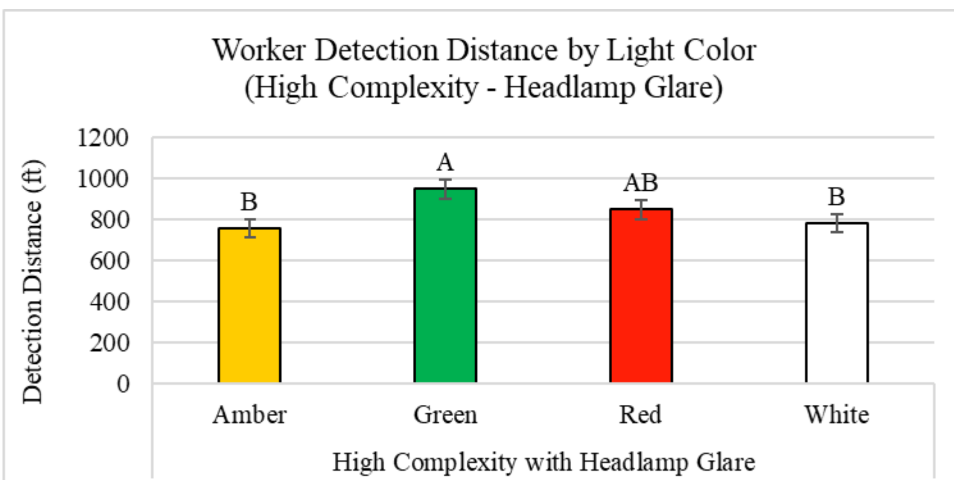

Figure 27. Worker Detection Distance by Color with Headlamp Glare – High Complexity

Additional pairwise comparisons for worker light color are shown in Figure 28 and represent detections as the participant vehicle was approaching downhill against the work vehicle's taillamps. Workers wearing the green light source (836 ft) were detected from 43% farther than amber (584 ft), and 22% farther than red (781 ft). The worker for the downhill approach was significantly influenced by the presence of visual clutter. The visual clutter included two sets of red taillamps from the work vehicles as well as two amber flashing beacons, which negatively impacted detections when the worker was also wearing those colors.

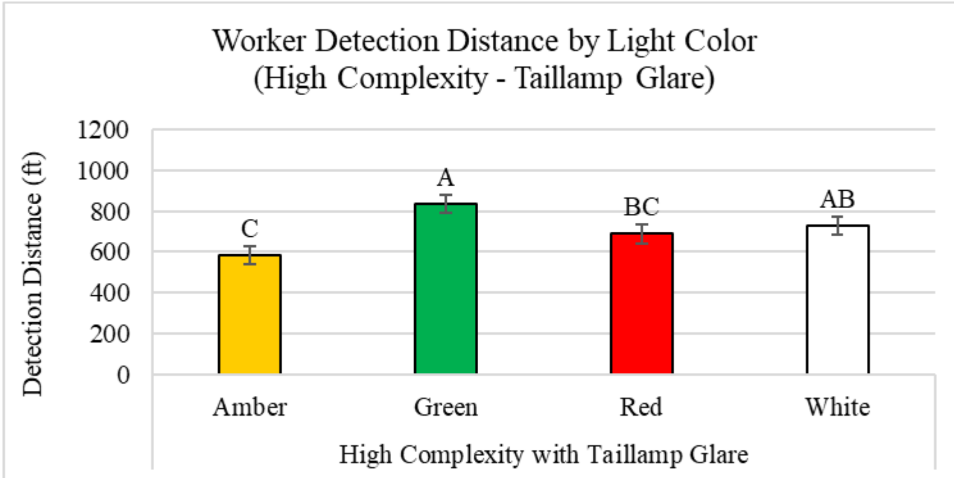

Figure 28. Worker Detection Distance by Color with Taillamp Glare – High Complexity

The relationship between worker detection and light source color at the high-complexity work zone is shown in Figure 29. Results are summarized across the direction of travel and reflect the proportion of all detections at a given distance. The green treatment was associated with a significantly larger proportion of detections at distances farther than 600 ft from the worker. Among the other colors, red and white were consistently associated with a larger proportion of detections than the retro only condition. The amber light source performed worse than the retro vest. Adding another amber light source to the high-complexity work zone may have resulted in confusion for the participants. The influence of color was most pronounced at distances between 600 and 1,200 ft from the work zone. These results highlight the importance of color choice relative to the existing work zone lighting.

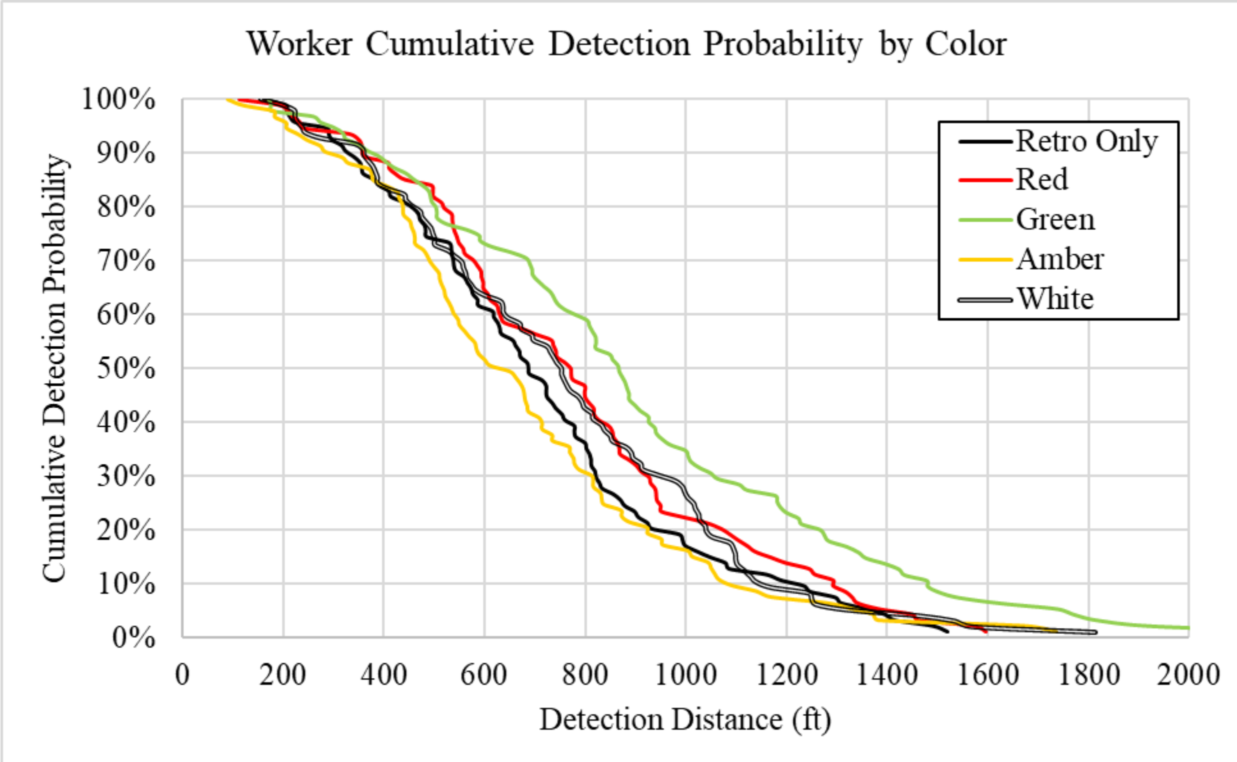

Figure 29. Cumulative Detection Probability of Worker by Color – High Complexity

Modeling results for the analysis of flagger detection by color at the high-complexity work zone are given in Table 19. Color was tested using a single light source located on the shoulder of the worker. The main effect of color was significant for the downhill approach against the work vehicle taillamps. The interaction term was not significant for either approach, suggesting the influence of color did not vary across age for the flagger.

The flagger position for the uphill approach was located on the opposite shoulder where the flagger was not backdropped by the work zone. Instead, the portable work zone light was the only nearby element of visual clutter. The relative reduction in background clutter may have contributed to the lack of difference between color treatments. The flaggers at this position were seen, on average, from 999 ft away wearing white, 1,034 wearing ft wearing amber, 1,083 ft wearing green, 1,091 ft wearing red, and 1,048 ft wearing the standard Class 3 retro vest. Suggesting that additional personal lighting for the flagger in this position provided minimal benefit.

Table 19. Type 3 Tests of Fixed Effects for Flagger Detection Color Modeling – High Complexity

Approach	Effect	Num DF	Den DF	F Value	Pr > F
Uphill Approach with Headlamp Glare	Color	3	139	1.48	0.2234
	Age	1	46.3	20.45	**<.0001**
	Color*Age	3	139	0.46	0.7129
Downhill Approach with Taillamp Glare	Color	3	134	6.88	**0.0002**
	Age	1	46.2	18.06	**0.0001**
	Color*Age	3	134	0.2	0.8934

Bold font indicates statistical significance.

Post hoc testing results for flagger light source color are shown in Figure 30 and reflect detections as the participant vehicle approached downhill against the work vehicle's taillamps. Workers wearing the green light source (871 ft) were detected from 21% farther than amber (717 ft), and 17% farther than white (743 ft). Although red was present as part of the work zone visual clutter, the movement of the worker may have aided participants in detecting them among the static vehicle taillamps.

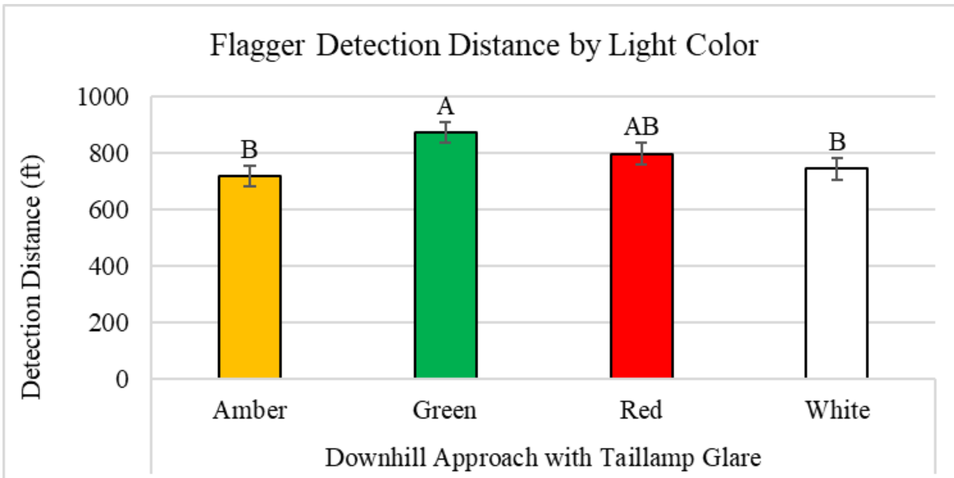

Figure 30. Detection Distance of Flagger by Color with Taillamp Glare – High Complexity

The relationship between flagger detection and light source color at the high-complexity work zone is shown in Figure 31. Results are summarized across the direction of travel and reflect the proportion of all detections at a given distance. The green and red treatments were consistently associated with a larger proportion of detections at distances farther than 600 ft from the flagger. The amber and white treatments performed similarly to the retro vest. The influence of color was not significantly closer than 600 ft from the flagger as none of the treatments resulted in a higher proportion of detections than the standard Class 3 vest. Overall, the choice of color was less impactful for the static flagger than the moving worker.

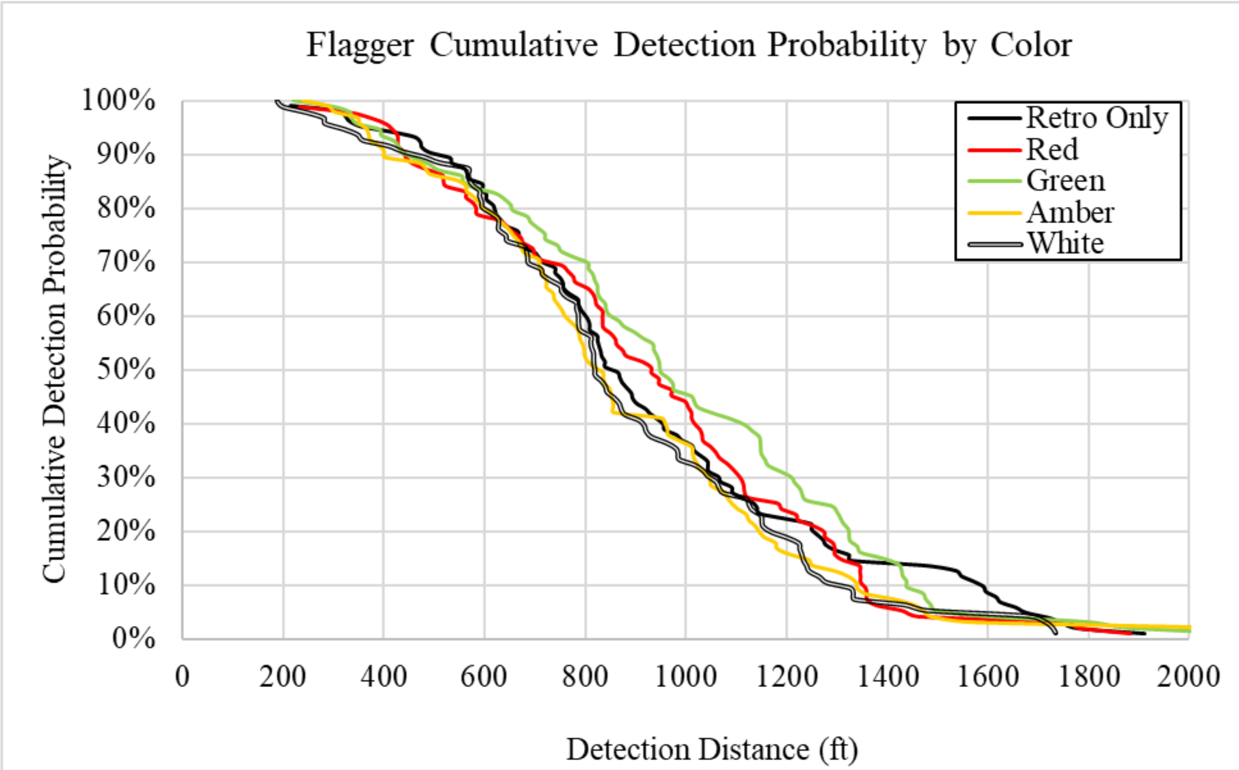

Figure 31. Cumulative Detection Probability of Flagger by Color – High Complexity

Flashing

Modeling found statistical difference in worker detection distance between flash conditions at the high-complexity work zone for both approaches (Table 20). Concerning the uphill approach where headlamp glare was present, workers using the steady-on setting (925 ft) were seen from 18% farther than when using the flashing setting (787 ft). Similarly, when the participant vehicle approached downhill against the influence of the work vehicle's taillamps, workers using the steady-on setting (802 ft) were seen from 16% farther than when using the flashing setting (691 ft). Among the high level of visual clutter, the moving worker was seen from significantly farther using the steady-on setting, suggesting that among other flashing lights the use of flashing personal lighting devices may make detections more difficult. Notably, the flash pattern for the tested device was slow (~1 Hz) and the light source color was red, which may have contributed to the difference.

Table 20. Type 3 Tests of Fixed Effects for Worker Detection Flashing Modeling – High Complexity

Analysis	Effect	Num DF	Den DF	F Value	Pr > F
Worker Detection, Uphill Approach, Headlamp Glare	Flashing	1	46.3	21.48	**<.0001**
	Age	1	46	36.73	**<.0001**
	Flashing*Age	1	46.3	1.59	0.214
Worker Detection, Downhill Approach, Taillamp Glare	Flashing	1	46	10.95	**0.0018**
	Age	1	46	22.74	**<.0001**
	Flashing*Age	1	46	2.29	0.1373

Bold font indicates statistical significance.

Modeling found no statistical significance between flash conditions for flagger detections at the high-complexity work zone (Table 21). For the uphill approach, the flagger was detected, on average, from 1,083 ft using steady on and 1,088 ft when flashing. For the downhill approach, the flagger was detected, on average, from 780 ft using steady on and 819 ft when flashing.

Table 21. Type 3 Tests of Fixed Effects for Flagger Detection Flashing Modeling – High Complexity

Analysis	Effect	Num DF	Den DF	F Value	Pr > F
Flagger Detection, Uphill Approach, Headlamp Glare	Flashing	1	42.3	0.01	0.925
	Age	1	44.4	16.01	**0.0002**
	Flashing*Age	1	42.3	2.69	0.1087
Flagger Detection, Downhill Approach, Taillamp Glare	Flashing	1	47.5	1.53	0.2216
	Age	1	46.4	16.8	**0.0002**
	Flashing*Age	1	47.5	0.19	0.6624

Bold font indicates statistical significance.

Intensity

Statistical modeling results for worker detections by intensity at the high-complexity work zone are given in Table 22. Intensity was tested using a single white light source located on the shoulder of the worker. The main effect of intensity was significant for each uphill approach where glare from the work vehicles headlamps was present. The interaction terms were not significant, suggesting that the influence of intensity did not vary across age.

Pairwise comparisons for intensity showed that workers using the high-intensity setting (894 ft) were detected from 14% farther than low (781 ft). The high setting may have helped to set the worker apart from the work vehicles headlamps while the lower setting could not outcompete them.

Table 22. Type 3 Tests of Fixed Effects for Worker Detection Intensity Modeling – High Complexity

Analysis	Effect	Num DF	Den DF	F Value	Pr > F
Worker Detection, Uphill Approach, Headlamp Glare	Intensity	1	46	5.75	**0.0206**
	Age	1	46	20.05	**<.0001**
	Intensity*Age	1	46	0.16	0.6918
Worker Detection, Downhill Approach, Taillamp Glare	Intensity	1	45	0.21	0.6496
	Age	1	45.7	6.15	**0.0169**
	Intensity*Age	1	45	0.01	0.9069

Bold font indicates statistical significance.

Statistical modeling results for flagger detections by intensity at the high-complexity work zone are given in Table 23. The main effect of intensity was significant for each uphill approach where glare from the work vehicles headlamps was present. The interaction terms were not significant, suggesting the influence of intensity did not vary across age. Pairwise comparisons showed that flaggers using the high-intensity setting (1,001 ft) were detected from 8% farther than low (928 ft). The high setting may have helped to set the flagger apart from the portable work zone lighting that was located in close proximity to the flagger station.

Table 23. Type 3 Tests of Fixed Effects for Flagger Detection Intensity Modeling – High Complexity

Analysis	Effect	Num DF	Den DF	F Value	Pr > F
Flagger Detection, Uphill Approach, Headlamp Glare	Intensity	1	46.9	4.44	**0.0404**
	Age	1	45.9	16.45	**0.0002**
	Intensity*Age	1	46.9	3.99	0.0515
Flagger Detection, Downhill Approach, Taillamp Glare	Intensity	1	45.7	0.78	0.3829
	Age	1	46.3	7.45	**0.009**
	Intensity*Age	1	45.7	4.04	0.0504

Bold font indicates statistical significance.

Worker Visibility Assessment

Participant subjective ratings of how visible the worker and flagger were at the high-complexity work zone were averaged and are reported in Table 24. The lighting design approach results for the worker and flagger followed the same pattern as the low- and medium-complexity work zones. On average, participants felt that workers were most visible when wearing the white helmet plus vest treatment or two of the white shoulder light sources and that the worker was least visible wearing just the standard Class 3 vest. Notably, participants rated the retro-only ensemble with decreasing visibility as work zone complexity increased. The opposite trend was observed for the treatments containing lighting, suggesting participants felt the retro vest was becoming less effective for the worker in more complex work zones, and that the lighted treatments were more effective among increased visual clutter. Participants indicated that the green color made the worker and flagger most visible; however, all colors were rated as less visible on the flagger than the worker. Participants felt the steady-on setting made the worker and flagger more visible compared to flashing and rated the worker and flagger similarly for the high- and low-intensity settings.

Table 24. Worker Visibility Assessment by Analysis – High Complexity

Analysis	Ensemble	Average Worker Rating	Average Flagger Rating
Lighting Design Approach	Retro Only	2.59	3.09
	White Vest	3.18	3.24
	White Helmet	3.26	3.31
	White Helmet plus Vest	3.78	3.34
	White Shoulder	3.37	3.16
	White Shoulder plus Vest	3.47	3.29
	White Shoulder × 2	3.72	3.50
Color	Amber Shoulder	3.20	2.97
	White Shoulder	3.37	3.16
	Green Shoulder	3.63	3.39
	Red Shoulder	3.20	3.03
Flashing	Red Helmet	3.51	3.24
	Red Helmet Flash	3.11	3.12
Intensity	White Shoulder	3.37	3.16
	White Shoulder Low	3.34	3.25

Driver Survey

The results of the driver survey are discussed below and reported as the number of responses for each age group.

Lighting Design Approach

Participants were handed a photo that pictured the vest, white helmet, white shoulder, white shoulder × 2, and retro-only ensembles, and asked to pick which of these options made the worker most visible. These ensembles represented the torso, head, shoulder, two-shoulder, and control lighting designs. The number of responses for each ensemble is shown in Figure 32. Participants overwhelmingly chose the white shoulder × 2 as the most effective design among these options, with a fairly even split between young and old drivers.

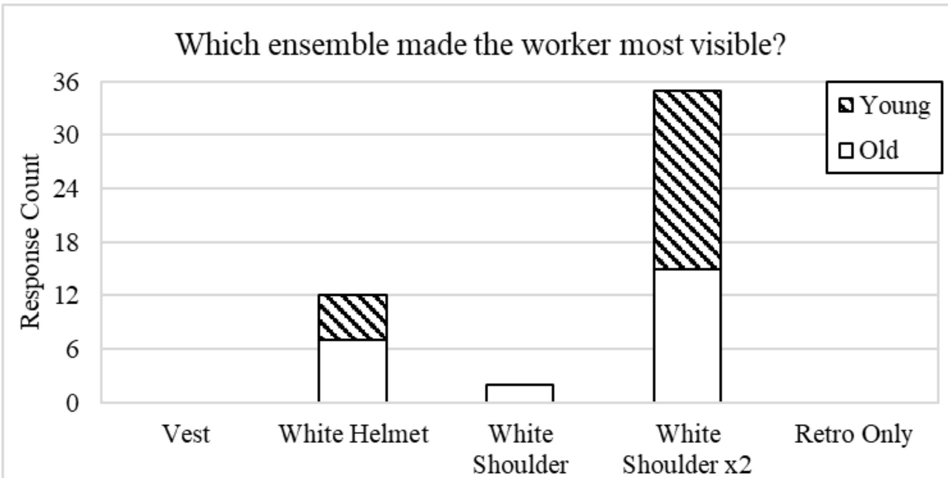

Figure 32. Ensemble Preference by Lighting Design

Light Color

Participants were handed a photo that pictured the amber, green, red, and white shoulder ensembles and asked to pick which one made workers most visible. Participants overwhelmingly selected green as the most effective color (Figure 33). Nearly all young participants and the majority of old participants selected green.

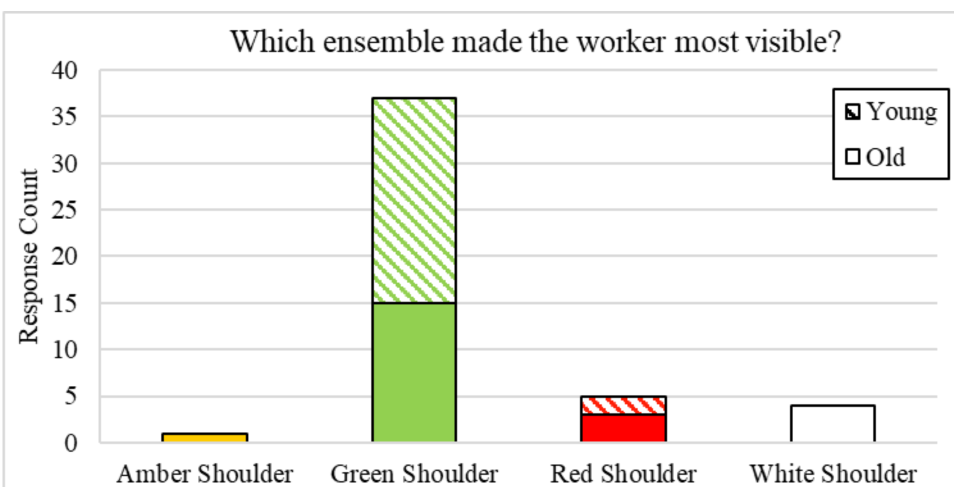

Figure 33. Ensemble Preference by Color

Flash Pattern

Participants were handed a photo that pictured the three head treatments (red, red flashing, and white) and asked which made the worker most visible. The red flashing configuration was the most frequently selected option overall, and the most popular among older participants (Figure 34). The next most popular option was the steady-on white configuration, which was selected by the majority of young participants.

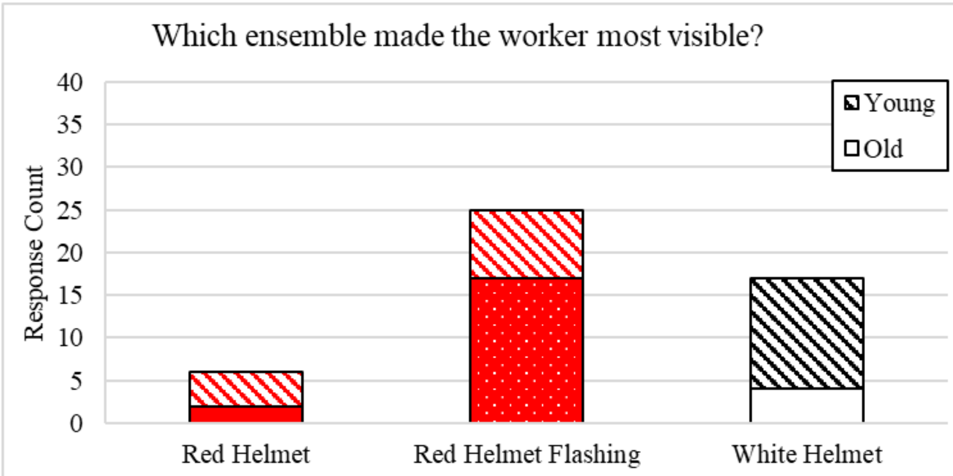

Figure 34. Ensemble Preference by Light Behavior

Flagger Ensemble

Participants were handed a photo that pictured all 14 ensembles and asked which ensemble made the flaggers the most visible. The green shoulder × 2 ensemble was the most popular choice (Figure 35). Half of all participants selected this ensemble, which was also the most popular choice by age group. The next most popular choice, with about half as many responses, was the white shoulder × 2 option. This seems to indicate that participants believed more lighting was beneficial.

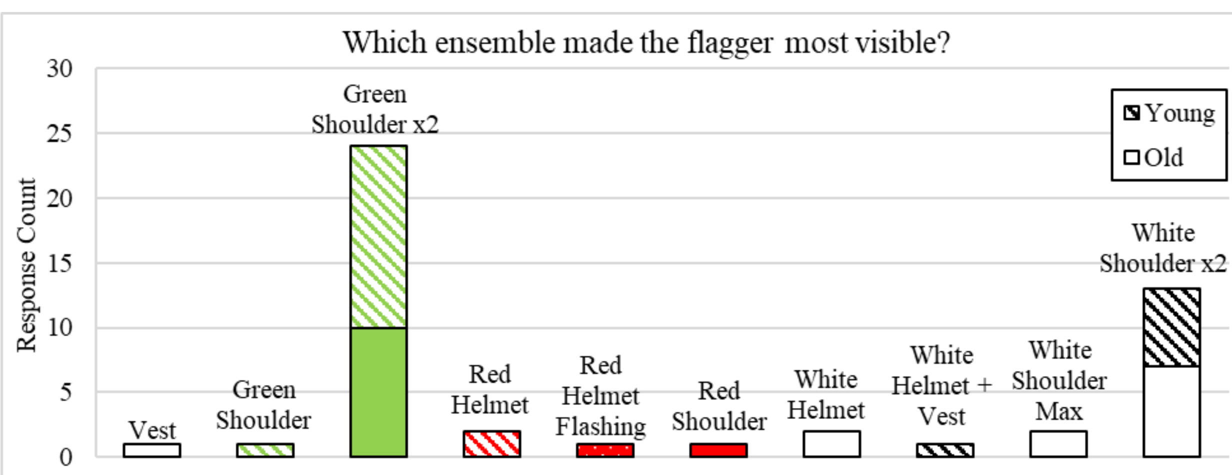

Figure 35. Ensemble Preference for Flaggers

Worker Ensemble – With Visual Clutter

Participants were asked which of the 14 ensembles made workers inside the cones most visible. This would be representative of the medium- or high-complexity work zones. Again, the green shoulder × 2 was by far the most popular choice (Figure 36). The white shoulder × 2 ensemble was the second most popular choice, but not as popular as for the flagger. The single green shoulder ensemble was the third most popular choice.

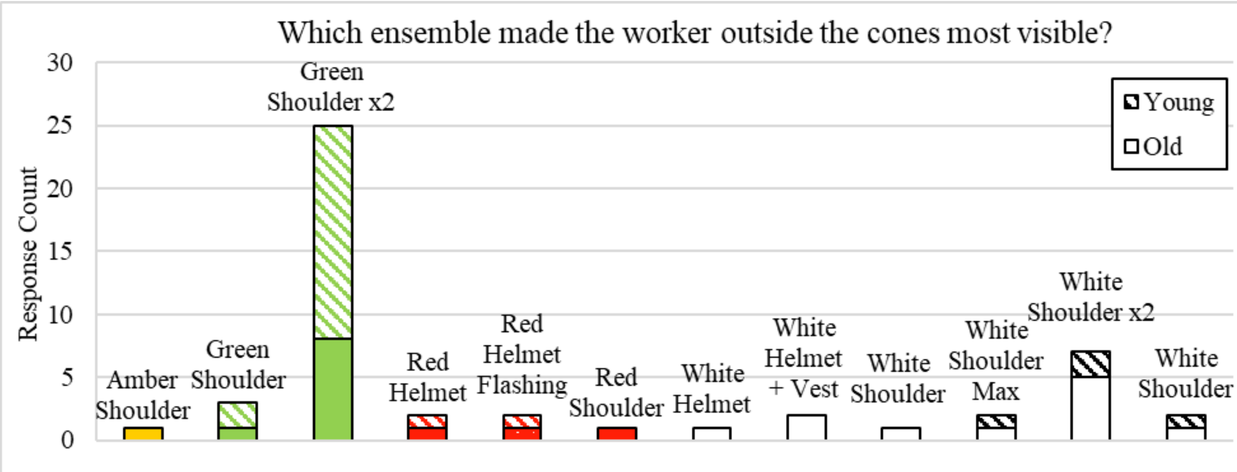

Figure 36. Ensemble Preference for Workers with Visual Clutter

Worker Ensemble – No Visual Clutter

Participants were asked which of the 14 ensembles made workers outside of the cones, such as the one at the low-complexity work zone, most visible. Again, the green shoulder × 2 ensemble was the most popular choice as over half of all participants, and the majority of young participants, selected it as the most effective option (Figure 37).

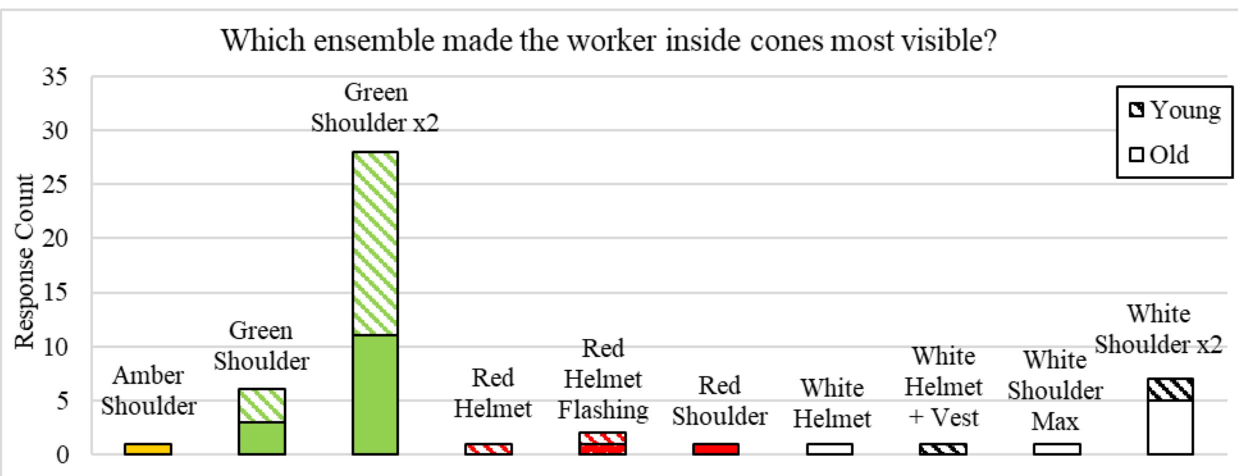

Figure 37. Ensemble Preference for Workers without Visual Clutter

Most Visible Ensemble

When asked which of the 14 ensembles was the most effective overall, the overwhelming majority of participants selected the green shoulder × 2 ensemble (Figure 38).

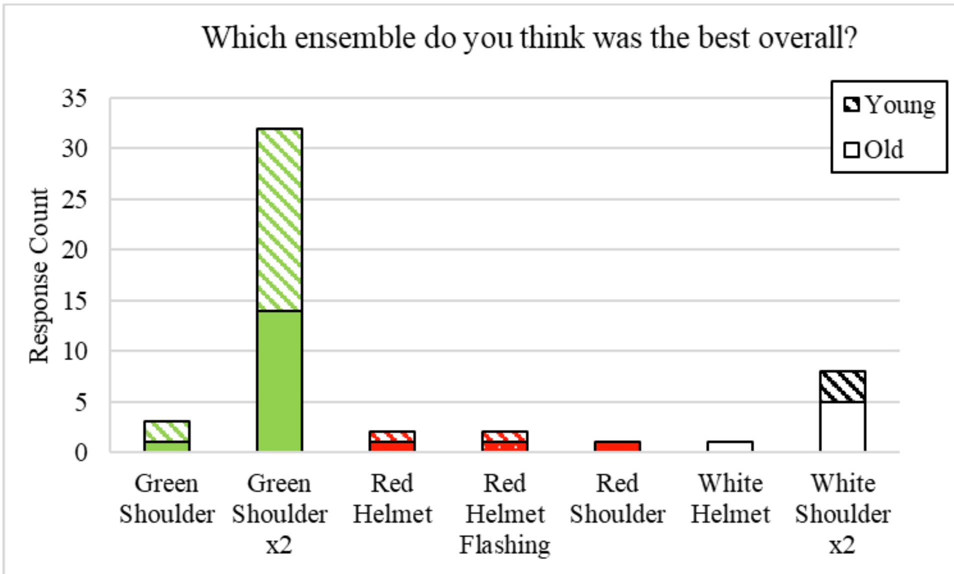

Figure 38. Overall Ensemble Preference

Photometric Characterization Results

The lighted apparel characterization results are detailed in the following section. Battery life was evaluated and visualized for an expected workday's worth of use.

Battery Life

The shoulder light source came with four intensity settings (Levels 1 to 4), where intensity decreased with level. Figure 39 shows that the device was able to operate for over 8 hr on the least intense setting (Level 4) while only functioning for 65 min on the most intense setting (Level 1). When operated at Levels 3 and 4, the device was able to maintain a consistent luminous intensity; however, when operated at Levels 1 and 2, there was a noticeable decline in luminous intensity that was correlated with usage.

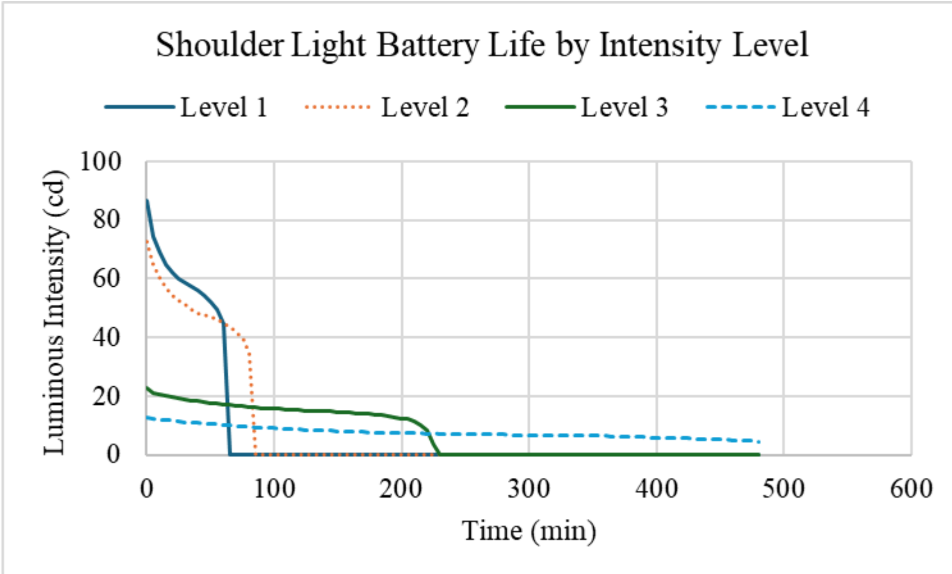

Figure 39. Shoulder Light Battery Life

The helmet light source came with a white or red color choice. Figure 40 displays the relationship between luminous intensity and time for each color. Results showed a marked decline in luminous intensity for the first hour when set to white and the first 90 min when set to red. The luminous intensity stabilized after 2 hr, and the device subsequently operated for 6 hr at a consistent luminous intensity for both colors. The magnitude of luminous intensity was consistently larger for the white light source color.

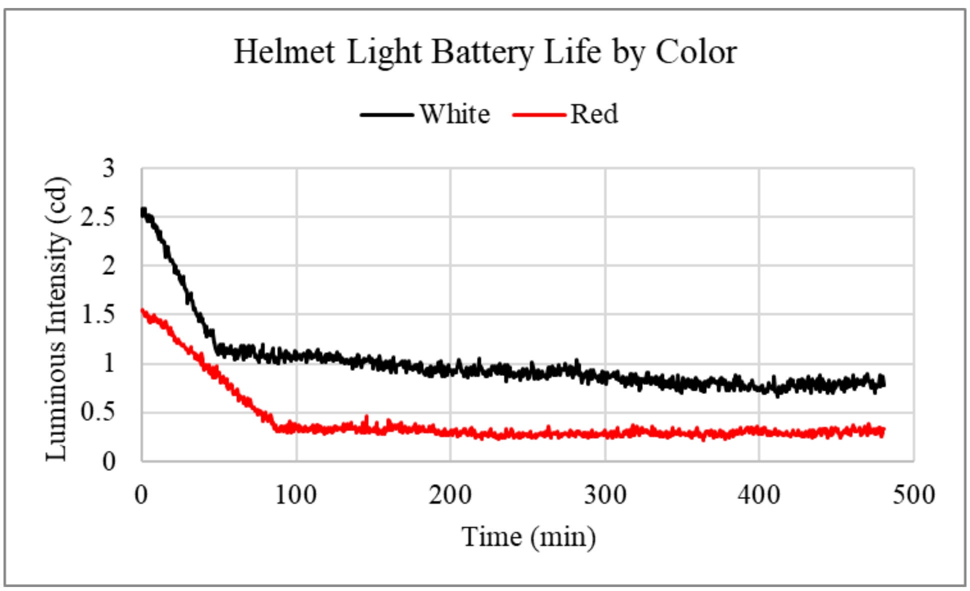

Figure 40. Helmet Light Battery Life

The vest light source only had a white light source. Figure 41 displays the relationship between luminous intensity and time for the vest light source. Results indicated a consistent luminous intensity for all 8 hr of operation.

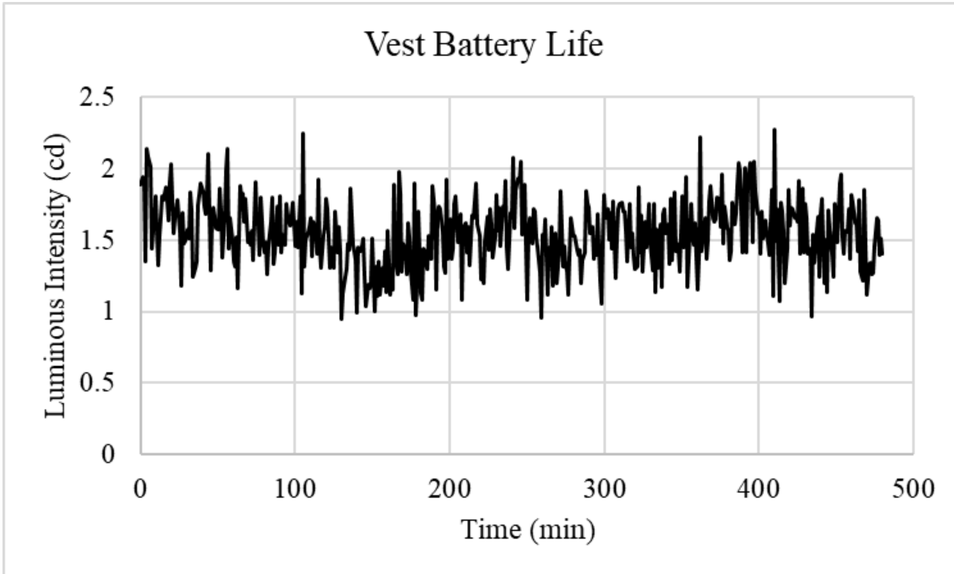

Figure 41. Vest Light Battery Life

Overall, the battery life analysis found significant variation between devices. The shoulder light source had the largest magnitude of luminous intensity (10 to 90 cd); however, the device was unable to maintain the highest intensity for significant periods of time and three out of four pre-programmed intensity levels significantly reduced the battery life. Concerning the head light source color, the white (1 cd) and red (0.25 cd) both operated for the full 8-hr test. The vest light source operated for the full 8-hr test and had the most consistent luminous output with respect to time of all the devices.

SPD

The SPD curves for each of the helmet light source colors is shown in Figure 42. The white light source power peaked at a wavelength of 451 nm, and the red light source peaked at a wavelength of 627 nm.

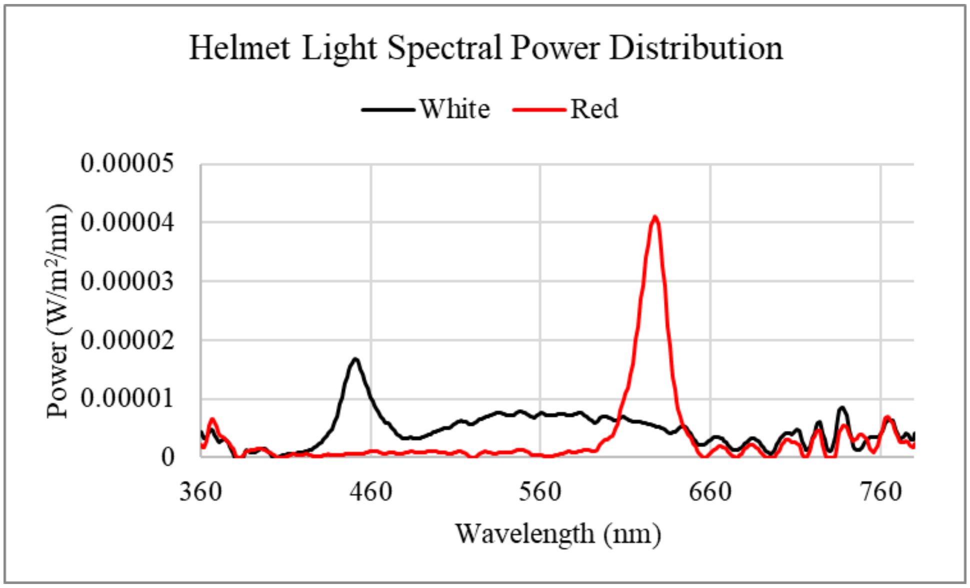

Figure 42. Helmet Light SPD

Figure 43 shows the SPD curves for each of the shoulder light source colors. The white light source peaked at a wavelength of 456 nm, the green light source peaked at a wavelength of 520 nm, the amber light source peaked at a wavelength of 606 nm, and the red light source peaked at a wavelength of 658 nm.

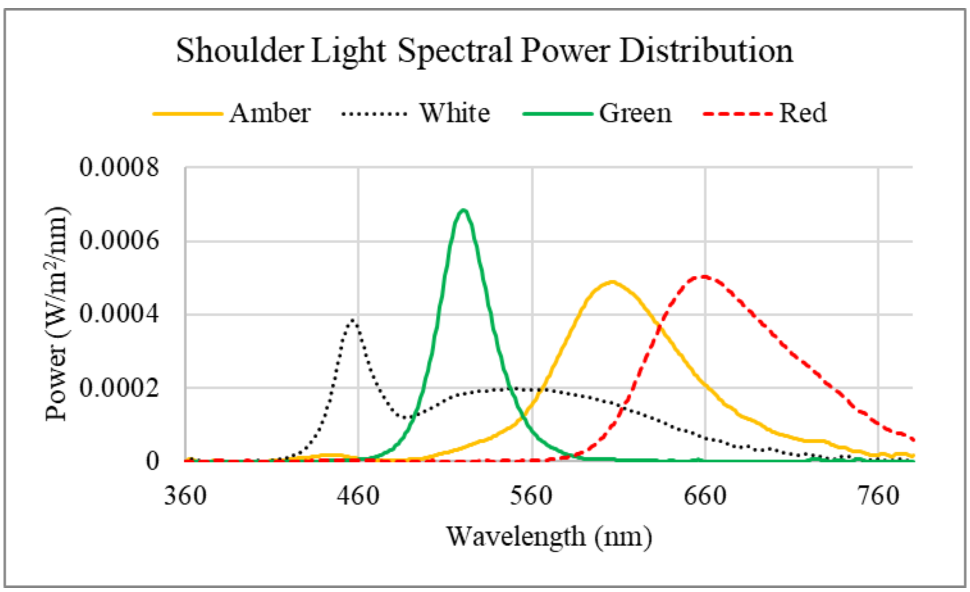

Figure 43. Shoulder Light SPD

The SPD curve for the vest light is shown in Figure 44. The white light source peaked at a wavelength of 448 nm.

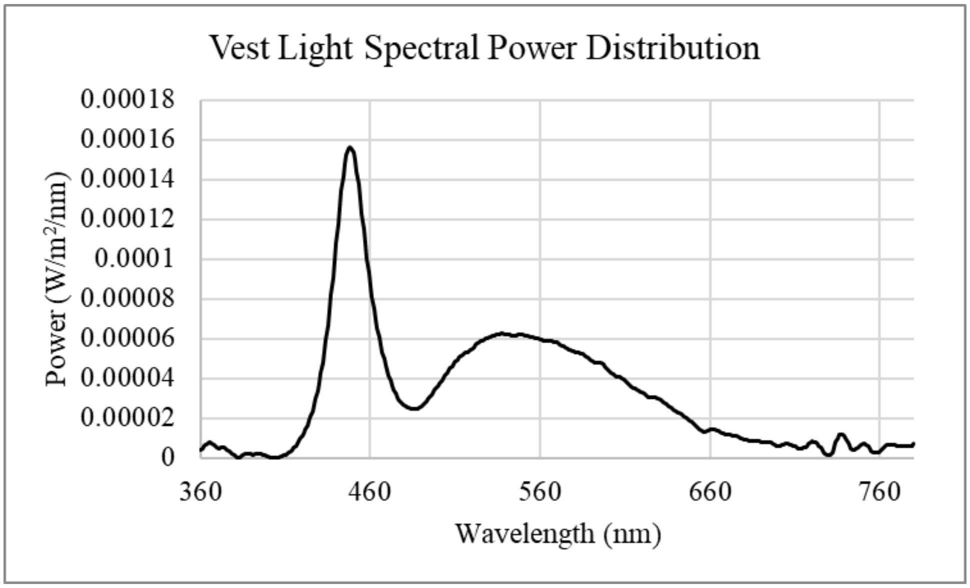

Figure 44. Vest Light SPD

Overall, the results of the SPD device characterization met the existing expectations for peak wavelength values.

Intensity

The shoulder light source intensity results are presented by color in Figure 45. All colors experienced an increase in luminous intensity as the device setting level decreased. In general, the red light source color was the least intense at all setting levels. Amber, green, and white were all similar in magnitude at each device level. The amber light source had the highest luminous intensity for Levels 1, 3, and 4, while white was measured at the highest value for Level 2.

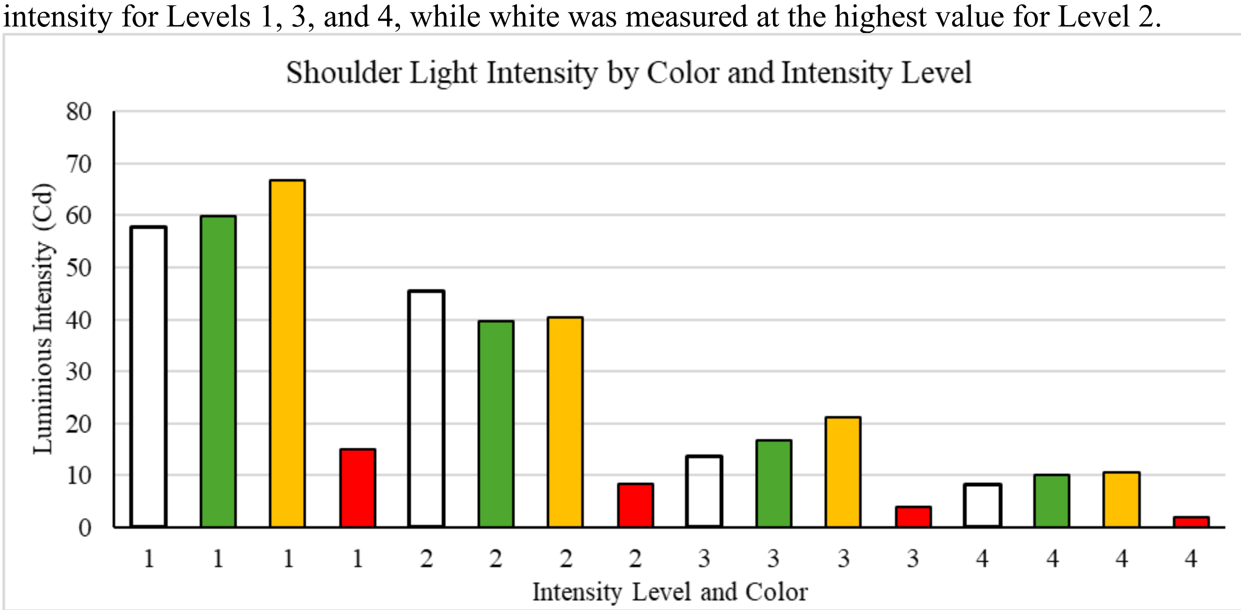

Figure 45. Shoulder Light Intensity Comparison by Color and Intensity Setting

Retroreflectivity Measurements

Retroreflectivity was measured for the vest device at three places: the tape, orange striping, and green mesh. The retroreflective tape affixed to the worker's helmet was also measured. The vest tape was measured at 260 cd/lx/m^2 and the helmet tape was measured at 320 cd/lx/m^2. The reflectivity was similar in magnitude for both tapes at all wavelengths, although the helmet tape was consistently higher. The vest's orange (2.5%) and green (1.5%) fabrics were measured at similar reflectivity percentage across wavelength (Figure 46).

Figure 46. Retroreflectivity of Vest Fabrics

Field Study User Feedback Results

Below is a summary of user feedback gathered from the field study. Devices evaluated included the lighted vest, the red helmet light (flashing and steady), and a single shoulder mounted beacon (both the white and green color variants). Work crews used each device for approximately 2 weeks, and feedback was gathered through surveys (approximately 12 responses) and a focus group discussion (5 participants). Feedback included the following:

- Lighted Vest:
  - Inconsistent perceptions of visibility and safety; some thought it was effective and others did not.
  - The battery was bulky and got in the way.
  - White light negatively affected night vision.
- Red Helmet Light:
  - Was the preferred device among those tested.
  - Durability was a concern as some of the devices were broken during use.
  - Felt that it encouraged drivers to move over.
  - Red color was attention-grabbing.
  - Glare was not an issue since the light was out of sight.
  - The work light was very useful for their tasks but could be blinding to other workers.
  - The red/green work light was also useful for task lighting while maintaining night vision.
- Shoulder Beacon:
  - Green color was best for visibility and safety.
  - A flashing option would be preferred over the steady-on option.

    - The location of the light on the shoulder was distracting.
    - A helmet-mounted option to reduce glare would be of interest.
- Light Color:
    - White and amber are ineffective as they are common colors in work zones.
    - Red is effective and does not impair night vision/dark adaptation.
    - Green is the most visible color and effective for visibility.
    - Open to other color options, such as purple, but worry that drivers might not recognize them as indicating worker presence.
- General Comments:
    - Lighted apparel is most effective (and needed) for workers in temporary, unlit work zones.
    - Lighted apparel is unnecessary in well-lit work zones and therefore should not be required.

When asked what an ideal device would look like, the focus group indicated that a rigid halo device with a flashing green halo and forward-facing white work lights would be ideal. They additionally suggested that the work light should have separate bright and dim beams to minimize glare to other workers when facing each other.

DISCUSSION

Lighting Design

Detection Distance Performance

Table 25 shows the detection distance performance comparison of each lighting design compared to the no-lighting control condition (retro only) across work zone complexity and approach. As a reminder, all designs were tested using white light and comparisons were not made for the medium-complexity taillamp approach due to limitations with the study design. The head + torso combination performed significantly better than the control in the medium- and high-complexity scenarios, while the two-shoulder design performed significantly better for the low-complexity headlamp approach.

Table 25. Performance Comparison to Control Condition by Lighting Design

	Low Complexity		Medium Complexity		High Complexity	
Design	**Headlamp**	**Taillamp**	**Headlamp**	**Taillamp**	**Headlamp**	**Taillamp**
Head	No Diff	No Diff	No Diff	NA	No Diff	No Diff
Head Torso	No Diff	No Diff	Better	NA	Better	Better
One Shoulder	No Diff	No Diff	No Diff	NA	No Diff	No Diff
Shoulder Torso	No Diff	No Diff	No Diff	NA	No Diff	No Diff
Torso	No Diff	No Diff	No Diff	NA	No Diff	No Diff
Two Shoulder	Better	No Diff	No Diff	NA	No Diff	No Diff

NA = Not Applicable

Although the head + torso combination had better performance in most scenarios, no single design outperformed the control in all conditions. However, at the same time, no design performed worse than the control in any scenario either. This means that decisions about lighting design can be made considering factors such as cost, durability, or user comfort without any detriment to the visibility of the worker.

Driver and User Feedback

Although participants chose the two-shoulder design as the most effective, this was not corroborated by the detection distance data or their own ratings of visibility. Table 26 shows the visibility rating for each lighting design relative to the control condition. While the two-shoulder and head + torso designs had the same overall rating, the head + torso design was rated higher for visibility for all worker positions. The two-shoulder design was only rated higher for the flagger position.

Table 26. Relative Visibility Rating by Lighting Design

	Low Complexity	Medium Complexity	High Complexity		
Design	**Worker**	**Worker**	**Worker**	**Flagger**	**Overall Rating**
Control (Retro)	0.00	0.00	0.00	0.00	0.00
Torso	0.27	0.46	0.58	0.15	0.37
Head	0.30	0.43	0.67	0.22	0.40
One Shoulder	0.40	0.59	0.77	0.07	0.46
Shoulder Torso	0.20	0.65	0.88	0.20	0.48
Two Shoulder	0.50	0.69	1.13	0.41	0.68
Head Torso	0.60	0.70	1.19	0.25	0.68

User feedback suggested a preference for head-mounted devices, with the absence of glare being a key factor. Users found the location of the shoulder beacon to be problematic as this presented glare and/or distraction particularly when turning their head toward the device. Opinions of the torso design were mixed, although there was agreement that the battery for the particular product used posed problems due to its size and placement.

Lighting Color

Detection Distance Performance

Table 27 shows the detection distance performance comparison of each light color compared to white light. As a reminder, this factor compared the various colors across the single shoulder design. Green performed significantly better across all work zone complexities and approaches. The results of this study confirm that among the tested colors, green is the superior choice that enhances detection in all scenarios.

Table 27. Performance Comparison to White by Lighting Color

Color	Low Complexity		Medium Complexity		High Complexity	
	Headlamp	Taillamp	Headlamp	Taillamp	Headlamp	Taillamp
Amber	No Diff	No Diff	No Diff	NA	No Diff	No Diff
Green	Better	Better	Better	NA	Better	Better
Red	No Diff	No Diff	No Diff	NA	No Diff	No Diff

NA = Not Applicable

While green was the clearly superior color for increasing the detection distance of the worker, questions remain about how drivers may interpret the color in real-world scenarios. In the context of driving, green lights are most often associated with traffic signals, in which green indicates the driver may proceed. This has the potential to cause confusion if a driver interprets the green light on a worker as giving information that conflicts with other traffic control devices. For example, a driver may interpret a green light on a flagger as permission to proceed, which may conflict with the STOP paddle. For this reason, VDOT may wish to restrict the use of green lighted apparel where a reasonable possibility for confusion may exist, such as on flaggers or workers near signalized intersections.

Driver and User Feedback

The performance of green was supported by driver feedback in which green was consistently chosen as the most visible color and rated higher for visibility across all conditions. Table 28 shows the visibility rating for each light color relative to the control condition. Interestingly, the addition of the amber shoulder beacon led to decreases in visibility ratings for the low-complexity worker and the flagger. Similarly, the red shoulder beacon had reduced visibility ratings when used on the flagger.

Table 28. Relative Visibility Rating by Lighting Color

Color	Low Complexity	Medium Complexity	High Complexity		Overall Rating
	Worker	Worker	Worker	Flagger	
Control (Retro)	0.00	0.00	0.00	0.00	0.00
Amber (Shoulder)	-0.10	0.16	0.60	-0.12	0.14
Red (Shoulder)	0.12	0.16	0.61	-0.06	0.21
White (Shoulder)	0.40	0.59	0.77	0.07	0.46
Green (Shoulder)	0.76	1.14	1.03	0.30	0.81

User feedback agreed that green was the most effective color for visibility. Users suggested that amber and white were ineffective colors due to being common colors in work zones, but that red was effective and reduced issues with glare and night vision.

Flash Pattern

Detection Distance Performance

Table 29 shows the performance comparison between flashing and steady-on light behavior. As a reminder, this factor compared the red helmet and flashing red helmet ensembles. Light behavior was only significant in the high-complexity work zone, in which the steady-on light performed better than flashing. One possible explanation for this effect may be that the steady-on light stood out from the other flashing lights in the work zone and may have enhanced the apparent biomotion of the worker by giving the participant a steady point of reference.

Table 29. Performance Comparison by Light Behavior

Behavior	Low Complexity		Medium Complexity		High Complexity	
	Headlamp	Taillamp	Headlamp	Taillamp	Headlamp	Taillamp
Flashing	No Diff	No Diff	No Diff	NA	Worse	Worse
Steady-on	No Diff	No Diff	No Diff	NA	Better	Better

NA = Not Applicable

These results suggest that in high-complexity work zones, worker lighted apparel should use steady-on configurations, while either steady-on or flashing options are equally effective in low- and medium-complexity work zones. However, these results are based on a single device and single flash pattern that had a flash rate of approximately 1 Hz. It is possible that other flash patterns may produce different results.

Driver and User Feedback

While drivers indicated that the flashing red helmet was more effective than the steady-on option, this was contradicted by the detection distance data and their own visibility ratings. Table 30 shows the visibility rating for each light behavior relative to the control condition. The steady-on light was consistently rated as more visible across all scenarios and was particularly high for the worker in the high-complexity work zone.

Table 30. Relative Visibility Rating by Light Behavior

Behavior	Low Complexity	Medium Complexity	High Complexity		Overall Rating
	Worker	Worker	Worker	Flagger	
Control (Retro)	0.00	0.00	0.00	0.00	0.00
Flashing (Red Helmet)	0.23	0.27	0.52	0.04	0.26
Steady-on (Red Helmet)	0.49	0.61	0.92	0.16	0.55

User feedback was at odds with these findings, however. There was a strong preference among users for flashing options, as this was seen as being much more attention-grabbing than steady lights. However, users indicated that they would prefer high flash rates, which is something that was not tested in this study. It is possible that higher flash rates and different flash patterns may indeed provide benefits compared to the relatively slow flash (~1 Hz) that was tested here.

Light Intensity

Detection Distance Performance

Table 31 shows the performance comparison of the high and low light intensities. As a reminder, this factor compared the white shoulder (Level 3 intensity) and white shoulder max (Level 1 intensity) ensembles. Intensity was only significant in the high-complexity work zone but had varying results depending on the direction of approach. When drivers were approaching the work zone facing into the headlamps of the work vehicles, the high intensity helped the worker stand out among the other white light sources. However, when approaching the work zone from the rear, the low intensity option enhanced the detection of the worker. A possible explanation for this may be that glare or bloom from the high-intensity light masked the other parts of the worker, such as the retroreflective striping, and made the worker appear more like a stationary light source, such as the balloon light.

Table 31. Performance Comparison by Light Intensity

	Low Complexity		Medium Complexity		High Complexity	
Intensity	**Headlamp**	**Taillamp**	**Headlamp**	**Taillamp**	**Headlamp**	**Taillamp**
High	No Diff	No Diff	No Diff	NA	Better	Worse
Low	No Diff	No Diff	No Diff	NA	Worse	Better

NA = Not Applicable

These results show that across work zones and approaches, there was no clear better option for intensity. Therefore, the selection of intensity can be determined by other factors such as glare considerations or battery life. However, this was tested only using two settings for a single device. It is possible that other devices or more varied intensities could produce different results.

Driver and User Feedback

Driver visibility ratings agreed with the detection distance findings in that there was very little difference between the two intensity levels. While users were not asked to evaluate different intensity levels, the potential for glare was often mentioned, both glare directly to the user and glare user-to-user. Therefore, the intensity of lighted apparel can be considered primarily based on its potential for glare.

Limitations

Due to the large number of factors, not every combination of factor levels could be tested. This means that some combinations the data point to as potentially promising were not directly tested. Additionally, due to the large number of variables, some factors had limited factor levels, such as flash pattern and intensity.

One of the gaps in knowledge discovered during the literature review was that there was very little information regarding the performance of lighted apparel on the extremities (wrists/arms and ankles/legs). This is something the research team originally wanted to address. However, during pilot testing, the extremity treatments were found to be cumbersome to put on, did not always fit, were uncomfortable, and could restrict movement. Additionally, these lights were ineffective as they were over-powered by the retroreflective material. For these reasons, these treatments did not seem practical and were therefore excluded.

CONCLUSIONS

- *The combination of lights on the head and torso led to significantly longer detection distances than the standard Class 3 vest and high-visibility pants in most scenarios.* All other designs did not increase the detection of workers over the standard Class 3 vest and high-visibility pants.

- *Green lights resulted in significantly longer detection distances than any other color and were preferred by both drivers and users. Amber should be avoided as it performed worse than the control condition in some scenarios.*

- *Steady-on lights resulted in significantly longer detection distances within the high-complexity work zone, but no difference was found between steady-on and flashing lights in any other scenario.* User feedback also suggested that flashing lights, and lighted apparel in general, were not necessary in well-lit high-complexity work zones.

- *Because a higher intensity was not found to increase detection distance and glare was a concern for workers, devices should be bright enough to be seen over the retroreflective stripes of high-visibility gear but not overly bright.*

- *The effectiveness of the wearable lighted apparel at increasing the visibility of workers in work zones was dependent on the color of the light more so than the design, flash pattern, or intensity. Color should be the primary factor when considering lighted apparel configurations.* Decisions regarding design, pattern, and intensity may prioritize worker comfort, glare considerations, cost, and durability, among others.

RECOMMENDATIONS

1. *Based on the results of this research, VDOT should evaluate a green, steady-on lighted apparel device in a pilot deployment to a small group of vulnerable workers such as Incident Management Coordinators (IMCs) or Safety Service Patrol (SSP) operators.* It is recommended that the device should be mounted in a manner to prevent glare to the user, such as being mounted on the helmet. Ideally, the device should also provide 360-degree visibility and not be obstructed by the user's body or other apparel. An evaluation of the piloted device(s) should be conducted to verify benefits and identify potential issues.

2. *The VDOT Traffic Operations Division should update the VWAPM to allow wearable green lights in certain circumstances and discourage or prohibit combinations shown to have a disbenefit.* The VWAPM currently states that "all wearable lights internal or external to the apparel shall be steady burn (not flashing or strobing) yellow/amber, white, red, or yellow-green." The research supports the restriction of flashing/strobing but would also support allowing green. VDOT should also consider prohibiting use of green or red lights by flaggers to avoid conflict with the meaning of the colors on the STOP and SLOW sides of the paddle. VDOT could consider recommending or requiring green lights to promote consistency among workers.

3. *VDOT should promote awareness of this study to the Virginia construction industry.* This study will be useful to contractors responsible for making PPE decisions for their employees. Typically, VDOT policies for its internal employees are more prescriptive than policies for non-VDOT employees, as each employer is responsible for their own Jobsite Hazard Assessments. However, awareness of this study could be useful for non-VDOT employers to make more informed PPE purchasing decisions and promote consistency with VDOT practices.

IMPLEMENTATION AND BENEFITS

The researchers and the technical review panel (listed in the Acknowledgments) for the project should collaborate to craft a plan to implement the study recommendations and determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendation 1, the pilot program should be initiated within 24 months of publication of this report with selected crews utilizing the devices during their normal operations. The VDOT Safety, Security and Emergency Management (SSEM) Division will be responsible for the selection of the product(s) to be pilot tested. A District Traffic Operations Manager (along with the TRP) will select the initial personnel to take part in the pilot program. Work crew experiences with the piloted device will be collected and monitored to ensure whether expansion of the pilot is warranted. The decision on whether to expand the pilot or change policy will be made by SSEM in consultation with the VDOT Traffic Operations Division Work Zone Safety Coordinator.

Regarding Recommendation 2, the Traffic Operations Division (TOD) will update the VWAPM Section 6C.05 within 24 months of the publication of this study to reflect the results of this study during the next VWAPM revision. TOD is responsible for updating the VWAPM, in coordination with the SSEM, Maintenance, and Construction Divisions. Note that updating the VWAPM is a complex process, as it requires review and approval by VDOT executive leadership, the Commonwealth Transportation Board, and FHWA, as well as Virginia's formal Regulatory Town Hall process. If a VWAPM update proves to not be feasible within 24 months, as an interim measure VDOT could instead issue an Instructional & Informational Memorandum superseding the VWAPM Section 6C.05.

Regarding Recommendation 3, TOD, in coordination with the SSEM and Construction Divisions, should promote awareness of this study with the Virginia Transportation Construction Alliance, Virginia Asphalt Association, and other similar industry organizations during relevant roundtables, meetings, and conferences. This will occur within 24 months of publication of this report in conjunction with VWAPM updates.

Benefits

The benefits of implementing Recommendation 1 include increasing the visibility of vulnerable road workers while gaining further understanding of how the chosen lighted apparel devices perform in real-world scenarios and further feedback regarding the user experience before adopting any organization-wide changes. If the pilot proves to be successful, then worker safety will be improved by increasing the visibility of workers that are exposed to traffic during nighttime operations.

The benefit of implementing Recommendations 2 and 3 will be standardizing how lighted apparel is used in Virgina, as well as increasing awareness in the construction industry of the benefits of specific lighted apparel combinations on worker safety.

ACKNOWLEDGEMENTS

The author thanks the following people who served on the technical review panel for this study: Marc Lipschultz, VDOT Traffic Operations Division (TOD); Bruce Martin, VDOT TOD; Rick Via, VDOT TOD (retired); Mike Corwin, VDOT TOD; Marchel Johnson VDOT SSEM; Nathan O'Kane, VDOT Salem District; Benjamin Cottrell, VTRC; and Michael Fontaine, VTRC. The research team would also like to thank Katie McGowan for coordinating the distribution of devices among VDOT and contractor personnel, and for her assistance gathering feedback through the user survey and focus group discussion.

REFERENCES

Abdi, H., & Williams, L. J. (2010). Tukey's honestly significant difference (HSD) test. *Encyclopedia of Research Design*, *3*(1), 1-5. https://personal.utdallas.edu/~Herve/abdi-HSD2010-pretty.pdf

American National Standards Institute. (2011). *ANSI/ISEA 207-2011: American national standard for high-visibility public safety vests.* https://webstore.ansi.org/standards/isea/ansiisea2072011

American National Standards Institute. (2020a). *ANSI/ISEA Z89.1-2014 (R2019): American national standard for industrial head protection*. https://webstore.ansi.org/standards/isea/ansiiseaz892014r2019?source=blog

American National Standards Institute. (2020b). *ANSI/ISEA 107-2020: American National Standard for high-visibility safety apparel*. https://www.ansi.org

ASTM International. (2018). *ASTM F2413-18: Standard specification for performance requirements for protective (safety) footwear*. https://www.astm.org/f2413-18.html

Balk, S. A., Tyrrell, R. A., Brooks, J. O., & Carpenter, T. L. (2008). Highlighting human form and motion information enhances the conspicuity of pedestrians at night. *Perception, 37*(8), 1276-1284.

Ball, K., & Sekuler, R. (1980). Models of stimulus uncertainty in motion perception. *Psychological Review, 87*(5), 435.

Barlow, H. B. (1978). The efficiency of detecting changes of density in random dot patterns. *Vision Research, 18*(6), 637-650.

Borzendowski, S. A. W., Sewall, A. A. S., Rosopa, P. J., & Tyrrell, R. A. (2015). Drivers' judgments of the effect of headlight glare on their ability to see pedestrians at night. *Journal of Safety Research, 53*, 31-37.

Bowden, R. (2000, July). Learning statistical models of human motion. In *IEEE Workshop on Human Modeling, Analysis and Synthesis, CVPR* (Vol. 2000).

Cavanagh, P., & Mather, G. (1989). Motion perception in peripheral vision. *Journal of the Optical Society of America A, 6*(2), 183-190.

Federal Highway Administration. (2023). *Manual on uniform traffic control devices 11th edition of the MUTCD, December 2023*. US Department of Transportation, Federal Highway Administration. https://mutcd.fhwa.dot.gov/kno_11th_Edition.htm

Fekety, D. K., Edewaard, D. E., Stafford Sewall, A. A., & Tyrrell, R. A. (2016). Electroluminescent materials can further enhance the nighttime conspicuity of pedestrians wearing retroreflective materials. *Human Factors, 58*(7), 976-985.

Grossman, E. D., & Blake, R. (2002). Brain areas active during visual perception of biological motion. *Neuron, 35*(6), 1167-1175.

Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Perception & Psychophysics, 14*, 201-211.

Mauss, A. S., Pankova, K., Arenz, A., Nern, A., Rubin, G. M., & Borst, A. (2015). Neural circuit to integrate opposing motions in the visual field. *Cell, 162*(2), 351-362.

National Work Zone Safety Information Clearinghouse. (n.d.). *Worker fatalities and injuries at road construction sites*. https://workzonesafety.org/work-zone-data/worker-fatalities-and-injuries-at-road-construction-sites/

Owens, D. A., Antonoff, R. J., & Francis, E. L. (1994). Biological motion and nighttime pedestrian conspicuity. *Human Factors, 36*(4), 718-732.

Piepho, H. P. (2018). Letters in mean comparisons: What they do and don't mean. *Agronomy Journal*, *110*(2), 431-434. https://doi.org/10.2134/agronj2017.10.0580

Pitcher, D., & Ungerleider, L. G. (2021). Evidence for a third visual pathway specialized for social perception. *Trends in Cognitive Sciences, 25*(2), 100-110.

Pollick, F. E., Lestou, V., Ryu, J., & Cho, S. B. (2002). Estimating the efficiency of recognizing gender and affect from biological motion. *Vision Research, 42*(20), 2345-2355.

Reflective Apparel Inc. (n.d.). *ANSI/ISEA made easy.* https://reflectiveapparel.com/pages/ansi-isea-107-2020

Sayer, J. R., & Mefford, M. L. (2004). High visibility safety apparel and nighttime conspicuity of pedestrians in work zones. *Journal of Safety Research, 35*(5), 537-546.

Tyrrell, R. A., Wood, J. M., Chaparro, A., Carberry, T. P., Chu, B. S., & Marszalek, R. P. (2009). Seeing pedestrians at night: Visual clutter does not mask biological motion. *Accident Analysis & Prevention, 41*(3), 506-512.

Virginia Department of Transportation. (2026a). *Work area protection manual (VWAPM) version 11.0*. https://www.vdot.virginia.gov/media/vdotvirginiagov/doing-business/technical-guidance-and-support/traffic-operations/work-zones/vwapm-2026-01-28_acc.pdf

Virginia Department of Transportation. (2026b). *Virginia manual on uniform traffic control devices.* https://ris.dls.virginia.gov/uploads/24VAC30/dibr/VA_MUTCD_09-10-2025_508_acc09192025_RM-20250922071023.pdf

Wood, J. M., Tyrrell, R. A., Marszalek, R., Lacherez, P., Chaparro, A., & Britt, T. W. (2011). Using biological motion to enhance the conspicuity of roadway workers. *Accident Analysis & Prevention, 43*(3), 1036-1041.

Wood, J. M., Marszalek, R., Lacherez, P., & Tyrrell, R. A. (2014). Configuring retroreflective markings to enhance the night-time conspicuity of road workers. *Accident Analysis & Prevention, 70*, 209-214.

Wood, J. M., Tyrrell, R. A., Lacherez, P., & Black, A. A. (2017). Night-time pedestrian conspicuity: Effects of clothing on drivers' eye movements. *Ophthalmic and Physiological Optics, 37*(2), 184-190.

Wood, J. M. (2023). Improving the conspicuity and safety of pedestrians and cyclists on night-time roads. *Clinical and Experimental Optometry, 106*(3), 227-237.