Report # 22-UR-118

NSTSCE

National Surface Transportation Safety Center for Excellence

Effectiveness of Lighted Work Zone Apparel

Effects on Visibility

Rajaram Bhagavathula • Andrew Kassing • Ron Gibbons • Alejandra Medina

Submitted: November 11, 2022

Technology Impairment Mobility Infrastructure

Housed at the Virginia Tech Transportation Institute
3500 Transportation Research Plaza • Blacksburg, Virginia 24061

ACKNOWLEDGMENTS

The authors of this report would like to acknowledge the support of the stakeholders of the National Surface Transportation Safety Center for Excellence (NSTSCE): Tom Dingus from the Virginia Tech Transportation Institute; John Capp from General Motors Corporation; Chris Hayes from Travelers Insurance; Terri Hallquist, Steven K. Smith, and Nicole Michel from the Federal Motor Carrier Safety Administration; Cathy McGhee from the Virginia Department of Transportation and the Virginia Transportation Research Council; and Jane Terry from the National Safety Council.

The NSTSCE stakeholders have jointly funded this research for the purpose of developing and disseminating advanced transportation safety techniques and innovations.

EXECUTIVE SUMMARY

In United States, collisions between vehicles and workers in a work zone are a major problem. In 2020, there were 157 worker fatalities in work zone in the United States. Increasing worker conspicuity has the potential to reduce to fatalities by making them more visible to motorists. Retroreflective vests (Class 3) and trousers (Class E) worn by workers in a nighttime work zone are passive in nature; i.e., they require light from oncoming vehicle headlamps to work. The advancement of LED technology has made it easy to install them on retroreflective vests and hard hats to increase their conspicuity. Multiple configurations of LEDs and flash patterns installed on vests and hard hats could be used to increase worker conspicuity. Further, equipment manufacturers are now offering work zone apparel and head protection which incorporate lights into portions of the retroreflective material, or adds light to a specific piece of equipment (hard hats). One of the major benefits is that these do not require external light sources for activation whereas retroreflective material relies on an eternal light source. According to manufacturers, the new apparel and equipment improve visibility, and the pieces are washable. There is also the potential for lighted apparel that uses colors or operating features (such as flash patterns) to further increase worker conspicuity. However, a typical work zone is a visually cluttered with flashing lights on work vehicles. Therefore, it is important that the selected configuration of lights on workers apparel are not masked by the visual clutter in the work zone. The conspicuity of passive (retroreflective material only) and active (both retroreflective and LEDs) apparel in a work zone will help in determining the apparel that would increase the conspicuity of the workers in the work zone.

The goal of the current study is to evaluate effectiveness of lighted work zone apparel under realistic conditions. More specifically, the goal is to compare the effectiveness of various kinds of lighted worker apparel (colors, flash patterns, lighted hard hat, etc.) to that of standard retroreflective material under varying visually cluttered conditions. In the current study, the effects of worker apparel and scene clutter on driver visual performance were evaluated under realistic work zone conditions. Driver visual performance was measured indirectly using the detection distance of work-zone workers as indicated by participants as they drove through the simulated work-zone environment.

The results of the current study show that lighted worker vests and helmet-mounted lights plays a critical role in increasing the conspicuity of workers in active nighttime work-zone environments with visually cluttered environments. Lighted work-zone vests with white-colored LEDs paired with helmet-mounted LEDs (also white colored), either in flashing or in a steady-on condition, had the longest detection distances. Standard Class 3 retroreflective vests had the lowest detection distances among all the garments evaluated. When workers wore the lighted apparel with red and white LEDs without the lighted helmet, the detection distances were shorter than with the lighted helmet but longer than with the retroreflective vest alone. Based on these results, a combination of lighted garments along with a lighted helmet, preferably in a flashing pattern or steady-on, are recommended to increase the conspicuity of workers in active nighttime work-zone environments.

TABLE OF CONTENTS

LIST OF FIGURES ..... **vii**

LIST OF TABLES ..... **ix**

LIST OF ABBREVIATIONS AND SYMBOLS ..... **xi**

CHAPTER 1. INTRODUCTION **1**

PASSIVE RETROREFLECTIVE TREATMENTS **1**
Materials ***1***
Configuration ***2***
LIGHTED WORKER APPAREL **2**
VISUAL CLUTTER **4**
GAPS IN EXISTING RESEARCH **4**

CHAPTER 2. METHODS **5**

PARTICIPANTS **5**
EXPERIMENTAL DESIGN **5**
INDEPENDENT VARIABLES **6**
Garment Type ***6***
Worker Movement ***8***
Clutter ***8***
DEPENDENT VARIABLE **9**
Detection Distance ***9***
PROCEDURE **9**
ANALYSIS **11**

CHAPTER 3. RESULTS **13**

INTERACTIVE EFFECT OF GARMENT TYPE, WORKER MOVEMENT, CLUTTER, AND AGE **13**
Effect of Age ***13***
Effect of Garment Type ***14***

CHAPTER 4. DISCUSSION **17**

CHAPTER 5. CONCLUSION **19**

REFERENCES **21**

LIST OF FIGURES

Figure 1. Photo. From left to right: ILLUMAGEAR Halo SL LED personal lighting device, and Global Glove LED Illuminated Class 3 Hi Vis Yellow Safety Vest. 3

Figure 2. Photo. Simulated worker in the Class 3 vest with white LEDs. 6

Figure 3. Photo. Simulated worker in the Class 3 vest with red LEDs. 7

Figure 4. Photo. Simulated worker in the Class 3 retroreflective vest.................................... 7

Figure 5. Photo. Simulated worker in the Class 3 vest with white LEDs and helmet-mounted LEDs.. 8

Figure 6. Photo. A view of the simulated work zone in the visually cluttered condition. 9

Figure 7. Illustration. Simulated work zone used in the study. 11

Figure 8. Graph. Effects of garment type on detection distance when clutter was absent. Values are means of detection distances and error bars indicate standard errors. Uppercase letters represent post hoc groups between garment types. 14

Figure 9. Graph. Effects of garment type on detection distance when clutter was present. Values are means of detection distances and error bars indicate standard errors. Uppercase letters represent post hoc groups between garment types. 15

Figure 10. Illustration. Lighted work zone apparel recommendations. 18

LIST OF TABLES

Table 1. Independent variables, their levels, and classification as used in the current study. 5

Table 2. Statistical results from LMM analysis of detection distance. Significant effects are highlighted in bold. 13

LIST OF ABBREVIATIONS AND SYMBOLS

ANSI	American National Standards Institute
DAS	data acquisition system
DF	degrees of freedom
DGPS	differential Global Positioning System
HVSA	high-visibility safety apparel
ISEA	International Safety Equipment Association
LED	light emitting diode
LMM	linear mixed models
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

Collisions between motorists and workers in work zones, particularly those on foot, are a major safety hazard. The American Road & Transportation Builders Association in cooperation with the U.S. Federal Highway Administration reported that 135 work-zone worker fatalities occurred in 2019 (American Road & Transportation Builders Association, 2022). Increasing worker conspicuity has been identified as a solution that could help in increasing the visibility of workers to drivers approaching the work zones and can potentially reduce the number of fatalities in work zones (Blackman, Debnath, & Haworth, 2014; Fontaine, Carlson, & Hawkins Jr, 2000).

Typically, work-zone apparel consists of various passive retroreflective treatments attached to vests, jackets, and other apparel, applied at key locations on the body. The current American National Standards Institute (ANSI)/International Safety Equipment Association (ISEA) 107 standards guide the placement, surface area, type, and performance class of passive retroreflective treatments, but they do not provide much guidance for active treatments. Advancements in LED technology now allow for the adaptation of LEDs and flash patterns to be applied to work-zone worker garments as active treatments in addition to the existing passive treatments. The literature review in this section includes an investigation of the current state of work-zone apparel with respect to passive and active treatments and a review of existing research on pedestrian conspicuity with respect to work-zone scene clutter.

PASSIVE RETROREFLECTIVE TREATMENTS

Materials

Work-zone apparel that is ANSI/ISEA 107 compliant is typically manufactured using synthetic materials (most commonly polyester). Using synthetic material allows for an even color distribution throughout the garment. The most common garment base colors are fluorescent yellow, yellow-green, and orange. Retroreflective material added to the base garment is typically applied using a tape (such as 3M Scotchlite® or Reflexite®) or vinyl backed strips. Studies have examined which combination of base color and retroreflective trim would make workers most conspicuous. A blaze orange retroreflective trim (344 m) was found to be detected from 56 meters further away than a fluorescent red trim (288 m) but performed similarly to a white/silver trim (329 m; (Sayer & Mefford, 2004). Researchers also observed that there was no effect of trim intensity on detection distance even when intensity was reduced to 16% of the original. Nighttime static field testing of trim and fabric color combinations has shown that participants found a combination of either fluorescent orange or fluorescent yellow fabric with high silver retroreflective trim to be most noticeable, while combinations with orange or yellow retroreflective trim were consistently judged the least noticeable (Sayer & Mefford, 2000). Investigation into the effect of apparel type on the conspicuity of pedestrians in work zones by Sayer and Mefford (2004) showed that pedestrians wearing a Class 3 jacket were detected from 20.3% further (355 m) away than when the pedestrian wore a Class 2 or Class 3 vest (295 m); however, all conditions performed significantly better than the dark-clad pedestrian condition (94 m). Using eye-tracking technology, retroreflective vests have been shown to improve a driver’s ability to recognize a pedestrian among road work zones by over 150 meters when compared to a non-reflective clothed pedestrian (Babić, Babić, Fiolić, & Ferko, 2021). The selection of a garment, trim color, and base color combination has been shown to be an essential component of work-zone worker safety.

Configuration

Retroreflective material can be applied in different amounts and to various areas of worker apparel to improve conspicuity. A vest or jacket will typically have strips of retroreflective material applied horizontally across the torso and vertically over the shoulders. Human visual processing can easily recognize human patterns of motion, such as walking. Johansson (1973) has shown that when lights or reflective material were attached to a walker's ankles, knees, hips, shoulders, elbows, and wrists, and a video was taken, observers were easily able to identify the disembodied moving lights as a walking person. This phenomenon held true held true even when lights were added and removed from the video, showing that human ability to detect other human motion is robust. The ability to selectively identify biological motion, or biomotion, is leveraged by many conspicuity aids. In order to take advantage of this phenomenon, additional retroreflective material can be applied to the extremities to further outline the worker. Material can be added to combinations of the ankles, thighs, knees, wrists, and elbows to achieve various levels of biomotion. Balk, Tyrrell, Brooks, and Carpenter (2008) found that, when a full biomotion configuration (ankle, knee, wrist, elbow, and vest) was compared to a worker just wearing a vest, study participants detected a still worker in a full biomotion configuration from 4.22 times further away. The response distances when comparing a pedestrian moving in a full biomotion configuration were 10.28 times greater than that of a worker standing still wearing just a vest. These results suggest that placement of retroreflective material could significantly improve the conspicuity of workers moving within a nighttime road closure.

Wood, Marszalek, Lacherez, and Tyrrell (2014) found that the detection distance of road workers increased from 68.8 meters while just wearing a vest to 190 meters while in full biomotion configuration. Furthermore, when participants were tasked with identifying the direction of travel of a moving pedestrian at night wearing different configurations of retroreflective material, the biomotion configuration produced the highest accuracy at 79.9% (Black et al., 2021). The biomotion (79.9%) and legs + torso (65%) configuration in Black et al.'s (2021) study both performed significantly better than all other configurations. The significant increase in accuracy between the biomotion and legs + torso configurations is likely driven by the spatial and perceptual cues given by the arms of the worker moving as they cross the street. Response distances were not affected by the orientation of the road worker (Wood et al., 2014), suggesting that while motion may play a key component in worker conspicuity, orientation may not. When considering work-zone worker safety, it is important to choose the appropriate configuration of retroreflective material that increases worker conspicuity.

LIGHTED WORKER APPAREL

Advancements in LED technologies have allowed the development of new high-visibility work-zone worker garments such as Global Glove's Class 3 high-visibility safety vest with 16 embedded blinking LED lights, shown in Figure 1 (Safety Smart Gear, 2022). Other personal lighting devices such as the Halo SL LED hard helmet light developed by ILLUMAGEAR and body-worn LED lights (both shown in Figure 1) are currently in use by industry professionals. Survey results by Gambatese and Jafarnejad (2018) found that 51% of roadway workers used a personal lighting device at night. All the respondents who used personal lighting devices indicated that they used a light attached to their hard hat or used a head lamp. One participant also used body-worn LED lights, and one respondent also used a high-visibility safety vest with LED lights. Although personal LED technologies are in use, there are currently no standards within the ANSI/ISEA 107 2020 version that guide their adaptation.

Figure 1. Photo. From left to right: ILLUMAGEAR Halo SL LED personal lighting device, and Global Glove LED Illuminated Class 3 Hi Vis Yellow Safety Vest.

In the past 5 years, researchers have investigated the impact of personal lighting devices on the conspicuity of road workers. When investigating the most visible garment assembly, Gambatese and Jafarnejad (2018) found that participants gave the highest mean visibility rating to the combination of Class 3 vest + pants + halo light. The halo light setting included flashing for the most visible condition. Based on the results of a case study of a nighttime grinding operation, Gambatese and Jafarnejad (2018) suggested that workers on foot should wear the normal Class 3 vest and a halo light on their helmet when working near heavy machinery to help make them more conspicuous. When investigating the conspicuity of police officers working a traffic stop, Terry (2020) found that officers using body-worn LED lights could be detected from significantly further away than officers just using the police cruiser's takedown lights when approached from behind.

Several results point to limitations in the adaptation of new LED technology. Results of a focus group survey of industry professionals found that multiple respondents thought the halo light looked like vehicle headlamps from a long distance (Gambatese & Jafarnejad, 2018). When using a balloon light or similar lighting apparatus in a night work zone, Gambatese and Jafarnejad (2018) found the halo light had no impact on the visibility of the road worker; however, the halo light made a big difference in visibility in the absence of work-zone lighting. Gambatese and Jafarnejad (2018) recommended that personal lights like the halo should only be used by highly exposed workers outside the coverage of work-zone lighting and that personal lighting devices will be most effective when worn by workers in motion to give the driver visual clues of movement in the work zone.

VISUAL CLUTTER

Visual clutter from flashing lights on vehicles operating within a work zone or the first response team at a crash can make it more difficult to see personnel in those areas. An investigation into the conspicuity of road workers at night by Wood et al. (2011) found that conspicuity ratings of road workers fell more dramatically at the visually complex suburban test site. Wood et al. (2011) posited that the high levels of visual clutter in typical suburban areas make it challenging to identify the presence of road workers.

GAPS IN EXISTING RESEARCH

Based on the review of the existing literature, the following gaps have been identified:

- There is a gap in comparing the effectiveness of different lighted work zone apparel colors and flash patterns to find the best combination for active nighttime work-zone conditions.
- There is a need to evaluate the effectiveness of lighted work-zone apparel in visually cluttered environments such as those found in active nighttime work zones, especially the effect of infrastructure-based or vehicle-mounted flashing lights on the conspicuity of lighted work zone apparel.

The goal of the current study is to evaluate effectiveness of lighted work zone apparel under realistic conditions. More specifically, the goal is to compare the effectiveness of different kinds of lighted worker apparel (colors, flash patterns, lighted hard hat, etc.) to that of standard retroreflective material under different visually cluttered conditions. The results of this study will inform guidelines on worker apparel that will increase their conspicuity in active nighttime work zones.

CHAPTER 2. METHODS

PARTICIPANTS

Sixteen participants participated in and completed the study. Participants were recruited from the Virginia Tech Transportation Institute (VTTI) participant database and through an advertisement posted in the Virginia Tech online newsletter. Two age ranges were considered for the study: 18 to 35 years (younger), and 65 years and over (older). These age ranges were intended to capture a range of driving experience and visual capabilities because the human eye undergoes physiological changes with age. The participant sample was age balanced to have an equal number of younger and older participants. All participants had a valid U.S. driver's license and a binocular visual acuity of at least 20/40 as measured by an Early Treatment Diabetic Retinopathy Study test with an illuminator cabinet.

EXPERIMENTAL DESIGN

A full factorial experimental design with repeated measures was used to assess the effects of worker apparel, worker movement, scene clutter, age, and light configuration on driver visual performance. Driver visual performance was measured indirectly using the detection distance of work-zone workers as indicated by participants as they drove through the simulated work-zone environment. Participant sessions took place at night on the Virginia Smart Roads Highway located at VTTI. The independent variables explored in this experiment are summarized in Table 1.

Table 1. Independent variables, their levels, and classification as used in the current study.

Independent Variable	Levels	Type
Age	• Young (18-35) • Old (65+)	Between Subjects
Clutter (Visual Complexity)	• No Clutter • Cluttered	Between Subjects
Garment Type	• Control - Class 3 Garment (Retroreflective) • Class 3 Garment White LED – Flashing • Class 3 Garment White LED – Steady-on • Class 3 Garment Red LED – Flashing • Class 3 Garment Red LED – Steady-on • Class 3 Garment White LED + Helmet Mounted LEDs – Flashing • Class 3 Garment White LED + Helmet Mounted LEDs – Steady-on	Within Subjects
Worker Movement	• Moving • Stationary	Within Subjects

INDEPENDENT VARIABLES

Garment Type

Four work-zone worker apparel configurations were presented in this study to evaluate how different worker garment assemblies influenced the visual performance of participants. All assemblies met the current Virginia Department of Transportation requirements for a work zone at a temporary road closure and were ANSI Class 3 compliant. Garments used in testing were

- a Class 3 ANSI-compliant vest outfitted with white LEDs (Figure 2; Manufacturer: Nite Beams; Model: Hi Vis Safety Vest – Canadian Style),
- a Class 3 ANSI-compliant vest outfitted with red LEDs (Figure 3; Manufacturer: Global Glove; Model: FrogWear® HV Lightweight Mesh Safety LED Vest – GLO-12LED),
- a Class 3 ANSI-compliant vest without any LED lights (Figure 4; Manufacturer: KISHIGO; Model: 1573), and
- a white-light LED worker vest with the hard hat light (Figure 5; Manufacturer: ILLUMAGEAR; Model: Halo® SL).

These garments were selected based on a market scan of available lighted apparel. All the garments selected are commercially available for use in work zones and the colors of the light and the flash patterns used were the features that were available on these garments. All garment combinations were paired with denim-colored scrubs to simulate the look of jeans. All garment combinations included a hard hat, and the halo light was worn in one garment assembly alongside the white LED vest. In addition, the garment combinations outfitted with LED lights were viewed under two conditions. The vests were either presented with a steady-on condition or with the LED lights flashing. The flashing light configuration was a within-subjects variable, and all participants saw all garment combinations with the LED lights both flashing and steady-on.

Figure 2. Photo. Simulated worker in the Class 3 vest with white LEDs.

Figure 3. Photo. Simulated worker in the Class 3 vest with red LEDs.

Figure 4. Photo. Simulated worker in the Class 3 retroreflective vest

Figure 5. Photo. Simulated worker in the Class 3 vest with white LEDs and helmet-mounted LEDs.

Worker Movement

Two worker movement configurations were shown in this experiment. Experimenters acting as the worker would either stand still or move in place. This variable was included to assess the effect of movement on the detection distance of workers, as previous work in the detection of pedestrians indicated that movement helps in detection (Abrams & Christ, 2003; Bhagavathula & Gibbons, 2013; Bhagavathula, Gibbons, & Edwards, 2012; Franconeri & Simons, 2003; Gros, Pope, & Cohn, 1996).

Clutter

Scene clutter was classified as a between-subjects variable where each participant drove past either a cluttered or non-cluttered simulated work zone. In the clutter condition, flashing beacons mounted on retroreflective barrels were turned on along with the simulated vehicle in the work zone, which had a flashing amber strobe light (see Figure 6). In the no-clutter condition, all the flashing beacons, as well the amber strobe light on the simulated work vehicle, were turned off. Visual scene clutter was a between-subjects variable, and each participant saw all experimental conditions in either a visually cluttered or non-visually cluttered work zone.

Figure 6. Photo. A view of the simulated work zone in the visually cluttered condition.

DEPENDENT VARIABLE

Detection Distance

Detection distance, measured in meters, is the distance at which a participant is able to detect a worker by the saying the work "worker." Detection distance was recorded with a button press when a participant verbally identified a worker. The button press was logged into a continuous stream of data by the vehicle's data acquisition system (DAS), which includes a very accurate differential GPS (DGPS) location. Later analysis of this data determined the distance of the vehicle to the worker at the time of detection.

PROCEDURE

For study recruitment, participants were first contacted via telephone and asked if they were interested in participating in a study. Those who were interested were read a script describing the study. If the participant was still interested in participating, they were asked for verbal consent to conduct a telephone screening to make sure that they were eligible for the study. The experimenter then read each question and recorded the participant's answers on a paper form. Those who were ineligible were thanked for their time and excluded from the study. Those who were deemed eligible were scheduled to come to VTTI for a nighttime session and were asked to provide an email address. An email message was sent to the participant containing a reminder of their scheduled time and a copy of the informed consent form that they could review prior to their scheduled session. An experimenter also called the participant the day before their appointment to remind them of their scheduled time.

At VTTI, participants took part in a screening process that occurred in one of the participant preparation rooms. If two participants were scheduled together, they were taken to separate rooms. Each participant was presented with the informed consent form and asked to review it. Participants were required to complete a basic visual test administered with a Snellen eye-exam chart using an illuminated cabinet. All participants who completed the study had a measured visual acuity of at least 20/40. Color blindness was an exclusionary factor, and each participant completed a color-blind screening administered using the Ishihara test. Participants were also required to fill out a W-9 form to receive compensation. During participant screening, each person's driving license was checked to confirm its validity and that they were an adult.

If a participant did not meet the criteria for participation, they were thanked for their interest and released from the study. If the participant met the criteria for participation, the experimenter went over the instructions for the study with them. Participants were then given an opportunity to use the restroom and get a drink of water before being escorted to the experimental vehicles parked outside of VTTI.

Eligible participants drove nine laps on the Smart Roads Highway, where they passed the simulated work zone in both directions (see Figure 7). The first lap was a practice lap so that the participant could become familiar with the experimental vehicle and the layout of the Smart Roads Highway. This lap was not considered in the data analysis. After the practice lap, the in-vehicle experimenters gave the participants an opportunity to ask questions in case anything was unclear. Once the participants indicated they were ready, experimental trials began. Each time participants drove through the test area; a different worker apparel condition was presented at the simulated work zone. As participants drove, they were instructed to say the word "worker" whenever they saw a worker. Participants were asked say the word "worker" only when they were *confident* that it was a worker, not when they only *thought* they saw something. The in-vehicle experimenter pressed a handheld button each time a worker was identified. Subsequent analysis of the data collected determined the distance between the experimental vehicle and the worker at the time of the button press, which was reported as the "Detection Distance." Presentations were randomized to prevent order-related confounding effects and included blank presentations as catch trials, where no workers were presented in the simulated work zone. During experimental sessions, each participant encountered either a cluttered or non-cluttered work zone. Every participant saw all four of the garment combinations with the work zone worker both moving and standing still.

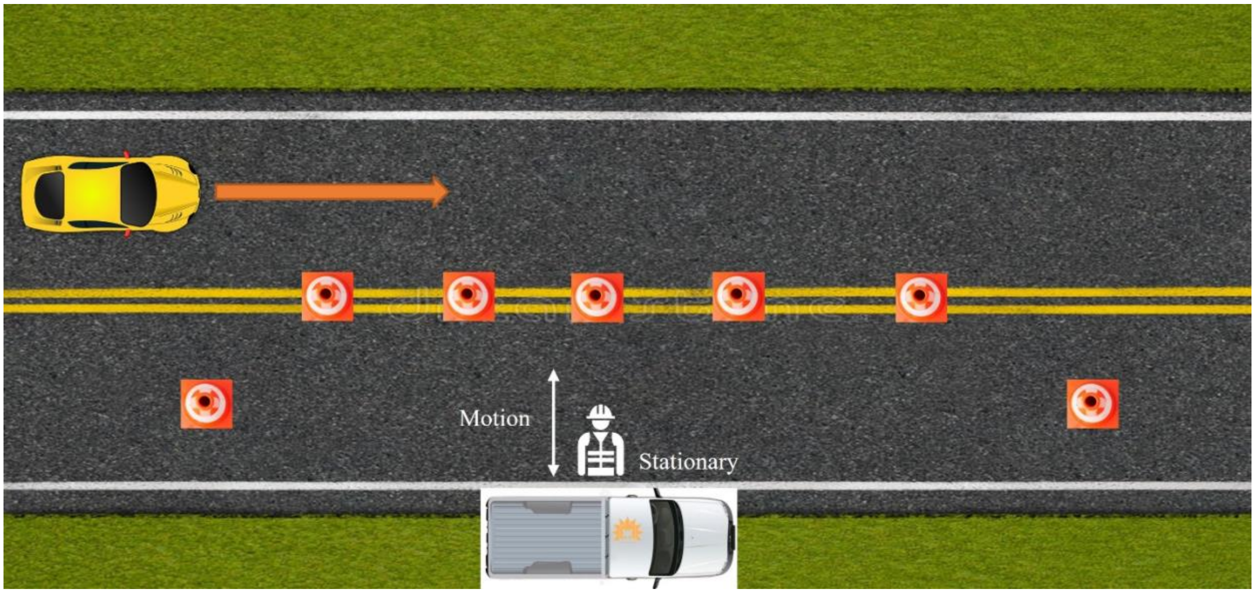

Figure 7. Illustration. Simulated work zone used in the study.

ANALYSIS

To assess the effects of garment type, clutter, and motion on detection distance, a linear mixed model (LMM) was used. Age was included as a blocking factor. The level of significance was $p < .05$ for all statistical tests. Where relevant, post hoc analyses (pairwise comparisons) were performed using Tukey's honest significant difference for main effects and simple effects testing for interaction effects.

CHAPTER 3. RESULTS

All LMM results are summarized in Table 2. The main effects of garment type, worker movement, and clutter were significant. Several two-way and three-way interactions were also significant. The four-way interaction involving all the independent variables was also significant. Subsequent subsections provide additional details on the results regarding the noted four-way interaction effect.

Table 2. Statistical results from LMM analysis of detection distance. Significant effects are highlighted in bold.

Effect	Numerator DF	Denominator DF	F-Value	P-Value
Garment Type (GT)	**6**	**156**	**15.37**	**<.0001**
Worker Movement (WM)	**1**	**156**	**47.31**	**<.0001**
Clutter (C)	**1**	**12**	**6.74**	**0.0234**
Age (A)	1	12	0.53	0.4818
GT × WM	**6**	**156**	**4.69**	**0.0002**
GT × C	6	156	1.32	0.2516
WM × C	1	156	0.72	0.3959
C × A	1	12	0.88	0.3669
GT × A	6	156	1.37	0.2293
WM × A	**1**	**156**	**9.08**	**0.003**
GT × WM × C	6	156	2.04	0.0629
GT × WM × A	**6**	**156**	**2.16**	**0.0493**
GT × C × A	**6**	**156**	**2.34**	**0.0344**
WM × C × A	**1**	**156**	**6.88**	**0.0096**
GT × WM × C × A	**6**	**156**	**3.86**	**0.0013**

INTERACTIVE EFFECT OF GARMENT TYPE, WORKER MOVEMENT, CLUTTER, AND AGE

The combined effect of garment type, worker movement, clutter, and age on detection distance is summarized below. Two analysis approaches were used to further assess this four-way interaction effect, with an emphasis on the two aspects that were considered most practically relevant. First, the effect of age was examined across the same garment type, clutter, and worker movement conditions. Second, the effect of garment type was assessed across each worker movement and clutter conditions.

Effect of Age

From the post hoc pairwise comparisons, there were no differences between the detection distances of younger and older participants across each garment type, worker movement, and clutter conditions.

Effect of Garment Type

When the worker was moving in the no clutter condition, post hoc pairwise comparisons showed that the vests with flashing and steady-on white LEDs with halo helmet light had detection distances that were significantly longer than the vests with the flashing white LEDs, flashing red LEDs, steady-on red LEDs, and the retroreflective vest (control; see Figure 8). When the worker was stationary in the no clutter condition, post hoc pairwise comparisons showed that the retroreflective vest had significantly shorter detection distances than every lighted apparel condition (see Figure 8).

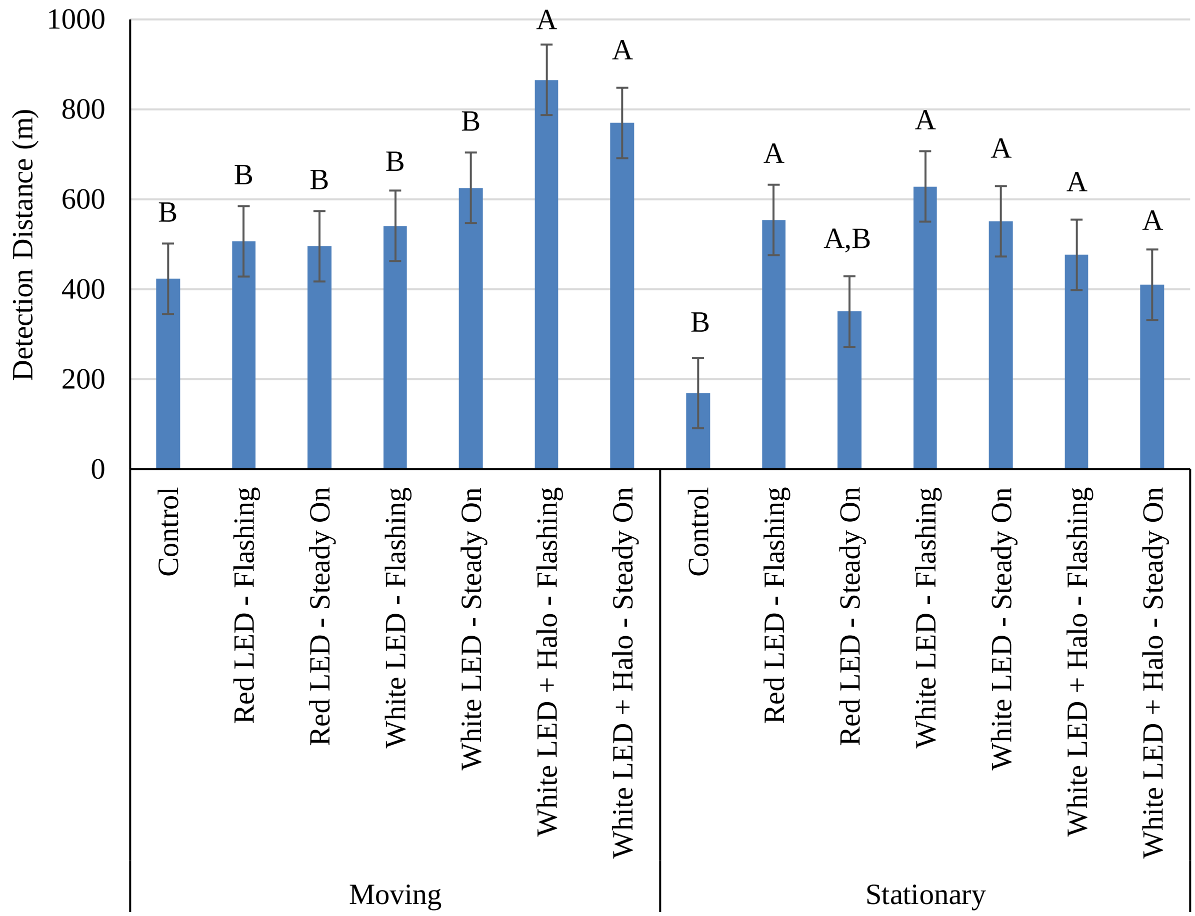

Figure 8. Graph. Effects of garment type on detection distance when clutter was absent. Values are means of detection distances and error bars indicate standard errors. Uppercase letters represent post hoc groups between garment types.

When the worker was moving in the cluttered condition, all the lighted garment types, except the steady-on red LED vest, had significantly longer detection distances than the retroreflective vest (see Figure 9). When the worker was stationary in the cluttered condition, there were no statistical differences in the detection distances among all the garment types; however, the flashing white LED vest with the halo helmet light had the longest detection distance compared to the other garment types evaluated in this study (see Figure 9).

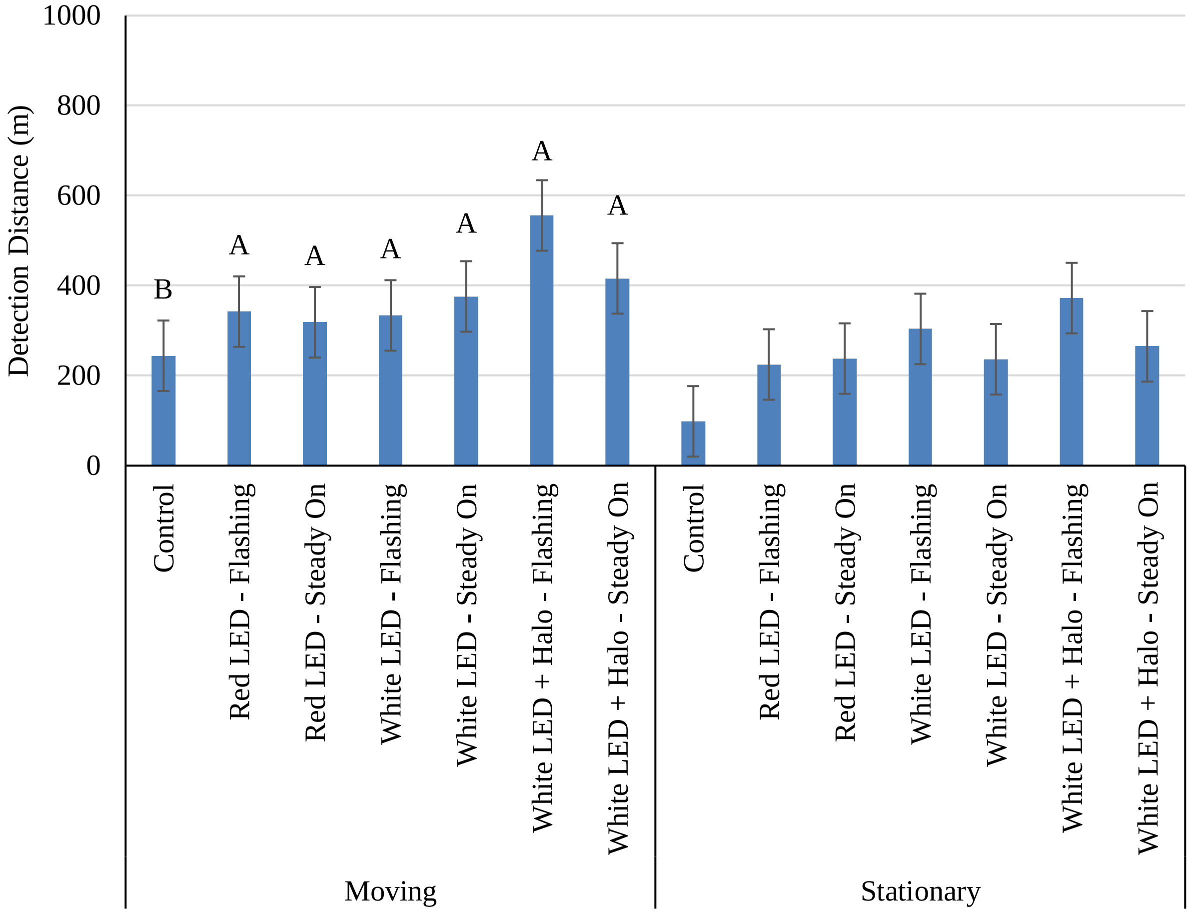

Figure 9. Graph. Effects of garment type on detection distance when clutter was present. Values are means of detection distances and error bars indicate standard errors. Uppercase letters represent post hoc groups between garment types.

CHAPTER 4. DISCUSSION

The goal of this study was to determine the effectiveness of lighted work-zone apparel under realistic conditions. Based on the results of this study, two major findings are evident. First, a combination of lighted vests and lighted helmets (halo) increased the conspicuity of the workers. Second, the color and the flash patterns of the vest also significantly increased the conspicuity of the workers.

The conspicuity of workers was significantly increased by the lighted vests and the lighted helmet, as evidenced by the longer detection distances. In every clutter and worker movement condition, the flashing white LED with the lighted helmet had the longest detection distance except in one (no clutter – stationary worker). Even when the white LED was steady-on, in combination with the lighted helmet, the detection distances were higher. These results also support existing research in the area of pedestrian and bicycle visibility that flashing lights increase detection distances (Bhagavathula, Gibbons, Williams, & Connell, 2020; Gambatese & Jafarnejad, 2018; Kwan & Mapstone, 2004, 2006).

Furthermore, there were no major differences between the two colors of lighted vest evaluated in this study. However, in every condition evaluated, the lighted apparel had longer detection distances than the retroreflective vest, even without the lighted helmet. These results indicate that the lighted apparel, irrespective of color, results in increased worker conspicuity.

In general, in both the cluttered and no-cluttered conditions, the detection distances were longer when the simulated worker was moving compared to when they were stationary. These results align with prior research that showed that motion is a major factor in detecting new objects and pedestrians (Abrams & Christ, 2003; Bhagavathula & Gibbons, 2013; Bhagavathula et al., 2012; Franconeri & Simons, 2003; Gros et al., 1996).

Clutter also lowered the conspicuity of the worker irrespective of the garment that was worn, as evidenced by the lower detection distances in the clutter condition compared to the no-clutter condition. These results are also supported by current work, which shows that visual clutter in a naturalistic environment (Moberly & Langham, 2002) and suburban work zones (Wood et al., 2011) can occlude retroreflective markers. It is interesting to note that in the above research, visually cluttered environments occluded the visibility of retroreflective markers; however, the results of the current study showed that visually cluttered environments, such as those in active nighttime work zones, also affect the visibility of lighted work-zone apparel in addition to retroreflective apparel. It should be emphasized that the detection distances for lighted work-zone apparel were higher than those of retroreflective apparel even in cluttered conditions.

Participant age also did not significantly affect the drivers' visual performance, as evidenced by the lack of significant main effect of driver age on detection distance. This could be because the detection of the worker was dependent on the visual acuity of the participants and all the participants had a visual acuity of at least 20/40. The lack of variation in the visual acuity and detection of a worker (stature = 173 cm) could have resulted in the absence of statistical differences between older and younger drivers.

The findings of this study have enormous implications in the areas of lighted work-zone apparel and work-zone safety at night. A combination of lighted work-zone garments along with a lighted helmet (see Figure 10), preferably in a flashing pattern or steady-on, are recommended to increase the conspicuity of workers in active nighttime work-zone environments. Also, this study reinforces the importance of motion in increasing the visibility of workers at night. Further, the findings also suggest that lighted work-zone apparel will increase the conspicuity of workers even in visually cluttered environments.

Figure 10. Illustration. Lighted work zone apparel recommendations.

This study has some limitations. First, there was only one worker in the work zone. Second, there was no other traffic in the test area other than a stationary work vehicle with a flashing light. These simplifications were made in the experimental design to eliminate the confounding effects that could arise due to the presence of more workers, moving vehicles in the work zone, and traffic. Adding more workers and vehicles could potentially reduce the detection distances as drivers would have to scan the work zone to perform the detection task. These results represent drivers' visual performance under optimal conditions, and a reduction in detection distances should be expected in real road conditions. To address the above-mentioned limitations, future work should evaluate the effects of work-zone equipment, traffic density, presence of temporary work-zone lighting, and other more complex scenarios to better understand the visibility of lighted work-zone apparel.

CHAPTER 5. CONCLUSION

The results of the current study show that lighted work-zone apparel, more specifically, lighted worker vests and helmet-mounted lights, plays a critical role in increasing the conspicuity of workers in active nighttime work-zone environments with visually cluttered environments. Lighted work-zone vests with white-colored LEDs paired with helmet-mounted LEDs (also white), either flashing or in a steady-on condition, had the longest detection distances. Standard Class 3 retroreflective vests had the lowest detection distances among all the garments evaluated. When workers wore the lighted apparel with red and white LEDs without the lighted helmet, the detection distances were shorter than with the lighted helmet but longer than with the retroreflective vest alone. Based on these results, a combination of lighted garments along with a lighted helmet, preferably in a flashing pattern or steady-on, are recommended to increase the conspicuity of workers in active nighttime work-zone environments.

REFERENCES

Abrams, R. A., & Christ, S. E. (2003). Motion Onset Captures Attention. *Psychological Science, 14*(5), 427-432. doi: 10.1111/1467-9280.01458

American Road & Transportation Builders Association. (2022). 2019 National Work Zone Fatal Crashes & Fatalities. Retrieved December 2021, 2021, from https://www.workzonesafety.org/crash-information/work-zone-fatal-crashes-fatalities/#national

Babić, D., Babić, D., Fiolić, M., & Ferko, M. (2021). Factors affecting pedestrian conspicuity at night: Analysis based on driver eye tracking. *Safety Science, 139*, 105257. doi: https://doi.org/10.1016/j.ssci.2021.105257

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. doi: 10.1068/p6017

Bhagavathula, R., & Gibbons, R. B. (2013). Role of Expectancy, Motion and Overhead Lighting on Nighttime Visibility. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 57*(1), 1963-1967. doi: 10.1177/1541931213571438

Bhagavathula, R., Gibbons, R. B., & Edwards, C. J. (2012). *Effect of Static and Moving Objects on Driver Eye Movements and Detection Distances.* Paper presented at the Transportation Research Board 91st Annual Meeting.

Bhagavathula, R., Gibbons, R. B., Williams, B., & Connell, C. (2020). Bicycle Visibility: Conspicuity of Bicycle Headlamps, Tail Lamps, and Retroreflective Garments in Nighttime Roadway Environments.

Black, A. A., Bui, V., Henry, E., Ho, K., Pham, D., Tran, T., & Wood, J. M. (2021). Using retro-reflective cloth to enhance drivers' judgment of pedestrian walking direction at night-time. *Journal of Safety Research, 77*, 196-201. doi: https://doi.org/10.1016/j.jsr.2021.03.002

Blackman, R., Debnath, A., & Haworth, N. (2014). *Work zone items influencing driver speeds at roadworks: worker, driver and expert perspectives.* Paper presented at the Proceedings of the 2014 Australasian Road Safety Research, Policing and Education Conference.

Fontaine, M. D., Carlson, P. J., & Hawkins Jr, H. G. (2000). Evaluation Of Traffic Control Devices For Rural High-Speed Maintenance Work Zones: Second Year Activities And Final Recommendations.

Franconeri, S., & Simons, D. (2003). Moving and looming stimuli capture attention. *Perception & Psychophysics, 65*(7), 999-1010. doi: 10.3758/bf03194829

Gambatese, J. A., & Jafarnejad, A. (2018). Use of Additional Lighting for Traffic Control and Speed Reduction in Work Zones.

Gros, B. L., Pope, D. R., & Cohn, T. E. (1996). Relative Efficiency for the Detection of Apparent Motion. *Vision Research, 36*(15), 2297-2302. doi: http://dx.doi.org/10.1016/0042-6989(95)00259-6

Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Perception & Psychophysics, 14*(2), 201-211. doi: 10.3758/BF03212378

Kwan, I., & Mapstone, J. (2004). Visibility aids for pedestrians and cyclists: a systematic review of randomised controlled trials. *Accident Analysis & Prevention, 36*(3), 305-312.

Kwan, I., & Mapstone, J. (2006). Interventions for increasing pedestrian and cyclist visibility for the prevention of death and injuries. *Cochrane Database of Systematic Reviews*(4).

Moberly, N. J., & Langham, M. P. (2002). Pedestrian conspicuity at night: failure to observe a biological motion advantage in a high-clutter environment. *Applied Cognitive Psychology*, *16*(4), 477-485. doi: https://doi.org/10.1002/acp.808

Safety Smart Gear. (2022). Global Glove LED Illuminated Class 3 Hi Vis Yellow Safety Vest GLO-12LED. Retrieved January 5, 2022, from https://www.safetysmartgear.com/global-glove-led-illuminated-class-3-hi-vis-yellow-safety-vest-glo-12led/

Sayer, J. R., & Mefford, M. L. (2000). The effect of color contrast on daytime and nighttime conspicuity of roadworker vests (pp. 34): University of Michigan, Ann Arbor, Transportation Research Institute.

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. doi: https://doi.org/10.1016/j.jsr.2004.08.007

Terry, T. N. (2020). *Assessment of the Effectiveness of Emergency Lighting, Retroreflective Markings, and Paint Color on Policing and Law Enforcement Safety.* Virginia Tech.

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., 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.