Assess the Effectiveness of Type 2 and Type 3 Safety Vests for Day and Night Use – Phase 2

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16. Abstract

Work zones are an essential component of any state transportation agency's construction and maintenance operations. As such, agencies apply numerous practices in order to keep their workers safe during construction operations. These strategies typically fall under the following categories: work zone traffic control (e.g., arrow boards, variable message signs, drums, etc.), work zone operational strategies (e.g., reduced speed limits in work zones), and personal protective equipment for highway workers. With regard to the last category, workers are typically provided with varying combinations of helmets, reflective vests, reflective pants, etc. to wear while on the job site depending on the location of the job (e.g., freeway vs. local road) and other conditions (e.g., whether or not nighttime work will take place). The Ohio Department of Transportation (ODOT) recently invested in several more advanced items to improve worker safety (and also traveler safety, by hopefully reducing the number of crashes overall). Specifically, ODOT invested in Type 2 and 3 safety vests, halo lights, and reflectors on the back of dump trucks. These materials were expected to provide the maximum safety effectiveness in terms of conspicuity of workers and work zone equipment. However, while these items separately are known to improve safety, there was concern that together they may not be as effective. This project sought to determine the effectiveness of each piece of safety equipment, collectively and individually, and determine if there are better methods for ensuring the safety of highway workers during both night and daytime operations. In order to accomplish this goal, the research team carried out several major tasks. First, they collected measurements of optical (material measurements under a selected region of the electromagnetic spectra) and photometric (luminous measurements under selected lighting environments) properties of various safety items (e.g., vests, lights, etc.) in order to prepare for simulation-based evaluation in the next step. The simulation-based evaluation used measurements from the first task to create realistic models of retroreflective vests, lights, and other safety equipment in virtual scenarios. These items were then placed in different virtual work zone environments, each of which had different conditions in terms of work zone set up, traffic control, vests worn by workers, time of day/ambient lighting, etc. Through an eye-tracking experiment measuring participants gaze on workers in different virtual work zone scenarios and a driving simulator experiment in which participants drove through virtual work zones and were asked follow up questions on worker conspicuity, subjective and objective measures of worker visibility were obtained. Conclusions from the simulation experiment (e.g., this type of vest made workers less visible at night, the presence of reflective tape had a negative effect on worker visibility in some cases, etc.) were then used to inform the development of work zone scenarios to test in a field experiment (a portion of the project that is not yet complete at the time of this draft report). Finally, results from each of the aforementioned steps were used to update a standard operations document on what types of safety equipment to use depending on specific work zone characteristics.

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1 Executive Summary

Construction and maintenance operations are an essential component of any state department of transportation's program. In order to ensure the safety of workers and provide them with more space to work, work zones are often set up in which portions of the roadway right of way (e.g., lanes and/or shoulders) are closed to through traffic. While work zones are delineated and physically separated from the travel lanes with live traffic (via drums, barriers, etc.), this hardly implies that the workers are safe. In fact, in the past couple of years, the number of construction workers killed in work zones has increased. In order to help improve the safety of workers, workers are often equipped with safety equipment they can wear (e.g., vests) or other equipment that can be used to help improve their conspicuity in the work zone (e.g., balloon lights). Recently, ODOT has invested in several more advanced items to improve worker safety (and also traveler safety, by hopefully reducing the number of crashes overall). Specifically, ODOT has invested in Type 2 and 3 safety vests, halo lights, and reflectors on the back of dump trucks. These materials are expected to provide the maximum safety effectiveness in terms of conspicuity of workers and work zone equipment. However, while these items separately are known to improve safety and enhance worker visibility, there is concern that together they may not be as effective. Part of the major rising concerns is the difficulty experienced by motorists in distinguishing between people (workers) and equipment within the same work zone environment. Thus, the overall goal of this project is to determine the effectiveness of each piece of safety equipment, collectively and individually, and determine if there are better methods for ensuring the safety and visibility of highway workers during both night and daytime operations.

To complete this objective, the research team proposed four tasks. The first task involved collecting measurements of optical (material measurements under a selected region of the electromagnetic spectra) and photometric (luminous measurements under selected lighting environments) properties of the safety items, in a controlled laboratory setting, in order to prepare for simulation-based evaluation in the next task. The optical and photometric properties were obtained through a series of measurements in a lighting laboratory and lighting/optical measurement equipment. All the property numbers obtained in the lab were used to configure the objects in the VR environment simulations (i.e., for use in the driving simulator experiment). The next task involved creation of a simulation study in which drivers would evaluate the impact of the different safety items on worker visibility in work zones (particularly combinations of items). Before conducting the study, the research team used 3D modeling software to create virtual work zone environments that were populated with different configurations of workers and safety equipment. Models of the safety equipment (e.g., vests, halo hat lights, etc.) to be used in the virtual environment were developed based upon results of the preceding lighting and photometric experiment. Following development of the work models, the team recruited participants from the general public to take part in a simulation study with both an objective and subjective component. The former component used eye-tracking glasses to evaluate participants' gaze behavior while they were shown a series of work zone videos with different configurations of workers and safety equipment. In this component, metrics such as how quickly participants noticed the workers were evaluated. The latter involved the participant driving through virtual work zones with varying set ups and answering survey questions after each drive on the how different safety items impacted worker visibility and conspicuity.

Following the simulation study, there were plans for a field test component during which the key results of the simulator study would be verified. At the time of writing this draft report, the research team is still waiting on approval from the university's Institutional Review Board (IRB) to conduct this portion of the experiment as it involves working with human subjects. The plan for the field experiment, however, was to evaluate similar metrics to those collected in the simulation study, and collecting data on drivers as they travel through real work zones (with different safety equipment used, different configurations, etc.). After the field test, the last component of the project involved development of a draft standard operations document which could be used to recommend different combinations of safety equipment that were shown to make workers most conspicuous under different work zone scenarios. Based on the results of the laboratory lighting experiment and simulation study, the research team reached several conclusions in terms of how different safety equipment impacts worker visibility/conspicuity. Based on a combination of laboratory lighting, eye-tracking, and driving simulation experiments, the study found that the presence of reflective tapes at work zones makes it difficult to see the workers under the Daytime with glare and the Nighttime conditions. Workers' conspicuity is not affected under Daytime work zones without glare. Further, while Amber/white lights have high bloom intensity and may be distracting to others, having the amber/green strobe and clearance lights was found to not affect seeing the workers. Finally with regard to the impact of vest type on worker visibility, switching from the Type 2 vests (yellow-green background and silver reflective materials) to the Type 3 vests (orange-red background) was found not to affect seeing the workers. Numerically, Type 2 vests were slightly better than Type 3, however, it was not statistically significant. The team hopes to expand these findings and deliver additional conclusions after completing the field test. It is believed that by modifying the usage of work zone safety equipment in accordance with the key conclusions, ODOT will be able to improve safety for both workers (by making them more conspicuous) and the traveling public alike.

2 Problem Statement

Work zones are an essential component of any state transportation agency's construction and maintenance operations. Whether it be a resurfacing operation, or construction of a new facility altogether, it is often necessary for agencies to block of portions of existing facilities in order to provide a safe working space for construction workers and other project personnel. Not only has the number of work zone (WZ) fatalities increased in the past couple of years, but so has the number of workers killed in traffic-related work zone crashes. The National Highway Traffic Safety Administration (NHTSA) noted that in 2019, 135 workers were killed in construction work zones (up from 124 in 2018) (FHWA, 2020). As such, agencies apply numerous practices in order to keep their workers safe. These strategies typically fall under the following categories: work zone traffic control (e.g., arrow boards, variable message signs, drums, etc.), work zone operational strategies (e.g., reduced speed limits in work zones), and personal protective equipment for highway workers. With regard to the last category, workers are typically provided with varying combinations of helmets, reflective vests, reflective pants, etc. to wear while on the job site depending on the location of the job (e.g., freeway vs. local road) and other conditions (e.g., whether or not nighttime work will take place).

While the Ohio Department of Transportation (ODOT) has always provided quality safety equipment for its workers, the agency has recently invested in several more advanced items to improve worker safety (and traveler safety, by hopefully reducing the number of crashes overall). Specifically, ODOT has invested in Type 2 and Type 3 safety vests, halo lights, and reflectors on the back of dump trucks. These materials are expected to provide the maximum safety effectiveness in terms of conspicuity of workers and work zone equipment. However, while these items separately are known to improve safety, there is concern that together they may not be as effective. Part of the major rising concerns is the difficulty experienced by motorists in distinguishing between people (workers) and equipment within the same work zone environment. In lieu of this, research is needed to ensure that ODOT is deploying the most effective safety measures for our personnel during both day and night operations. The overall goal of this project is to determine the effectiveness of each piece of safety equipment, collectively and individually, and determine if there are better methods for ensuring the safety and visibility of highway workers during both night and daytime operations. It is believed that accomplishment of this goal will help equip highway workers with effective safety gear allowing for better conspicuity at night and during the day, as well as safer driving conditions for the motoring public.

3 Research Background

As indicated by the report title, this is the second phase of the project. In Phase 1 of the project, the research team conducted an extensive analysis of the current practices of different Departments of Transportation (DOTs), including ODOT's current process for workers' safety vests, dump truck reflectors, and cones at highway work zones. Following this, new and emerging technologies that could potentially improve workers' conspicuity and reduce the complexity of the WZ environment for the traveling public were also investigated. This led to the development of matrices of alternatives related to ODOT current practices in terms of safety vests, reflectors, cones, lighting features, and new technologies. Then, various WZ scenario settings were developed to evaluate the effectiveness of ODOT practices, the observed recommended practices from literature, and the combination of these practices with new technologies in typical WZ environments. Using technical expertise, the research team developed a preliminary flow chart for selecting various WZ features under various environmental conditions; interested readers are directed to the Phase 1 report for more detailed information.

As a result of the Phase 1 project, it was determined that there were numerous gaps in the knowledge surrounding selection of safety equipment and work zone items in order to create the safest work zone. Specifically, the team noted the following issues remained open:

1. There were few studies conducted to identify the best design of the combination of vests and WZ lighting. Studies that individually assessed the effectiveness of these features did not cover all the possible scenarios to adequately identify the best ones, hence casting doubt on any complex conclusions.

2. The combination of all the conspicuity-improving materials in a typically cluttered environment has not been evaluated. This poses the extremely important question: could there be some confusion in identifying a worker in a work zone with numerous conspicuous items used for traffic control, on vehicles etc. (e.g., could a worker wearing a reflective vest behind a dump truck with reflectors under varying lighting conditions?)? No study has provided sufficient evidence through experiments to answer this question.
3. The competing light sources within WZs, including wearable lights (e.g., hat halo lights) and equipment lighting may reduce the conspicuity of workers, yet another issue that needs to be investigated as to its effect on worker visibility, if any.
4. Many studies have assumed there is no sun glare during the day and all workers are assumed to be conspicuous. This may not actually be the case, especially during the late afternoon when solar positions are low. Experimental testing also needs to be done during the daytime (with and without glare), as critical as nighttime. No studies have suggested best practices for solving sun glare issues during the daytime from the vest and WZ setup perspective.
5. Under nighttime conditions, there are new and emerging wearable technologies that can improve workers' conspicuity in work zones. To the best of our knowledge, coverage of studies evaluating any of these materials is very limited.

In order to address the important issues identified in the Phase 1 project about improving worker conspicuity in work zones, especially under conditions where items in the work zone may hinder visibility of workers, the following tasks were proposed for this phase of the project.

- Laboratory Lighting Evaluation
  - The purpose of this task is to collect measurements of visual and luminous properties of various safety equipment (e.g., different vest types, reflective tape, etc.) and prepare for the simulation-based evaluation.
- Simulator-based Evaluation
  - Due to a large number of evaluation scenarios (i.e., different combinations of equipment, time of day, work zone set up, etc.), a simulation-based approach will be used for evaluation of different work zone scenarios under a completely controlled environment.
  - Based on the existing studies on WZ visual conspicuity, a series of measures will be carried out, including both subjective and objective data.
  - The resulting data will be used to evaluate the effectiveness of different combinations of technologies under the selected environmental settings, as well as to inform the selection of testing scenarios for the field test.
- Field Testing
  - The field testing can be either a simulated WZ in a parking lot or built on an existing WZ.
  - The purpose of field testing is for validation. The new recommendations from simulation evaluation will be compared with the benchmark scenario.
  - Participants with different attributes will be invited to the research lab to participate in the experiments in the virtual reality environments.
- Standard of Practice (SOP) development

- Based on the obtained results, the research team will prepare an addendum to the existing standard practice of the WZ safety vests and WZ settings.

4 Research Approach

In this project, the research team focused on the conspicuity of workers in the work zones, rather than pure comparisons among vest materials, work zone items, and other safety accessories. The following section outlines the major tasks in the project and the research/work conducted to carry out each one. The section begins with a discussion of the laboratory lighting and material optical property test, followed by a detailed description of the procedures used in both the simulation and field tests. Finally, a brief overview of the SOP development is outlined. Please note that the main literature review component for this project was conducted in Phase 1; interested readers should refer to the Phase 1 report.

4.1 Laboratory Lighting Evaluation via Photometric Measurements of Safety Apparel

As this research will utilize the virtual reality (VR) system to perform subjective testing of worker conspicuity and vest design ratings, it is necessary to guarantee the accuracy of the visual characteristics of the safety items modeled in the VR environment. Such items include safety vests, reflective tape, halo hat lights, etc. The purpose of this task is to collect measurements of optical (material measurements under a selected region of the electromagnetic spectra) and photometric (luminous measurements under selected lighting environments) properties of the safety items in order to prepare for simulation-based evaluation in Task 2. The optical and photometric properties were obtained through a series of measurements in a lighting laboratory and lighting/optical measurement equipment. All the property numbers obtained in the lab were used to configure the objects in the VR environment simulations (i.e., for use in the driving simulator experiment).

Conspicuity is generally enhanced by high contrast between the safety garment and the ambient background against which it is seen. This step provides potential performance information for conspicuous materials to be used in WZs and specifies minimum amounts of background, retroreflective and combined-performance materials, colors and placement of materials for garments, and supplemental items used to enhance the visibility and safety of workers. Along with the vest design consideration, the lighting condition at WZs, especially at night is also important. A badly illuminated work zone environment can lead to road users not being able to identify workers early enough, which may result in crashes. Due to various colors already present in WZs such as those that can be seen on vests, equipment, control devices, roadway markings, surrounding environment, and the likes, the illumination of WZs at night is usually complicated and must be designed to ensure no color conflicts for distinguishing workers from equipment. Well-designed WZ lighting can improve worker safety, driver safety, worker morale, productivity, work quality, and work inspection. Some of the problems with WZ lighting include excessive glare which often creates serious driving safety hazards, uneven patterns of light and darkness that make it difficult to spot workers, strong shadows that increase injury risks and block the view of workers while performing their tasks, excessively bright areas that may cause workers to obscure details, in turn making it difficult to see changes in terrain created by trenches and manholes, and an overall degradation in workmanship.

Based on the American National Standard ANSI/ISEA 107-2020, the project team has performed comprehensive measurements on the safety apparel, including color, retroreflection, physical properties, minimum areas of background, retroreflective, and combined-performance materials. Test methods were compiled based on accepted procedures and required standards. In particular, the color-related measurement data were used to preliminarily assess the conspicuity and make the initial selections for items to test in three situations in the simulation and field test scenarios– daytime, daytime with glare, and nighttime.

4.1.1 Measurement of Optical Properties of Materials

The optical properties of a safety apparel material determine how it will interact with sunlight during daytime and electrical light during the night. Obtaining these quantitative data was not only useful to configure the VR environment and item settings, but also to provide the research team the basic understanding and accurate comparison opportunities on different vest materials and designs. In this subtask, the research team measured the optical properties of the fabric samples of vests and other safety items.

The following three major parameters were measured for the safety items of interest, and those parameters are as follows: chromaticity, retroreflectivity, and luminance.

Chromaticity is the objective specification of the quality of vest color (regardless of its luminance). It consists of two independent parameters, often specified as hue (h) and colorfulness (s), where the latter is alternatively called saturation, chroma, intensity, or excitation purity. This number of parameters follows from the trichromacy of vision of most humans, which is assumed by most models in color science. The research team used a CM-2500C Portable spectrophotometer for the measurement (ISO 17025) (see Figure 1).

Figure 1. Spectrophotometer

Retroreflectivity is mainly measured for the retroreflective materials used in safety apparel, and it is measured with a retroreflectivity meter (see Figure 2). Retroreflective materials can reflect and return a relatively high proportion of light in a specific direction close to the incident light direction. The effectiveness of retroreflective material depends on returning light to its source, and it is measured in terms of the coefficient of retroreflection. Based on the ANSI/ISEA 107-2020, retroreflective materials may be used in a split-trim design consisting of two different stripes with a minimum width of 25mm. In this measurement, the research team focused on the trim materials, which are especially important for nighttime visibility. Here, retroreflectivity was measured in units of candelas per lux per square meter (cd/lx/m²). The research team used the Retrochecker RC 1000 (ISO 20471) for this measurement.

Figure 2. Retroreflectivity Meter

The final parameter the research team measured for the safety items was luminance. The luminance factor in this work is used to specify the performance of fluorescent material used in the safety vests. Fluorescent material instantaneously emits optical radiation within the visible range at wavelengths longer than absorbed and for which emission ceases upon removal of the source of irradiation. These materials enhance daytime visibility, especially during dawn and dusk. The luminance factor of a diffusing material is defined as the ratio of the luminance of the surface of the material to that of a perfect (Lambertian) diffuser under specified conditions of illuminance and angle of view. Measurement of this quantity has always been rather difficult, involving visual photometric measurements at widely different levels of illuminance. A physical method of measuring luminance factor is described which has given more repeatable results and better interlaboratory agreement than the former visual method. In this work, LS-100 Luminance Meter (ISO 17025) (see Figure 3) is used for measuring luminous accessories' brightness.

Figure 3. Luminance Meter

In addition to collecting the aforementioned properties of vests, the research team also collected the IES data of ODOT's balloon lamp and the representative vehicle headlights (Halogen, HID, and LED). Subsequently, the team built the safety vest items, ambient balloon lamp, and the vehicle headlights in the VR environment (i.e., for use in the driving simulator scenarios). The overall VR environmental settings (exposure time, ISO, etc.) used the default values initially and adjusted during the verification process in the subtask.

4.2 Simulation-based Evaluation

This task focused on the evaluation of the combination of various safety apparels and work zone features based on visual (i.e., color) and luminous properties obtained from the lab measurement of the materials' optical properties as aforementioned. Due to a large number of evaluation scenarios (e.g., varying combinations of safety equipment, traffic control, work zone configuration, etc.), the simulation-based approach was used to evaluate the scenarios under a completely controlled (simulation) environment. First, the research team built the 3D models to be used for the simulation experiments. These models consisted of virtual environments/scenarios in which participants of the study would view work zones in VR, and this process is discussed more in the following subsections. The comparison between the visual characteristics in VR and photometric measurements in the lab was carefully conducted and subsequently used to inform the initial design parameters of the safety items in the VR environment. The ultimate goal of this comparison is to attain identical lighting performance of the safety vests under the selected light sources in the VR/simulation scenario as they are in the real world. After the models were validated, participants with different attributes were invited to the research lab to participate in the experiments in virtual reality environments. Based on the existing studies on WZ visual conspicuity, a series of measures were gathered from each participant, including both subjective data (e.g., visibility, conspicuity, glare levels) and objective data (e.g., time to the first fixation on a particular entity in the work zone, total duration of fixation, gaze areas, etc.), to evaluate the effectiveness of different combinations of technologies under the selected environmental settings.

4.2.1 Simulation Modeling and Scenario Development

The modeling team, led by Professor Ming Tang of the UC team, created various models for the vests, other safety items (e.g., halo hat lights), and models of work zones in which workers wearing the modeled safety items are present. Using the 3D modeling software, Autodesk Maya, 3dsMax, and real-time Unreal Engine, the digital environment of each simulated work zone was created and compiled to run on a driving simulator at the UC campus. Specifically, the safety vest and testing scenarios of a working zone are assembled in the following steps.

4.2.1.1 Modeling of Workers wearing Vests

Modeling the safety vests to be worn by workers in the virtual work zones included the design of four vest types and one pants type. Based on the reference data provided in the preceding lighting experiments, the modeling team matched the RGB values of the actual safety vest's measurement to the virtual texture in Photoshop (see Figure 4) and used this data to create a model of the vests and pants in Autodesk Maya (see Figure 5). The team then transferred the image textures (i.e., 3D models) to the Unreal engine (the authoring program to set up the virtual materials), as seen in Figure 6. The vest emissive materials were refined for evening light to simulate the proper retroreflectivity of the material by editing the material's reflectivity and RGB color to match the look of the actual fabric, as shown in Figure 7 and Figure 8.

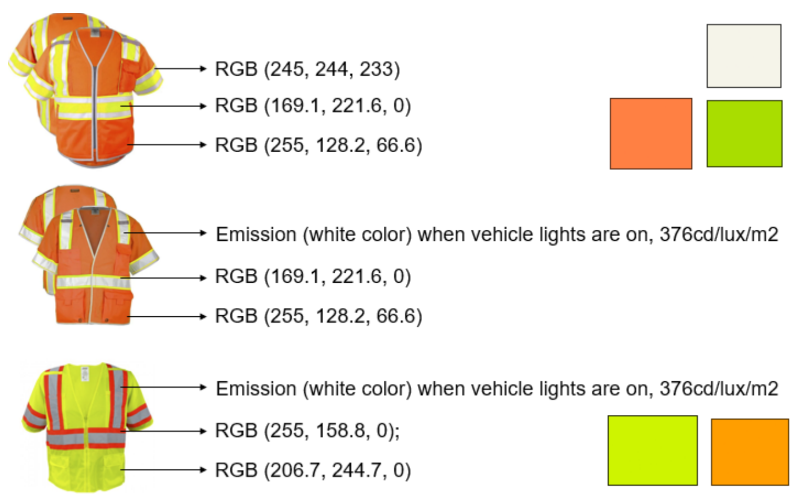

Figure 4. RGB Values of Sample Modeled Vests

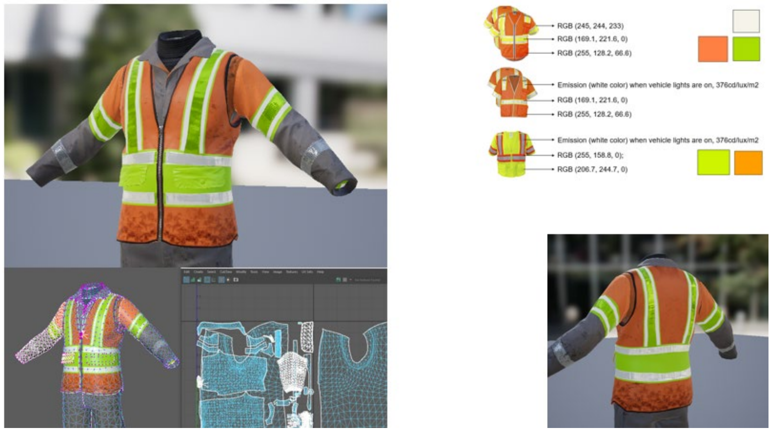

Figure 5. 3D Vest Geometry Modeled in Autodesk Maya

Figure 6. Four Vests and Pants Designed for Project (as Rendered in Unreal Engine)

Figure 7. Test Renderings of Retroreflective Materials under Night Light Conditions

Figure 8. Test Renderings of Retroreflective Materials under Afternoon to Evening Light Conditions

Following the aforementioned steps, the vests were integrated onto 3D models of workers that were in turn placed into various work zone models as seen in Figure 9; the design of such models is discussed in the following subsection. The team created an extensive library of 3D character models, as seen in Figure 10 (i.e., many different virtual construction workers). This was done by adjusting parameters such as vest type, pose, etc. In addition to making the workers look different, they also created several animation sequences to animate construction workers, based on various tasks they do on-site (e.g., walking, working on an object, talking, etc.) (see Figure 11). Finally, besides creating 3D models of workers and their vests, models of elements such as halo hat lights (see Figure 12) were also created based on the results of the lighting tests in a method similar to that of the vest creation.

Figure 9. Integrating Vest and Construction Worker Models

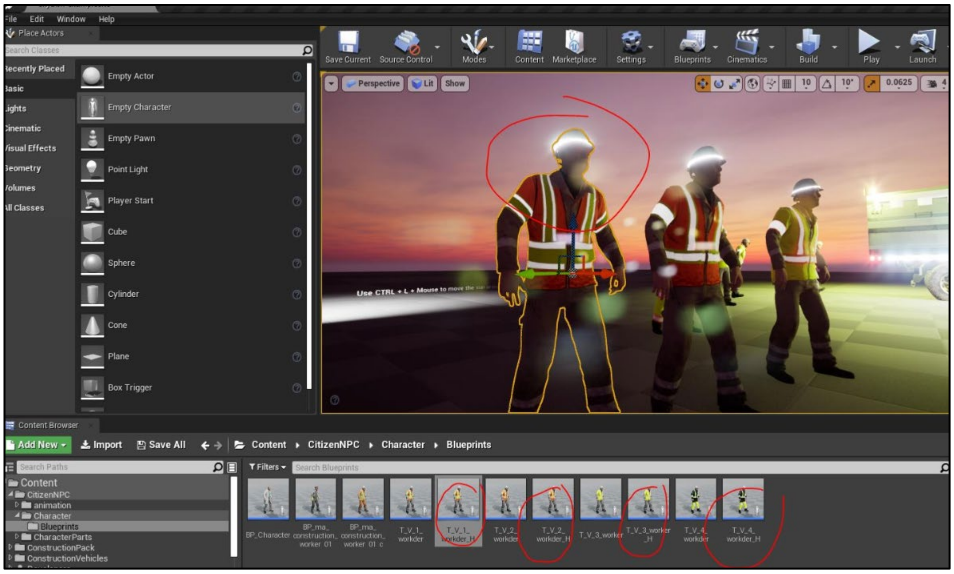

Figure 10. Example of Character Models in Library for use in Work Zone Models


Figure 11. Animated Characters Rendered in Unreal Engine

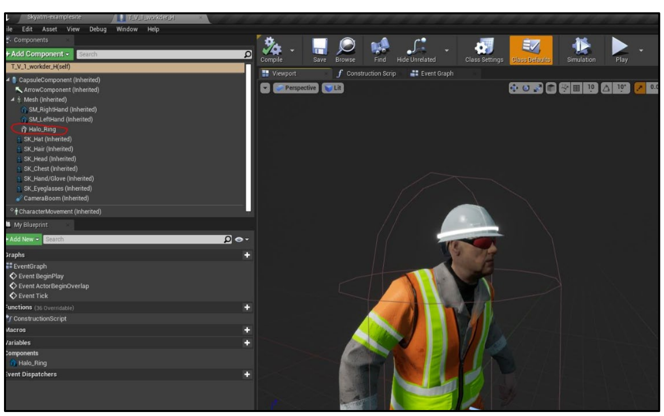
Figure 12. Model of Worker with Functional Halo Hat Light (i.e., turns on and off)

4.2.1.2 Modeling of Work Zone Lighting Elements

As an important portion of the project involved evaluating worker conspicuity under various lighting scenarios, modeling of different types of lights in the work zone (as seen in Figure 13), as well as ambient lighting, was also performed. The lighting modeling task included matching the simulated light with the reference data collected from various light fixtures and environment light sources, as discussed in the preceding task. The process began with integrating the Illuminating Engineering Society (IES) profiles of various light sources into the light fixture simulation in the Unreal engine. The IES files were obtained either from manufacturers (e.g., Balloon Light) or from the IES data sources based on the US Federal Motor Vehicle Safety Standard. To consider the emerging trends in the vehicle headlamp design, the research team intentionally incorporated two lighting colors (3,000 K and 4,500 K correlated color temperature), representing standard Tungsten-Halogen light source and LED/HID headlamps.

Item	Manufacturer	Lighting output	IES files
Balloon light 	Multiequip Cor.	117,000lm	Modified
Truck light 	WHELEN ENGINEERING	1,000lm	Modified
Truck light 	WHELEN ENGINEERING	1,000lm	Modified
Headlamps of incoming vehicles 	Standard/Generic	6,000lm	Modified

Figure 13. Various Light Sources Modeled for Work Zones and their Corresponding IES Data as Collected in the Lighting Evaluation

The modeling team imported the photometric IES files of light fixtures into the Unreal engine and created several light simulation models (see Figure 14), including those for balloon lights (Figure 15), animated flashing lights (Figure 16), animated tuck flashing lights, and vehicle headlights (Figure 17).

Figure 14. Various Light Simulations based on IES Light Profiles

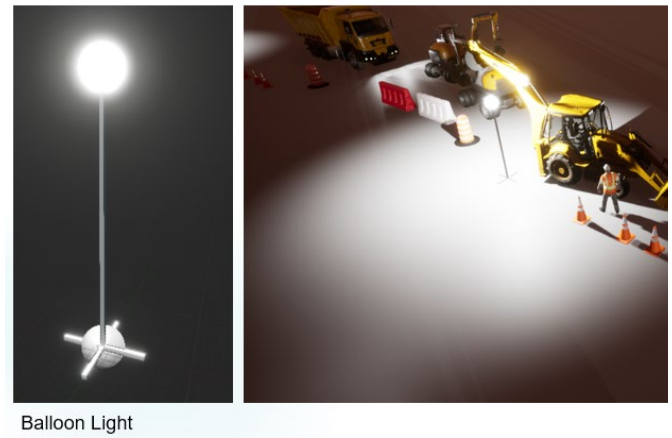

Figure 15. Balloon Light Distribution and Simulation

Item	Manufacturer	Lighting output	IES files
Balloon light	Multiequip Cor.	117,000lm	Modified
Truck light	WHELEN ENGINEERING	1,000lm	Modified
Truck light	WHELEN ENGINEERING	1,000lm	Modified
Headlamps of incoming vehicles	Standard/Generic	6,000lm	Modified

Figure 16. Animated Flashing Light Simulation

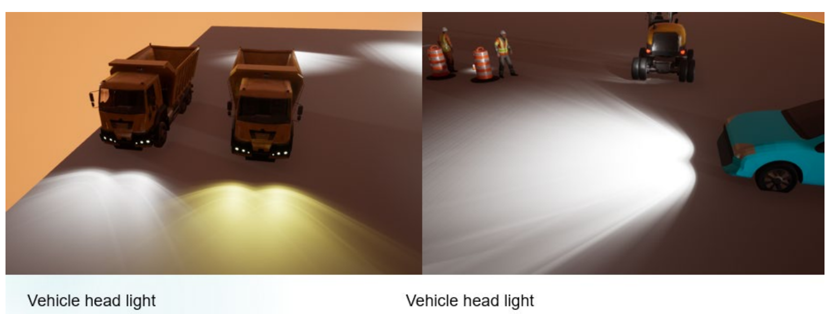

Figure 17. Vehicle Headlight Simulation

The environmental lighting system (i.e., the ambient light conditions) was modeled to allow the data collection team the maximum flexibility to customize the sunlight and skylight system (Figure 18) to simulate various sun intensity, color, positions, and atmosphere effects such as bloom (Figure 19), sun glare, lens flare effects (Figure 20), scattering (Figure 21), and fog. Ultimately, the team used three main environmental light settings in the simulations: day without glare (noon), daytime with glare, and nighttime conditions.

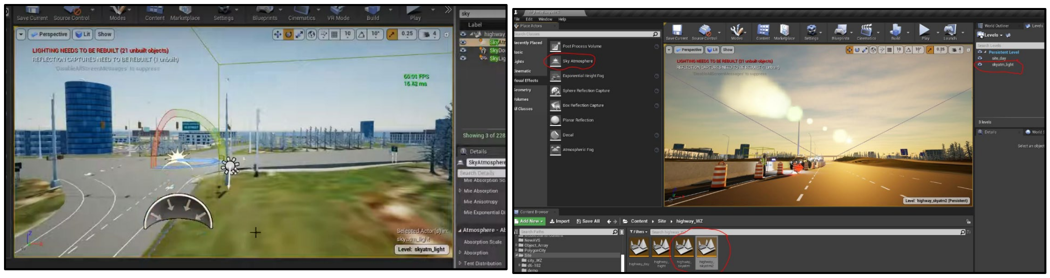

Figure 18. Sky atmosphere System to Simulate Sunlight and Skylight in Unreal Engine

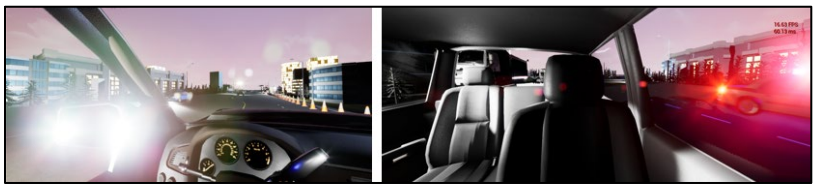

Figure 19. Bloom Light Effects of Headlight and Vehicle Lights

Figure 20. Lens Flare Effects of Road Markers

Figure 21. Light Scattering and Bloom of Reflective Ribbon on Construction Vehicle

4.2.1.3 Modeling of Virtual Work Zones

In order to create virtual environments through which participants in the driving simulator experiment could drive, various work zone models had to be created. The work zone models were created based on the engineering standards and work zone setup guidelines (such as those in the *Manual on Uniform Traffic Control Devices*) (Figure 22). Models of the roadway itself, barriers, drums, cones, and various props were modeled to match the dimensions and layouts of work zones. The road model includes the lanes, curbs (if applicable), railing, and streets light based on highway and local road standards. Ultimately, models of work zones on roadways of different functional classifications were created (Figure 23 and Figure 24).

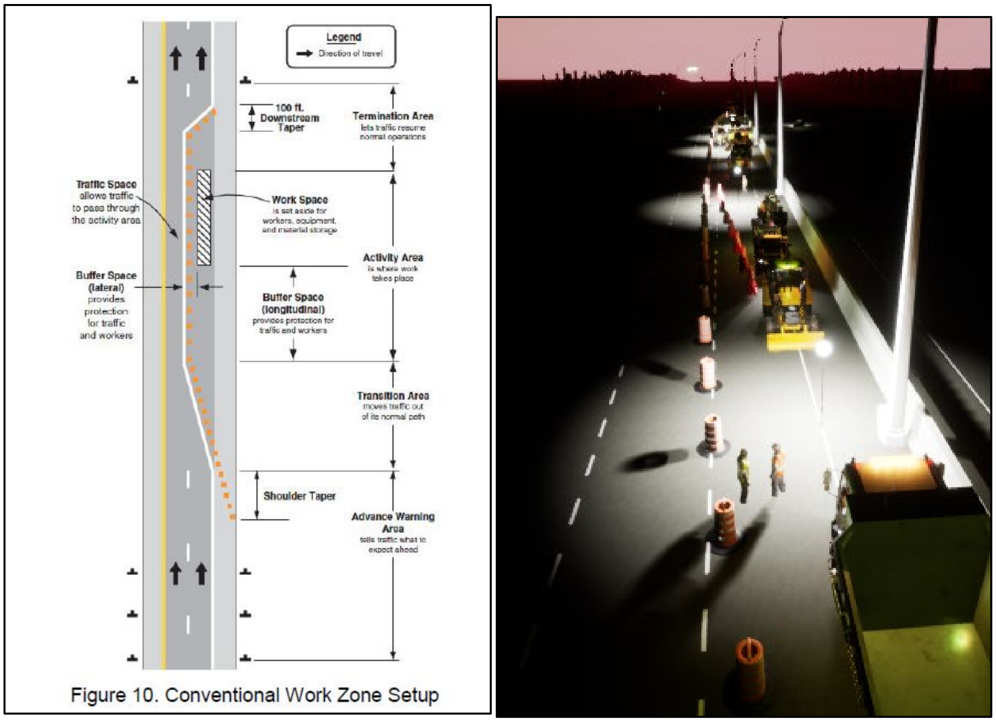

Figure 22. Left: Reference Plan of Work Zone (via FHWA MUTCD), Right: Virtual Model based Work Zone Plan

Figure 23. Highway Work Zone Scenario

Figure 24. Local Road Work Zone Scenario

4.2.1.4 Modeling of other Work Zone Items

In addition to the work zones themselves (i.e., the roadway, traffic control, workers, etc.), numerous other items were modeled for inclusion in the virtual work zones, including various types of vehicles, animated lights on cars, barriers, cones, and signs (Figure 25). The process of creating the 3D models was similar for each item, so the following gives an example for the modeling of a construction vehicle in a work zone. The modeling of the vehicle starts with a collection of reference pictures, videos, and interviews to make sure the digital model matches the actual vehicles as close as possible (Figure 26 and Figure 27). The vehicles are then modeled in the standard 3D modeling programs, Maya and 3dsMax. Next, the modeling team added 3D details and textures, and then transferred the model into the Unreal engine to set it up for use in the simulation scenarios. An example of another work zone prop is shown in Figure 28.

Figure 25. Collection of Various Props in a Scenario

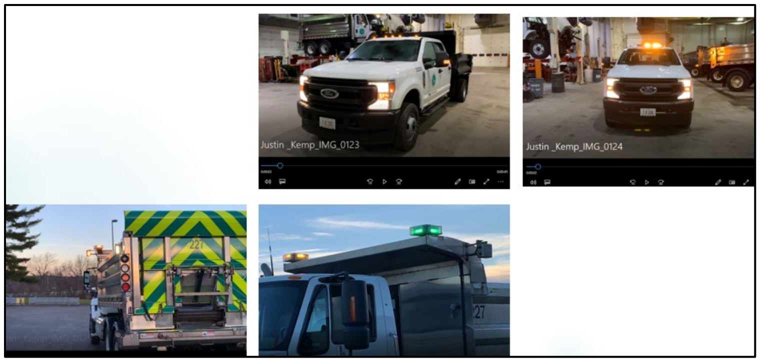

Figure 26. Reference Pictures of a Construction Vehicle from ODOT

Figure 27. 3D Truck Model, with Accurate Texture, Animated Lights, is Created and Set in Work Zone

Figure 28. Police Car with Animated Lights (another Work Zone Prop)

4.2.1.5 Additional 3D Modeling Components for the Simulator Experiment

To simulate an immersive and realistic driving experience, the modeling team also created models of the vehicle interior, including a virtual dashboard, windshield, and side and rear mirrors to match an actual vehicle (Figure 29). These models were displayed on-screen in the simulator while the participants were driving. The team also created a traffic simulation system, which can automatically populate the road with moving vehicles. Hence, different volumes and configurations of vehicles driving along the section of roadway with the work zone could be simulated (Figure 30). Finally, the modeling team also created a collision simulation between the vehicle with cones and barriers. The interactions between the driven vehicle and physics objects were simulated based on the speed of a vehicle, the physical property of objects, and collision angle further increasing the degree of realism in the simulator.

Figure 29. Digital Model of Dashboard and Vehicle Interior in Simulator

Figure 30. Vehicles in Traffic Simulated for Work Zone Scenario

4.2.2 Driving Simulator and Human Factors Study Design

Driving simulators have been widely used for human factors research and automobile driver assessment for decades. Driving simulators offer several advantages over real-world driving including safety and reproducibility of scenarios and ability to test scenarios that may not yet exist in the real-world (e.g., future construction). Research simulators are often used for human factors and cognitive psychology experiments to study the behavior and reaction of drivers to stimuli while driving. This allows professionals to evaluate the interactions between humans, vehicles, and other surrounding features under a typical driving environment. The data from these evaluations can then be used to assess the effectiveness of existing infrastructure, investigate the reaction of drivers of various demographic characteristics, and recommended potential improvements to infrastructure.

As this project is human-factors-related, a driving simulator was used to perform a first round investigation on measuring the conspicuity of workers under various WZ environments and conditions can be effectively done using driving simulators under controlled conditions. Further, since there are numerous possible scenarios of the WZ environment, making examination of them extremely tasking and cost-prohibitive for real-life WZ experiments, use of a driving simulator is ideal. The University of Cincinnati (UC) driving simulator, capable of virtual reality environment presentation (i.e., of the environments and objects shown in the previous subtask), and used for the simulator experiments in this project is shown in Figure 31. In addition to the driving simulator, another human factors study was conducted that monitored participants' gaze behavior to a variety of work zone scenarios. The human factors experiments are described in more detail in the following.

Figure 31. UC Driving Simulator

4.2.2.1 Human Factors Experiments

As this portion of the study involved working with human subjects, the research team sought and received approval for the experiments from UC's Institutional Review Board (IRB). After the broader IRB approval was obtained, the research team invited participants to the driving simulator lab on campus to take part in the experiment. Each participant in the experiment took part in the steps described as follows.

<u>Step 1: Obtain Individual Consent</u>
Each participant that took part in the study was briefed on the nature of the study, their rights during the study, and asked for signed consent before taking part in the experiment. This consent process is standard for any IRB-approved human subjects research and was conducted upon participant arrival. Participants were also informed that they would receive a $50 pre-loaded debit card for taking part in the study (which was given to them upon completion of their visit).

<u>Step 2: Obtain Demographic Information</u>
Participants were also asked to fill out a series of survey questions on basic demographic data including age, gender identity, years driving, driving frequency, and experience driving in work zones. These demographic data were used in latter statistical analysis components of the simulation study.

<u>Step 3: Experiment Part 1 – Eye Tracking Experiment</u>
The first part of the experiment was focused on collection of objective data. Specifically an eye-tracking study was conducted in which participants were asked to sit behind a desktop computer (as shown in Figure 32), while wearing a pair of eye-tracking glasses, and view a series of virtual work zone environments. Each work zone environment contained elements designed based on previous laboratory experiments and included

elements as discussed in the preceding section (e.g., blinking lights, moving workers, etc.) to enhance realism. Each virtual work zone environment contained various combinations of work zone elements including different vest types, different time of day (i.e., daytime without glare, daytime with glare, and nighttime conditions), and different environmental complexity (e.g., different work zone traffic control, different work zone length, etc.). Specifically, the following elements were used as variables in this part of the experiment:

- Work zone complexity
  - Corresponds to length/duration of work zone and in turn traffic control used (low, medium, high);
- Workers wearing different vest types
  - Type 1, Type 2, or Type 3
- Pants warn by workers
  - Standard or yellow reflective
- Workers wearing halo lights
  - Yes or no
- Ambient lighting
  - Daytime with no glare (also called “Noon”), daytime with glare (referred to as Glare), and nighttime
- Traffic control
  - Cones, drums, barriers
- Use of balloon lights
  - Yes or no
- Use of reflective tape on trucks
  - Yes or No
- Use of strobe lights on trucks
  - Yes or no
- Use of clearance lights on trucks
  - Yes or no
- Use of amber/green truck lights
  - Yes or no.

The full list of 24 environments with their respective variable settings is shown in Table 1. Participants were shown each virtual environment for a period of five seconds during which the eye tracking glasses would track their gaze on the elements in the virtual work zone (notably the workers). In total, each participant was shown 24 different work zone environments. It is important to note that in the work zone environments shown to participants, the location of the workers was changed in different scenarios.

Figure 32. Participant in Eye Tracking Experiment

Table 1. Variable Settings for Eye Tracking Experiment

Complexity	Vest Type	Ambient Lighting	Traffic Control	Balloon Lights	Truck Reflective Tape	Strobe	Clearance	Halo Lights	Pants	Truck Lights (amber/green)
Low	Type 1	Glare	Cones	N/A	N	N/A	N/A	N/A	Standard	N/A
Low	Type 2	Glare	Cones	N/A	N	N/A	N/A	N/A	Standard	N/A
Low	Type 3	Glare	Cones	N/A	N	N/A	N/A	N/A	Yellow reflective	N/A
Med.	Type 1	Glare	Drums	N/A	Y	N/A	N/A	N/A	Standard	N/A
Med.	Type 2	Glare	Drums	N/A	Y	N/A	N/A	N/A	Standard	N/A
Med.	Type 3	Glare	Drums	N/A	Y	N/A	N/A	N/A	Yellow reflective	N/A
High	Type 1	Glare	Barriers	N/A	Y	N/A	N/A	N/A	Standard	N/A
High	Type 2	Glare	Barriers	N/A	Y	N/A	N/A	N/A	Standard	N/A
High	Type 3	Glare	Barriers	N/A	Y	N/A	N/A	N/A	Yellow reflective	N/A
Low	Type 1	Noon	Cones	N/A	N	N/A	N/A	N/A	Standard	N/A
Low	Type 2	Noon	Cones	N/A	N	N/A	N/A	N/A	Standard	N/A
Low	Type 3	Noon	Cones	N/A	N	N/A	N/A	N/A	Yellow reflective	N/A
Med.	Type 1	Noon	Drums	N/A	Y	N/A	N/A	N/A	Standard	N/A
Med.	Type 2	Noon	Drums	N/A	Y	N/A	N/A	N/A	Standard	N/A

Med.	Type 3	Noon	Drums	N/A	Y	N/A	N/A	N/A	Yellow reflective	N/A
High	Type 1	Noon	Barriers	N/A	Y	N/A	N/A	N/A	Standard	N/A
High	Type 2	Noon	Barriers	N/A	Y	N/A	N/A	N/A	Standard	N/A
High	Type 3	Noon	Barriers	N/A	Y	N/A	N/A	N/A	Yellow reflective	N/A
Low	Type 1	Night	Cones	Y	N	Y	N	Y	Standard	Y
Low	Type 2	Night	Cones	Y	N	Y	N	Y	Standard	Y
Med.	Type 1	Night	Drums	Y	N	Y	Y	Y	Standard	Y
Med.	Type 2	Night	Drums	Y	N	Y	Y	Y	Standard	Y
High	Type 1	Night	Barriers	Y	Y	Y	Y	Y	Standard	Y
High	Type 2	Night	Barriers	Y	Y	Y	Y	Y	Standard	Y

The main goal of this portion of the experiment was to collect various eye-tracking metrics to determine participants' fixation on workers under varying conditions. The following metrics were obtained from using the eye tracking glasses:

- Time to first fixation (TTF): time elapsed (in seconds) from the environment presentation to the first fixation on the workers;
- Total fixation duration (TFD): total fixation duration (in seconds) on the workers over the environment presentation; and
- Number of Fixations (NF): the total number of fixations on the workers over the environment presentation.

Step 4: Experiment Part 2 – Driving Simulator Study

After the eye-tracking experiment, the participants took part in a component involving the driving simulator as shown in Figure 31. Here, the participants drove through different virtual work zone environments (the modeling of which was described in Section 4.2.1, which itself was based on the procedures in Section 4.1). The objective was to collect subjective data on worker visibility/conspicuity under different work zone scenarios. In this case, participants only drive in high complexity work zones in order to reduce the number of simulation runs to make the experiment a reasonable length and to help reduce the potential for simulator sickness (temporary vertigo and nausea). Further, it was assumed that inferences made at the high complexity level of the work zone would also be valid for the other lower complexities. The variables that were examined and changed in the driving simulator study were the same as those discussed for the eye tracking experiment, and the full list of scenarios tested along with corresponding variable levels for each is shown in Table 2.

In total, the participants drove through 10 different simulated work zones with different set ups. The first two were used to familiarize the participant with the simulator's operations, while the other eight (as shown in Table 2) were used for data collection purposes. After driving each scenario, the participant was asked to fill out a brief survey with the following questions (all with answers ranked on a Likert Scale from Very Low (1) to Very High (5)) (see Appendix 8.1 for the full list of questions asked to participants):

- Rate the **brightness** of the workers wearing the safety vest relative to the work zone;
- Rate the **sharpness** of the workers wearing the safety vest relative to the work zone;
- Rate the **visibility** of the workers wearing the safety vest relative to the work zone; and
- Rate the **ease of seeing the workers**.

In the aforementioned survey questions, the key terms were defined as follows:

- **Sharpness**: the contrast of the workers wearing vests (and the vest color scheme) relative to the other elements in the work zone;
- **Brightness**: the reflectivity of the vest color scheme itself, as worn by the worker;
- **Visibility**: the ease of spotting the worker in a safety vest while driving by the work zone; and

- **Ease** of seeing the workers: this measures the participants’ subjective opinion of the workers' conspicuity.

Table 2. Driving Simulator Work Zone Scenario Descriptions

Complexity	Vest Type	Ambient Lighting	Traffic Control	Balloon Lights	Truck Reflective Tape	Strobe Lights	Clearance Lights	Halo Lights	Pants	Truck Lights (amber/green)
High	Type 1	Noon	Barrier	N	Y	N	N	N	Yellow reflective	N
High	Type 1	Glare	Barrier	N	Y	N	N	N	Yellow reflective	N
High	Type 3	Noon	Barrier	N	Y	N	N	N	Standard	N
High	Type 3	Glare	Barrier	N	Y	N	N	N	Standard	N
High	Type 2	Noon	Barrier	N	Y	N	N	N	Standard	N
High	Type 3	Night	Barrier	Y	Y	Y	Y	Y	Standard	Y
High	Type 2	Glare	Barrier	N	Y	N	N	N	Standard	N
High	Type 2	Night	Barrier	Y	Y	Y	Y	Y	Standard	Y

Step 5: Analysis of Experimental Data

The results of the analysis of the simulation data are shown in the next chapter of the report. However, in the following section, the methods of analysis are briefly described. In general, three types of analysis were used. First, bar charts were used to visualize data from the eye tracking experiment (e.g., a bar chart of average time to first fixation on the workers under different scenarios). Further, histograms were used to visualize the Likert scale response data from the simulator scenario follow up questions. Finally, for both the eye tracking and simulator portions of the experiment, the Kruskal Wallis test was also used to examine the potential for any significant differences in performance measures among the vests. The Kruskal Wallis (KW) test, also called one-way ANOVA on ranks, is a non-parametric statistical hypothesis test that tests if samples from n (n at least 2) groups come from the same distribution; it has an added benefit that it can be used for both continuous data (i.e., the eye tracking fixation data) and ordinal data (the simulator study Likert response data). If one assumes the distribution of each of the n groups is the same, then the Kruskal Wallis test can be viewed as examining if the groups have the same median. If the null hypothesis of the KW test is rejected (meaning at least one pair of the n groups do not come from the same distribution), one can use Post-Hoc tests, specifically Dunn's test, to examine what if any differences may exist in terms of the distributions for each pair of groups. Interested readers may refer to any common text on experimental design for more details on the above statistical tests.

4.3 Field Test Evaluation

The simulation-based experiment in the preceding task is planned to be used to make recommendations for new technologies or new WZ settings, which can then be validated in the field. The field testing is planned to take place at actual ODOT work zones in differing environments. The purpose of field testing is for validation of key conclusions obtained from the simulation study. Just like in the simulation study, the research team prepared the necessary IRB paperwork describing this portion of the experiment in which participants will drive through actual work zones and complete a series of questions after each drive asking them subjective questions (on a Likert scale) on different aspects of worker visibility (see Appendix 8.2 for the full list of questions). Participants with different attributes will be invited to the testing site to participate in the experiments in several work zone environments over a course of several days. Further, conspicuity (in terms of distance at which a worker is detected) will be collected to evaluate the effectiveness of different combinations of technologies.

As another component of this task, the project team will take the photometric measurements of different safety items on-site to assess the new recommendations resulting from the preceding task, compared with the benchmark scenario. Procedures used will be similar to those described in Section 4.1, but will take place at actual work zone sites in the field.

At the time of writing this draft report, the IRB paperwork is still hung up in the review process, hence the field data collection has not yet taken place. The research team is doing everything it can to complete the field study prior to the end of the project and will update the report upon obtaining results.

4.4 Standard Operations Development

Based on results from all the previous tasks, the research team prepared an addendum to the existing standard practice of the WZ safety vests and WZ settings (as delivered in Phase 1). The team worked with the ODOT maintenance office to ensure the SOP addendum is consistent with existing documents and practices. As this step is partially dependent upon results of the field test, the research team is still in the process of drafting the SOP at the time of this draft report submission.

5 Research Findings and Conclusions

The following section breaks down the results of the different tasks of the project. Specifically, results are shown from of the photometric analyses in the laboratory lighting experiment, the simulation-base evaluation, and the field test evaluation (forthcoming).

5.1 Findings and Conclusions from Laboratory Lighting Experiment

5.1.1 Measurement Results for Vests and other Safety Items

The research team obtained three sets of vests and made the aforementioned measurements on chromaticity and luminance factors for fluorescent materials. Two vests were planned to be used for daytime and nighttime, respectively. The research team also included the vest currently used by ODOT. The following table (Table 3) provides the data summary that includes brief information of the vests and their use purposes, background-color chromaticity, trim color chromaticity, and fluorescent material's luminance factor.

Table 3. Optical Measurements for Vests

Vest	Brief Info	Background Color	Trim Color	Standards
	• **Daytime use** • ML Kishigo 1573/1574 Brilliant Series Class 3 • Two 1" wide reflective material with 4.5" contrasting color • Cost $40-50	Fluorescent orange-red Luminance factor: 0.43 x: 0.535, y: 0.375	Yellow/Lime x: 0.395, y: 0.575	ANSI 107 Type R, Class 3 compliance
	• **Nighttime use** • ML Kishigo 1552B/1553B Brilliant Series Class 3 • 2" reflective stripes placed over 3" contrasting color • Cost $30-40	Fluorescent orange-red Luminance factor: 0.43 x: 0.535, y: 0.375	White/Silver Retroreflective coefficient in cd/lux/m^2 RA=376	ANSI 107 Type R, Class 3 compliance
	• **ODOT current use** • Goodwill Industries • ANSI Class 3	Fluorescent yellow-green Luminance factor: 0.78 x: 0.401, y: 0.545	White/Silver Retroreflective coefficient in cd/lux/m^2 RA=376 Orange-red Trim x: 0.565, y: 0.395	ANSI 107 Type R, Class 3 compliance

For the other WZ items, including traffic cones, balloon lights, truck safety light, and reflective tapes, the research team also obtained samples from manufacturers or ODOT and made optical measurements. Table 4 provides the measurement summary. Notably, because the focus of this work is about conspicuity, the optical measurement was concentrated on the chromaticity.

Table 4. Optical Measurements for Work Zone Items

Item	Manufacturer	Model number	Colors	Chromaticity coordinates
Traffic cones	Hill & Smith Inc. or WAPCO	28PVCS* or 28 PVCH*	Orange	x | y 0.551 | 0.421
Balloon light	Multiequip Cor.	Globug – GBS*	Warm white	x | y 0.43 | 0.41
Truck light 1	WHELEN ENGINEERING	01-0286361813J	Amber and White	x | y 0.477 | 0.501 0.418 | 0.397
Truck light 2	WHELEN ENGINEERING	01-0286361814J	Amber and Green	x | y 0.477 | 0.501 0.081 | 0.469
Reflective tape	ORAFOL	V98	Green and Yellow	x | y 0.171 | 0.495 0.505 | 0.465 Luminance factor: Green-0.6, Yellow – 0.4

As proposed in Phase I of this project, the research team planned to test several wearable accessories for WZ workers during the nighttime, including halo hat lights, GA lights, and halo belts. The light/color measurements were also conducted for these items, and these results are shown in Table 5.

Table 5. Optical Measurements on Suggested Accessories

Item	Manufacturer	Model number	Colors	Lumens	Chromaticity coordinates
Halo Hat	ILLUMAGEAR, Inc.	#HAWF-01A	White[1]	202 lm	x | y 0.380 | 0.377
GA light	Guardian Angel	GA-ELT-WR	Red and White	500 lm	x | y 0.665 | 0.305 x | y 0.358 | 0.355
Halo Belt	HALO BELT CO.	HB-S	Blue	25-95 lm	Blue

5.1.2 Preliminary Analysis on Conspicuity

Dr. David MacAdam developed the analysis of color difference expectations in 1942. MacAdam's used visual observation of the "Just Noticeable Color Difference (JND)" when examining two lights very similar in color. Here, the "Just Noticeable Difference" refers to the color difference between two sources at which 50% of viewers see a difference and 50% do not. The zones with standard deviations of color matching (SDCM), were shown to have an elliptical shape in the CIE 1931 2 deg observer color space from a series of experiments. In such diagram, the size and rotation of the ellipses shows many differences depending on where they rest in the color space diagram. These zones were largest in the green area and were smaller in the red and blue regions. Essentially, MacAdam's experiments showed that the SDCM ellipse is quite small, implying that humans do well in noticing color differences in the context of seeing two light sources at once.

In this work, to understand whether the objects' colors are noticeable, especially for the workers' vests, the research team performed the following analytical steps:

- Calculate the color coordinates based on the given information;
- Place the item color coordinates into the CIE color space;
- Convert color coordinates xyY to Lab and calculate the color difference; and
- Compare the calculated values with the suggested color different thresholds.

The following two figures (Figure 33 and Figure 34) provide the visual comparisons of the chromaticity coordinates measured for major objects used in work zones.

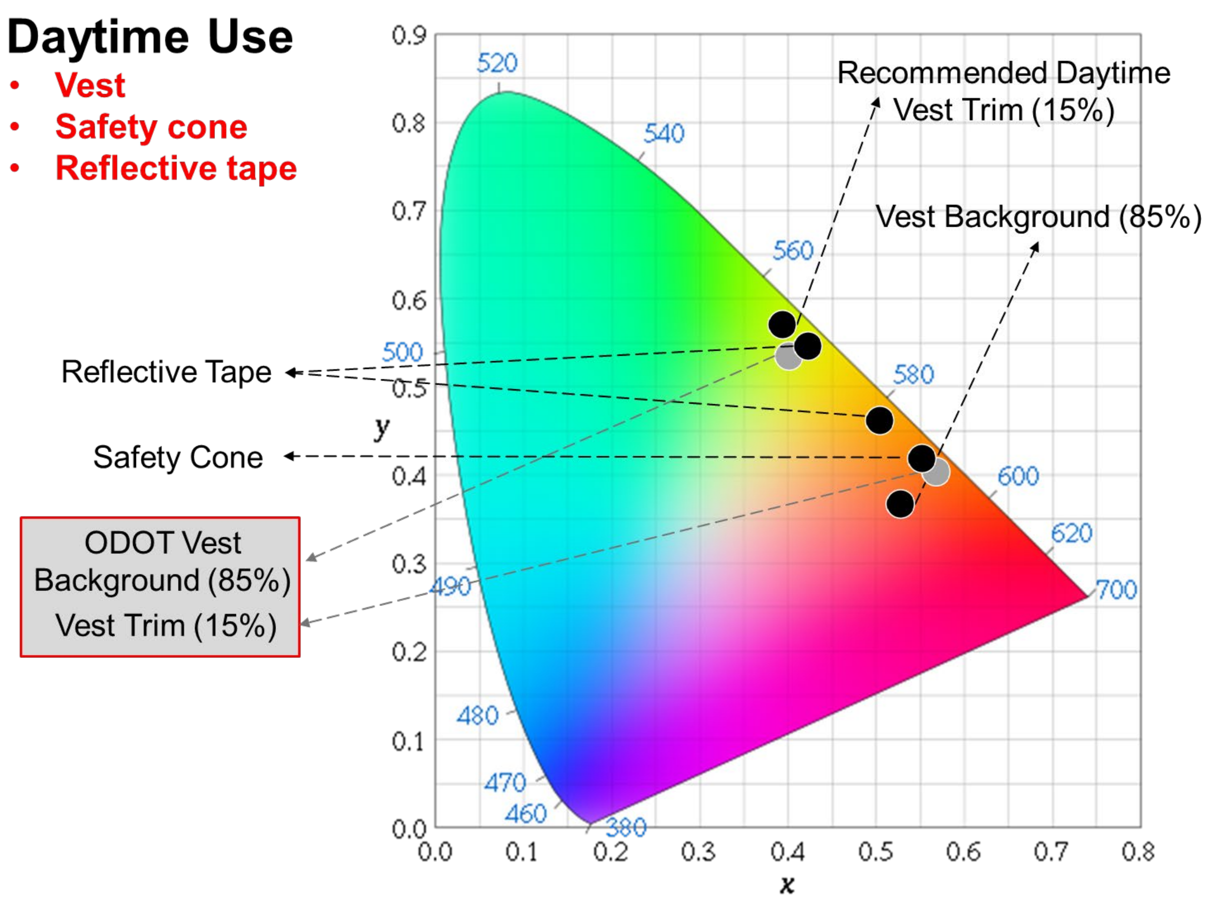

Figure 33. Chromaticity Coordinates of the Vests and Background Objects during Daytime

Based on the information shown in Figure 33, the research team concluded some preliminary results of the daytime use of the suggested vests and the baseline vest (ODOT vest) as follows:

The ODOT current vest color are not distinguishable within the daytime environment (cone and reflective tape);

- The recommended vest color is acceptable, but the reflective tape may bring some inconspicuous issues;
- The preliminary result aligns with the recommendation in Phase I - use the Recommended Vest and remove or significantly reduce the use of green and yellow reflective tape;
- It is possible that using ODOT current vest only (w/o reflective tape) is effective, which needs to be further tested; and
- Subjective testing and cost-benefit-analysis to be conducted for further verification.

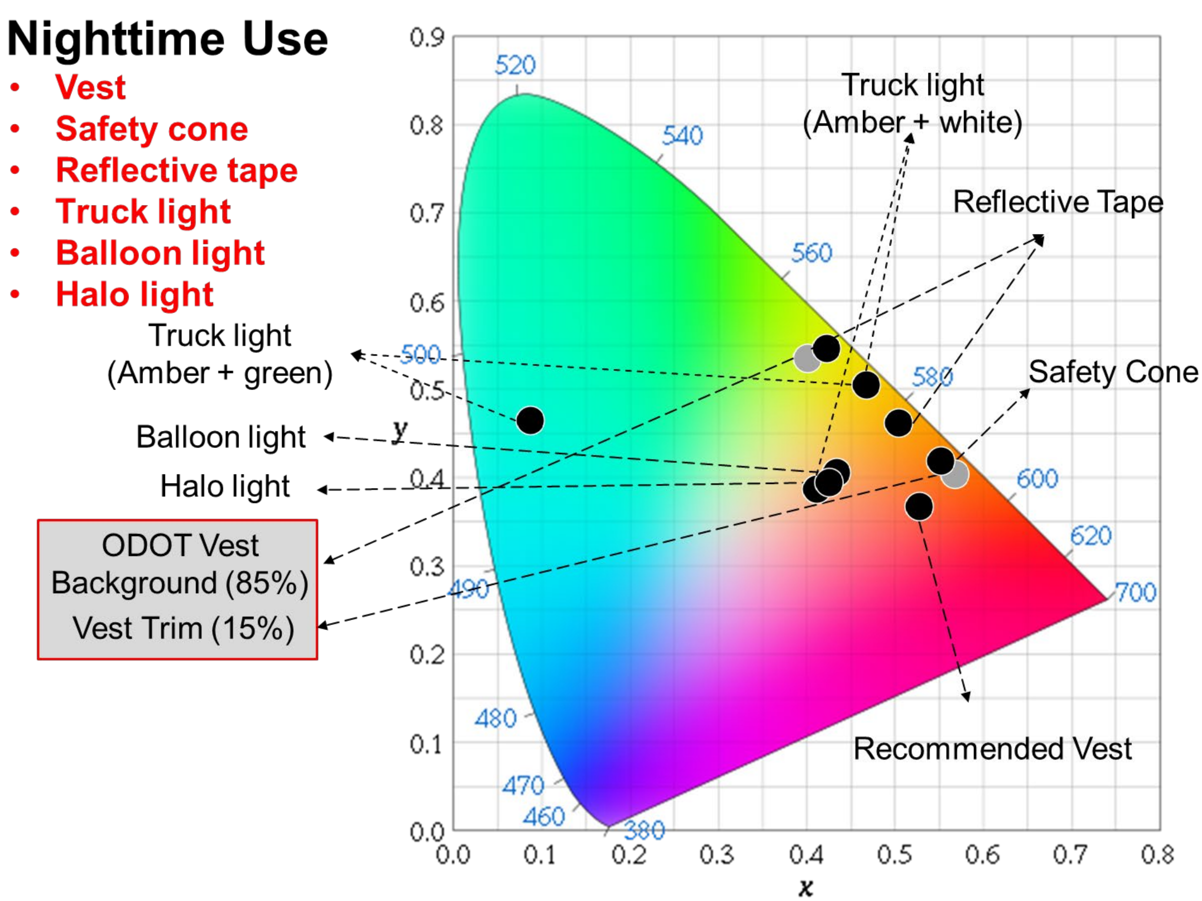

Figure 34. Chromaticity Coordinates of the Vests and Background Objects during Nighttime

Similarly, based on the information shown in Figure 34, the research team concluded some preliminary results of the daytime use of the suggested vests and the baseline vest (ODOT vest); the results are shown as follows:

- Neither the ODOT vest nor the recommended vest is distinguishable within the environment with the truck light and the reflective tape;
- The recommended vest has fewer color types compared with the ODOT vest;
- The reflective tape and amber/white truck light may bring inconspicuous issues;
- The preliminary results suggest removing the reflective tape and amber/white color during the nighttime;
- Using the amber/green truck light needs to be verified in subjective studies; and
- Subjective testing and cost-benefit analysis to be conducted to compare the ODOT vest and the recommended vest.

5.1.3 Daylight Glare Situation Analysis

Glare is a vision-related condition that happens when an eye cannot discern details or objects due to uneven illuminance distribution or large differences in contrast. Glare can be quite dangerous for drivers, making it difficult for them to see oncoming traffic and even workers in a work zone (if the glare is impacting their visibility); the latter issue could lead to numerous work zone related fatalities. The major disadvantage is that the glare can be blinding to drivers of oncoming traffic and may cause serious safety consequences to work zone workers if the vests are not noticeable. Most previous studies have assumed there is no glare during the day due to natural lighting from the sun and all assumed workers are conspicuous. This may not actually be the case. Some studies about safety vest analysis have attempted to develop applicable solutions, such as avoiding sun positions, applying road geometric re-directions, and wearing anti-glare glasses. None of these strategies have fully solved the problem. In this project, the research team proposed one type of vest that is designed with the black background and high visible trims. This specific combination of vest colors follows the traffic signal light design methods – providing a black plate as the background to block the glare and then highlighting the signs. The measurement summary is provided in Table 6. Apparel Suggested for Daytime Glare Situation Use. Consequently, the color and retroreflective coefficients were used in the virtual environment development, which can be used to further test the effectiveness of the proposed vest for glare-situation use.

Table 6. Apparel Suggested for Daytime Glare Situation Use

Vest	Brief Info	Background Color	Trim Color	Standards
	• **Glare situation use** • Work King ST10 • 4" contrast backing • Cost $20-30	Black N/A	Lime and retroreflective x: 0.386, y: 0.552 Retroreflective coefficient in cd/lux/m^2 RA=380	ANSI 107 compliance
	• **Glare situation use** • ML Kishigo 3932/3933 • 2" reflective stripes • Cost $20	Black and Lime x: 0.412, y: 0.540	Orange and retroreflective x: 0.546, y: 0.418 Retroreflective coefficient in cd/lux/m^2 RA=350	ANSI 107 compliance

5.2 Findings and Conclusions from Simulation-based Evaluation

In total, the research team was able to recruit 18 participants for the driving simulation-based evaluation; 12 participants were male and 6 were female. The age range breakdown of participants was as follows: 4 young drivers (18 to 25) and 14 middle-aged drivers (26 to 64). Further, the vest types referenced in the following sections are referred to as shown in Figure 35.

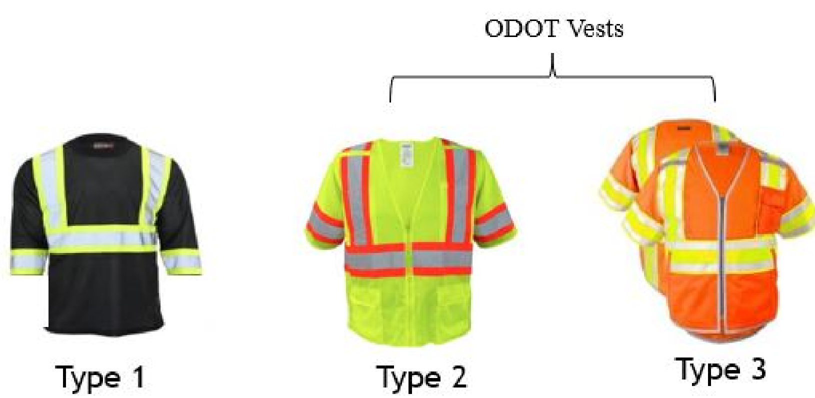

Figure 35. Vest Type Designation for Simulation-based Evaluation

5.2.1 Results from Eye Tracking Experiment

The first portion of the experiment focused on collecting eye-tracking data while participants were shown a series of videos with modeled work zones (each work zone was set up differently in terms of location of workers, time of day/ambient lighting condition, and amount/usage of work zone safety and traffic control devices). The primary performance measure evaluated in the eye-tracking experiment was time-to-first fixation (essentially, how quickly did the participant see an item of interest, where here that item was a group of workers). This metric can help indicate the presence of "distracting" elements in a subject's field of view. Once an area of interest is selected (again, in this case, the workers), one can measure how the time-to-first fixation changes across conditions and infer if the addition of specific elements to a visual scene can attract a participant's attention and possibly distract them from seeing the workers earlier.

Figure 36 shows the time-to-first fixation on the workers under each scenario (note below each bar in the chart, the items in the scenario are described, e.g., DT= dump truck). Visually, the results show the marginal effects of reflective tape and truck lights (applies only to Nighttime conditions) on how early the participant fixates on the workers under Noon conditions, Glare conditions, and at Night. For Noon and Glare conditions, the time-to-first fixation increases as more reflective tapes are added to the scene, which indicates that adding reflective tapes to the work zones makes it harder to see the workers under these conditions. At Night, the research team tested the effects of truck lighting fixtures and reflective tape on trucks. From the figures, one can observe that the time taken to fixate on the workers when trucks are equipped with either strobe lights or a combination of both strobe and clearance lights does not change (adding clearance lights has no effect on seeing the workers). However, upon adding reflective tape to the trucks, one can see a slight increase in the time-to-first fixation, indicating their negative effects again as observed under Noon and Glare conditions. To support these findings statistically, the research team conducted significance tests between groups using the Kruskal Wallis test and Dunn's test with Bonferroni corrections for within groups comparison.

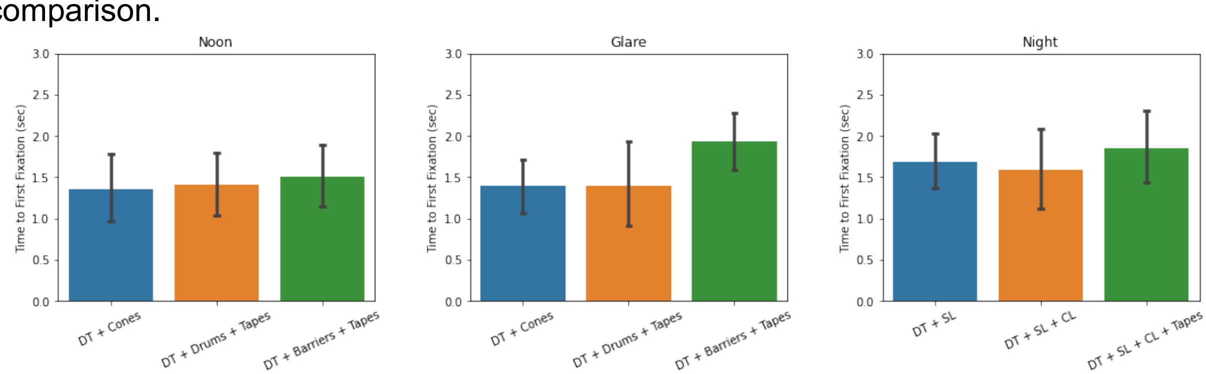

Figure 36. Time-to-first Fixation for Different Combinations of Safety Items

Under Noon time, the Kruskal Wallis test showed no significant effects (p-values = 0.6) of having reflective tape on the dump trucks or not. Therefore, the presence of reflective tapes in the work zone scene does not appear to affect seeing the workers under noon conditions (i.e., daytime without glare). Under glare conditions, one can see a statistically significant negative effect (p-value = 0.057) of adding reflective tape to the work zone scene. This may indicate an interaction between the glare from sunlight and the reflective properties of the tape and their effects on workers' conspicuity. The research team hence conducted a within-group test to determine which groups were significantly different. Results showed that the time-to-first fixation on workers under group 3 (Dump trucks with Barriers with Tapes is significantly higher than that of group 2 (Dump trucks with Drums with Tape) and group 1 (Dump trucks with Cones with Tape). This means that workers are more difficult to see when there are reflective tapes in the work zone under Glare conditions. Summarily, it may be necessary to reduce the presence of reflective tape under Glare conditions, either from the delineating devices or from the trucks to reduce their interaction with the glare ambient lighting condition. Under nighttime conditions, the Kruskal Wallis test did not show significant effects (p-values = 0.7) of having reflective tape and clearance lights on the dump trucks or not. Therefore, having lighting fixtures and reflective tapes does not affect seeing the workers at night, regardless of their vest type.

Figure 37 shows the time-to-first fixation on the workers under each time of day (i.e., ambient lighting condition), vest type, and set of design variable conditions (i.e., configuration of traffic control and work zone safety devices). Under noon and glare conditions, the trends of the workers wearing Type 1 vests seem to align with expectations across the design groups. As the reflective tape is added to the trucks, one can see the conspicuity of workers decreasing, indicating an interaction between the black background of the vest and relative amount of reflective tape in the work zone. If there is too much reflective tape, workers are more difficult to see when wearing the Type 1 vests. This test finding confirms the aforementioned design rationale of the vest, using the combination between the strong and high visible trims and the general dark background including vest background color as well, during the glare situations. Under noon and glare conditions, the performance of ODOT vests (Type 2 and Type 3) is inconsistent across conditions. In some cases, one can see a reduction and, in some cases, an increase in conspicuity. To evaluate the significance of these changes, the research team also conducted similar statistical tests as earlier for each vest under all conditions. For Type 1 vests, the changes are significant (p-value = 0.06 for noon, and p-value = 0.03 for glare), and the earlier conclusions are valid. These conclusions can be interpreted as follows: The presence of reflective tape makes it difficult to see the workers' when using Type 1 vests. For vests of Type 2 and Type 3, the presence of reflective tapes does not affect seeing the workers under the Noon and Glare conditions (p-value = 0.6 for Noon, and p-value = 0.6 for Glare). For the Nighttime conditions, similar results were obtained (p-value = 0.59). Thus, the truck lighting and reflective tape does not affect seeing the workers when they are wearing either the Type 2 or Type 3 vests at Night. Since the proposal for using the Type 3 vest was aiming at the use for workers during the general daytime and nighttime, one can exclude the data and performance of Type 1 and glare situations, and then only compare the conspicuity of workers wearing Type 3 vests performance relative to those one wearing the currently-used ODOT vest (Type 2). This shows that when the reflective tapes are not in use, the workers wearing the Type 3 vest are more visible/conspicuous than the workers wearing the Type 2 vest. When the reflective tapes are in use, the vest impact on worker visibility is mixed.

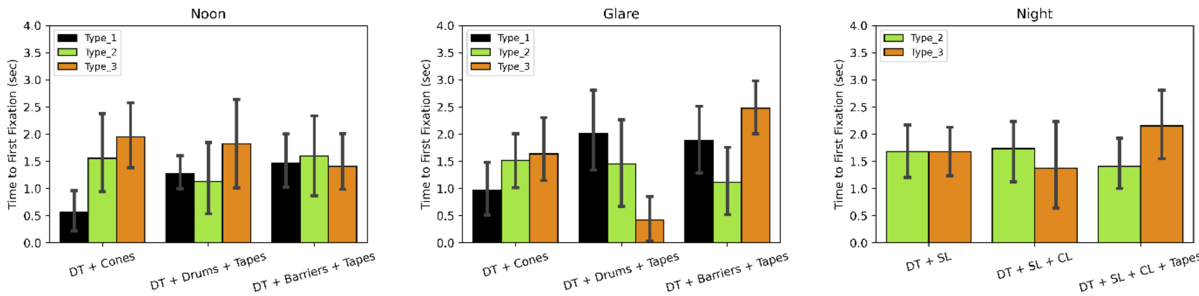

Figure 37. Time-to-first Fixation for Each Combination of Elements, for time-of-day, for each Vest Type

5.2.2 Results from Driving Simulator Study

In the driving simulation experiment, the research team used subjective evaluation measures as obtained from the literature review, they include sharpness, brightness, visibility, and the ease of spotting the workers while driving through the work zone (as defined previously in Section 4.2). As aforementioned, to reduce the time spent in the driving simulator for each participant (necessary (1) to reduce chances of vertigo for participants and (2) in order to constrain the experiment to a reasonable length for participants), the research team focused on the experiment on the highest level of element combinations (i.e., most complex) in the work zone (combination 3 under Noon, Glare, and Night). Hence, the results in the driving simulator will only compare the effectiveness of each vest type on worker's conspicuity under the work zones where all the confounding elements (reflective tape, barriers, strobe lights, clearance lights) are used simultaneously. The results are provided for each time of day (noon, glare, and night) and the three vest schemes (Type 1, Type 2, Type 3). Note that the Type 1 vest is only applicable for noon and glare conditions. In total, there were eight drives for each participant.

Figure 38 shows the results for the noon conditions (representing the combinations of all confounding elements). Each histogram shows the frequency of participant ratings for each category of each performance measure (all ranked 0 to 5, with 5 being the best). By comparing each row in the array of histograms, each vest can be evaluated with each performance measure in terms of conspicuity. Overall, all the vest types performed relatively similarly, however, one can see that the spread of the data for the Type 1 vest has more data on the positive ratings side than the other vest type. This provides some anecdotal evidence that the wearing the Type 1 vests makes it easier to see the workers under Noon conditions when all the confounding elements (dump trucks, reflective tape, and barriers) are present. However, in all cases, the results were not statistically significant (p-values >> 0.05). Hence, while numerical results show that participants feel that wearing the Type 3 vests make it slightly easier to see the workers, the results are not statistically significant.

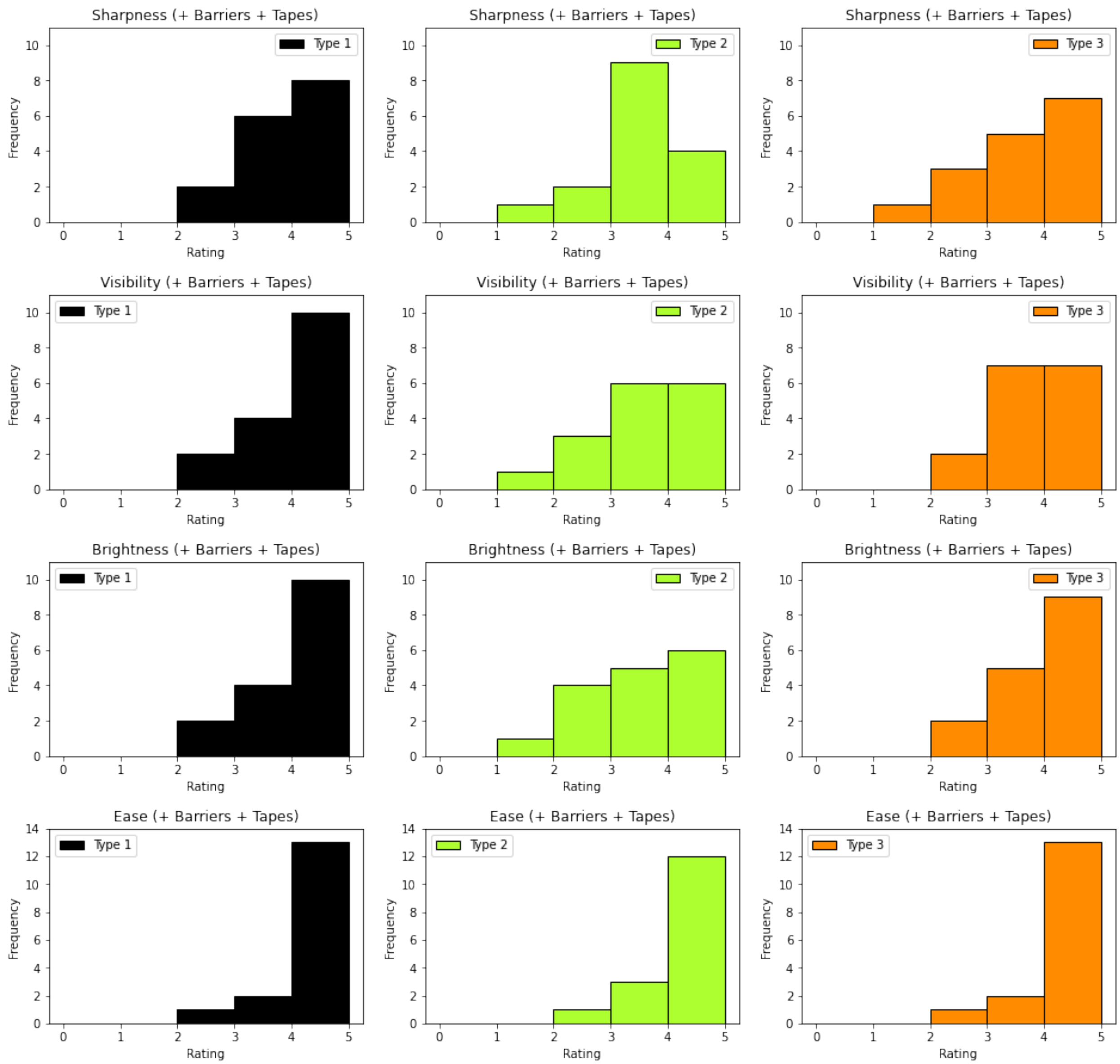

Figure 38. Participants Rating Distribution under Noon conditions

In Figure 39, the results under glare conditions are shown. One can see a relatively similar trend for both Type 2 and Type 3 vests in which the ratings are spread equally over all the Likert levels (0 to 5 scale). For Type 1, the spread is more on the positive ratings side of the scale, which anecdotally indicates slightly better performance. Similar to the noon conditions, significance tests showed no significant difference (p-values >> 0.05) between the workers when they wear different vest types for all performance measures, showing that participants do not think switching between any of the vests makes it easier to see the workers under Glare conditions

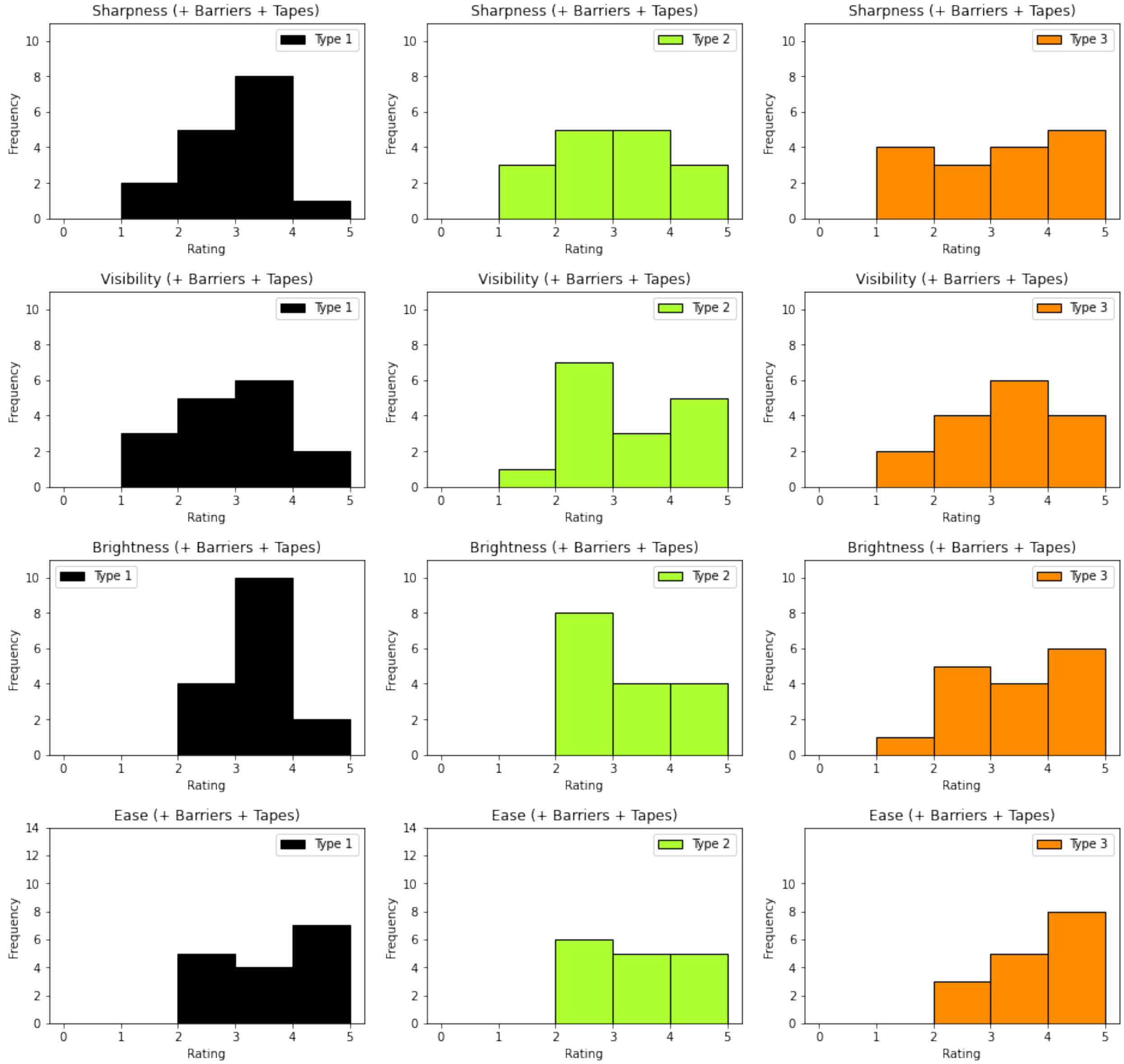

Figure 39. Participants Rating Distribution under Glare conditions

Lastly, Figure 40 shows the impact of Type 2 and Type 3 vests on worker conspicuity under Nighttime conditions. Note that these scenarios were evaluated with Halo Lights on the workers' helmets, as well as the use of all of the aforementioned confounding elements (dump truck with tape, strobe lights, clearance lights, and barriers). The research team assumed that these helmets with halo lights are already being used by ODOT with Type 2 and Type 3 vests (hence, their inclusion in both scenarios). The results do not show clear differences by visual evaluation. Further, the significance test did not show statistical differences (p-values >> 0.05) between the performance of both vest types under the nighttime conditions. Hence, switching between any of the vests at Night does not affect seeing the workers at night.

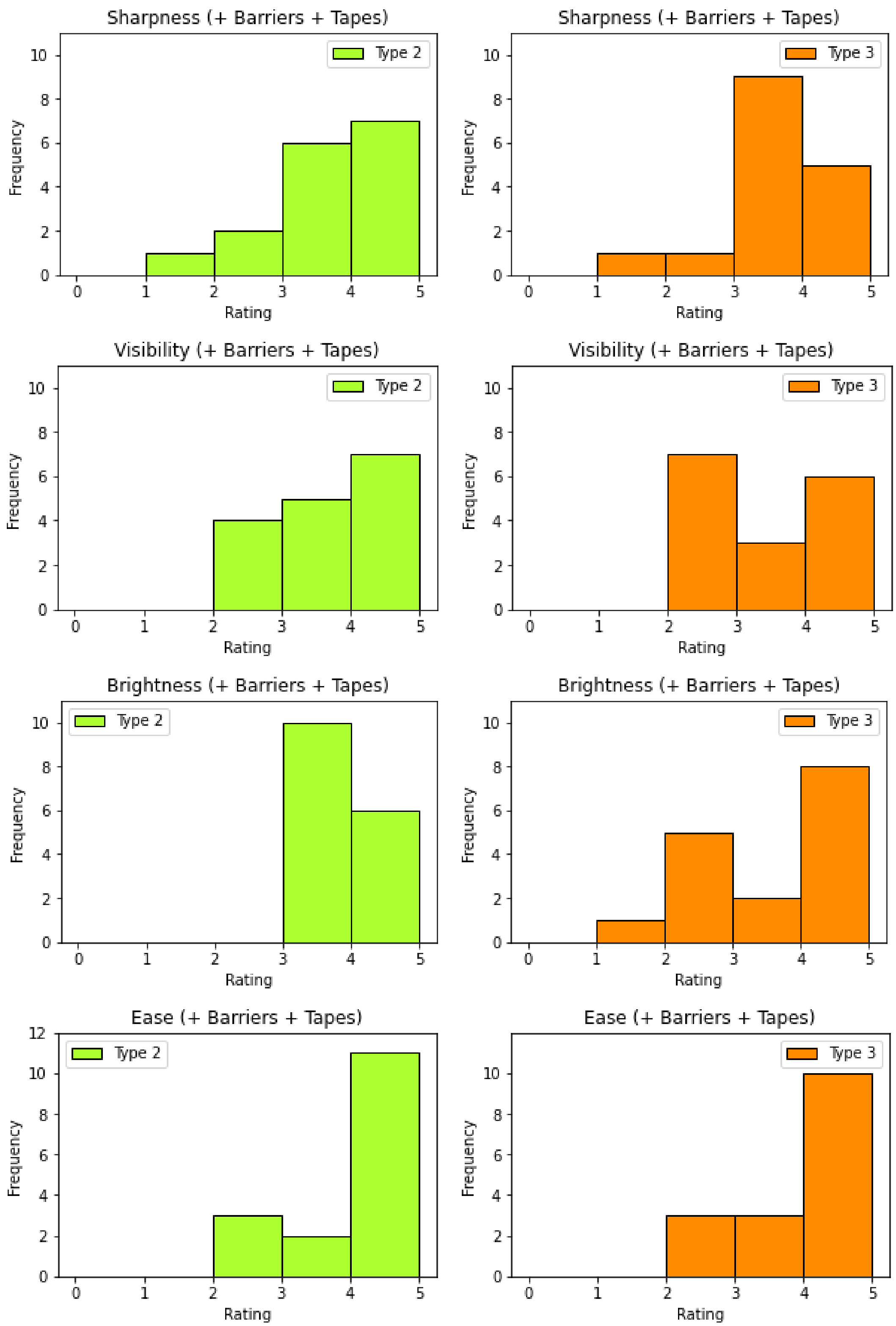

Figure 40. Participants Rating Distribution under Night conditions

5.2.3 Summary of Conclusions from Simulation-based Experiment (Impacts on Worker Visibility)

The following shows a summary of key results obtained from the simulation-based experiment (both the eye tracking and driving simulator portions) in terms of different safety items' impacts on worker visibility.

- Effects of Reflective Tape on Workers Conspicuity
  - Generally, there is strong evidence indicating the negative effects of adding reflective tape to dump trucks on the conspicuity of workers in the vicinity of the trucks and that having reflective tapes makes it difficult to see the workers
    - Under Noon conditions, numerical results show that adding reflective tapes to the work zones makes it harder to see the workers. However, the results are not statistically significant. When the reflective tapes are not in use, the Type 3 vest performs better than the ODOT current use – Type 2, i.e., workers are more visible when wearing the Type 3 vest when reflective tapes are not in use.
    - Under Glare conditions, adding reflective tape to the dump trucks shows a statistically significant difference. The reflective tape reduces the conspicuity of the workers to a significant level, making it difficult to see the workers.
    - Under Nighttime conditions, numerical results show that adding reflective tapes worsens the workers' conspicuity and makes it difficult to see them. However, it is not to a statistically significant level.
- Effects of Clearance Lights
  - First, it should be noted that at Nighttime, the trucks were equipped with strobe lights by default under all the evaluated scenarios. Upon adding the clearance lights (which had the same color scheme as the strobe lights), the conspicuity of the workers was not impacted (both by visually examining the results and by statistically comparing the results). Hence, the clearance lights have no impact on seeing the workers.
  - The research team strongly recommends that these results be further tested and validated in the field experiments due to the limitations of the simulation testing. The rendering of the lights in the simulator is only as realistic as the rendering of the screen or monitors used. Therefore, the results may not be as accurate for lighting fixtures such as the clearance lights.
- Effects of Halo Hat Lights with ODOT vests
  - The effectiveness of the halo hat lights was tested with each ODOT vest type. The research team did not see a statistically significant difference between using the Type 2 and the Type 3 vests. Based on the simulation test, switching from the Type 2 vest to Type 3 vest does not have any impact on seeing the workers.

    - Similar to clearance lights, the rendering of the halo lights is only as accurate as of that of the screen rendering, and thus, the research team strongly recommends that halo lights also be tested in the field experiment in the hopes of obtaining more definitive conclusions.
- Effectiveness of Different Vest Types
    - Under Noon conditions, the Type 1 vest performs better than the ODOT Type 2 and Type 3 vests. This conclusion was confirmed via statistical tests. Recall that due to their color scheme, the Type 1 vest were not tested under Nighttime conditions. Hence, wearing the Type 1 vest under the Noon condition makes it slightly easier to see the workers.
    - Under Glare and Nighttime conditions, only when the reflective tapes are still used with trucks, the Type 2 vest exhibits slightly better performance than the Type 3 vest, making it easier to see the workers. However, the results are not statistically significant. Also, taking the suggestion of reflective tape removal into account, the current ODOT vest (Type 2) does not deliver any better performance in terms of increasing worker conspicuity. For field testing, any (or both) of Type 2 or Type 3 vests can be tested depending on the flexibility of the work zone sites and the safety of the testing conditions.

5.3 Findings and Conclusions from Field Test Evaluation

Per Section 4.3, the research team is still waiting on IRB approval for the field test at the time of drafting this report and plans to fill in this section upon completion of the field test.

6 Recommendations for Implementation

The following results for implementation are presently based on the results of the laboratory lighting evaluation and the simulation study. The research team plans to extend the recommendations to include those from the field study after it is completed. In terms of key recommendations to improve the visibility/conspicuity of workers in work zones, the research team recommends the following based on the conclusions of their analysis:

- Reduce usage of reflective tape at work zones under Daytime with glare and nighttime conditions.
    - Based on a combination of laboratory lighting, eye-tracking, and driving simulation experiments, the study finds that the presence of reflective tapes at work zones makes it difficult to see the workers under the Daytime with glare and the Nighttime conditions. Workers' conspicuity is not affected under Daytime work zones without glare.
- Amber/green lights should be used in place of the Amber/white lights for truck clearance and strobe lights.

    - While Amber/white lights have high bloom intensity and may be distracting to others, having the amber/green strobe and clearance lights was found to not affect seeing the workers.
- Either Type 2 or Type 3 vests can be used for workers in work zones in a variety of conditions without significant differences.
    - Switching from the Type 2 vests (yellow-green background and silver reflective materials) to the Type 3 vests (orange-red background) was found not to affect seeing the workers. Numerically, Type 2 vests were slightly better than Type 3, however, it was not statistically significant.

In order to implement the aforementioned recommendations, it is recommended ODOT make the appropriate changes to their safety equipment, as well as encourage their contractors to do so when appropriate. The expected benefits of these efforts (e.g., reducing or removing the confounding elements as in the case of reflective tapes) is a reduction in the interaction between the reflective elements and lighting sources, thereby reducing driver distractions and enhancing workers visibility and safety. It is further believed this will lead to a reduction in work zone crashes. Risks and obstacles to implementation at present mainly rest on the fact that the results should be verified in a field study. While the team strived to make the simulation experiment as realistic as possible, they are hopeful the field study will help strengthen the overall conclusions. Yet another obstacle to the implementation exists in the fact that due to the number of safety items in use and the complexity of work zones, it is impossible to study the impacts of all possible scenarios on worker conspicuity. The team attempted to address this issue with a thorough experimental design for the simulation study, focusing on the safety elements deemed most important by ODOT, and based on conclusions from the laboratory lighting evaluation. As ODOT has already started to use some of the safety items described herein (e.g., the vests), the time table for implementation is only as long as is needed to purchase the other necessary items and modify existing items as necessary (e.g., removing reflective tape when applicable). In order to evaluate ongoing performance of the implemented results, the research team proposes a follow up analysis consisting of two parts, each to be conducted after the implementation has been in place for some time. First, the team would recommend interviewing both workers and drivers on their thoughts about the conspicuity of the workers in the work zone. Second, an analysis of crash data before and after the changes could also be conducted; however, care would have to be taken to define control work zones similar to those at which the new safety practices were implemented, as there are numerous other confounding factors impacting crash potential.

7 Bibliography

Federal Highway Administration (FHWA). (2020). FHWA Work Zone Facts and Statistics, < https://ops.fhwa.dot.gov/wz/resources/facts_stats.htm> (Sep. 30, 2021).

8 Appendix

8.1 Questions for Simulator Study

The following questions were posed to participants after each of the 10 simulation runs.

Kindly provide your opinion on the conspicuity of workers in the work zone based on the just-concluded driving experiment.

Rate the sharpness of the workers vest relative to the work zone environment

- ☐ Very low
- ☐ Low
- ☐ Average
- ☐ High
- ☐ Very High

Rate the visibility of the workers vest relative to the work zone environment

- ☐ Very low
- ☐ Low
- ☐ Average
- ☐ High
- ☐ Very High

Rate the brightness of the workers vest relative to the work zone environment

- ☐ Very low
- ☐ Low
- ☐ Average
- ☐ High
- ☐ Very High

I easily saw the workers while driving through the work zone

- ☐ Strongly disagree
- ☐ Somewhat disagree
- ☐ Neither agree nor disagree
- ☐ Somewhat agree
- ☐ Strongly agree

8.2 Questions for Field Study

The following questions are planned to be asked to drivers after their drives through each work zone in the field test.

Q1 Rate the sharpness of the workers' vest relative to the work zone environment

- ◯ Very low
- ◯ Low
- ◯ Average
- ◯ High
- ◯ Very High

Q2 Rate the visibility of the workers' vest relative to the work zone environment

- ◯ Very low
- ◯ Low
- ◯ Average
- ◯ High
- ◯ Very High

Q3 Rate the brightness of the workers' vest relative to the work zone environment

- ◯ Very low
- ◯ Low
- ◯ Average
- ◯ High
- ◯ Very High

Q4 The color of the traffic cones/barriers made it difficult to distinguish the workers

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q5 I confused the colors on the trucks with the color of the workers' safety vest

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q6 The colors on the equipment made it difficult to spot the workers

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q7 I easily saw the workers while driving through the work zone

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q8 The work zone lighting did not help to see the workers

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q9 The lights on the cones/barriers were made it difficult to spot the workers

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q10 The clearance light on top of the trucks should be removed so the workers can be easily seen

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q11 The reflectors on the trucks make it difficult to distinguish the workers

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q12 The strobe lights on the trucks should be removed

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q13 The Halo Lights on the workers' hats are helpful to spot the workers

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree