Immersive Work Zone Inspection Training Using Virtual Reality

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16. Abstract
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Abstract

Can virtual reality tools be used to train engineers that inspect work zones? In this report, we share the findings of a research project that developed an interactive and immersive training platform using virtual reality to train state department of transportation (DOT) staff that inspect work zones for compliance. Virtual reality offers an immersive platform that closely replicates the actual experience of an inspector driving through a work zone, but in a safer, cheaper, and quicker way than field visits. The current training practice involves reviewing temporary traffic control procedures and reports and pictures from previous inspections. The developed platform consists of a learning module and an immersive module. The learning module is founded on the historical knowledge gained by DOT staff from inspections dating back at least five years. This knowledge incorporated representative inspection reports from prior years from all DOT districts including photographs of deficiencies. The synthesized knowledge was converted into a concise easy-to-consume format for training. The immersive module places the trainee in a vehicle moving through a work zone, thus providing a realistic experience to the engineer prior to inspecting a real work zone. The research team developed and tested two immersive scenarios of a freeway work zone. The training platform was tested by 34 individuals that worked for the Missouri Department of Transportation. An overwhelming majority (97%) agreed that virtual reality offered a realistic and effective way to train inspectors. One additional scenario of flagger operations in a two-way one lane work zone was also created for the purposes of training work zone inspectors. The scenario was developed in Unity using drive through video data, mapping software, and motion capture technology for replicating manual flagger movements. The use of flagger scenario in the immersive training module is particularly recommended for staff that inspect work zones in rural areas of the state where two-lane roadways are more prevalent.

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Chapter 1 Introduction

1.1 Overview

The Work Zone Safety and Mobility Rule (23 CFR § 630 Subpart J) established requirements and offers guidance to state transportation agencies for addressing the traffic safety and mobility impacts of work zones. As per § 630.1008(d), "Training. States shall require that personnel involved in the development, design, implementation, operation, inspection, and enforcement of work zone related transportation management and traffic control be trained … States shall require periodic training updates that reflect changing industry practices and State processes and procedures" (FHWA 2004). Work zone management has incorporated the use of new technologies. For example, the use of ITS technologies and application of simulation tools for impact analysis and scheduling has risen in the past decade. In contrast, work zone training has not taken advantage of new technologies that could improve training effectiveness, immersion, cost, availability, and flexibility.

Work zone inspection is an essential process for ensuring the safety of both workers and the traveling public. This annual exercise is demanding, as each work zone is inspected and rated based on several factors. Factors range from proper use of signage, channelizing devices, barriers, and lighting to signalization and traffic management. Any discrepancies from satisfactory performance are also recorded. A rating value is assigned for each factor based on discrepancies and deficiencies. The inspection team, typically consisting of 4 to 5 personnel, compiles the ratings for all work zones operational in the district, prepares a summary, and presents the findings to the district management. Staff on the inspection team are trained in several areas. They need to be familiar with the inspection worksheet and the different evaluation categories. They also need to be familiar with the Manual on Uniform Traffic Control Devices (MUTCD) typical applications (TAs) for different facilities and work activities. TAs provide the standard layout and specifications for the placement of signage and temporary traffic control devices. Finally, an understanding of the discrepancies and deficiencies of various work zone elements is necessary in order to satisfactorily rate them. The aforementioned knowledge attainment requires robust training of the personnel, which is difficult to accomplish without extensive field visits (i.e. prior experience). The current state of practice is to review the documents related to temporary traffic control and reports from previous inspections, typically power point files with pictures. It would be beneficial if a new mechanism for training could be developed that is as effective as field visits but without the amount of time and effort required to visit multiple field sites. Alternately, this new training method could complement existing training by requiring fewer site visits.

This project offers an alternative training platform using virtual reality (VR) and illustrates it using Missouri DOT data. The platform consists of two steps. The first step is a *learning* module which is founded on the historical knowledge gained by DOT staff from inspections dating back five years. This knowledge base synthesized representative inspection reports from prior years from all districts including photographs of deficiencies. The synthesized knowledge was converted into a concise, easy-to-consume format for training. The second step is an *immersive* module that places trainees in virtual work zones where their inspection performance will be observed and assessed (e.g., quiz on work zone deficiencies such as poor signage or misaligned cones). Two training scenarios of a freeway work zone were created using the Unity 3D engine and the Oculus Rift VR headset. Participants, wearing a VR headset, are placed in the passenger seat of a vehicle that drives through a work zone. As the subject travels past various signs and temporary traffic control devices, they note any issues. A focus group study of DOT engineers produced feedback on the utility and usability of the VR training module. Two questionnaire surveys were administered upon completion of the module. One additional scenario of flagger operations on a two-lane highway work zone was also developed for inclusion in the immersive module.

Chapter 2 Literature Review

In the United States, someone is injured in a work zone every 5.4 minutes. In 2015, 96,626 crashes occurred in work zones which resulted in 70,499 property damage, 25,485 injuries, and 642 fatalities, an increase of 7.8% from 2014 (FHWA 2015). Many factors contribute to crashes in a work zone. Speeding, inattention, and driving under the influence of alcohol are some examples of contributing factors. Transportation agencies have made numerous efforts to reduce the work zone injuries and fatalities by using several methods including improved work zone inspection practices and personnel training. Effective work zone inspection could improve safety for drivers and workers, reduce agency risk, and increase mobility (ATSSA 2013).

This chapter provides a state of the practice synthesis consisting of work zone inspection and training applications of virtual reality. The synthesis is divided into three sections. In Section 1, a review of the literature on current training practices in work zone inspection is presented. In Section 2, the work zone inspection process in Missouri is reviewed. In Section 3, virtual reality applications for training are reviewed.

2.1 State of Practice in Work Zone Inspection Training

Effective work zone inspection practices help improve the safety of workers and motorists. The Federal Highway Administration provides a procedure for work zone review to improve safety and mobility, comply with standards, and reduce agency risk (ATSSA 2013).

According to (FHWA 2017a), there are several agencies providing training for inspecting work zones including the National Highway Institute (NHI) and state DOTs. NHI provides training in the inspection of traffic control devices, traffic control zones, and flagger operation

(FHWA 2017b). State DOTs offer customized training for their staff. For example, Kansas DOT offers inspection training for both construction and maintenance personnel in temporary traffic control design, set-up, maintenance, management and evaluation of a work zone. Another example, in New Jersey, Rutgers Center for Advanced Infrastructure and Transportation offers training for inspecting sign retroreflectivity which should meet MUTCD requirements (FHWA 2017a).

The American Traffic Safety Services Association (ATSSA) offers training programs for traffic control supervisors and traffic control technicians (ATSSA 2013). In these training programs, they include reviewing standards and guidelines, traffic control devices, and human factors in order to make the temporary traffic control area safer for workers, motorists, and pedestrians. The current training practice uses pictures and slides for the inspection section.

2.2 Work Zone Process Review in Missouri

In Missouri, there are seven districts: Northwest, Northeast, Kansas City, Central, St. Louis, Southwest, and Southeast. Each year, inspection of work zones in two to three districts is conducted by a team of MoDOT and FHWA personnel, each over a one-week period. The inspection involves the team visiting each work zone in the district and rating the work zone based on established criteria. The inspectors rate a work zone on a scale of A to F, with A being the best to F being unacceptable (MoDOT 2013). Signing, channelizers, barricades, crash cushions, and pavement marking are examples of items that are inspected. Inspectors document any issues and concerns they observe during their inspection. For example, among the 32 work zones inspected in Kansas City during 2016, 17% had signs in unacceptable condition and 22% had issues with channelizers. (MoDOT 2016).

2.3 Virtual Reality Application for Training and Education

Virtual reality (VR) has been used for training in diverse disciplines such as education, medicine, media, and military. By immersing the learner into a 3D environment, virtual reality can provide a more realistic setting for learning and knowledge discovery. Winn (1993) discussed the value of using virtual reality for education and mentioned several reasons for its use. These reasons, including the knowledge and experience gained from using virtual reality, are different from those gained using traditional methods of education. VR offers an attractive learning environment for students and motivates them.

Use of VR for training has been documented in a few previous studies. McComas et al. (2002) explored using virtual reality to train children to safely cross an intersection. The authors wanted to determine how useful is a virtual reality to train pedestrian safety skills for crossing intersections and whether the skill is transferred back to the real world. They tested desktop virtual reality applications with students at two schools – one urban and one suburban. The students were trained on staying on the sidewalk, stopping at the curb, looking L-R-L (left, right, and left) and remaining attentive while crossing the road. Analysis of variance (ANOVA) was conducted to compare scores of the real-world behavior pre and post training in order to determine whether the training by virtual reality transferred to real world or not. The researchers concluded from the virtual reality intervention that students from the suburban school displayed a significant improvement ($F (1181) = 4.22$, $p < 0.05$) after training and successfully transferred their skill to actual intersections. The intervention was not found to improve the performance of students from the urban school.

Virtual reality training applications were also used in the field of education. Koskela et al. (2005) conducted a study to determine how virtual learning is appropriate in an occupational safety engineering course and compared it with a conventional lecture. Fifty-four students participated in a virtual learning session, and forty-nine students participated in a conventional lecture. The results revealed that 20 students with virtual learning session were able to receive 14 points whereas only 5 students with conventional lecture were able to receive 14 points, which showed that virtual learning outperformed the traditional lecture. The students with virtual learning required less time to study the subject than other students trained using the traditional lecture. Also, Shirazi and Behzadan (2013) established a mobile augmented reality visualization in the field of construction and civil engineering for students and instructors. The researchers created a tool using which the students could scan graphs and images from a book and convert them into various forms of virtual material; - 2D, 3D, video, and audio. The students were asked to fill out a survey to rate the learning experience by augmented reality and how likely they recommend using this technology for other courses. The survey was measured by a five-point Likert scale ranging from 1 (lowest) to 5 (highest). The results revealed that the mean value for the learning experience and using this technology for other courses was 4.00 and 3.88 respectively, which indicated high satisfaction rate and excitement about using augmented reality. Most of the students found augmented reality served as a useful tool for enhancing student knowledge.

In the mining field, conveyor belt safety is important, and improper use could lead to severe injury or death. Lucas and Thabet (2008) conducted a study on using virtual reality to train new miners on the safe use of a conveyor belt. The conventional practice is for a miner to undergo a total of 24 hours of training. The Mine Safety and Health Administration (MSHA) requires 4 hours training before hire and the remaining 20 hours need to be completed within the first 60 days of employment. Training includes slides, videos, and handouts. The researchers developed a VR-based training module. The training environment allows trainees to safely interact with the 3D prototype. Eight individuals, two experts and six novices, participated in the subjective survey for measuring usefulness of the study. The novice participants were involved in the conventional training and the proposed VR-based training module. The expert participants were involved in the proposed VR-based module, and they were familiar with conventional training method. Then, the participants were asked to complete a subjective survey in order to gather information about their preferences, advantages, and shortcomings of both training modules. Five of the participants preferred virtual reality because of its safe interactive experience. While the other three participants preferred the conventional training method, although they agreed that virtual reality is an effective method for training the current generation of miners who are more computer literate.

In another study, Hui (2017) developed a training module by virtual reality for drilling underground mines. The author evaluated two virtual reality training systems – one based on a head mounted display (HMD) and the other using a screen projection. The participants in the training system by HMD could experience the first person view which is considered fully immersive. The participants in the training system by screen projection used a joystick to drill in the scenario; the person operator is shown on the screen which is considered as less immersive. The two systems were evaluated by questionnaires in order to determine the level of immersion, intuitiveness, interactivity, ease of use, and ease of learning by a study group of ten participants. Virtual reality training by HMD had a higher score (4.8 out of 5) according to the immersion level than the screen-based. The HMD system scored 1.5 to 2 times higher than screen-based for the intuitiveness, interactivity, and ease of use. The results showed that both systems were easy to learn. Also, the results showed that 90% of the trainees preferred training with HMD because it provided a better overall experience and was easy to use.

Virtual reality has also been used for training in the medical field. Ahlberg et al. (2007) explored training by virtual reality for residents, and their performance on the first 10 entire cholecystectomies surgeries was measured to realize the effect of virtual reality training before performing actual surgery on patients. Thirteen inexperienced residents were involved in this study to measure their performance. In addition, five experts in laparoscopy were tested on the virtual module in order to determine the baseline. Each trainee was assigned to the training and practiced under supervision, receiving feedback from the designed VR module in order to reach the proficiency level. The performance of each participant was assessed on surgery number 1, 5, and 10. The results revealed that virtual reality training led to significantly fewer errors (P= 0.0037) made by residents.

Yang et al. (2008) conducted a study using training by virtual reality to improve ambulation for people with stroke. They divided 20 participants into two groups. Nine participants were in the control group who received nine sessions of treadmill training. The participants were asked to do several tasks such as lifting legs, walking fast, and uphill and downhill walking. In addition, eleven participants were in the experimental group who received nine sessions of virtual reality-based treadmill training. Both groups were trained by three sessions a week over three weeks which each session lasted for 20 minutes. The participants in VR tried different levels such as walking fast, uphill and downhill walking, and decision-making to avert collisions. The designed virtual environment consisted of street crossing, lane walking, park strolling, and obstacles striding across. The participants in this study were evaluated before training, at the end of training sessions, and one month after training on walking speed, community walking time, and a walking ability questionnaire (WAQ). For instance, the mean and standard deviation before and after training by virtual reality for walking speed (m/s) were (0.69 ± 0.30) and (0.85 ± 0.31) respectively, which shows the participants walk speed improved after the training. The results showed that the participants who trained by virtual reality had a significant improvement also in community walking time and WAQ, whereas the first group only showed improvement in walking time and WAQ.

Johnsen et al. (2005) explored immersive virtual reality to train medical students on communication skills. The participants found the interaction experience by immersive virtual reality between patient and medical doctor is a powerful tool for training and teaching. Seven students were involved in this study in which four students were in the third year and three students were in the fourth year as physician assistants. The participants were tested on correct greeting, acute abdominal pain diagnosis, and differential diagnosis. The results showed that four participants passed the test. All the participants expressed that they would like to use the designed system frequently for training. The World Health Organization (WHO) introduced the surgical safety checklist in order to reduce the risk of surgical crisis. Ferracani et al. (2014) developed a scenario using virtual reality to train the medical staff on the surgical safety checklist in which the trainees can interact using voiced input and hand gestures. Finally, Stevens et al. (2005) developed a module by virtual reality to train medical students to diagnose and treat a patient with head injury. The researcher conducted a survey in order to determine the ease of identifying objects in virtual reality (10 questions) and using tools (18 questions). The mean rating for identifying objects and tool usage was (3.49/4) and (2.79/4), respectively. A paired t-test was performed and resulted in ($t = 4.58$, $p = 0.0002$). The result revealed that identifying objects is easier than using tools in virtual reality. In conclusion, studies found that after training by virtual reality student knowledge became similar to an expert's knowledge.

Some researchers studied the use of virtual reality in training firefighters. Tate et al. (1997) developed a training module by using virtual reality for shipboard firefighters in order to enhance their experience and to be familiar with the ship parts and compare it with the traditional method. The participants in the study were divided into two groups. The first group trained by traditional method, and the second group trained by virtual reality. For the navigating shipboard test, the second group averaged 30 seconds which was more than two minutes faster than the first group. The result revealed that virtual reality training improved firefighter skills and their performance translated well into the real world. Virtual reality has been used for a firefighter to navigate around a virtual world and view a house on fire (St. Julien and Shaw 2003). Smith and Ericson (2009) explored immersive virtual reality to train children to understand fire dangers and escape procedures. The mean of pre-test and post-test scores for participants in the experimental group was 11.33 and 13.33 respectively. There was no significant difference in knowledge gained, but the children found training by virtual reality more enjoyable than the traditional way. A few other areas reported sparse use of virtual reality for training. These include teaching about earthquake safety, welding procedures, training substation electricians, and teaching dance lessons. First, Li et al. (2017) developed a virtual module to train people on how to survive from earthquakes in an indoor environment. 96 participants were involved in this study including undergraduate and graduate students from different majors. The participants were divided into four groups and each group had different training conditions. The training conditions were by virtual reality, video, manual, and no training. After the training, participants were tested using virtual reality immediately and one week after training on three different scenes (living room, dining room, and office). The smaller physical damage value represents a better performance. The results of the evaluation, one week after the training showed that the participants who trained by virtual reality had the lower mean physical damage score (living room = 51, dining room =45, and office = 20). The authors concluded that the virtual training module was effective in training people about successful practices related to earthquake safety. Xie et al. (2015) established real-time welding training by virtual reality. After a series of experiments using single camera vision to track the position of the welding and helmet, they found that the error of tracking was < 1.5mm which meets the requirement of the welding training system. The designed module also provides an interactive, realistic, and immersive experience for trainees.

Third, Tanaka et al. (2017) developed a virtual substation to train electricians for operating equipment and for emergency cases. The main advantage of the designed module is providing a realistic experience in a safe environment. Seventy participants were involved to test the designed module. Most of instructors and electricians found it easy to check for the equipment whereas some participants faced difficulty dealing with a motion controller and required assistance. The trainees and instructors found this module to be a useful tool for training.

Finally, Chan et al. (2011) established a new dance training based on virtual reality and motion capture. To assess the new system, participants dance skills were tested before and after the training in order to determine whether it improved or not. The mean score before the training was 40.58, and the mean scores after training was 51.41 with the p-value of 0.000012. The results revealed that the training helped improve student skills in dancing.

In summary, virtual reality has been applied in several disciplines for training. A majority of the studies reported improvement in performance due to the use of virtual reality for training personnel. There are no studies documenting the experiences, advantages, and limitations of using virtual reality to train work zone inspectors.

Chapter 3 Methodology

This chapter is divided into two sections. In Section 1, the learning module was developed as a set of slides to be consistent with current training practice at MoDOT. In Section 2, two scenarios of a virtual work zone with a lane closure were developed for inspection training to provide a 3D immersive environment for the trainees.

3.1 Learning Module Development

There are multiple elements that need to be inspected in order to ensure safety and mobility in a work zone. To be consistent with current training practice at MoDOT, the learning module was developed as a set of PowerPoint slides. Historical data in the form of previous inspection documents, i.e., photographs and videos from MoDOT staff were synthesized. The learning module also synthesized the guidance on typical applications, traffic control devices, and positive protection from the MoDOT Engineering Policy Guide (EPG) and the Manual on Uniform Traffic Control Devices (MUTCD). In addition, historical reports were reviewed to synthesize commonly observed issues in work zones. The knowledge generated is useful to train future inspection personnel. After a trainee reviews the learning module, their learning is assessed using a quiz.

The learning module was developed to train an inspector on various elements of the work zone consisting of a lane closure scenario as shown in Figure 3.1. A work zone with lane closure consists of four different areas: advance warning, transition, activity, and termination area. Each area of the work zone will be discussed in detail in the following sections.

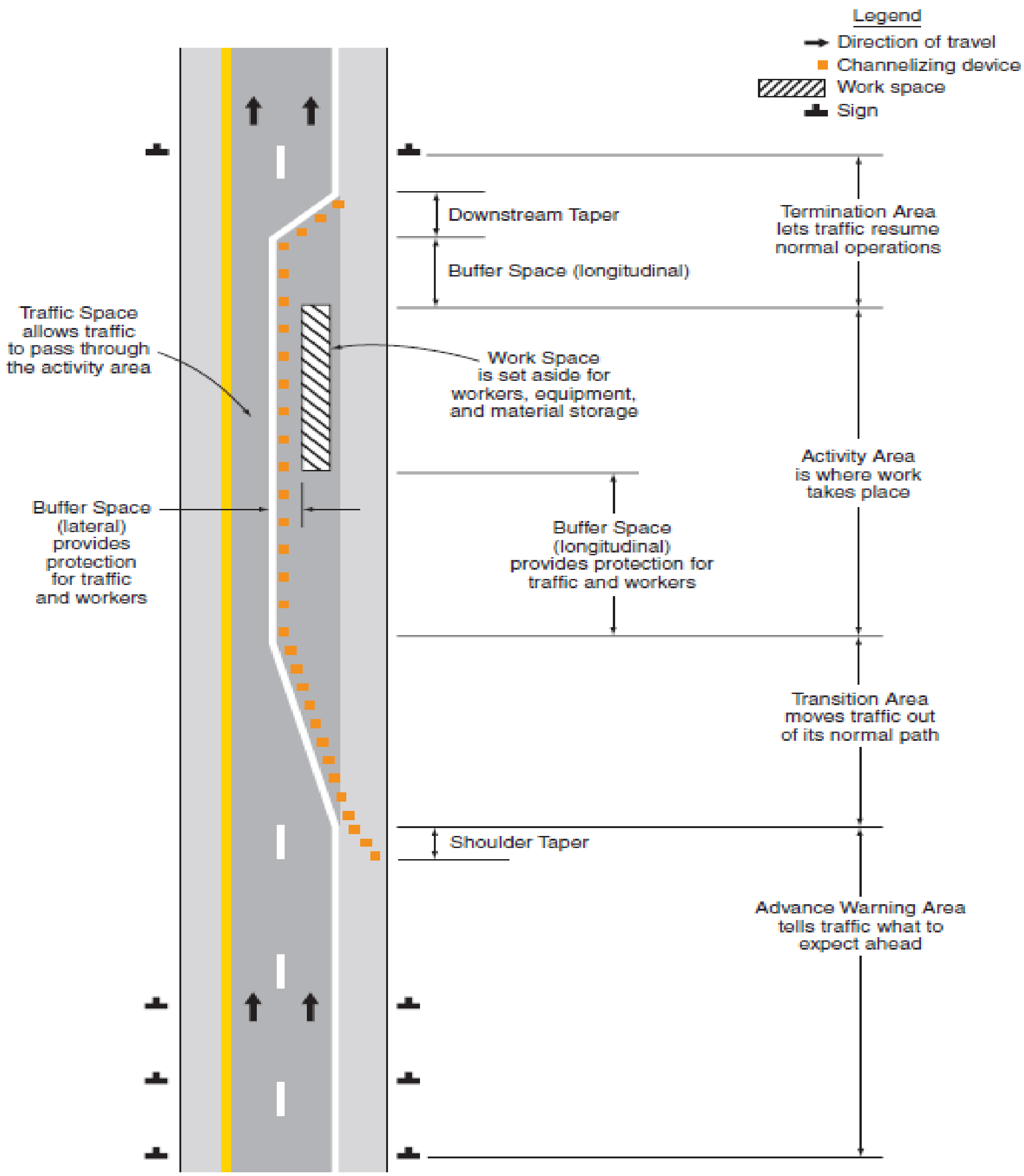


Figure 3.1 Component parts of work zone (MUTCD Fig.6C-1)

3.1.1 Advance Warning Area

The advance warning area is the first part of the temporary traffic control zone. It is used to inform drivers about the presence of a work zone. In the advance warning area, there are a series of signs which provide different information to the motorists. The first warning sign is for attention as shown in Figure 3.2.

Figure 3.2 ROAD WORK AHEAD sign (Attention)

The second sign is a right (or left) lane closed ahead that provides detailed information as shown in Figure 3.3.

Figure 3.3 RIGHT LANE CLOSED AHEAD sign (Detailed information)

The right lane closed and merge signs are the third signs in the advance warning area that provide specific lane closure information for the motorists as shown in Figure 3.4.

(a) (b)

Figure 3.4 (a) RIGHT LANE CLOSED, (b) MERGE signs (Specific information)

Figure 3.5 shows the layout of the aforementioned advance warning signs. In addition, the advance warning rail system (AWRS) and flags are required on the first advance warning sign, i.e. the road work ahead sign.

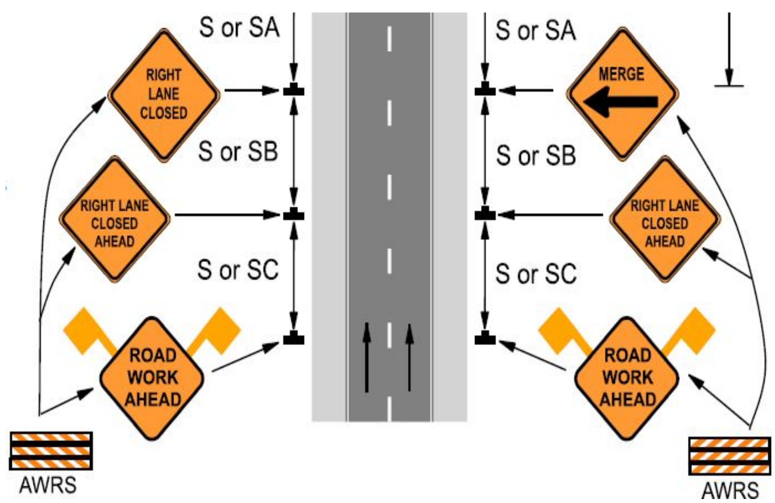


Figure 3.5 Advance warning signs layout (MoDOT EPG 616.8.33-MT)

The spacing between signs depends on the permanent (non-work zone) posted speed limit and the type of highway. For example, Table 3-1 shows the recommended spacing between advance warning signs with a lane closure on a divided highway, as shown as SA, SB, and SC in Figure 3.5.

Table 3-1 Recommended spacing with lane closure on divided highway (MoDOT EPG 616.8.33-MT)

Speed	Sign Spacing(ft.)		
Permanent Posted (mph)	**S or SA**	**S or SB**	**S or SC**
0-35	200	200	200
40-45	500	500	500
50-55	1000	1000	1000
60-70	1000	1500	2640

3.1.2 Transition Area

The transition area is the second part of the temporary traffic control zone. The role of the transition area is to direct the traffic movement from the normal path to the new path as shown in Figure 3.6. The transition area is a high crash risk location. For instance, in North Dakota about 40% of work zone crashes occurred in the transition area (NDSC 2012). There are several types of taper including merging, shifting, shoulder, one-lane of two-way traffic, and downstream taper. For lane closures, the merging taper is used in the transition area.

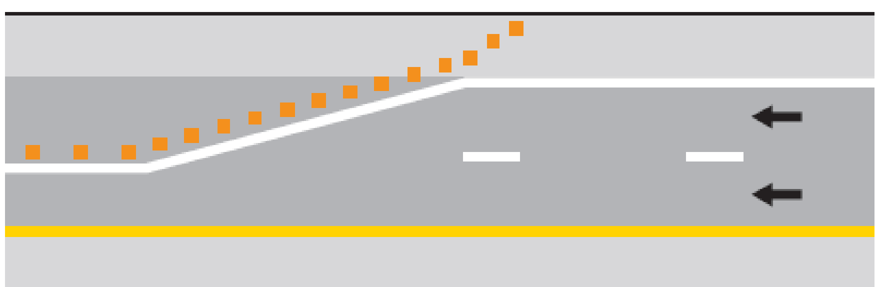


Figure 3.6 Transition area (MUTCD)

The merging taper closes one lane of a multilane roadway and merges traffic into the other lane. The length of the merging taper should be enough for drivers to move safely to the open lane. The taper is created by using a series of channelizing devices. The taper layout and recommended length are shown in Figure 3.7. The distances T1 and T2 shown in Figure 3.7

depend on the posted permanent speed limit and are provided in Table 3-2. The arrow panel is located on the shoulder at the beginning of merging lane taper.

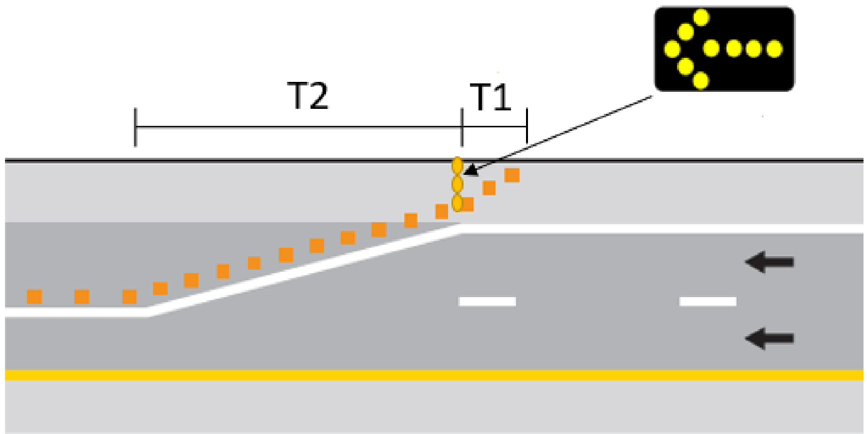


Figure 3.7 Shoulder and lane taper layout, and arrow panel (MUTCD)

Table 3-2 Recommended merging taper length for shoulder and lane (MoDOT EPG 616.8.33-MT)

Speed	**Taper Length (ft.)**	
Permanent Posted (mph)	**Shoulder * (T1)**	**Lane ** (T2)**
0-35	70	245
40-45	150	540
50-55	185	660
60-70	235	840

* Shoulder taper length based on 10 ft. offset. ** Lane taper length based on 12 ft. offset (standard width)

Currently, MoDOT uses two types of channelizing devices in the merging taper, trim-line and direction indicator barricades (DIBs) as shown in Figure 3.8. The recommended channelizer spacing for merging taper depends on the permanent posted speed limit as shown in Table 3-3.

(a) (b)

Figure 3.8 Example of channelizing devices. (a) Trim-line, (b) DIBs (MoDOT)

Table 3-3 Recommended spacing for channelizer device in merging taper (MoDOT EPG 616.8.33-MT)

Speed	**Channelizer Spacing (ft.)**
Permanent Posted (mph)	**Taper**
0-35	35
40-45	40
50-55	50
60-70	60

3.1.3 Activity Area

The activity area is the third part of the temporary traffic control zone. The activity area is where the work takes place. Activity area is further divided into three spaces – buffer space, protective vehicle roll ahead space, and work space as shown in Figure 3.9.

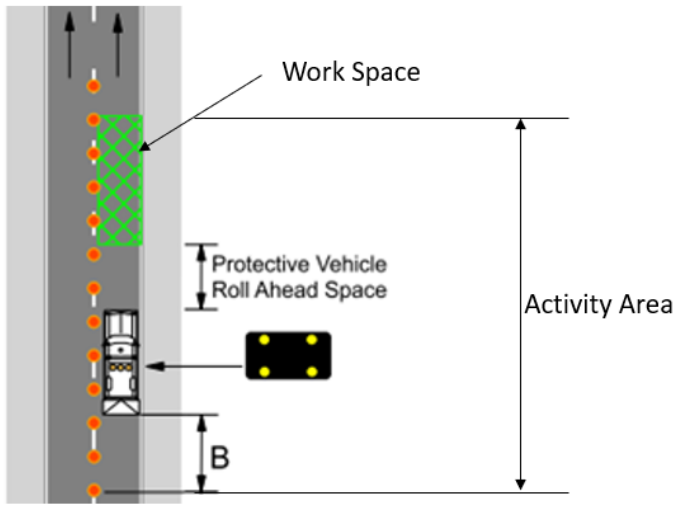


Figure 3.9 Activity area layout (MoDOT EPG 616.8.33-MT)

3.1.3.1 Buffer Space

The buffer space is unoccupied and serves to protect workers from traffic. Also, it is a recovery area for out-of-control vehicles. There are two buffer spaces in an activity area - longitudinal and lateral buffer space. The length of the longitudinal buffer space at the beginning of the activity area depends on the permanent posted speed limit. The recommended longitudinal buffer length is shown in Table 3-4. The lateral buffer space is provided based on engineering judgment.

Table 3-4 Recommended longitudinal upstream buffer space (MoDOT EPG 616.8.33-MT)

Speed	**Optional**
Permanent Posted (mph)	**Buffer length (ft.) (B)**
0-35	280
40-45	400
50-55	560
60-70	840

The trim-line are used as channelizing devices in the activity area. The channelizer spacing, according to the permanent posted speed limit, is shown in Table 3-5.

Table 3-5 Recommended channelizer spacing for buffer/work area (MoDOT EPG 616.8.33-MT)

Speed	**Channelizer Spacing (ft.)**
Permanent Posted (mph)	**Buffer/ Work Area**
0-35	40
40-45	80
50-55	80
60-70	120

3.1.3.2 Work Space

The work space is where the actual work activity takes place in the work zone. This area could be occupied by workers, equipment, and construction materials. The work space is delineated by channelizing devices such as a trim-line. Temporary traffic barriers could be used in the work zone to prevent an errant vehicle from entering the work area. Example of temporary traffic barriers is shown in Figure 3.10 (below). The crash cushion could be used at the upstream end of the barrier to absorb the energy for impacting vehicle and reduce the force on occupants.

Figure 3.10 Example of temporary traffic barriers (MoDOT)

Truck-mounted attenuators (TMAs) are placed upstream of the work space as shown in Figure 3.11. The role of a TMA is to shield workers and absorb the impact of an errant vehicle crashing into it.

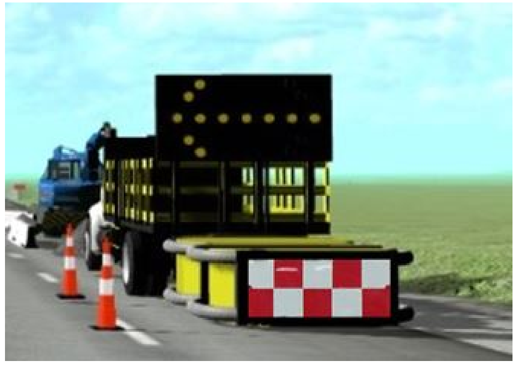


Figure 3.11 Truck-mounted attenuators

3.1.4 Termination Area

The termination area is the last part of the temporary traffic control zone. It is used to return traffic into the normal traffic lane. The end road work sign is used to inform motorists of the end of the work zone as shown in Figure 3.12.

Figure 3.12 End road work sign

The termination area is divided into two components as shown in Figure 3.13, which are longitudinal buffer space and downstream taper. The minimum downstream taper length is 50 ft while the maximum length is 100 ft (FHWA 2009).

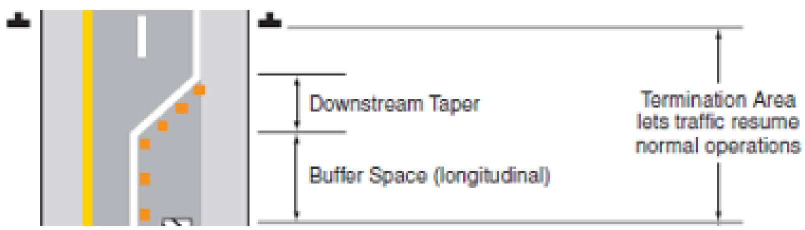


Figure 3.13 Termination area

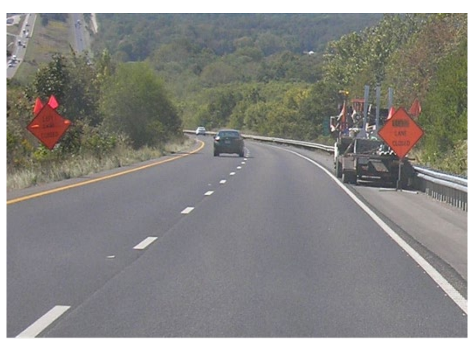
3.1.5 Examples of Poor and Good Control Devices

The last part of the training module was to develop some examples of good and poor signage and temporary traffic control devices in the work zone. Documentation from previous MoDOT work zone inspections was reviewed. Specifically, photographs of deficiencies in a work zone were extracted. These photographs would help a new trainee become familiar with potential deficiencies in a work zone. The following pictures, Figure 3.14 (below), provide several examples of deficiencies in signage, arrow panel, channelizing device, and TMA. The deficiency observed in each picture is also labeled.

Damage (North Dakota)

Duct tape (North Dakota)

Sign obstructed by tree (MoDOT)



Damage and duct tape (MoDOT)

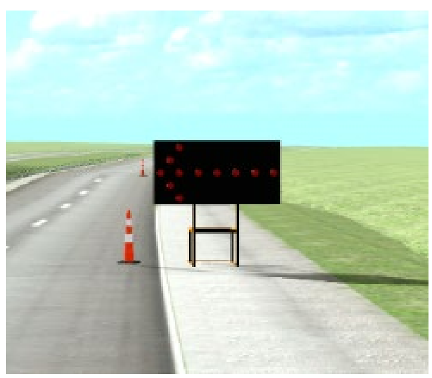
Damage and placed incorrectly (MoDOT)

Duct tape (MoDOT)

Damage (MoDOT)

Damage and placed incorrectly (NDSC)

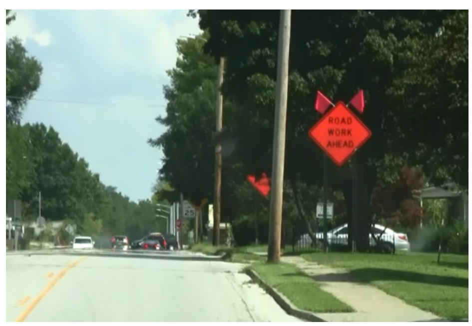
Damaged slow paddle sign (MoDOT)



Red arrow panel (virtual reality)

Lamp out (TTCD)

TMA hidden by concrete barriers (virtual reality)



Second sign hidden behind a tree (MoDOT)

Signs obstructed by tree and other sign (MoDOT)

Improper setup (North Dakota)

Upside down sign (MoDOT)

Sign obstructed by fence (North Dakota)

Decimal number

Sign shape (North Dakota)

Arrow panel obstructed by truck (North Dakota)

Damaged trim-line (MoDOT)

Damage (North Dakota)

Dirt on devices (North Dakota)

Damage (MoDOT)

Damage (MoDOT)

Figure 3.14 Examples of deficient conditions in a work zone

Inspection staff needs to be familiar with the appearance of good signage without any deficiencies. Thus, the training module also provides some examples of optimal signage. The following pictures, Figure 3.15, show several examples of good conditions for signs, arrow panels, channelizing devices, and TMA s.

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT EPG)

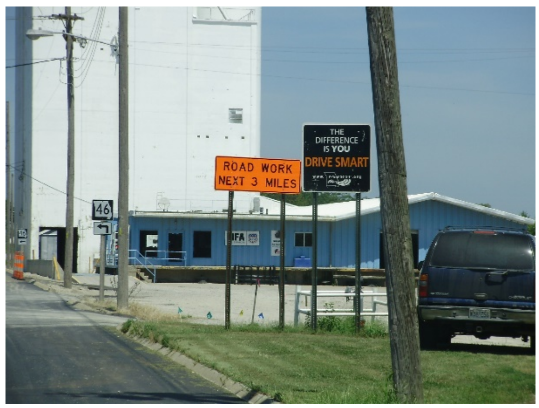
(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)



(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(MoDOT)

(VR re-creation at highway speed)

(VR re-creation at highway speed)

Figure 3.15 Examples of good signage in work zones

3.1.6 Design of Learning Assessment Quiz

After a trainee reviews the learning module, their learning is assessed using a quiz. The quiz includes questions from the MoDOT inspection worksheet (described below); the trainee rates the quality of temporary traffic control and signage. The quiz is administered online with real-time feedback. Qualtrics survey and polling system was used. MoDOT's Temporary Traffic Control Inspection Worksheet uses a rating system to assess the quality of various components of a work zone. The rating system is discussed here, and the entire worksheet is provided in Appendix B.

The three categories of severity (Standard Section 616 of MoDOT EPG) are defined as:

Category 1- Presents an immediate safety issue for the traveling public or workers and needs to be addressed immediately

Category 2- The situation does not pose an immediate safety issue for either the public or the workers, but can impact the proper functioning of the work zone

Category 3- The situation does not impact the functioning of the work zone but is more of a maintenance or aesthetic issue

The five quality ratings are:

A- Above and beyond the standards and specifications of the project

B- Meeting the standards and specifications of the project

C- A couple of deficiencies meeting Category 3

D- Several deficiencies meeting Category 3 or a few deficiencies meeting Category 2

F- Several deficiencies meeting Category 2 severity level or one or more deficiencies meeting Category 1

For the learning assessment quiz, each question was designed to have the same MoDOT five-level rating system. After the trainee answers a question, they are provided with instant feedback indicating if their answer is correct or incorrect. If incorrect, then the correct rating that an expert inspector would have chosen is provided. Thus, the learning quiz serves as both assessment and training. Thirteen questions are included in the quiz and are provided next. While the EPG's description of categories was included with each question, they are not shown here to avoid repetition.

1- How would you rate this sign?

[ ] **A-** Above and beyond the standards and specifications of the project.

[ ] **B-** Meeting the standards and specifications of the project.

[ ] **C-** A couple of deficiencies meeting the Category 3 severity.

[ ] **D-** Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

*If any participant selects an incorrect answer such as B, C, D, or F, they will get the instant feedback that shows the recommended rating is **A-** Above and beyond the standards and specifications of the project.*

2- How would you rate this sign?

[ ] A- Above and beyond the standards and specifications of the project.

[ ] B- Meeting the standards and specifications of the project.

[ ] C- A couple of deficiencies meeting the Category 3 severity.

[ ] D- Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] F- Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

*If any participant selects an incorrect answer such as A, B, C, or F, they will get the message that shows the recommended rating is **D-** Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity. The participant will also be shown an example of accurate sign placement as shown below.*

3- How would you rate this sign?

[ ] **A-** Above and beyond the standards and specifications of the project.

[ ] **B-** Meeting the standards and specifications of the project.

[ ] **C-** A couple of deficiencies meeting the Category 3 severity.

[ ] **D-** Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

If any participant selects an incorrect answer such as A, B, C, or D, they will get the message that shows the recommended rating is ***F-*** *Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity. The participant will also be shown an example of better sign condition as shown below.*

4- How would you rate this sign?

[ ] **A-** Above and beyond the standards and specifications of the project.

[ ] **B-** Meeting the standards and specifications of the project.

[ ] **C-** A couple of deficiencies meeting the Category 3 severity.

[ ] **D-** Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

*If any participant selects an incorrect answer such as A, B, C, or D, they will get the message that shows the recommended rating is **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity. The participant will also be shown an example of better sign condition as shown below.*

5- How would you rate this sign?

[ ] A- Above and beyond the standards and specifications of the project.

[ ] B- Meeting the standards and specifications of the project.

[ ] C- A couple of deficiencies meeting the Category 3 severity.

[ ] D- Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] F- Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

If any participant selects an incorrect answer such as A, B, C, or D, they will get the message that shows the recommended rating is ***F-*** *Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity. The participant will be shown an example of better sign condition as shown below.*

6- How would you rate this sign?

[ ] **A-** Above and beyond the standards and specifications of the project.

[ ] **B-** Meeting the standards and specifications of the project.

[ ] **C-** A couple of deficiencies meeting the Category 3 severity.

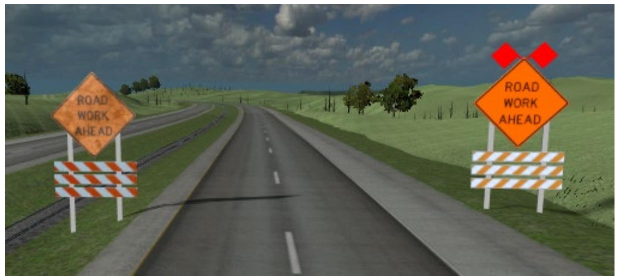
[ ] **D-** Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

[ ] F- Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

If any participant selects an incorrect answer such as A, B, C, or D, they will get the message that shows the recommended rating is ***F-*** *Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity. An example of a better sign condition is shown below.*

7- How would you rate this sign?



[ ] **A-** Above and beyond the standards and specifications of the project.

[ ] **B-** Meeting the standards and specifications of the project.

[ ] **C-** A couple of deficiencies meeting the Category 3 severity.

[ ] **D-** Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

*If any participant selects an incorrect answer such as A, B, C, or F, they will get the message that shows the recommended rating is **D-** Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity. The participant will also be shown an example of better sign condition as shown below.*

8- How would you rate this paddle used for flagging operations?

[ ] **A-** Above and beyond the standards and specifications of the project.

[ ] **B-** Meeting the standards and specifications of the project.

[ ] **C-** A couple of deficiencies meeting the Category 3 severity.

[ ] **D-** Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

*If any participant selects incorrect answer such as A, B, C, or D, they will get the message that shows the recommended rating is **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity. The participant will also be shown an example of better slow paddle sign condition as shown below.*

9- How would you rate this arrow board?

[ ] **A-** Above and beyond the standards and specifications of the project.

[ ] **B-** Meeting the standards and specifications of the project.

[ ] **C-** A couple of deficiencies meeting the Category 3 severity.

[ ] **D-** Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

*If any participant selects an incorrect answer such as A, B, C, or D, they will get the message that shows the recommended rating is **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity. The participant will also be shown an example of better arrow board condition as shown below.*

10- How would you rate this setup?

[ ] **A-** Above and beyond the standards and specifications of the project.

[ ] **B-** Meeting the standards and specifications of the project.

[ ] **C-** A couple of deficiencies meeting the Category 3 severity.

[ ] **D-** Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

*If any participant selects an incorrect answer such as B, C, D, or F they will get the message that shows the recommended rating is **A-** Above and beyond the standards and specifications of the project.*

11- How would you rate this setup?

[ ] A- Above and beyond the standards and specifications of the project.

[ ] B- Meeting the standards and specifications of the project.

[ ] C- A couple of deficiencies meeting the Category 3 severity.

[ ] D- Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] F- Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

If any participant selects an incorrect answer such as A, B, C, or F, they will get the message that shows the recommended rating is ***D-*** *Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity. The participant will also be shown an example of better setup condition as shown below.*

12- How would you rate this trim-line channelizer?

[ ] **A-** Above and beyond the standards and specifications of the project.

[ ] **B-** Meeting the standards and specifications of the project.

[ ] **C-** A couple of deficiencies meeting the Category 3 severity.

[ ] **D-** Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] **F-** Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

If any participant selects an incorrect answer such as A, B, C, or D, they will get the message that shows the recommended rating is ***F-*** *Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity. The participant will also be shown an example of better trim-line channelizer use as shown below.*

13- How would you rate this crash cushion?

[ ] A- Above and beyond the standards and specifications of the project.

[ ] B- Meeting the standards and specifications of the project.

[ ] C- A couple of deficiencies meeting the Category 3 severity.

[ ] D- Several deficiencies meeting the Category 3 severity or a couple of deficiencies meeting the Category 2 severity.

[ ] F- Several deficiencies meeting the Category 2 severity or one or more deficiencies meeting the Category 1 severity.

If any participant selects an incorrect answer such as A, C, D, or F, they will get the message that shows the recommended rating is ***B-*** *Meeting the standards and specifications of the project.*

3.2 Immersive Virtual Reality

The immersive virtual reality module for work zone consists of three steps. The first step involves the design of roadway geometrics and traffic control using a 3D modeling program (e.g. SketchUp). An I-70 road segment aerial photograph from Google with contour line information is imported into SketchUp. The SketchUp program allows for the capture of the terrain of the selected segment. The roadway section is coded in SketchUp by adding the materials (pavement textures) and striping. A screenshot of a roadway section coded in SketchUp is shown in Figure 3.16 (below).

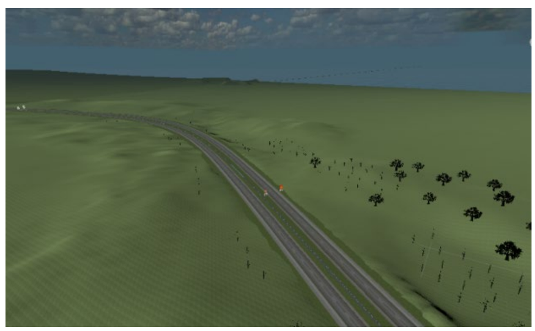
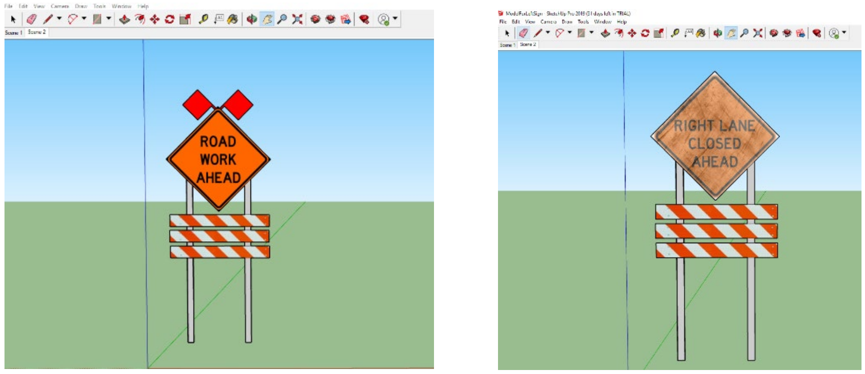


Figure 3.16 Section of roadway geometrics coded in SketchUp

In addition, temporary traffic control devices are created in Sketchup as 3D objects such as signs, channelizers, and arrow boards. Each object consists of different components. For example, the "ROAD WORK AHEAD " sign has three different components which are signage, flags, and advance warning rail system (AWRS). Screenshots of the temporary traffic control devices coded in SketchUp are shown in Figure 3.17. In order to present objects realistically in the virtual environment, objects are scaled according to the MUTCD. Finally, the designed roadway and temporary traffic control devices are exported into Filmbox (.fbx) using the default setting to prepare it for next step.



(a) (b)

Figure 3.17 Examples of temporary traffic control devices coded in SketchUp (a) Good signage and (b) Poor signage.

The second step involves the use of a simulation engine and C# programming language to simulate the movement of a vehicle in a virtual work zone environment. The simulation software used is the Unity engine. The Unity engine allows virtual reality and interactive experiences to be created in both 2D and 3D, and the engine offers C# to move or program any object. The roadway geometrics and temporary traffic control devices (signage, channelizers, etc) created in the previous step are imported into the simulation environment. A screenshot in the Unity simulation engine is shown in Figure 3.18. The C# code is being used to move the car at a constant pace in the designed scenario with predefined waypoints (car locations). The car is programmed to move without a driver. The screenshot of the C# code snippet is shown in Figure 3.19. The snippet shows the many variables used, including ones defining the physical car tires, and how the car dynamics behave during the simulation. The Unity engine provides a terrain editor which is used to simulate the real terrain in order to match it with the recorded video of the I-70 road segment.

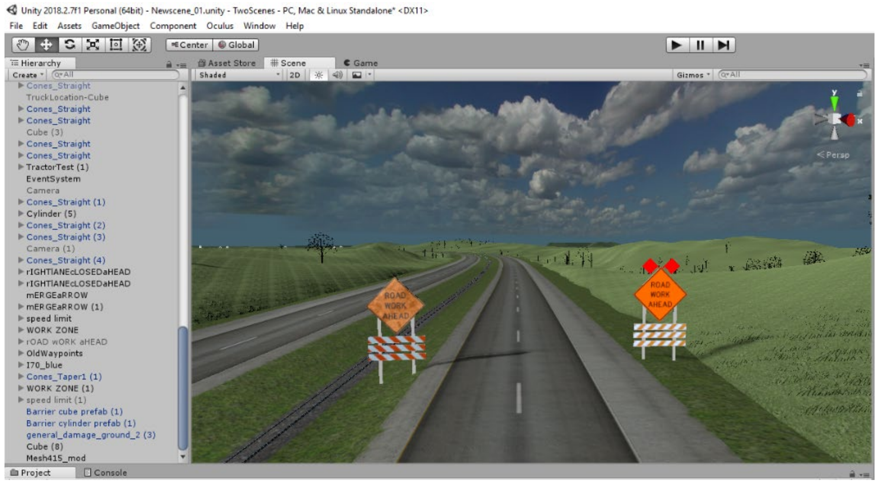


Figure 3.18 Screenshot of the 3D environment in Unity

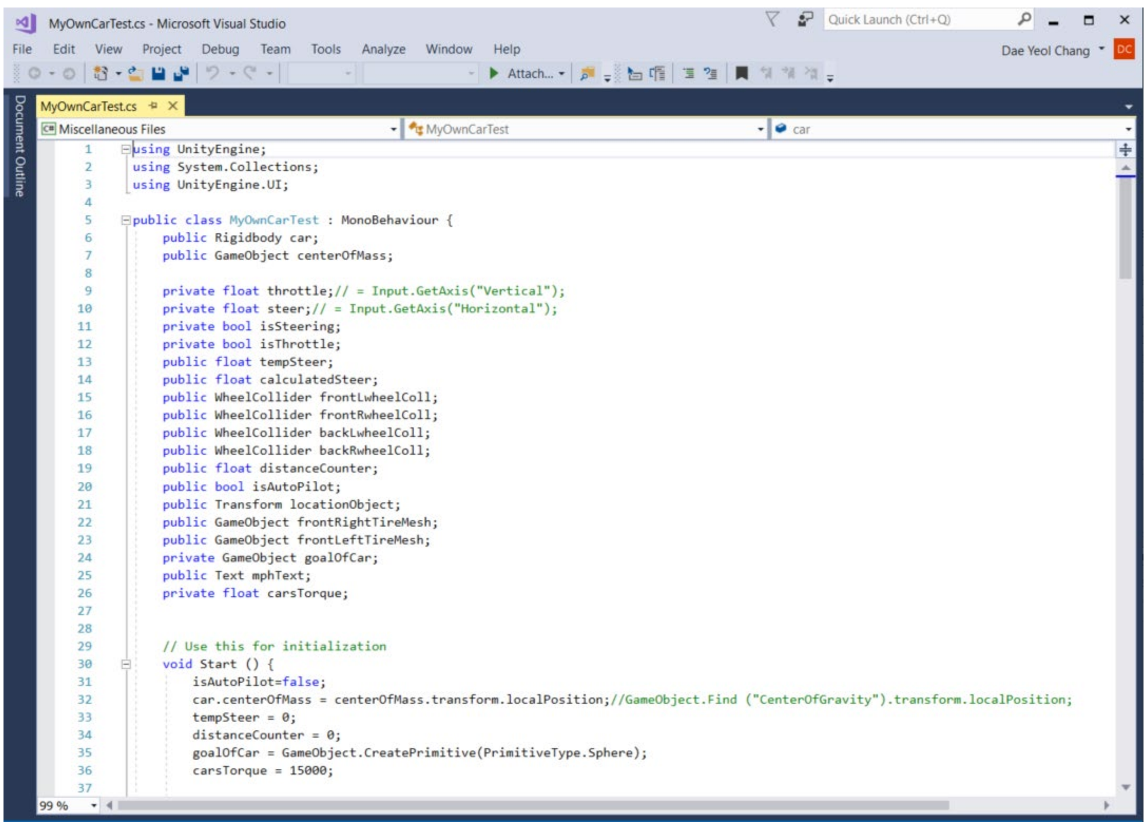


Figure 3.19 Screenshot of the C# script for car movement in Unity

The third step of the immersive module is to port the simulation scenario into a head mounted device (HMD) or VR headset. HMD will provide the visual and immersive experience in the virtual work zone. The HMD software development kit (SDK) settings, using the in-scene setting of Unity software, supports HMD for visualizing the designed scenario in a 3D environment as shown in Figure 3.20.

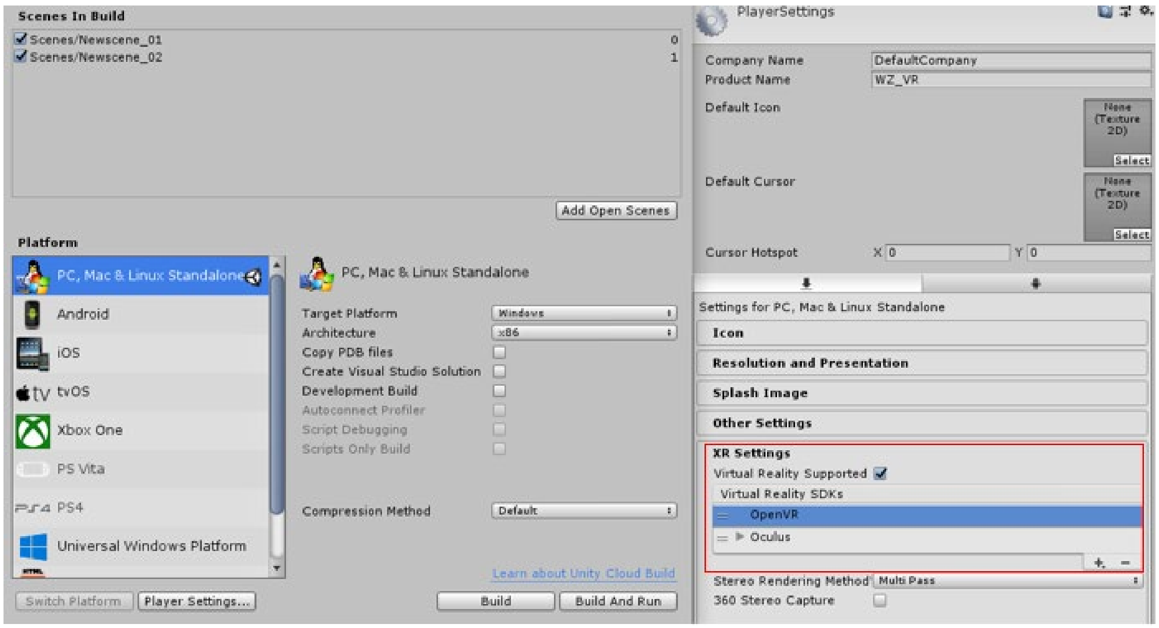


Figure 3.20 Screenshot of the setting scene in Unity

Several HMDs are commercially available such as Oculus Rift, HTC Vive, and Google Cardboard. In this study, the Oculus Rift VR headset was used to immerse participants in the virtual work zone scenario as shown in Figure 3.21. Two simulation scenarios of a virtual work zone were developed. Both work zones consisted of closing one of the two lanes on a freeway in one direction. The first scenario serves as practice and the second scenario is used to test trainee performance. Both scenarios include a mix of good and poor signage. MoDOT’s EPG guidance on temporary traffic control was used for specifying the correct spacing between signage, channelizers, etc.

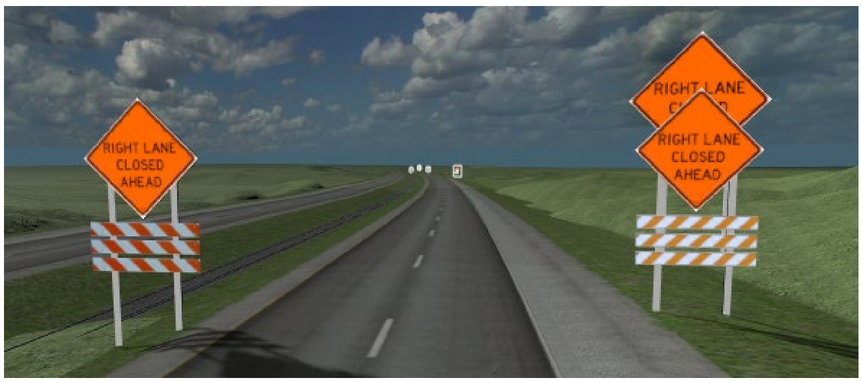
Figure 3.21 Participant immersed in a virtual work zone scenario

A few examples of deficient signage presented in the first scenario are shown in Figure 3.22.

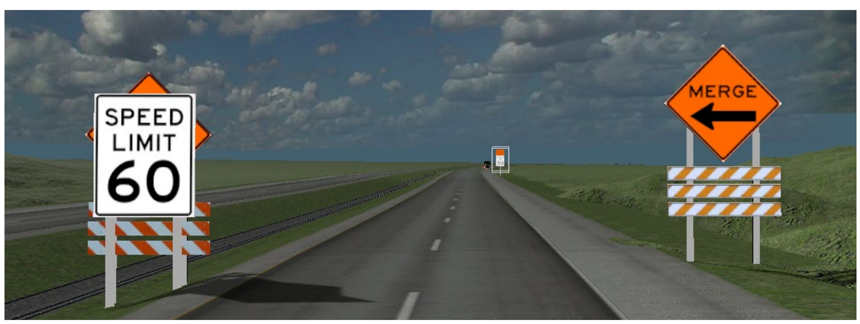
Duct tape

Damage or problem with visibility and tilted

Left sign damaged or dirty and no flags



Stacked signs on the right



Right lane closed sign covered by speed limit sign

Figure 3.22 Screenshots of deficient signage presented to the trainees in first scenario

Examples of deficient signage in the second scenario, in which trainees are tested, are shown in Figure 3.23.

Right side sign pink color or faded and large mound of sandbags

Left sign damaged and tilted

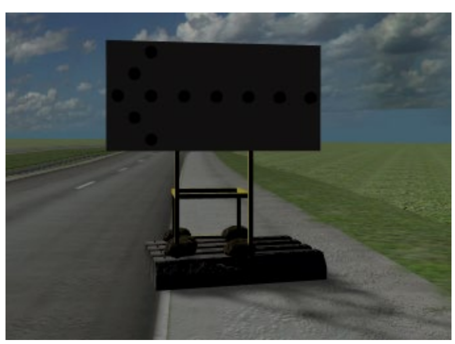
Damaged speed limit sign

Covered speed limit sign

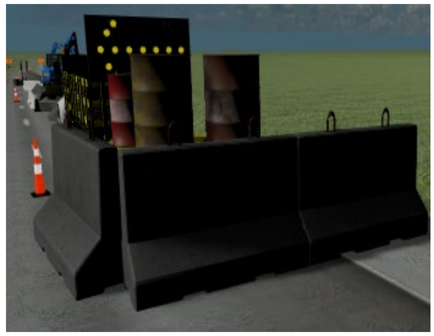
Damaged merge sign

Work zone speed limit sign, damaged and tilted

Trim-line channelizer down



Arrow board not working



TMA covered by concrete barriers and drums

End road work sign covered by speed limit sign and large mound of sandbags

Figure 3.23 Screenshots of deficient signage presented to the trainee in the second scenario

3.3 Testing of the Learning and Immersive Modules

The training modules were tested by Missouri DOT staff, and their performance was recorded. The testing occurred in two sessions. In the first session, the participants included work zone experts from MoDOT's Work Zone Quality Circle. Thirteen participants took the online learning quiz, tried the two immersive simulation scenarios, and completed a questionnaire survey. Their performance during the second simulation scenario was also recorded. In the second session, 21 attendees at the Missouri DOT Innovation Showcase Challenge participated in the study. They took the online learning quiz and tried the two simulation scenarios. The data from both sessions were combined to create a database of 34 participants. There were 25 male and 9 female participants.

3.4 Feedback Survey

A survey was administered after the trainees completed the immersive training module. The goal of this survey was to gather qualitative feedback on virtual reality technology. The survey included questions regarding their experience wearing the head-mounted display, ability to discern deficiencies in the work zone scenarios, and the overall utility of immersion. The complete list of questions in the feedback survey is presented next.

1- I believe the virtual reality module provided a realistic representation of an actual work zone.

[ ] Strongly Agree

[ ] Agree

[ ] Neutral

[ ] Disagree

[ ] Strongly Disagree

2- I was comfortable wearing the virtual reality headset.

[ ] Strongly Agree

[ ] Agree

[ ] Neutral

[ ] Disagree

[ ] Strongly Disagree

3- I was able to distinguish between good and bad signage in the work zone.

[ ] Strongly Agree

[ ] Agree

[ ] Neutral

[ ] Disagree

[ ] Strongly Disagree

4- I did not find the virtual reality module to be challenging.

[ ] Strongly Agree

[ ] Agree

[ ] Neutral

[ ] Disagree

[ ] Strongly Disagree

5- I had enough time to read the work zone signage.

[ ] Strongly Agree

[ ] Agree

[ ] Neutral

[ ] Disagree

[ ] Strongly Disagree

6- I did not feel nauseated while using the virtual reality headset.

[ ] Strongly Agree

[ ] Agree

[ ] Neutral

[ ] Disagree

[ ] Strongly Disagree

7- I had sufficient time to notice any concerns in the work zone.

[ ] Strongly Agree

[ ] Agree

[ ] Neutral

[ ] Disagree

[ ] Strongly Disagree

8- Overall, I believe that the virtual reality module is useful for training staff that inspect work zones.

[ ] Strongly Agree

[ ] Agree

[ ] Neutral

[ ] Disagree

[ ] Strongly Disagree

Chapter 4 Results and Discussion

This section presents the results of the learning module quiz, immersive virtual work zone test, and the feedback survey.

4.1 Learning Module Quiz Results

The learning module quiz was completed by all 34 participants. Each question in the learning module quiz could be rated on A to F scale (see Section 3.1.6). The percentage of correct answers was calculated for each participant. The individual score is presented in Figure 4.1. The average score for participants was 44%. The results revealed only nine participants who received a score above 50% (those that were involved with work zones in their job – work zone coordinator, maintenance supervisor, etc.). Over half of the participants scored under 50%. These scores further demonstrate the need for proper training of staff before they inspect and rate actual work zones.

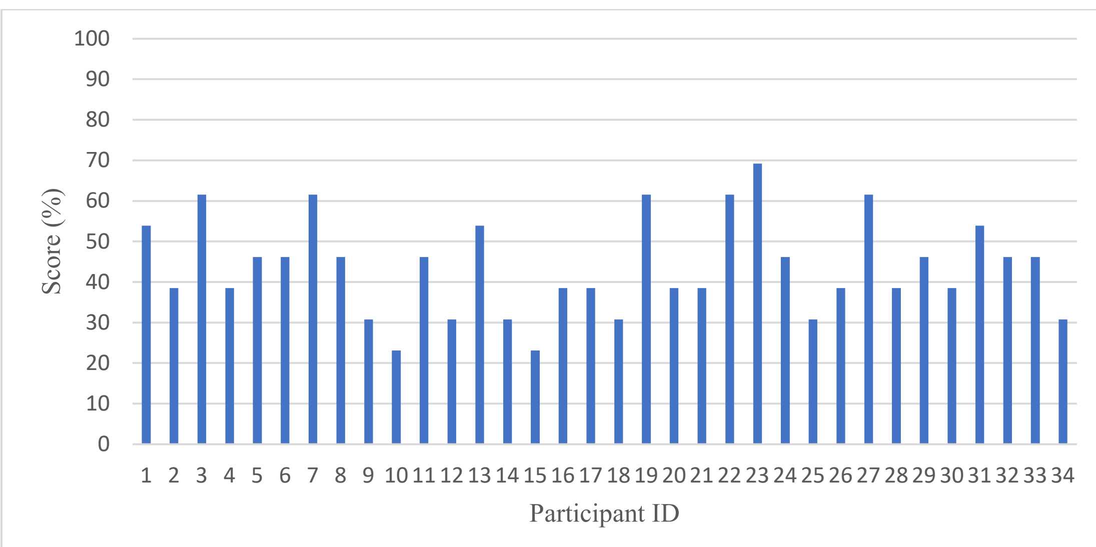


Figure 4.1 Participant performance on the learning module quiz

The quiz consisted of 13 questions. The number of participants that correctly answered each question was also tallied and is shown in Figure 4.2. The best performance was observed for questions 5 and 9, answered correctly by approximately 88% and 79% of the participants, respectively. Question 5 asked the participant to rate signage that is damaged and placed incorrectly, and an arrow board with some light bulbs out was rated in question 9. The next highest performance was on questions 3 (71%) and 4 (74%) where participants rated damaged signage and trim-line channelizers. On the other hand, participants performed poorly on other questions. Questions 2 and 4 were answered correctly by 26% and 29% of the participants, respectively. Question 2 included an overturned sign and question 4 had sign with duct tape covering part of it and was directly on the shoulder. Questions 1 and 10 showed examples above and beyond the standards and specifications. However, very few participants rated them as "A-above and beyond the standard and specification". For question 1, one participant selected A, 18 selected B, and 12 selected C. In question 10, while the TMA was in good condition, only 15% of the participants rated it as above and beyond the standards. Most of the participants stated that they were concerned with the distance between TMA and workspace and not just the condition of the TMA. In the future, the question could be better phrased to be specific about the TMA condition rather than the distance to workspace. Similar behavior was observed in response to question 11 where participants were asked to rate the taper and arrow board setup shown in Figure 4.3. All participants cited the crooked pavement marking and responded with a low rating. The trim-line channelizers and arrow board were in good condition. Again, the phrasing can be changed in future surveys to be specific about the condition of the channelizers and arrow board and not pavement markings.

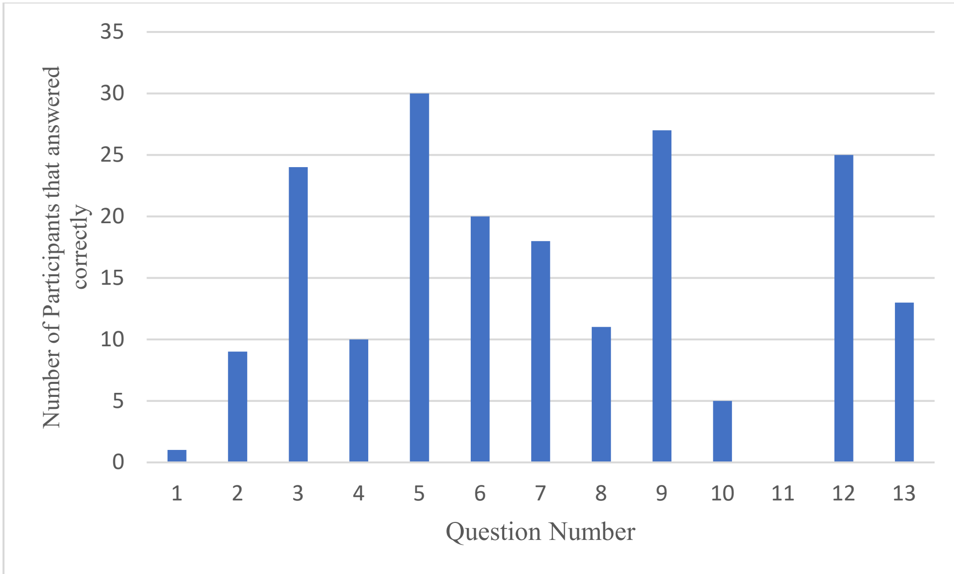


Figure 4.2 Performance on each question in the learning quiz

Figure 4.3 Arrow board and trim-line

4.1.1 Additional Analysis of Learning Module Quiz Results

The recommended rating for each question in the learning module quiz was based on the consensus of work zone experts from MoDOT who have prior experience of inspecting work zones across the state. In many questions, the experts recommended a more conservative rating, indicating higher expectations on the quality of signage. As the ratings are subjective, a good-enough sign would be rated A (above and beyond the standards and specifications of the project) whereas an expert would rate it as B (meeting the standards and specifications of the project).

The participant responses were re-analyzed by treating an answer as correct if it is within one rating of the expert recommendation. Three instances commonly occurred – a sign rated as A when an expert rated it as B or vice versa, a sign rated as C and the expert rating was D and vice versa, and a sign rated as D and the expert rated it as F.

The new scores for each participant were computed and are plotted in Figure 4.4. The average score for participants jumped from 44% to 79%. Approximately seventy-six percent of the participants scored above 70%. Two participants answered all questions correctly. In addition, three participants answered 92% of the questions correctly while ten participants answered 85% correctly. Only three participants scored less than 62% on the quiz.

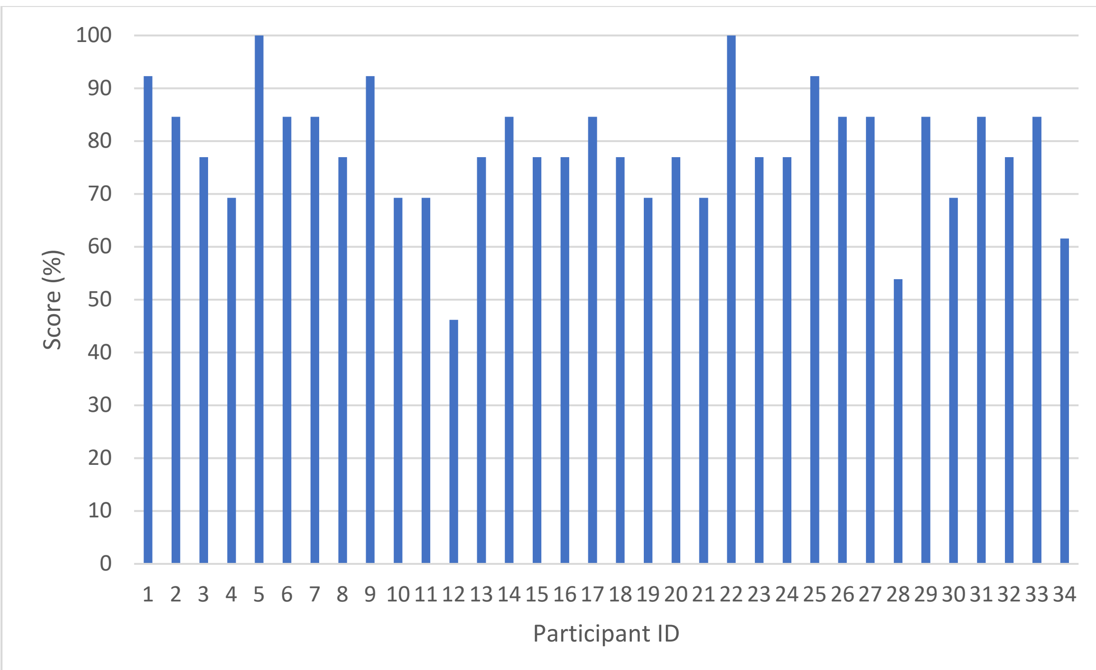


Figure 4.4 Revised scores for each participant

The number of the participants answering correctly each question was also recomputed. The results are shown in Figure 4.5 (below). Once again, the performance improved after relaxing the correctness of ratings between A&B, C&D, and D&F. Question number 5 was answered correctly by all participants. Question number 2, 4, 9, and 12 were answered correctly by approximately 97% of the participants. Only questions 10 and 11 still had low performance – answered correctly by 11 and 10 participants, respectively.

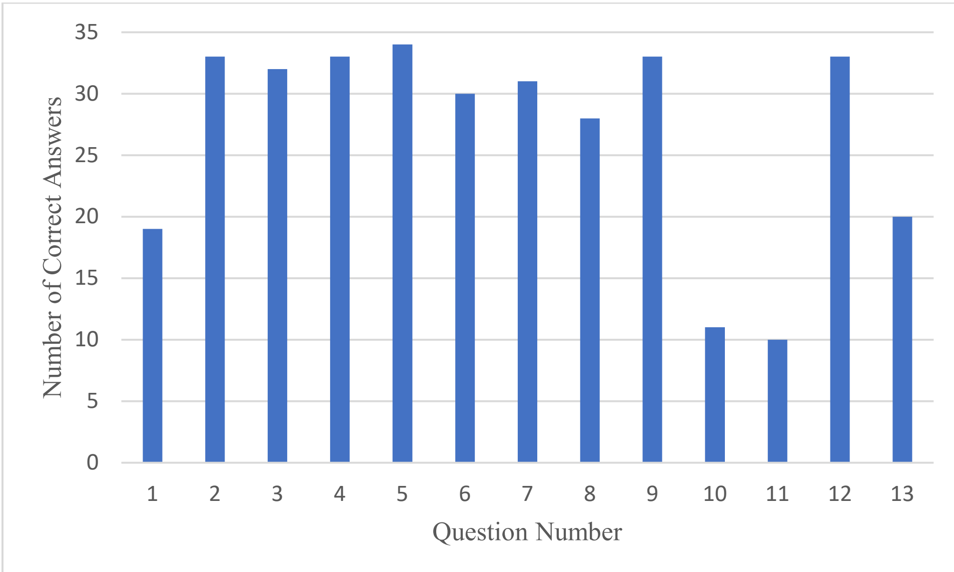


Figure 4.5 Revised total correct responses for each question in the learning quiz

4.2 Immersive Work Zone Scenario Test Results

All 34 participants also participated in the immersive module and the testing exercise for the virtual work zone. The participants experienced two scenarios of virtual work zones – a practice scenario and a test scenario. In the test scenario, the participants called out any deficiencies they noticed while going through the scenario. The research team developed a rubric (shown in Appendix A) to record the participant responses. There were 10 main instances where there were deficiencies (with signage, channelizers, etc.) in the work zone. In four of these instances, there were two deficiencies at the same location. Thus, the rubric had grading for 14 questions. The number of deficiencies correctly identified by each participant were counted and the percentage shown in Figure 4.6 (below). On average, the participant score was 79% while

88% of the participants earned a score over 70%. Two participants were able to call out all deficiencies. Seven participants identified 93% of deficiencies while another eight participants identified 86% of deficiencies. Twenty-four percent of the participants answered 79% of test correctly while fifteen percent of the participants answered 71% of test correctly. MoDOT can establish a minimum passing score (e.g. 70%) and recommend the trainee to review the learning module and retake the immersive module test. Only four participants scored less than 64% on the test.

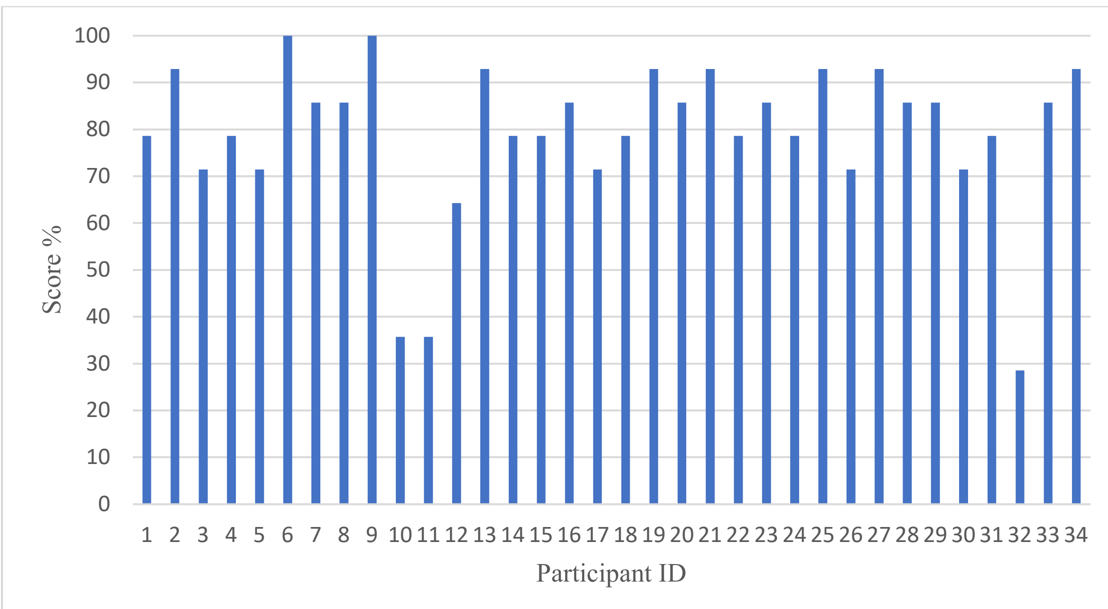


Figure 4.6 Summary test results of immersive virtual work zone for participants

The number of participants correctly answering each question was also tallied, and the results are shown in Figure 4.7. Eighty-six percent of the deficiencies within the work zone were correctly identified by at least 71% of the participants. While most deficiencies were correctly identified, two deficiencies, 2B and 10B, were missed by 38% and 74 % of participants, respectively. Both 2B and 10B related to the incorrect use of mound of sandbags to hold signage in place.

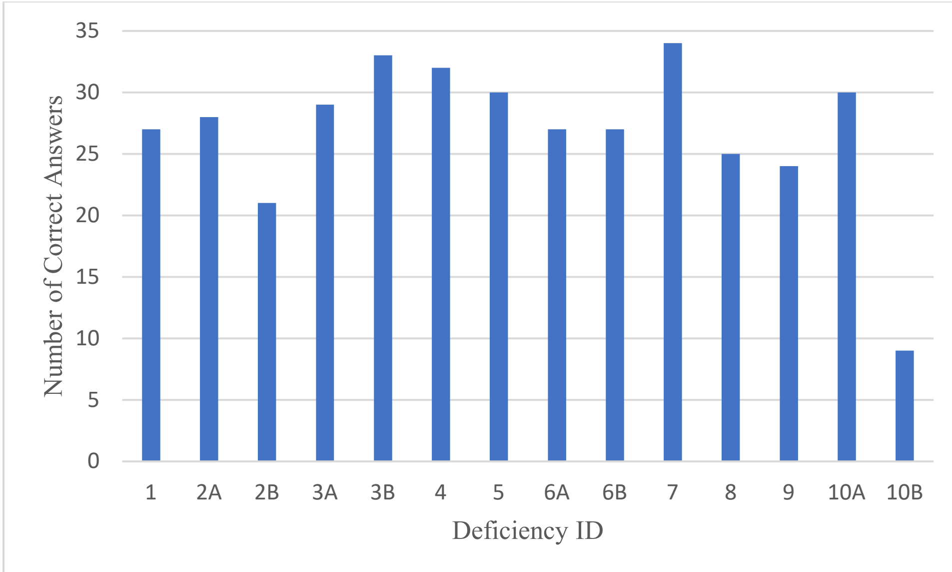


Figure 4.7 Number of participants correctly identifying each deficiency noticed in the immersive scenario

4.3 Virtual Reality Technology Feedback Survey Results

Upon completion of the immersive module, the participants were asked to complete a short survey on the virtual reality technology and its use to train work zone inspectors. The list of questions included in the survey were previously discussed in Section 3.4.

The survey results are summarized in Table 4-1. All participants agreed that the virtual reality module provided a realistic representation of an actual work zone with 47% agreeing and 53% strongly agreeing. Over 90% strongly agreed or agreed that they were comfortable wearing the head mounted device. Most of the participants indicated that they were able to distinguish between good and poor signage in the virtual work zone - 65% strongly agreeing and 35% agreeing.

When asked if the virtual reality immersive module was challenging, about 50% said they did not find it challenging, 32% were neutral, and 18% found it to be challenging. Ninety four percent of participants said they did not feel nauseated while using the virtual reality headset. Overall, 97% of participants either strongly agreed or agreed that the virtual reality module was useful for training staff to inspect work zones.

Table 4-1 Survey results for the virtual reality technology

Question	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
1- I believe the virtual reality module provided a realistic representation of an actual work zone.	53%	47%	0%	0%	0%
2- I was comfortable wearing the virtual reality headset.	35%	56%	9%	0%	0%
3- I was able to distinguish between good and bad signage in the work zone.	65%	35%	0%	0%	0%
4- I did not find the virtual reality module to be challenging.	9%	41%	32%	18%	0%
5- I had enough time to read the work zone signage.	35%	56%	6%	3%	0%
6- I did not feel nauseated while using the virtual reality headset.	56%	38%	3%	3%	0%
7- I had sufficient time to notice any concerns in the work zone.	32%	68%	0%	0%	0%
8- Overall, I believe that the virtual reality module is useful for training staff that inspect work zones.	62%	35%	3%	0%	0%

Chapter 5 Flagger Scenario

5.1 Scenario Generation Process

In this chapter, the development of a scenario for flagging operations on a two-lane one way work zone is presented. The objective of this module is to create a scenario with a human flagger directing traffic through a work zone. The scenario was created using field video of flagger operations on a two-lane highway in rural Missouri. The scenario creation process consisted of four steps. In the first step, the field video was analyzed to determine the exact location of the work zone. After determining the location, the geometric design for the entire stretch of the work zone (from the advance warning signage to the end of work zone) was obtained as the second step. In the third step, motion capture technology was used to replicate the behavior of a human flagger. The final step of the process involved the creation of the environment, roadway section, flagger, and the inspection vehicle in the virtual environment.

5.2 MoDOT EPG Guidance on Flagger Operations

MoDOT's Engineering Policy Guide provides guidance on flagging procedures in work zones. The guidance pertaining to flagging procedures in long, intermediate and short-term stationary operations consists of four steps as explained in Table 5-1.

Table 5-1 Long/Intermediate and short-term stationary operations 3 cones procedures

(MoDOT EPG 616.5.7.2)

Step 1

- Setup cones as shown and return to shoulder
- Remain facing traffic, with STOP paddle visible
- Keep visual contact with drivers of stopping vehicles
- Keep left hand raised with palm facing driver, signaling to stop

Step 2

- Once traffic has stopped, move out towards the center of the lane
- Keep Stop/Slow paddle in your right hand and position it out towards the center line, be sure not to cross the line with the Stop/Slow paddle
- Keep visual contact with drivers of stopped vehicles
- Keep left hand raised with palm facing driver, signaling to stop, until traffic has completely stopped

Step 3

- Once you have confirmed opposing traffic is clear, pick up the middle cone and make your way back to the shoulder taking the cone with you
- Be sure to keep Stop paddle visible to stopped traffic

Step 4

- Once on the shoulder, rotate the Stop/Slow Paddle to Slow and release traffic
- Direct traffic by signaling with your arm and waving vehicles through

5.3 Designing Flagger Scenario

5.3.1 Determining Location from Field Video

MoDOT's work zone staff provided two drive-through videos of work zones in Missouri. Exact location and the boundary of the work zone was determined using online maps and video footage. The work zone was located at 38°44'38.4"N, 91°42'40.3"W on Rte. D in Callaway County in central Missouri. Figure 5.1 shows the horizontal alignment of the route containing the work zone.

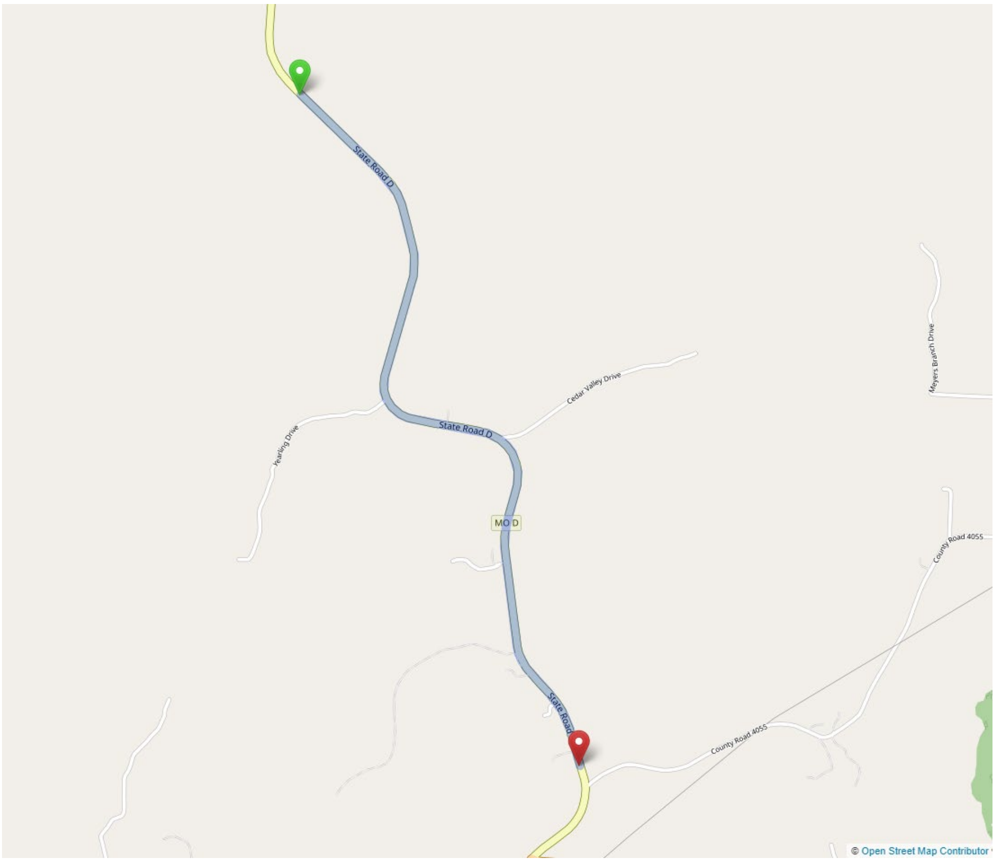
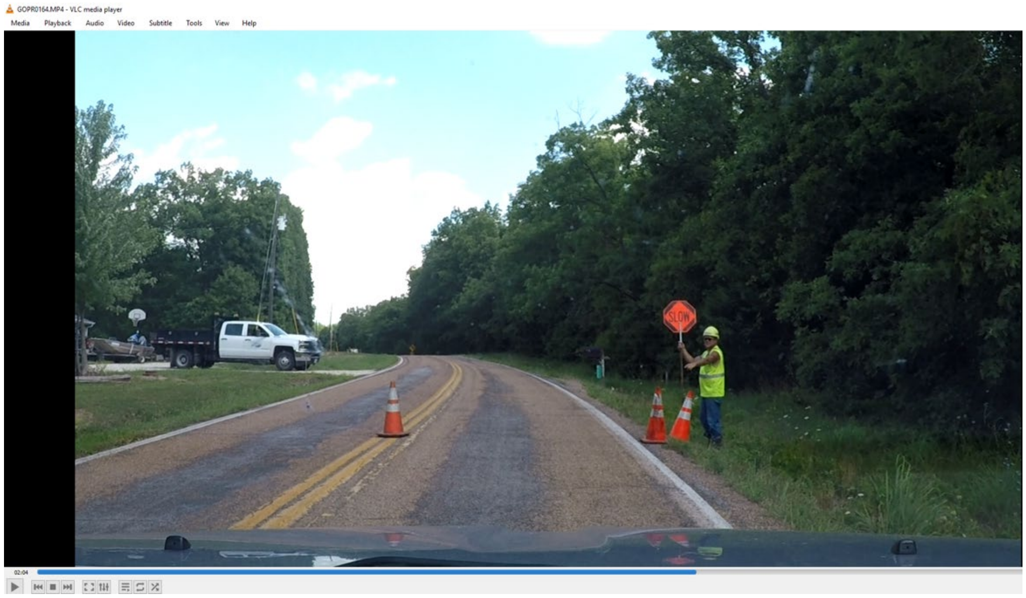


Figure 5.1 Location of the flagger work zone

The position of temporary traffic control signage and flagger was also extracted from the drive through videos and overlaid on the maps. Figure 5.2 shows an example of mapping the flagger location onto the roadway map.



Actual flagger video

Mapped using Google Street View

Figure 5.2 Mapping positions from videos to maps

5.3.2 Geometric Design

In this step, we created the topology and landscape of the roadway segment using a Height Map. A Height Map is a raster image containing surface elevation data that can be displayed in 3D. Figure 5.3 shows the Height Map for the study segment. The darker areas correspond to lower elevations and the lighter areas correspond to higher elevations.

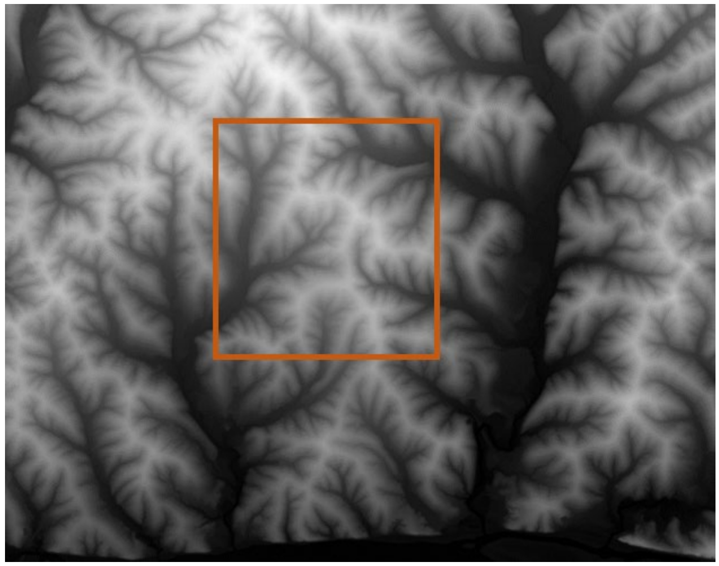


Figure 5.3 Topology and landscape from Height Maps

5.3.3 Motion Capture of Human Flagger

In this step, a simulation model of a human flagger was created using motion capture technology. The movement of the flagger was collected from the field video. The Motive software was used to motion capture a 3D model from the video that is compatible with Unity. Figure 5.4 shows a researcher wearing sensors to emulate the flagger movement. The cameras mounted on the tall tripods shown in Figure 5.4 captured the researcher's movements. An avatar of the flagger is then created using the captured movements and is shown in Figure 5.5.

Figure 5.4 Motion capture process

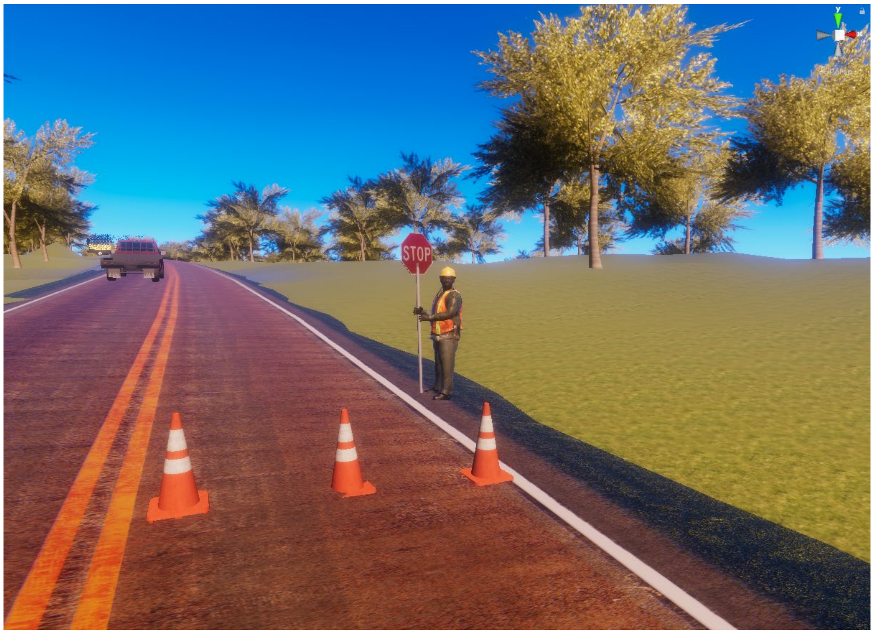


Figure 5.5 Mapping motion data to flagger avatar

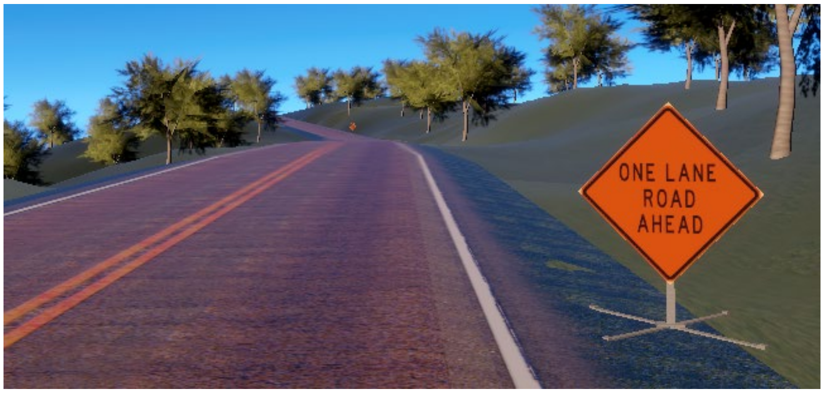
5.3.4 Creating the Virtual Environment

In this step, we synthesized all objects from the previous step, including the car model, the flagger, and the roadway geometrics. The car movement and path were implemented using C# script. Figure 5.6 shows the car model editor in the Unity engine.

Figure 5.6 Managing car movement in Unity

Screenshots from the virtual environment are shown in the next few pages. The work zone signage upstream of the flagger is shown in Figure 5.7 (i.e. Road Work Ahead, One Lane Road Ahead Sign and Flagger Sign).

Road work ahead sign



One lane road ahead sign

Flagger sign

Figure 5.7 Examples of signage in flagger scenarios

The VR scenarios were created using field video footage of a work zone. One flagger was located at each end of the work zone. The current EPG (Chapter 616.5 Flagger Control) only provides guidance to a flagger directing traffic through the open lane as shown in Figure 5.8.

Flagger holding the stop sign

Flagger moving the cones

Flagger releasing traffic with slow sign

Figure 5.8 Screenshots of flagger following EPG guidelines

A second flagger is located in the closed lane in front of a work truck or a truck mounted attenuator as shown in the screenshots in Figure 5.9. While the EPG does not provide specific guidance on how the flagger should direct traffic. It is assumed that the flagger receives communication from the other flagger that they stopped traffic, and performs a visual check of the open lane and then directs traffic to proceed slowly. EPG provides the following guidance on stationing of the flagger: “A flagger’s normal station is on the shoulder of the road, minimum of 500 ft. from the flagger symbol sign and minimum of 100 ft. from the workspace.”

Flagger holding the stop sign

Flagger preparing to release traffic

Flagger releasing traffic with slow sign

Figure 5.9 Flagger in the closed lane

5.4 Test Questions

The flagger scenarios can be incorporated into the inspector training module presented in Section 3. A short survey consisting of four questions is suggested to test the performance. These questions correspond to each step in the EPG flagger procedure. In Figure 5.10, there are four rows with each row corresponding to one step. The first column describes the step, the second column provides a picture of the guidance, the third column provides a picture from the scenario that the participant experienced in the VR environment, and the fourth column poses the question. The answer key is shown in the fourth column but will not be shared with the participant. Two approaches are feasible to conduct this survey. One approach is to ask the participant to call out any deficiencies while they are immersed in the virtual reality scenario. The other approach is to conduct the survey upon completion of the immersive scenarios. The flagger scenarios were created after the completion of the participant studies reported in Section

4. The scenarios were revised based on feedback obtained from MoDOT staff. However, the short scope (i.e., four questions) of the scenario did not warrant a separate focus group study. For inspector training, the flagger scenario is expected to complement the other work zone training scenarios instead of a stand-alone application.

Step	MoDOT EPG	Post-VR test	Question
Step1 :Stopping traffic			• Q: Is the flagger accurately positioned? • A: No. The flagger needs to face the driver of an approaching vehicle with the hand raised to indicate the driver to stop the vehicle.
Step2 :Traffic has stopped			• Q :Is the flagger correctly approaching the cones? • A: No. The flagger needs to move toward the centerline with the hand raised.
Step3 :Preparing to release traffic			• Q: Is the flagger correctly approaching the cone? • A: No. The flagger needs to approach the cone and face the driver.
Step4 :Releasing traffic			• Q: Is the flagger releasing the traffic correctly? • A: No. The flagger needs to point the direction of travel to the driver.

Figure 5.10 Test questions for the flagger scenario

Chapter 6 Conclusions

The goal of this research was to enhance the training for work zone inspectors. Virtual reality technology has been used for training in other fields and shown to be more effective than traditional methods. A training platform was developed using virtual reality and illustrated using Missouri DOT data. The platform consists of two steps. The first step is a *learning* module which is founded on the historical knowledge gained by DOT staff from inspections dating back at least five years. The second step is an *immersive* module that places trainees in virtual work zones where their inspection performance will be observed and assessed. The training platform could be used to train staff who inspect work zones annually and contractors and maintenance inspectors who monitor work zones daily. The developed training platform was assessed by 34 participants from MoDOT. The participants' background knowledge of work zones ranged from expert to novice.

The learning module quiz was developed to measure participants' performance. The quiz included questions from the MoDOT inspection worksheet and the trainees rated the quality of temporary traffic control and signage. The quiz was administered by an online Qualtrics survey with real-time feedback. The feedback shows the recommended rating and pictures of correct signage when a participant selects an incorrect answer. The quiz results revealed that the average score for participants was 44%. These scores validated the need for proper training of staff that inspect and rate work zones. The recommended rating for each question was based on the consensus of work zone experts from MoDOT. The experts rated more conservatively, indicating higher expectations on the quality of signage and other temporary traffic control features. The participant responses were re-analyzed by treating an answer as correct if it is within one rating of the expert recommendation; for example, a sign rated as A when an expert rated it as B or vice versa. The re-analyzed responses increased the quiz performance from 44% to 79%.

In the second part of the study, two scenarios of immersive virtual work zone were developed – a practice scenario and a test scenario. In the test scenario, the participants called out any deficiencies in temporary traffic control and signage they noticed while going through the scenario. The test results indicated that the average score for the participants was 79%, while 88% of the participants earned a score over 70%. Only four participants (out of 34) scored less than 64% on the test. It is recommended that MoDOT establish a minimum passing score (e.g. 70%) and recommend reviewing the learning module and retaking the immersive module test to obtain a passing score.

MoDOT staff that participated in the study indicated that virtual reality technology provided a realistic representation of an actual work zone. They also indicated that the virtual environment allowed trainees to explore various temporary traffic control features inside a work zone. A few participants indicated that some signage appeared blurry from a distance. The VR scenarios created in this study place the participant in the passenger seat of a moving vehicle (not the driver seat for safety reasons). Due to the motion at highway speeds, it was not feasible for a participant to accurately estimate the distance between traffic control devices.

Additional scenarios involving flagger operations on two-way one lane work zones were added to the training module. The scenarios developed in this project can be used by other DOTs. The use of virtual reality technology for training can be extended to other work zone training. Future research could explore additional work zone scenarios such as daytime versus nighttime conditions, weather effects, and work zones at complex interchanges. Non-work zone applications include developing training modules for pavement inspection, night-time sign inspection, and bridge inspection.

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Appendix A Grading Rubric for Virtual Reality Test

Participant No.__

Second Scenario:

1- Speed Limit sign " damage or problem with visibility" **Point [1]**

[ ]correct wrong[ ] Note:____________________________

2- First sign of advance warning area "a-right sign pink color or faded, b-large mound of sandbags"

2A. Right sign pink color or faded **Point[1]**

2B. Large mound of sandbags **Point[1]**

[ ]correct wrong[ ] Note:____________________________

3- Right lane closed ahead “a-left sign damage or dirty, b-tilted”

3A. Left sign damage **Point [1]**

3B. Tilted **Point[1]**

[ ]correct wrong[ ] Note:____________________________

4- Speed limit and work zone “Covered” **Point [1]**

[ ]correct wrong[ ] Note:____________________________

5- Right lane closed and merge sign “merge sign damage or dirty” **Point [1]**

[ ]correct wrong[ ] Note:____________________________

6- Speed limit and work zone “a-work zone sign damage, b-tilted”

6A. Work zone sign damage **Point [1]**

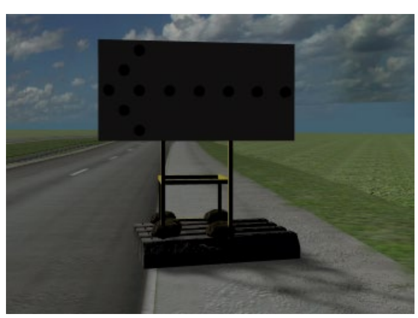
6B. Tilted **Point[1]**

[ ]correct wrong[ ] Note:____________________________

7- Trim-line channelizer “fall down” Point **[1]**

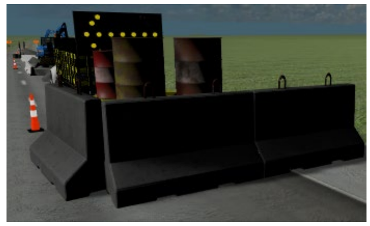
[ ]correct wrong[ ] Note:____________________________

8- Arrow board “lamp out or light not working” **Point [1]**



[ ]correct wrong[ ] Note:___________________________

9- Truck mounted attenuators TMA “covered by concrete barriers and drums” **Point [1]**



[ ]correct wrong[ ] Note:___________________________

10- End road work sign “a-covered by speed sign, b-large mound of sandbags left sign”

10A. Left sign covered by speed sign **Point [1]**

10B. Large mound of sandbags left sign **Point[1]**

[ ]correct wrong[ ] Note:___________________________

Appendix B MoDOT Temporary Traffic Control Inspection Worksheet

PROJECT INFORMATION

District: __________ County: ______________________________ Route: ____________________

Project No.: __________________ Location: ____

Date/Time: __________________ Weather: __________________ Inspector: __________________

PROJECT SUMMARY

RATINGS	A	B	C	D	F	N/A
Signs	☐	☐	☐	☐	☐	☐
Channelizing Devices	☐	☐	☐	☐	☐	☐
Barricades	☐	☐	☐	☐	☐	☐
Temporary Traffic Barrier	☐	☐	☐	☐	☐	☐
Crash Cushions	☐	☐	☐	☐	☐	☐
CMS/Flashing Arrow Panels/Traffic Signals	☐	☐	☐	☐	☐	☐
Lighting	☐	☐	☐	☐	☐	☐
Flagger Operations	☐	☐	☐	☐	☐	☐
Paint/Tape/Pavement Markers	☐	☐	☐	☐	☐	☐
Tapers/Transition Areas/Lane Widths/Crossovers	☐	☐	☐	☐	☐	☐
Roadway Conditions/Temporary & Uneven Pavement/Unprotected Hazards	☐	☐	☐	☐	☐	☐
Entrance & Exit Ramps	☐	☐	☐	☐	☐	☐
Truck & Equipment Crossings/Access	☐	☐	☐	☐	☐	☐
Traffic Management	☐	☐	☐	☐	☐	☐
Overall	☐	☐	☐	☐	☐	

RATINGS:

A – Above and beyond the standards and specifications of the project.
B – Meeting the standards and specifications of the project.
C – A couple of deficiencies meeting the Category 3 severity level of the Standard Section 616.
D – Several deficiencies meeting the Category 3 severity level of the Standard Section 616 or a couple of deficiencies meeting the Category 2 severity level of the Standard Section 616.
F - Several deficiencies meeting the Category 2 severity level of the Standard Section 616 or one or more deficiencies meeting the Category 1 severity level of the Standard Section 616.

Category severity levels are as follows:
Category 1 – Presents an immediate safety issue for the traveling public or workers and needs to be addressed immediately.

Category 2 – The situation doesn't pose an immediate safety issue for either the public or the workers, but can impact the proper functioning of the work zone.

Category 3 – The situation doesn't impact the functioning of the work zone but is more of a maintenance or aesthetic issue.

PROJECT SPECIFICS

SIGNS

Types

☐ Metal Signs	☐ Roll-Up Signs	☐ Wood Signs	☐ Plastic Signs
☐ w/ Lights	☐ w/ Flags	☐ w/ Cones	☐ w/ AWRS
☐ on Portable Stand	☐ on Temporary Stand	☐ on Barrier Mount	☐ on PSST Post
☐ on U-Channel Post	☐ on Wood Post	☐ on Truck	

Discrepancies

☐ Legibility	☐ Need	☐ Conflicting	☐ Faded/Dirty
☐ Advance Warning	☐ Splicing	☐ Reflectivity	☐ Lights
☐ Bracing	☐ Fluorescent	☐ Mounting Height	☐ Support
☐ Lettering	☐ Legend/Symbol	☐ Leaning	☐ Visibility
☐ Encroaching	☐ Twisted	☐ Location	☐ Distance
☐ Misleading	☐ NCHRP 350	☐ Covering	☐ Missing Signs
☐ Condition			

Rating ☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

CHANNELIZING DEVICES

Types

☐ Trim-Line	☐ Drum-Like	☐ Cones	☐ Direction Indicator Barricades
☐ Tubular Markers	☐ Vertical Panel		
☐ w/ Lights			

Discrepancies

☐ Alignment	☐ Reflectivity	☐ Use	☐ Condition
☐ Size	☐ Location	☐ Spacing	☐ Missing Devices
☐ Ballasting	☐ NCHRP 350		

Rating ☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

BARRICADES

Types

☐ Type I ☐ Type III

☐ w/ Lights ☐ w/ Signs

Discrepancies

☐ Alignment	☐ Signing/Marking	☐ Reflectivity	☐ Condition
☐ Size	☐ Location	☐ Quantity	☐ Lighting
☐ Ballasting	☐ NCHRP 350		

Rating

☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

TEMPORARY TRAFFIC BARRIER

Types

☐ Concrete Type F ☐ Water-Filled Plastic ☐ Other

☐ w/ Tabs ☐ w/ Glare Screen ☐ w/ End Treatment

Discrepancies

☐ Alignment	☐ Taper	☐ Marking	☐ Condition
☐ Delineation	☐ Offset	☐ Blunt End	☐ NCHRP 350
☐ Connection	☐ Anchoring		

Rating

☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

CRASH CUSHIONS

Types

☐ TMA ☐ Impact Attenuator ☐ Other

Discrepancies

☐ Alignment	☐ Delineation	☐ Marking	☐ Condition
☐ Wrong Quantity	☐ Location	☐ Ballasting	☐ NCHRP 350

Rating

☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

CMS / FLASHING ARROW PANELS / TRAFFIC SIGNALS

Types

☐ CMS ☐ Flashing Arrow Panel ☐ Portable Traffic Signal ☐ Temporary Traffic Signal

☐ w/ Lighting

Discrepancies

☐ Alignment ☐ Level ☐ Location ☐ Height
☐ Visibility ☐ Delineation ☐ Timing ☐ Operation
☐ Need ☐ Message ☐ Display

Rating ☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

LIGHTING

Types

☐ Fleet ☐ Work Area ☐ Overhead

Discrepancies

☐ Color ☐ Usage ☐ Visibility ☐ Glare
☐ Hot Spots ☐ Output

Rating ☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

FLAGGER OPERATIONS

Types

☐ Flagger ☐ Pilot Vehicle ☐ AFAD ☐ Portable Flagger Device

Discrepancies

☐ Certification ☐ Communications ☐ Procedures ☐ Location
☐ Attire ☐ Signing

Rating ☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

PAINT / TAPE / PAVEMENT MARKERS

Types
☐ Paint ☐ Removable Tape ☐ Short-Term Tape ☐ Type 1 Marker
☐ Type 2 Marker ☐ 'No Center Stripe' Signing

Discrepancies
☐ Quality ☐ Installation ☐ Reflectivity ☐ Placement
☐ Quantity ☐ Color ☐ Dimension ☐ Removal
☐ Scarring ☐ Conflict

Rating ☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

TAPERS / TRANSITION AREAS / LANE WIDTHS / CROSSOVERS

Types
☐ Shoulder Taper ☐ Shifting Taper ☐ Merging Taper ☐ One-Lane/Two-Way Taper
☐ Median Crossover ☐ Head-to-Head Traffic

Discrepancies
☐ Alignment ☐ Location ☐ Length ☐ Width
☐ Delineation ☐ Signing ☐ Hazards ☐ Design

Rating ☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

ROADWAY CONDITIONS / TEMPORARY &UNEVEN PAVEMENT / UNPROTECTED HAZARDS

Discrepancies
☐ Ruts ☐ Dips ☐ Pot Holes ☐ Stability
☐ Wedges ☐ Dirt/Debris ☐ Plates ☐ Joints
☐ Drainage ☐ Drop-Offs ☐ Equipment ☐ Material
☐ Open Excavations ☐ Blunt Ends ☐ NCHRP 350

Rating ☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

ENTRANCE & EXIT RAMPS

Discrepancies

☐ Alignment ☐ Location ☐ Length ☐ Width
☐ Delineation ☐ Signing ☐ Merge Area ☐ Diverge Area

Rating ☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

TRUCK & EQUIPMENT CROSSING / ACCESS

Discrepancies

☐ Location ☐ Length ☐ Width ☐ Delineation
☐ Signing ☐ Design

Rating ☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments

TRAFFIC MANAGEMENT

Discrepancies

☐ Speed Reduction ☐ Speed Limit ☐ Traffic Queue ☐ Detour
☐ Road Closure

Rating ☐ A ☐ B ☐ C ☐ D ☐ F ☐ N/A

Comments
