IMPROVING WORK ZONE SAFETY THROUGH SPEED MANAGEMENT

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16. Abstract

Safety hazards are increased in highway work zones as the dynamics of a work zone introduce a constantly changing environment with varying levels of risk. Excessive speeding through work and maintenance zones is a common occurrence which elevates the dangers to both drivers and motorists in the work zone. Although most work zones are controlled by reduced speed limits or state law enforcement, driver adherence to these regulations and laws in very minimal, especially in work zones. Several studies have shown a correlation between speeding in work zones and traffic crashes which lead most traffic safety professionals to conclude that excessive speeding and speed variance are the contributing factors in a large percentage of traffic crashes, injuries or fatalities. The most influential factor in achieving speed compliance in the work zone is the driver's perception of heightened risk. The main objective of this study was to determine the safest and most effective countermeasure for the reduction of vehicular speeds within construction and maintenance work zones. The purpose of the simulator experiment was to determine the effectiveness of a 20 countermeasures on the reduction of speed through work zones in a controlled laboratory setting. The literature review identified several past research studies utilizing speed reduction countermeasures in work zones and under normal traffic conditions. From this review, 20 countermeasures were selected for evaluation based upon discussions with ODOT personnel.The post hoc tests indicated that the presence of construction workers, presence of construction vehicles, law enforcement, speed photo enforcement and shifting lanes were most effective at reducing speeds in work zones. The least effective speed reduction countermeasures included 3 sets of 3 rumble strips, concrete barriers, other channelizing devices and changeable message signs with speed reductions less than 10 mph.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.452	centimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
yd^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	millimeters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

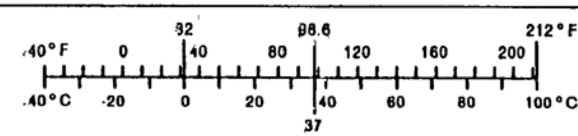

Table of Contents

1. INTRODUCTION……………………………………………………………...……………10
2. BACKGROUND………………………………………………………………….……11
3. OBJECTIVE………………………………………………………………......……..17
4. METHODOLOGY..………………………………………………………..………..18
   4.1. Virtual World Design and Development ……………………………………….18
   4.2. Focus Group Selection……………………………………..……………………46
   4.3. Simulator Experiment Procedure………………………………………….……49
   4.4. Data Collection……………………………………………………………….…50
   4.5. Sample Size…………………………………………………………………..…54
   4.6. Statistical Analysis…………………………………………………………...…55
5. RESULTS………………………………………………………………………………58
   5.1. Speed……………………………………………………………………………58
   5.2. Lane Placement…………………………………………………………………58
   5.3. Focus Group Post-Test Summary……………………………………….………62
6. CONCLUSIONS………………………………………………………….……………63
7. RECOMMENDATIONS AND IMPLEMENTATION……………………………..67
8. REFERENCES…………………………………………………………………………67
APPENDIX A: Institutional Research Board Documents…….……………………………72

List of Tables

Table 1. Organization of the Virtual Scenarios 19
Table 2. Speed Data Summary 51
Table 3. Lane Placement Data Summary 53
Table 4. Speed Statistical Results 58
Table 5. Speed Reduction Countermeasure Effectiveness 59
Table 6. Lane Placement Statistical Results 60
Table 7. Speed Reduction Countermeasure Effectiveness via Lane Placement 62
Table 8. Results of the participant post-test questionnaire 63
Table 9. Countermeasure Conclusive Summary 65

List of Figures

Figure 1. ‘ROADWORK 1 MILE’ Sign 20
Figure 2. Lane Closed Ahead Sign 21
Figure 3. ‘LEFT/RIGHT TWO LANES CLOSED ½ MILE’ Sign 21
Figure 4. Sequential Flashing Lights 22
Figure 5. Speed Trailer Signs 23
Figure 6. Dynamic Message Sign 24
Figure 7. Changeable Message Sign 25
Figure 8. Orange Barrel /Orange Tube Cone 25
Figure 9. Monetary Fine sign 26
Figure 10. Schematic drawing of highway work zone with changeable message signs 28
Figure 11. Schematic drawing of highway work zone with concrete barriers 29
Figure 12. Schematic drawing of highway work zone with dynamic message signs 30
Figure 13. Schematic drawing of highway work zone with the Emergency Flasher Control Device 31
Figure 14. Schematic drawing of highway work zone with the highway work zone billboard ... 32
Figure 15. Schematic drawing of highway work zone with a lane reduction of 12 foot lanes to 10 foot lanes 33
Figure 16. Schematic drawing of highway work zone with law enforcement 34
Figure 17. Schematic drawing of highway work zone with a monetary fine sign 35
Figure 18. Schematic drawing of highway work zone with optical speed bars 36
Figure 19. Schematic drawing of highway work zone with other channeling devices 37
Figure 20. Schematic drawing of highway work zone with 3 sets of 3 rumble strips each 38
Figure 21. Schematic drawing of highway work zone with 4 sets of 3 rumble strips each 39
Figure 22. Schematic drawing of highway work zone with sequential flashing lights 40
Figure 23. Schematic drawing of highway work zone with shifting lanes 41
Figure 24. Schematic drawing of highway work zone with speed photo enforcement 42
Figure 25. Schematic drawing of highway work zone with speed trailer and law enforcement .. 43
Figure 26. Schematic drawing of highway work zone with speed trailer 44
Figure 27. Schematic drawing of highway work zone with variable speed limit signs 45

Figure 28. Gender Distribution 46
Figure 29. Age Distribution 47
Figure 30. Driving Limitations 47
Figure 31. Daily Distance Driven 48
Figure 32. Daily Driving Time 48
Figure 33. Acknowledged Speeding through Work Zones 49
Figure 34. Frequency of Highway Work Zone Encounters 49

1.0 INTRODUCTION

Safety hazards are increased in highway work zones as the dynamics of a work zone introduce a constantly changing environment with varying levels of risk. An error in the assessment of risk and/or performance of the driver, may lead to traffic crashes involving injury or fatalities to the construction workers or motorists. Without a distinct separation of the workers and the motorists through rigid barriers, the potential for danger is further increased. Other dynamics of the work zone including the work zone location, working conditions, and the duration also make safety planning on a project even more difficult. A work zone on the shoulder of the roadway in broad daylight is much safer than a work zone in the middle of the roadway at night. The risk is further complicated by the lack of speed limit compliance on behalf of the motorists.

Excessive speeding through work and maintenance zones is a common occurrence which elevates the dangers to both drivers and motorists in the work zone. Although most work zones are controlled by reduced speed limits or state law enforcement, driver adherence to these regulations and laws in very minimal, especially in work zones. Several studies have shown a correlation between speeding in work zones and traffic crashes which lead most traffic safety professionals to conclude that excessive speeding and speed variance are the contributing factors in a large percentage of traffic crashes, injuries, or fatalities. The most influential factor in achieving speed compliance in the work zone is the driver’s perception of heightened risk.

According to a recently released report by the National Highway Traffic Safety Administration (NHTSA), speeding is one of the major contributing factors to traffic crashes. In the 2005 and 2008 *Traffic Safety Facts*, it was reported that excessive speed was the contributing factor in 30 and 31 percent of all traffic crashes, respectively [1,2]. Unfortunately, while traffic crashes have been declining, speed, as a contributing factor to crashes, has been trending positively. When considering the economic impact of these speed-related crashes on society, the most recent NHTSA figures estimate an annual cost of $40.4 billion [2]. Across the nation, speeding related crashes claimed 11,767 lives in 2008, while Ohio speeding related crashes claimed 269 lives [2].

These fatal crashes are not restricted to adverse environmental or roadway conditions. In 2008, 29 percent of speed-related fatal crashes occurred on dry roads while 35 percent occurred on wet roadways [2]. Fatal crash data indicates an increase in fatalities on interstates and highways and a decrease in fatalities on local arterials and rural roadways between 1992 and 1998. However, data presented in the NHTSA report *Analysis of Speed-Related Fatal Motor Vehicle Crashes*, published in 2005 indicated fatalities on local and collector roadways has increased significantly since 2000 [3]. The 2008 NHTSA *Traffic Safety Facts* reported that nearly 88 percent of the speeding-related fatal crashes occurred on roadways other than interstates [2]. When considering the fatal crashes by gender and age, drivers 15-24 years old are the most likely to be involved in a speeding-related fatal crash, with males being involved more often than females [2]. Studies have also determined that crash severity can be substantially reduced with adherence to posted speed limits [4].

Speed control on roadways resides with the jurisdiction of local city, county and state law enforcement agencies [3]. While enforcement has been determined to be the most responsive method of improving speed limit adherence, agencies do not have adequate staff or budget to conduct speed enforcement in addition to their other public safety responsibilities resulting in unenforced speed limits. Combining the increase in speed-related fatal crashes with restrictive law enforcement agencies budgets and staff, there is an ever present need for effective, low-cost, speed mitigation measures.

With work zones being an integral part of roadway improvements and maintenance, they are constantly creating changing traffic patterns, reducing speed limits, causing congestion, and providing an influx of construction workers and equipment on the roadway. The proper use of traffic control devices is an important part of every work zone where the safety of the workers and motorists is the number one concern while also maintaining an efficient flow of traffic. In order to determine what impact alternative traffic control devices or modifications to the work zone have on speed reduction, various devices and methods were evaluated for their effectiveness in terms of danger to the workers and motorists safety through the use of the Ohio Research Institute for Transportation and the Environment's (ORITE's) driving simulator.

2.0 BACKGROUND

A literature review was conducted to determine known causes of increased vehicular speeds/crashes, previous countermeasures utilized in work zones as well as non-work zones and the factors that contribute to that specific work zone. Some of the factors that were researched with each published report was the placement of the countermeasure used, the work zone geometry, (placement of on/off ramps, approach to the work zone, lane closures), as well as traffic volumes and the posted and 85th percentile speed. The literature review was conducted using several web-based queries including some from specific reputable agencies, the Transportation Research Board being the major search engine used. From there, each report was critically reviewed and certain criteria were determined in order to come up with the most appropriate and practical countermeasures that would be tested in this study. Some of the criteria that were determined were the objectives and concerns of each report, data collection and analysis methods used, performance measure(s) utilized, any innovative technology used, and impacts/results each report concluded. Published reports used in the literature review dated back no later than 2006 to ensure recent up-to-date standards and regulations by Ohio Department of Transportation (ODOT), the American Association of State Highway Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA). A summary of the literature review is detailed below.

The National Highway Transportation Safety Administration (NHTSA) found that speeding is a contributing factor in 30 percent of all crashes and fatalities [5]. In response to this finding and other similar findings that emphasize the negative effects of speeding in work zones, there has been a significant emphasis on reducing speed and enforcing compliance with posted limited in work zones. A 2002 study in Alabama identified police presence in work zones as the most effective method of reducing vehicle speeds; this was verified by Kamyab et al., as well as by studies in Virginia, Maryland and Ohio [6-10]. There is often an unforeseen consequence of reduced speeds in work zones; increased speed differential between vehicles. Many studies have concluded that drivers select their own safe speed based on road conditions, regardless of the posted speed. Thus, if speed is reduced unnecessarily, some drivers will continue at their own perceived speed while other drivers will obey the reduced speed limit, thereby creating an unintentional and dangerous speed differential [11-15]. Studies that emphasize safety improvements from reduced speeds in work zones typically use metrics such as average reduced speed rather than reduced number of crashes. In fact, a review of the literature found no studies that showed a reduction in crashes as a result of enforcing reduced speed in work zones.

Richards et al. [16] indicated that one of the primary problems with enforcement of speed limits in work zones is credibility with the driving public caused by conditions such as “using unreasonably low speed limits and leaving reduced speed limits in place after the work activity is removed”. The authors described a procedure for implementing effective speed controls in work zones which involves four steps: 1) determination of the need for speed reduction based on engineering studies, 2) selection of a reasonable speed by examining existing speeds, design speed of the work zone and the work zone conditions, 3) selection of a speed treatment based on duration of potential hazards, roadway type, desired speed reduction, treatment cost and institutional constraints, and 4) selection of location for speed control treatment.

Research related to traffic control devices and countermeasures to control speeding in work zones indicates the most effective techniques for reducing mean speeds and speed variance in work zones (in addition to police enforcement) are flaggers, speed display units, and automated radar detection with citations issued to the vehicle owner. Signs, pavement markings, and other standard traffic control devices are largely ineffective in reducing speeding in work zones, especially during low volume and low density conditions. This summary is based on results and conclusions published in various research papers [17-32].

Most highway construction work zones experience higher crash rates as compared with the overall highway system. The most common crash type in work zones is rear-end collisions, with speed variance and congestion cited as the typical causes. The work activity site is the most frequent location for work zone crashes, and bridge work appears to be the most hazardous construction type. Trucks are significantly more likely to be involved in work zone crashes than non-work zone crashes. Study results indicate 22 percent of construction worker injuries are due to the presence of traffic, increasing the hazard for workers in work zones as compared with other construction sites. Furthermore, pedestrian workers are more vulnerable if they are working near traffic lanes [9,33-36].

Based upon the increase in speed-related crashes and the limits on active enforcement, efforts must be made to increase passive enforcement, or self-enforcement of posted speed limits. Several passive enforcement traffic calming alternatives have been found to be effective on local roadways. These include but are not limited to: Chicanes, Speed Humps, Speed Tables, Lane Narrowing, and Traffic Circles. Each of these methods has been found effective at reducing the travel speed; however, they are not always feasible due to existing roadway conditions nor are applicable for high speed or high volume roadways. The cost of the design and installation of these traffic calming measures may also limit the ability of local municipalities to implement these options effectively for local roads. Other methods, including increasing the reflectivity of speed limit sign sheeting and pavement markings have been used; however, the desired speed reductions have not been realized [4].

Another passive enforcement speed reduction tool is dynamic speed signs (DSS). These signs can be trailer mounted or permanently mounted to telephone or light poles and use laser detectors to measure the speed of approaching vehicles. The sign displays the approaching vehicle's speed to the driver in addition to the posted speed limit. Studies have determined that DSS, when used in relation to construction work zones, can reduce the traveled speed of vehicles by as much as five miles per hour [37,38]. Similar results were found when these devices were used near speed limit transition locations. These studies reported speed reductions of six to eight miles per hour [4,39,40]. Speed trailers have also been used by law enforcement agencies instead of active enforcement. Unfortunately, even though proving effective over a short-time period, the cost and placement options for these trailers are also restrictive. Research has been performed to determine the long-term effects of the DSS, as well as the impact on vehicular speed after the signs have been removed [4, 40]. The research indicated that the long-term impact of the DSS signs were slightly less than the immediate speed reductions; however, after a year, the reductions were still statistically and practically significant. Immediately after the removal of the DSS, traveled speeds returned to similar levels prior to the installation [4, 39,40]. Research has also been performed to determine the effectiveness of these signs prior to school zones with similar results.

Additional research has been performed with respect to the use of DSS as permanent traffic calming measures on arterial and collector roads with constant speed limits. A before and after study performed by Chang et al. along a corridor in King County, Washington found a speed decrease of 1.19 - 2.21 miles per hour at three of four DSS installation locations seven and 22 months after the installation [39]. One site had a 0.51 mile per hour speed increase after the installation of the DSS. The researchers attributed this increase to the sign's proximity to the presence of a school speed zone where speed limit compliance was not a prior concern. The data collected at three of the sites indicates that adherence to the posted speed limit immediately after the DSS install was sustained for 22 months. These results indicate that the permanent use of DSS as a speed reduction measure may be effective [39].

Variable Speed Limit (VSL) signs have an electronic display of the posted speed limit and are generally found in longer highway work zones. They allow the operator to change the sign to any desired speed without changing the physical appearance of the sign. The signs may be adjusted via telephone, email, or even directly on the job site. This allows the speed to be changed as the job site moves through a long work zone. In past studies, this method has been known to be statistically significant in lowering speeds in a 95 percent confidence interval [41].

Sequential Flashing Lights (SFL) are generally selected for their effect on reducing speed in work zones as well as their effect on early merging. In a previous study conducted, the SFL were set at 60 flashes per minute and were used close off the right lane on a two lane interstate highway with a 60 mile per hour speed limit and minimal horizontal and vertical curves [42]. Based on the results found, a decrease in the 85th percentile speed by 1 mile per hour was found along with a decrease in mean speed by 2.21 miles per hour, an increase in driver speed compliance by 6.7 percent, and an improvement in early merging behavior in drivers by 19 percent for trucks and 6.74 percent for cars.

Rumble strips are either grooves built into the road or pieces of rubber or plastic that sits on top of the roadway. The point of rumble strips is to cause vibrations in the vehicle to alert drivers. In a previous study conducted, there were four sets of rumble strips placed 500 feet, 650 feet, 900 feet and 1400 feet from the start of the work zone [43]. Then speeds were measured at 600 feet and 5500 feet from the start of the work zone during the day as well as during the evening. At 5500 feet the rumble strips were not effective but at 600 feet they were really effective. At 5500 feet the mean speed was 57 miles per hour with and without rumble strips. At 600 feet, the mean speed was approximately 45 miles per hour without rumble strips and 36 miles per hour. Based on these results, there were rumble strips placed at 1400, 900, 650, and 500 feet away from the beginning of the work zone.

A speed trailer is an electronic sign with a built in speed gun the automatically determines the current speed of the vehicle closest to the trailer and displays that speed. Some speed trailers flash the speed if the driver is traveling over the posted speed limit. In a previous study, the speed trailer was placed along the side of an urban road [44]. The speeds were measured before the implementation of the sign and after the implementation of the sign. The speed trailer was effective lowering speeds only by 0.3 - 2 miles per hour.

Dynamic Message Signs are permanently mounted along highways and each sign has certain characteristics to meet in order to be an effective message sign; problem, location, effect, attention, and action. Each sign was put into three categories; danger and warning messages, informative messages, and regulatory messages. The MUTCD specifies that a driver must be able to read the sign twice while driving at the posted speed limit. In a previous study conducted, a warning message was displayed on the signs and the signs were studied in several ways with the signs being on for ten minutes and then off for ten minutes and vice versa. The results of the study showed that in the on-off cases about 82.9 percent were unaffected or increased and in the off-on case revealed that speeds increased more when the message was removed [45,46].

Changeable Message Signs are signs that display changeable messages and are portable. In a previous study, the message signs were place at 250, 750, and 1250 feet from the work zone. Data was then collected from 7 AM until 7 PM for two two-week periods in May and September. The signs either read “WORK ZONE AHEAD SLOW DOWN” or “FLAGGER AHD PREP TO STOP”. The results of the study showed that by placing the portable changeable message signs anywhere between 556 feet and 575 feet from the work zone, the signs would be more effective in reducing driver speeds [47].

Monetary fines are fines that each driver is required to pay should they get caught violating the speed limit. In a previous study, two different messages were used on signs reading “YOUR SPEED IS ## mph” alternating between “SLOW DOWN” for message one and “MINIMUM FINE $200” for the second message [47]. The results of this study found that the percentage of people driving 5, 10, 15, 20, and 25 miles over the speed limit were reduced by 20, 20, 10, 3, and 0.3 percent, respectively.

Speed Photo Enforcement (SPE) works similarly to red light cameras, where if a vehicle is speeding through a work zone, a photo of that vehicles license plate is taken and a speeding ticket is sent to the owner of that vehicle. The presence of the SPE van did an equally successful job lowering the speeds of the vehicles the most ranging in speed reductions from 6.4 - 8.4 miles per hour. In another study using SPE, it was effective in lowering speeds by 7.7 - 7.9 miles per hour in cars and 5.5 – 6.6 miles per hour for trucks and heavy vehicles [44].

An Emergency Flasher Traffic Control Device (EFTCD) is a sign that warns drivers to lower speeds in the case that they are speeding. When a vehicle approaches a work zone, they would turn on their emergency hazard lights thus warning the vehicles behind them to turn on their hazard lights, creating an array of hazard lights traveling together through the work zone. This would serve as a warning to construction workers to keep them as well as the drivers safe.

In a previous study using the EFTCD, the study showed that at a five percent confidence level, the EFTCD was successful at lowering the speeds of vehicles traveling through the work zone. This equates to a 5 mile per hour speed reduction in the 65 miles per hour speed zone and a 2.5 mile per hour reduction in speeds in the 55 miles per hour speed zone [48].

Optical Speed Bars are generally white lines painted on the surface of the roadway perpendicular to the flow of traffic. The lines are placed and decreasing intervals along the roadway to give the perception that the driver is increasing their speed [49].

3.0 OBJECTIVES

The main objective of this study was to determine the safest and most effective countermeasure for the reduction of vehicular speeds within construction and maintenance work zone. Between 2007 and 2009, Ohio averaged 3.5 crashes in work zones per hundred million dollars spent on construction funding, which 42 of those crashes resulted in a fatality. Without improvements to the current methods used to reduce vehicular traffic work zones, the current trend that exists may continue to occur. The goal of this research was to determine driver performance and behavioral changes as a result of the presence of various speed reduction techniques during work zone roadway conditions. The following outlines the tasks which were performed to complete the research objectives:

Task 1: Conduct a literature review to identify traffic control devices or countermeasures which have the potential to reduce vehicular speeds through work zones as well as non-work zones.

Task 2: Select up to twenty speed countermeasures for simulator testing based upon discussions with and recommendations from ODOT's Division of Highway Operations Office of Traffic Engineering.

Task 3: Design schematic traffic control plans for the selected countermeasures and upon approval from ODOT, develop the virtual worlds in the simulator.

Task 4: Conduct controlled laboratory experiments to quantify driver behavior and performance of a representative focus group using ORITE's driving simulator.

Task 5: Statistically analyze the effect of the countermeasures tested in the simulator.

Task 6: Develop recommendations for field implementation.

Task 7: Prepare and submit a final report.

In order to meet the research objectives, goals and tasks outlined above, the methodology detailed in Section 4 of this report was developed and utilized.

4.0 METHODOLGY

The purpose of the simulator experiment was to determine the effectiveness of a 20 countermeasures on the reduction of speed through work zones in a controlled laboratory setting. The literature review identified several past research studies utilizing speed reduction countermeasures in work zones and under normal traffic conditions. From this review, 20 countermeasures were selected for evaluation based upon discussions with ODOT personnel. The simulator experiment research methodology was designed to allow active participation by the subjects in the driving simulator instead of passive participation. The data was also extracted without the presence of the participants making the participants unaware of the measure of performance collected for analysis. Therefore, the participants were able to utilize the driving simulator without knowing the ramifications of their actions. Several countermeasures chosen have been previously researched on different roadway geometrics and configurations. The comparison for this simulator study allowed all of the countermeasures to be conducted on a similar roadway in similar conditions.

The driving simulator used for the controlled laboratory experiment is owned by the Ohio Research Institute for Transportation and the Environment (ORITE). The driving simulator was manufactured by DriveSafety, Inc. of Salt Lake City, Utah. The simulator allows for creation of custom virtual reality scenarios based upon various roadway types (urban, rural, two-lane highways, four-lane highways, divided and undivided roadways), different levels of interactive ambient traffic, variable weather conditions and varying levels of roadway friction. The simulator included a vehicle cab which included all the entities associated with the front portion of a vehicle such as a windshield, front seats and doors, roof, safety belts, all standard dashboard instrumentation and driver controls, a rear view mirror, two side mirrors, an audio system, a steering wheel, gas and brake pedals, starting ignition, a motion platform and a 180 degree screen for graphics display. The motion platform provides real time motion simulation based upon inertial cues from the vehicle cab.

4.1 Virtual World Design and Development

After the list of twenty countermeasures was approved by ODOT, the virtual worlds depicting various work zones with the countermeasures were designed. Twenty countermeasures were chosen to allow that each participant would have the time allowed for two-30 minute sessions. Based on and past and present studies using the driving simulator, it is known that boredom and/or motion sickness occur within participants at around 45 minutes of driving in the simulator, so keeping the amount of time driving at a minimum was key in order to gain true unbiased or unaltered results. To further reduce the time driving, five scenarios were decided upon, each containing four countermeasures each, which would allow participants to drive for approximately 10 minutes followed a brief break, if needed, before beginning the next scenario. The order in which countermeasures appeared was randomized. The twenty countermeasures used were divided up into the following five scenarios as follows:

Table 1. Organization of the Virtual Scenarios

Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Variable Speed Limit Sign	Speed Trailer	Law Enforcement	Speed Trailer + Law Enforcement	Speed Photo Enforcement
Sequential Flashing Lights	Dynamic Message Sign	Changeable Message Sign	Monetary Fine	Emergency Flasher Traffic Control Device
4 sets of 3 Ruble Strips	Concrete Barriers	Other Channeling Devices	3 sets of 3 Rumble Strips	Optical Speed Bars
Highway Work Zone Billboard	Presence of Construction Workers	Lane Reduction (12’ → 10’ lane)	Shifting Lanes	Presence of Construction Vehicles

The simulated driving environments were designed to replicate the temporary traffic controls commonly present in field conditions based upon Part 6, Temporary Traffic Control of the Ohio Manual on Uniform Traffic Control Devices (OMUTCD). Each countermeasure was designed in the virtual world of the driving simulator. To ensure that the only factor that affected the measurement and data collection was the countermeasure, each scenario was exactly alike. The participant began driving on a three-lane, straight, flat highway. After proceeding approximately a half mile down the roadway, the driver would then encounter the first cautionary sign warning them about the approaching work zone. Following all of the ODOT regulations and guidelines for temporary traffic control on a multiple lane highway, the warning signs were placed at the appropriate distance from the start of the work zone. Once the driver reached the work zone, they would encounter a single lane closure, followed by two lane closures, leaving the participant driving in either the far left lane or the far right lane. The driver then encountered a mile long work zone and was exposed to the countermeasure in that particular scenario. Once the driver exited the work zone, they entered three open lanes of traffic. This layout was repeated a total three times to give drivers five scenarios equal in length and layout. Figures 1 through 3 show the warning signs present prior to the work zone.

Figure 1. 'ROADWORK 1 MILE' Sign

Figure 2. Lane Closed Ahead Sign

Figure 3. 'LEFT/RIGHT TWO LANES CLOSED ½ MILE' Sign

Along with the layout for each scenario, each countermeasure was created as well. Some of the countermeasures were as simple to create as placing tube cones instead of barrels where others called for more complex computer programming in order to create a realistic clone in the virtual world. The description of how each countermeasure was created in the virtual world is included herein.

Two VSL signs were placed within the work zone. The first sign was placed at the beginning of the second lane closure where construction workers were present with a posted speed limit of 55 miles per hour. The second VSL sign was placed approximately half way into the work zone where there were no workers present anymore with a posted speed limit of 65 miles per hour. The SFL were set at 60 flashes per minute and were placed atop the barrels on the two merging tapers of the work zone lane closures and shown in Figure 4.

Figure 4. Sequential Flashing Lights

There were four sets of rumble strips placed 500 feet, 650 feet, 900 feet and 1400 feet from the start of the work zone. For one of the scenarios, three sets of three rumble strips were used at 500, 650, and 900 feet. For the other scenario, four sets of three rumble strips each were placed at 500, 650, 900, and 1400 feet. The highway billboard was placed approximately a half mile into the work zone. A speed trailer was created and placed at the beginning of the work zone.

The speed trailer displayed the drivers speed to the nearest 5 miles and flashed if the driver was speeding over the posted speed limit as shown in Figure 5.

Figure 5. Speed Trailer Signs

A countermeasure using dynamic message signs were designed. The message type chosen for this study was danger and warning messages. The sign was displayed on a permanently mounted display and read “REDUCE SPEED” as shown in Figure 6.

Figure 6. Dynamic Message Sign

In the virtual world, in place of orange barrels, concrete barriers were placed along the entire length of the work zone. Within the virtual world, workers were placed along the entirety of the work zone. There were construction vehicles visible as well, but were stationary. Each worker traversed a predetermined path throughout the work zone to give the driver a sense of a real, working construction zone. In the virtual world, law enforcement vehicles were placed approximately halfway into the work zone. The law enforcement vehicle was placed perpendicular to the flow of traffic within the closed lanes of traffic. The vehicle was stationary with no audible noises or visible lights on the vehicle. In the virtual world, due to visual restrictions within the scenario and the graphics of the projector for the monitor, portable signs were too small and uneasy to read. Instead, the sign was placed overhead on a permanent sign to simulate a changeable message sign displayed at the beginning of the work zone and read the message “WORK IN PROGRESS/SLOW DOWN” and is shown in Figure 7.

Figure 7. Changeable Message Sign

In the virtual world, thin orange tube cones were used in place of the standard orange barrel as shown in Figure 8.

Figure 8. Orange Barrel /Orange Tube Cone

In the virtual world, a monetary fine sign was placed at the beginning of the work zone and warned drivers of possible fines if caught speeding and is shown in Figure 9.

Figure 9. Monetary Fine sign

In the virtual world, the driver was shifted from the far left lane of traffic to the far right lane over a gradual distance using proper signage and placement of channeling devices, according to Ohio's MUTCD. In the virtual world, a sign was placed at the beginning of the work zone, warning drivers that the work zone was photo enforced. Approximately half way through the work zone, a mini-van sits perpendicular to the flow of traffic, simulating a real life photo enforcement vehicle. In the virtual world, the EFTCD is an electronic sign that is completely blank unless the driver exceeds the speed limit. If that happens, the sign reads "REDUCE SPEED." In the virtual world, the optical speed bars were placed along the merging taper leading into the work zone. The bars were initially placed at 22 feet apart and decreased one foot every 3-4 bars. In the virtual world, the normal lane width is 12 feet, which was reduced to 10 feet lanes by placing the barrels closer to the lane of moving traffic than the barrels would normally be.

Schematic drawings for each countermeasure subsequent work zone were drawn using AutoCAD. Each drawing was drawn up in accordance to Ohio's Manual for Uniform Traffic Control Devices (MUTCD), ODOT's Traffic Engineering Manual, ODOT's Temporary Traffic Control Manual, and ODOT's Standard Construction Drawings. The schematic drawings are shown in Figures 10 through 27. Upon final design in the simulator, Reynaldo Stargell of ODOT reviewed in person the virtual worlds created and approved the virtual worlds with a few suggestions for modifications which were implemented.

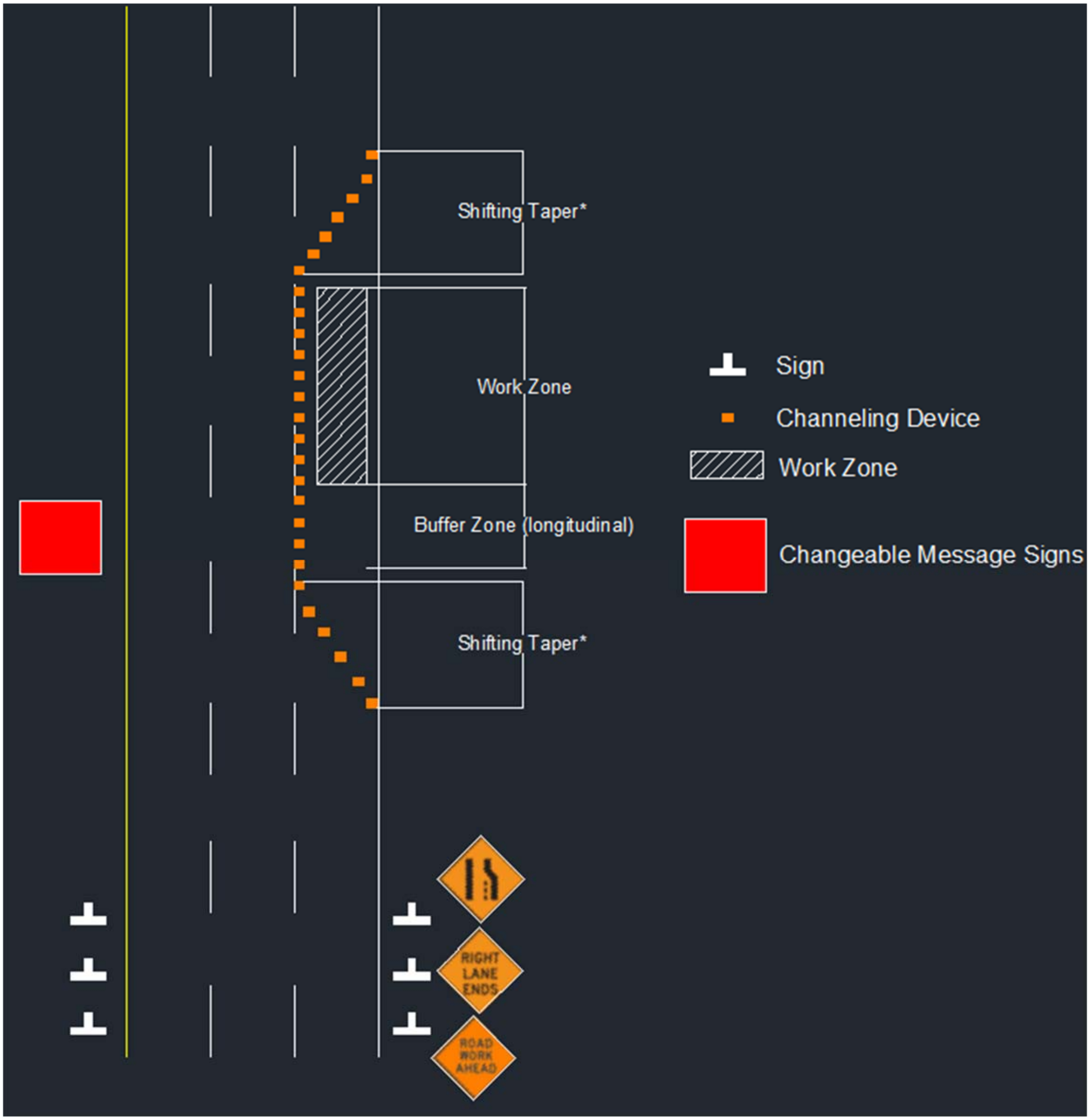

Figure 10. Schematic drawing of highway work zone with changeable message signs

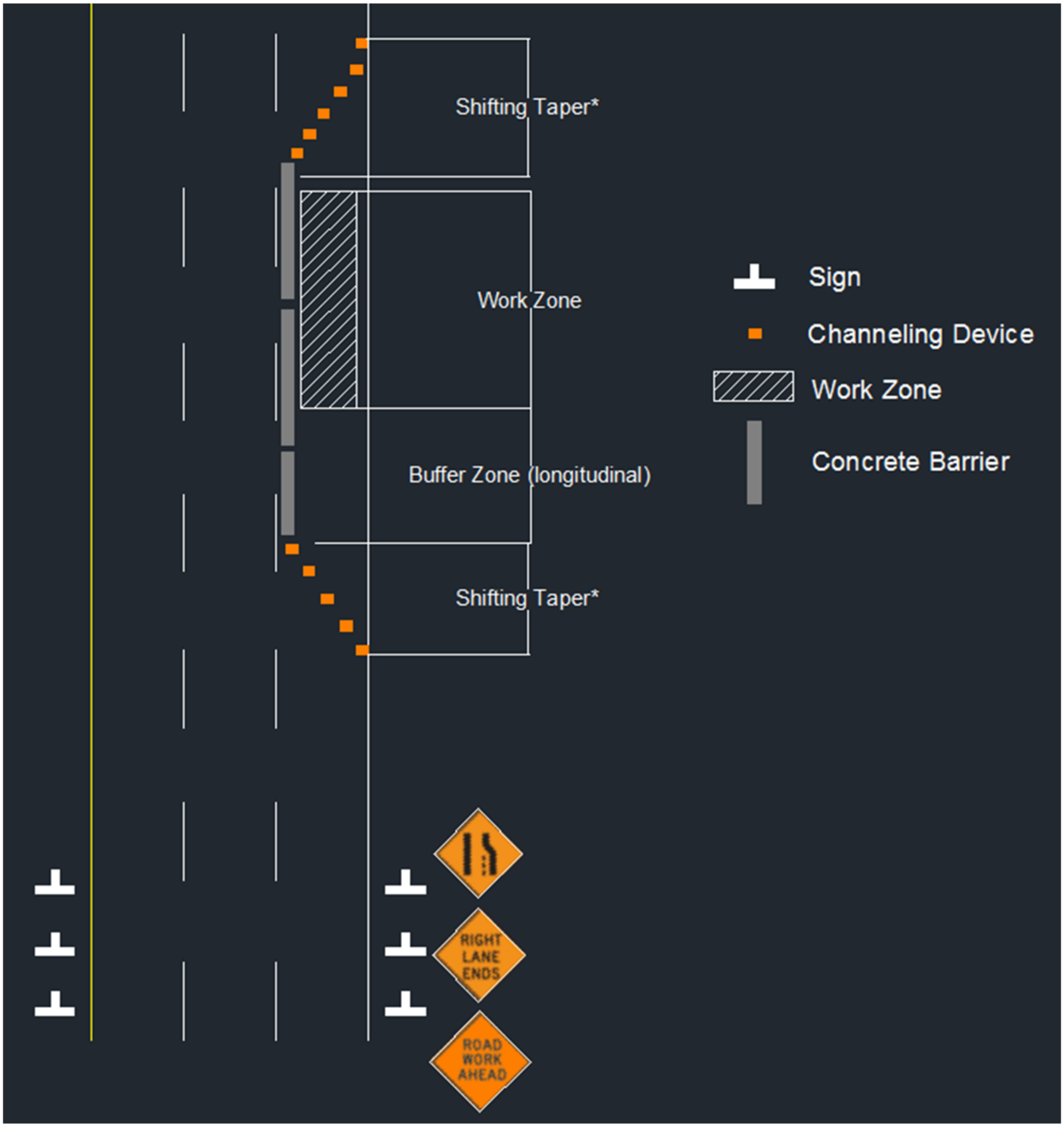

Figure 11. Schematic drawing of highway work zone with concrete barriers

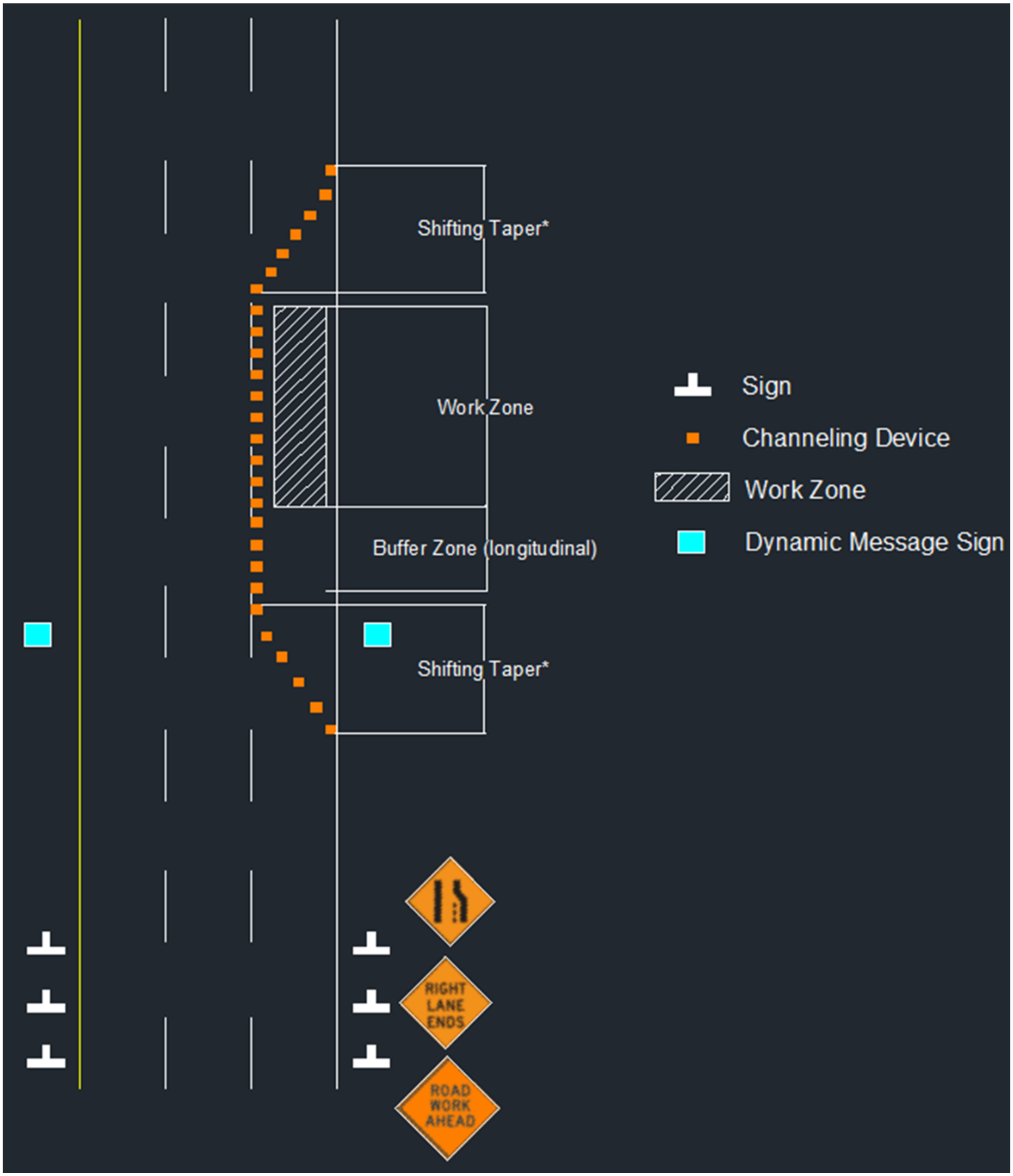

Figure 12. Schematic drawing of highway work zone with dynamic message signs

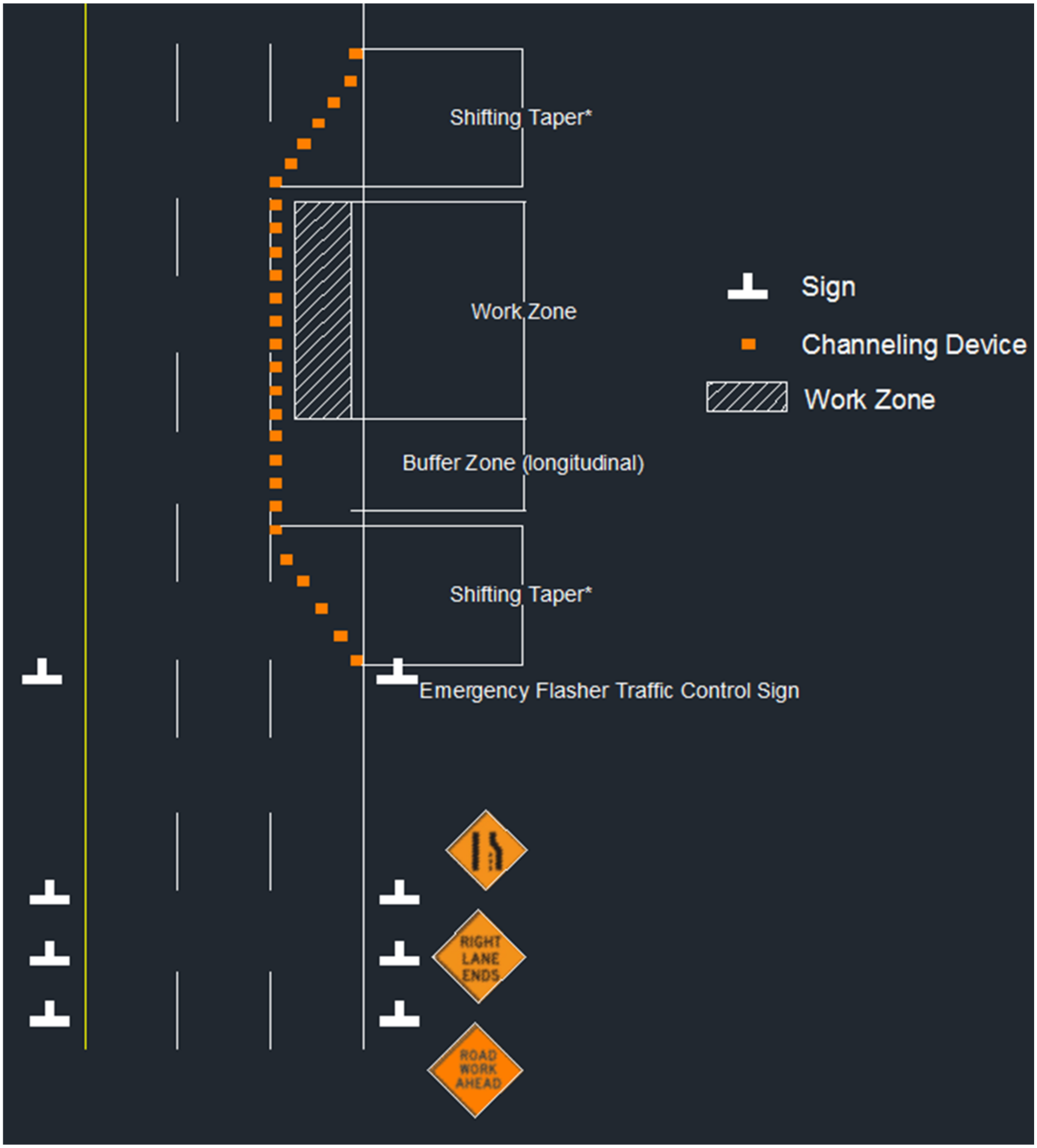

Figure 13. Schematic drawing of highway work zone with the Emergency Flasher Control Device

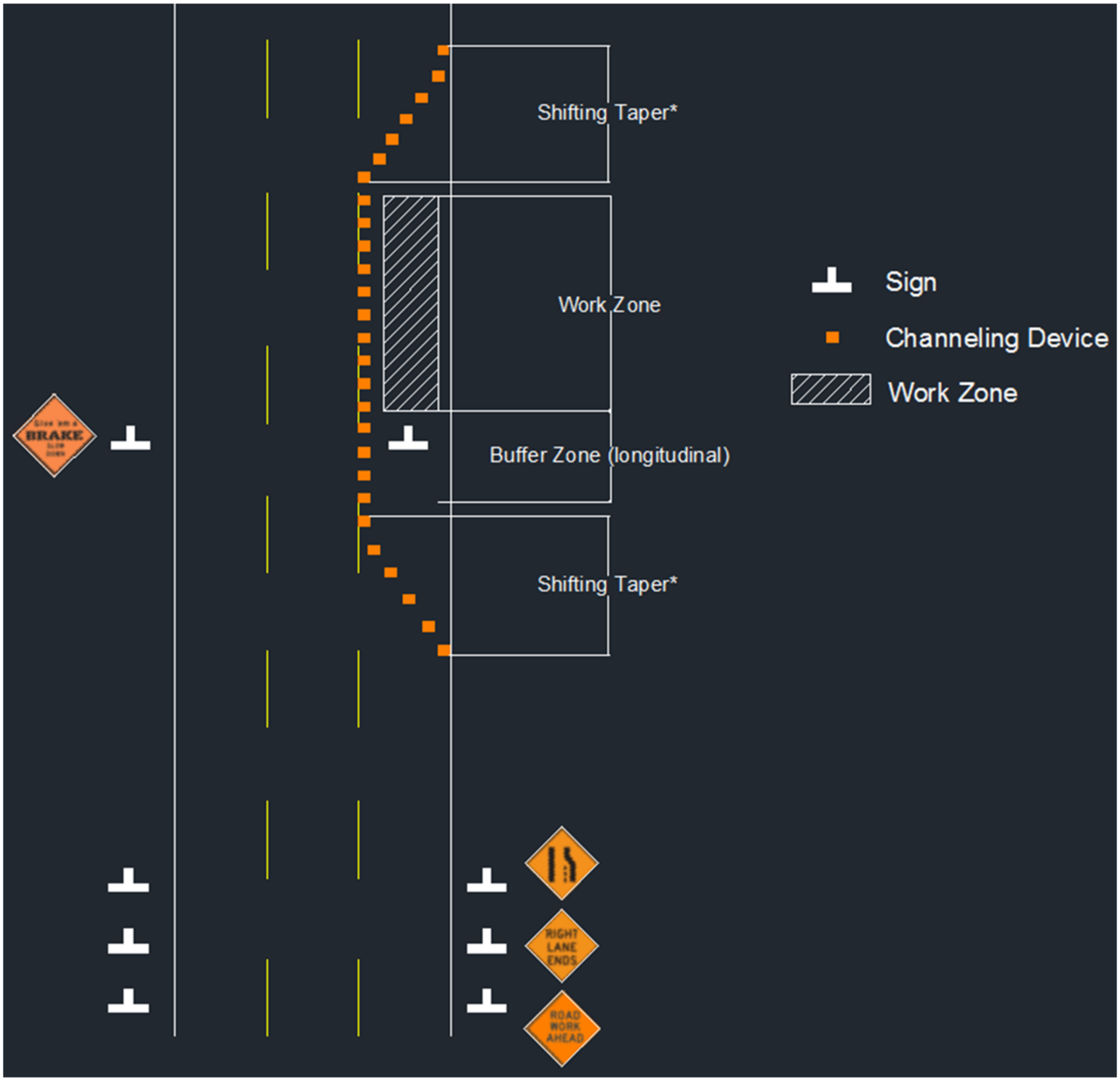

Figure 14. Schematic drawing of highway work zone with the highway work zone billboard

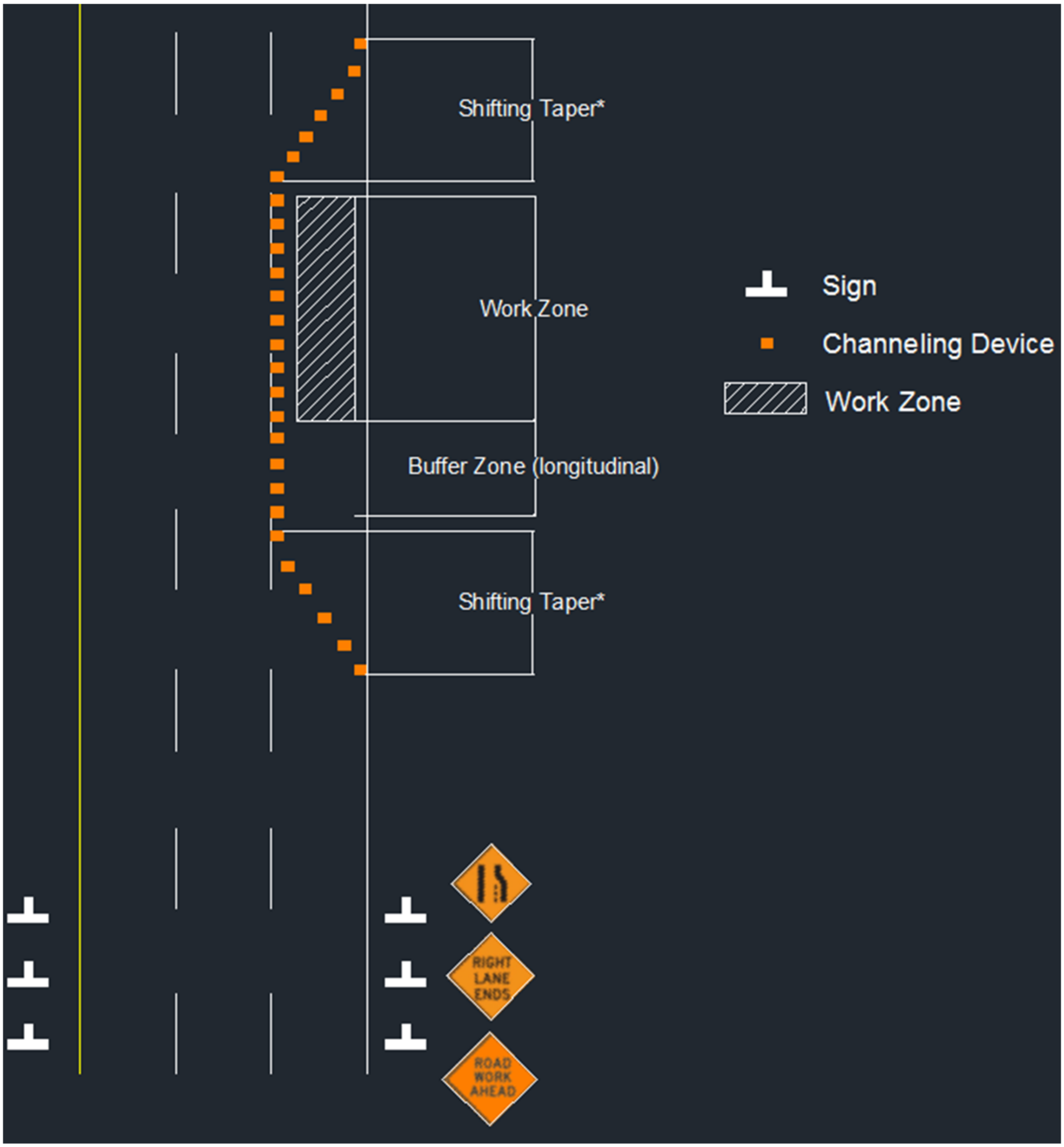

Figure 15. Schematic drawing of highway work zone with a lane reduction of 12 foot lanes to 10 foot lanes

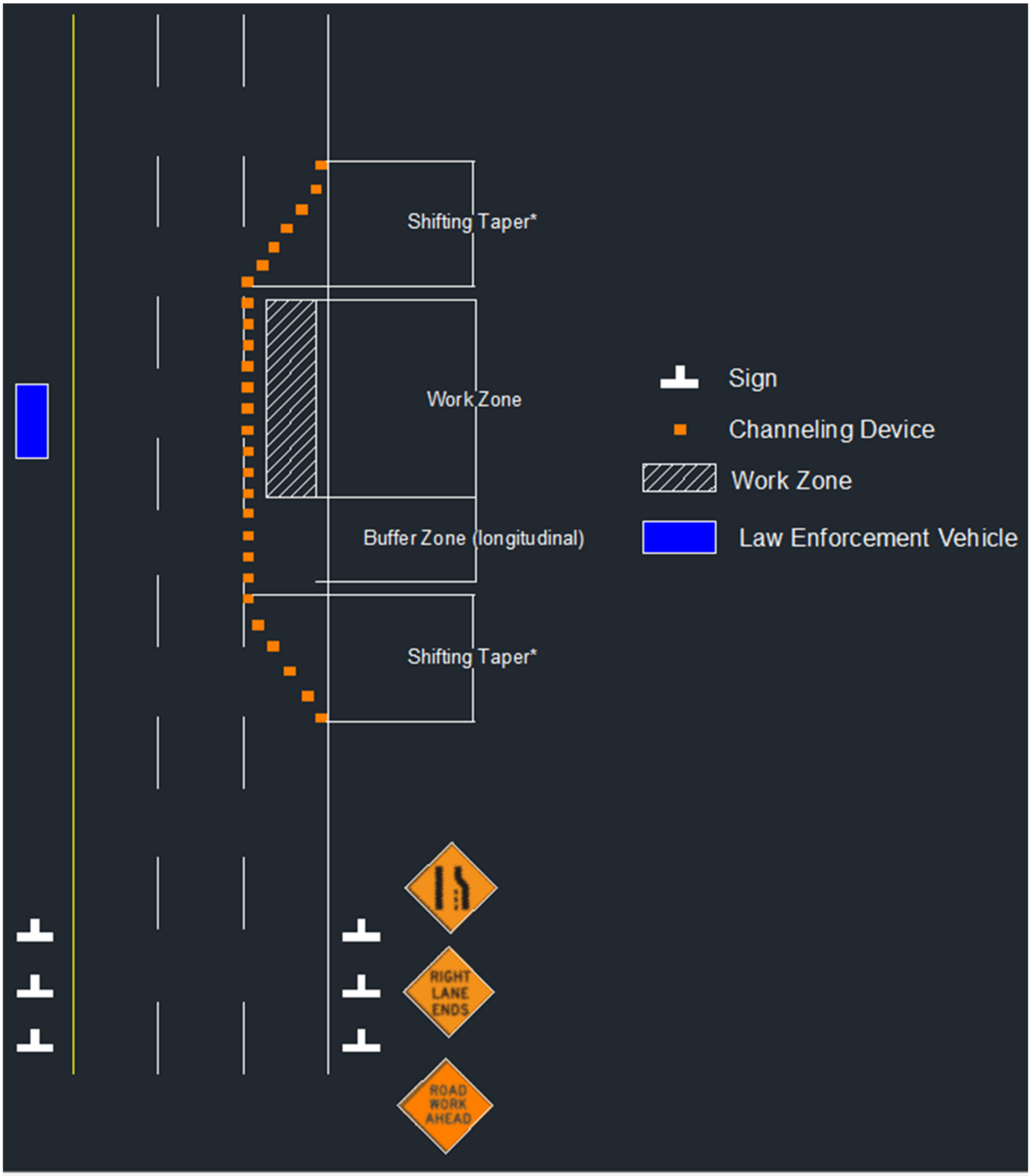

Figure 16. Schematic drawing of highway work zone with law enforcement

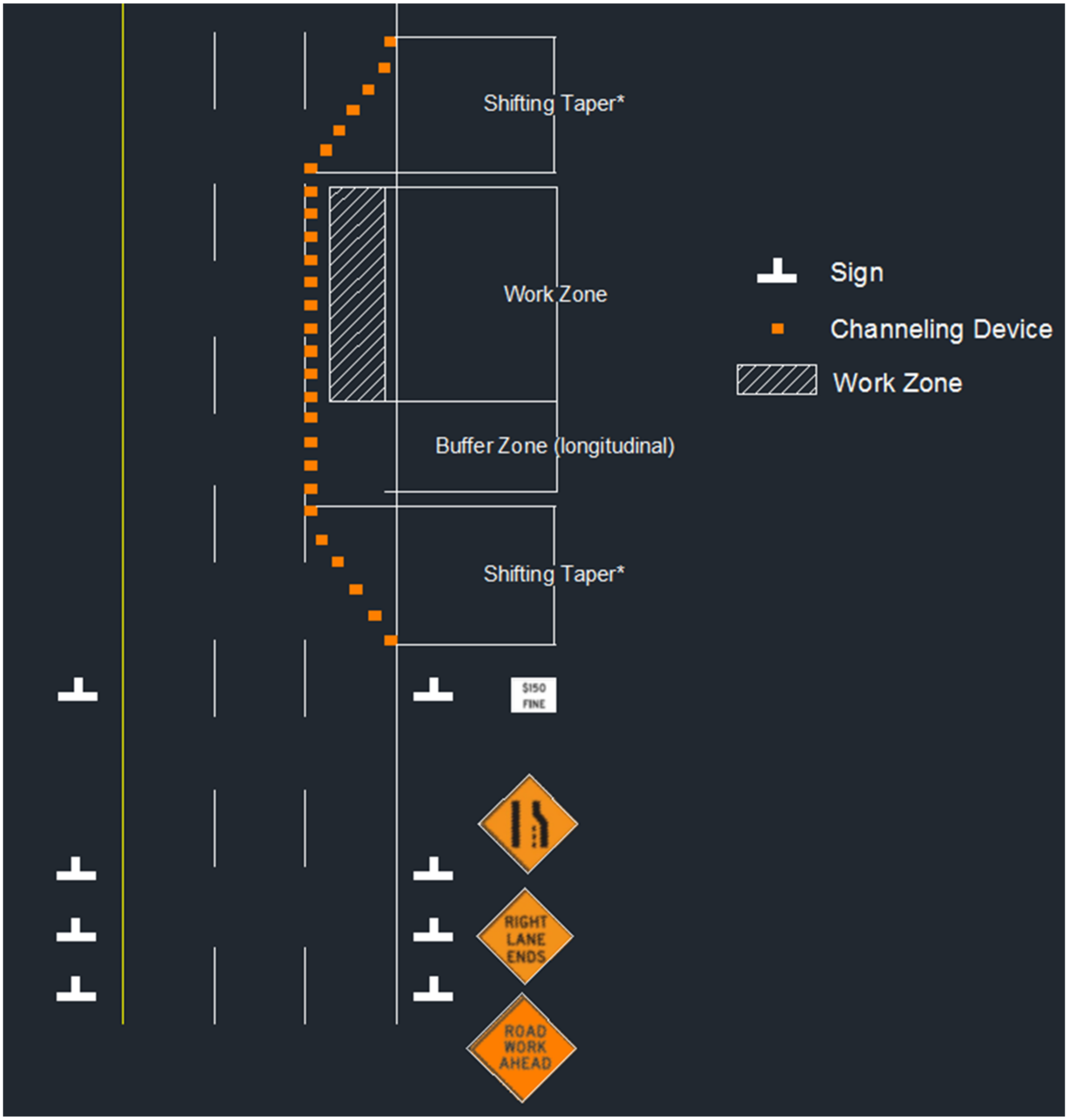

Figure 17. Schematic drawing of highway work zone with a monetary fine sign

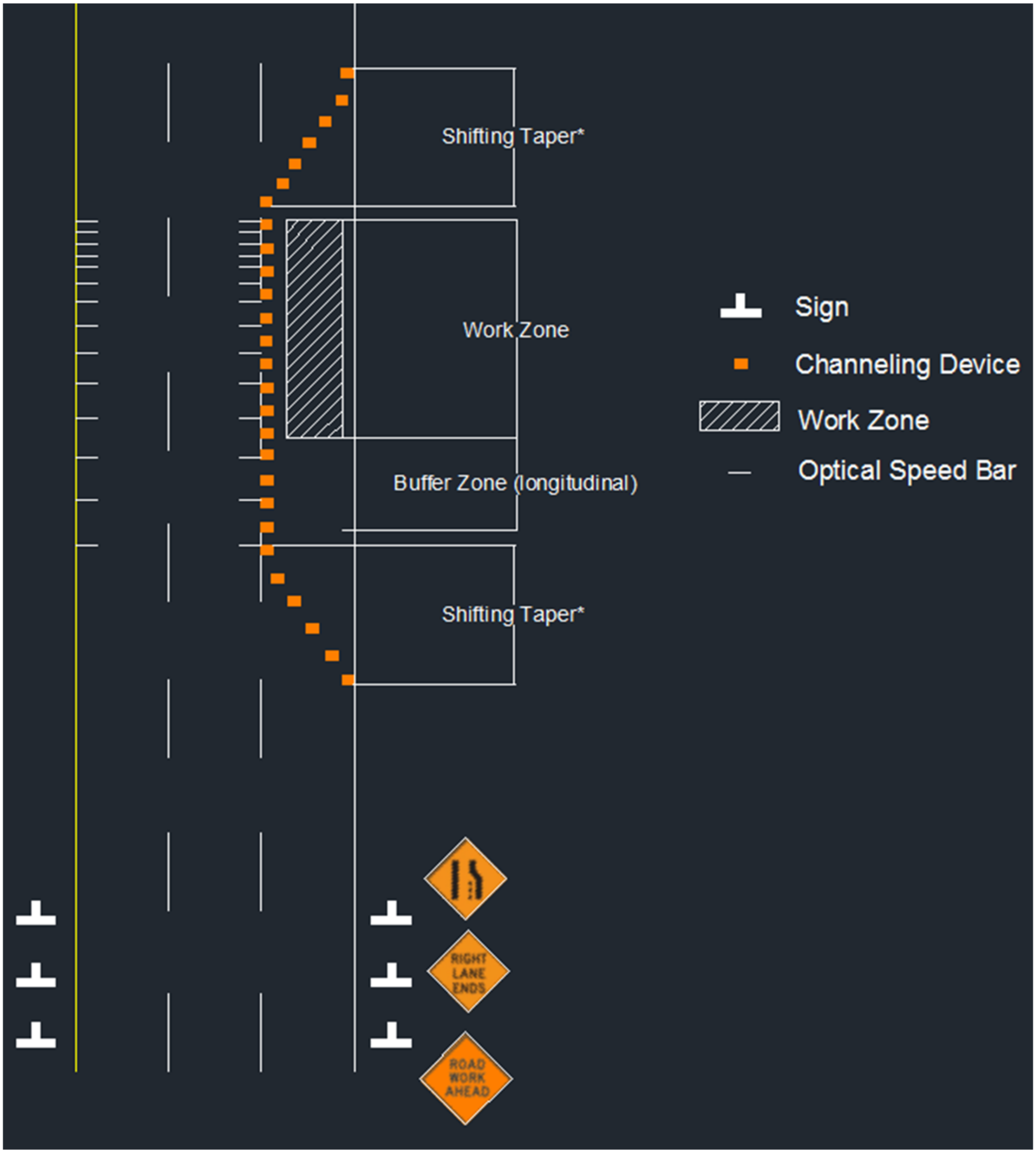

Figure 18. Schematic drawing of highway work zone with optical speed bars

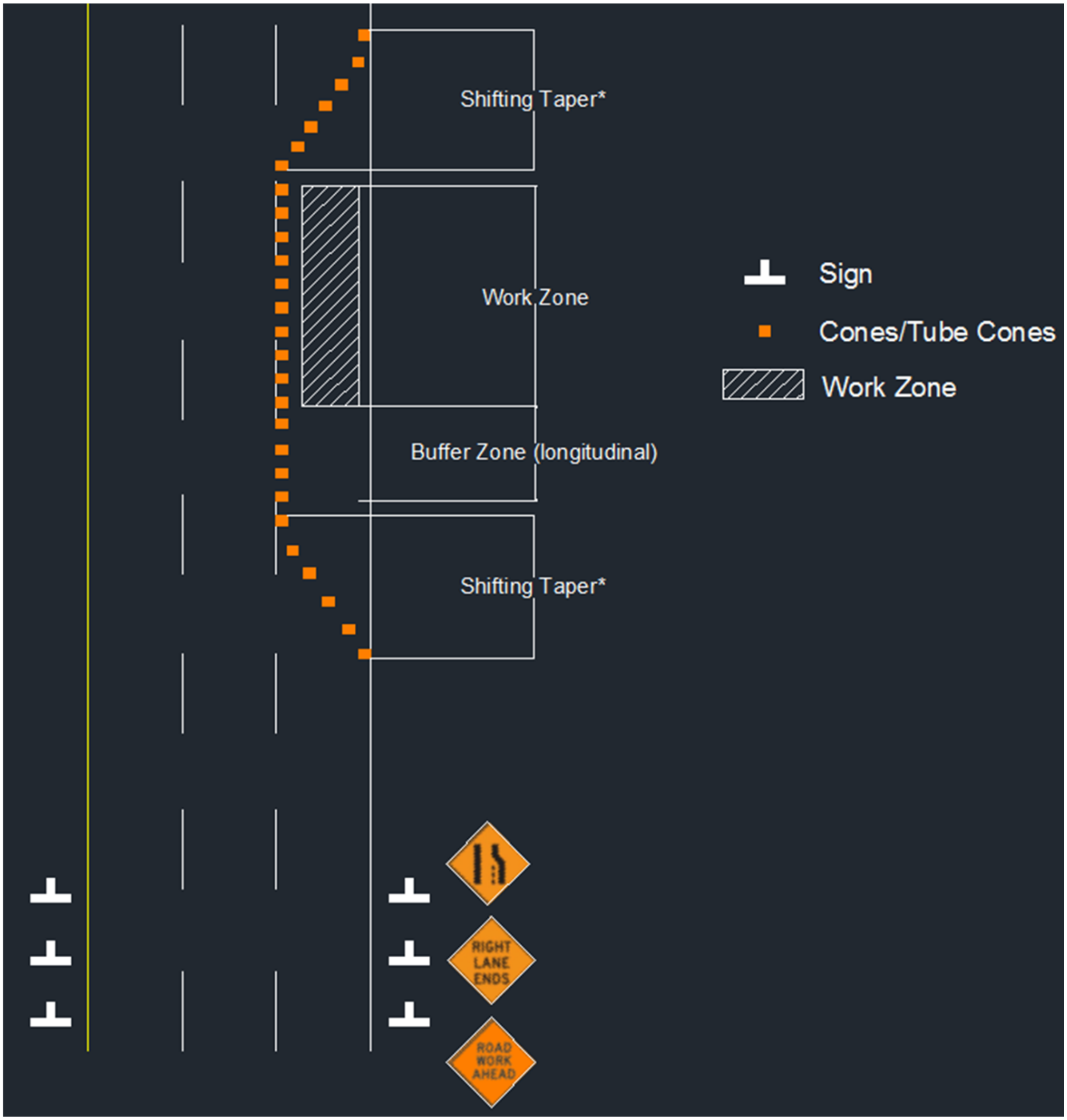

Figure 19. Schematic drawing of highway work zone with other channeling devices

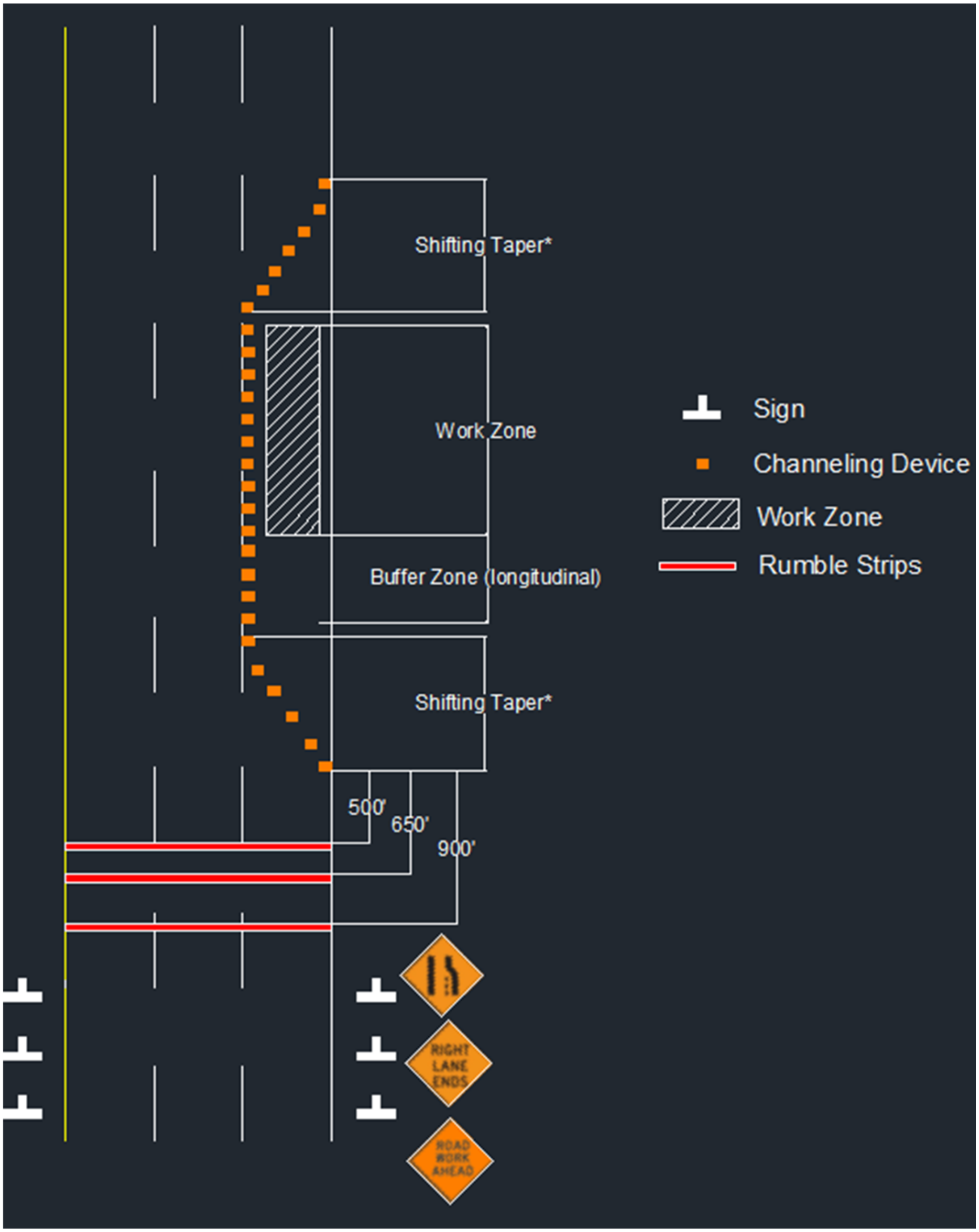

Figure 20. Schematic drawing of highway work zone with 3 sets of 3 rumble strips each

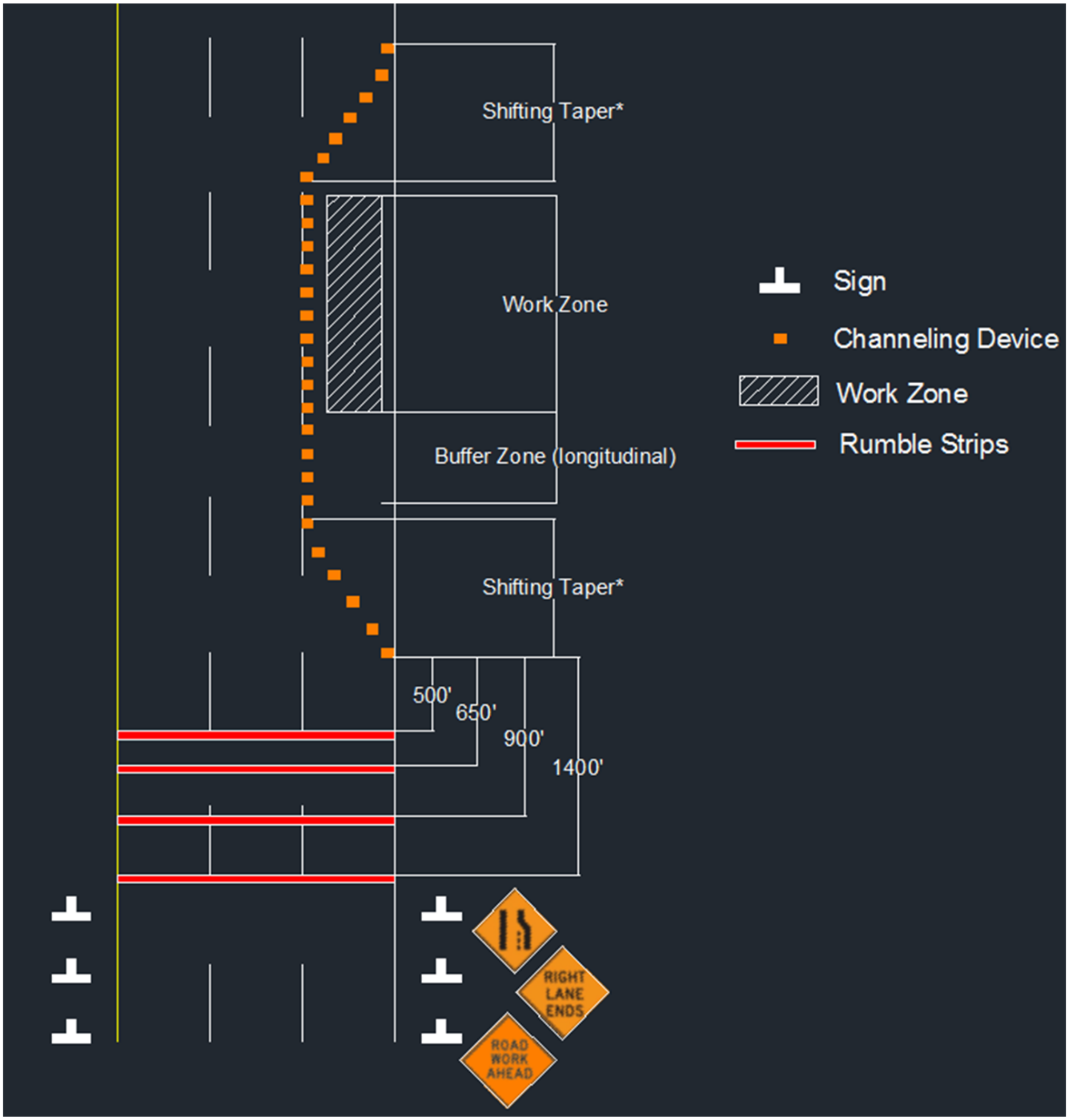

Figure 21. Schematic drawing of highway work zone with 4 sets of 3 rumble strips each

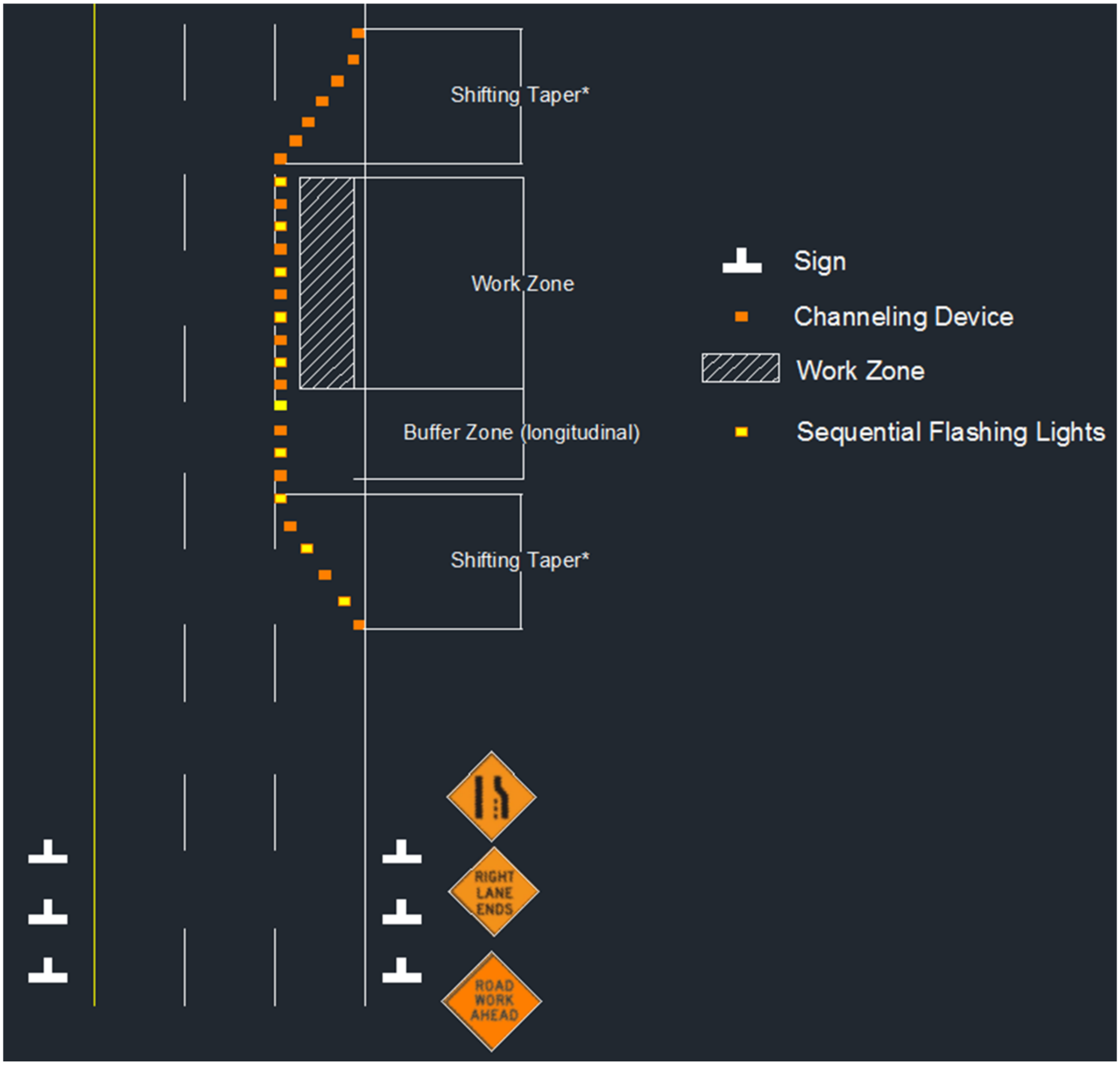

Figure 22. Schematic drawing of highway work zone with sequential flashing lights

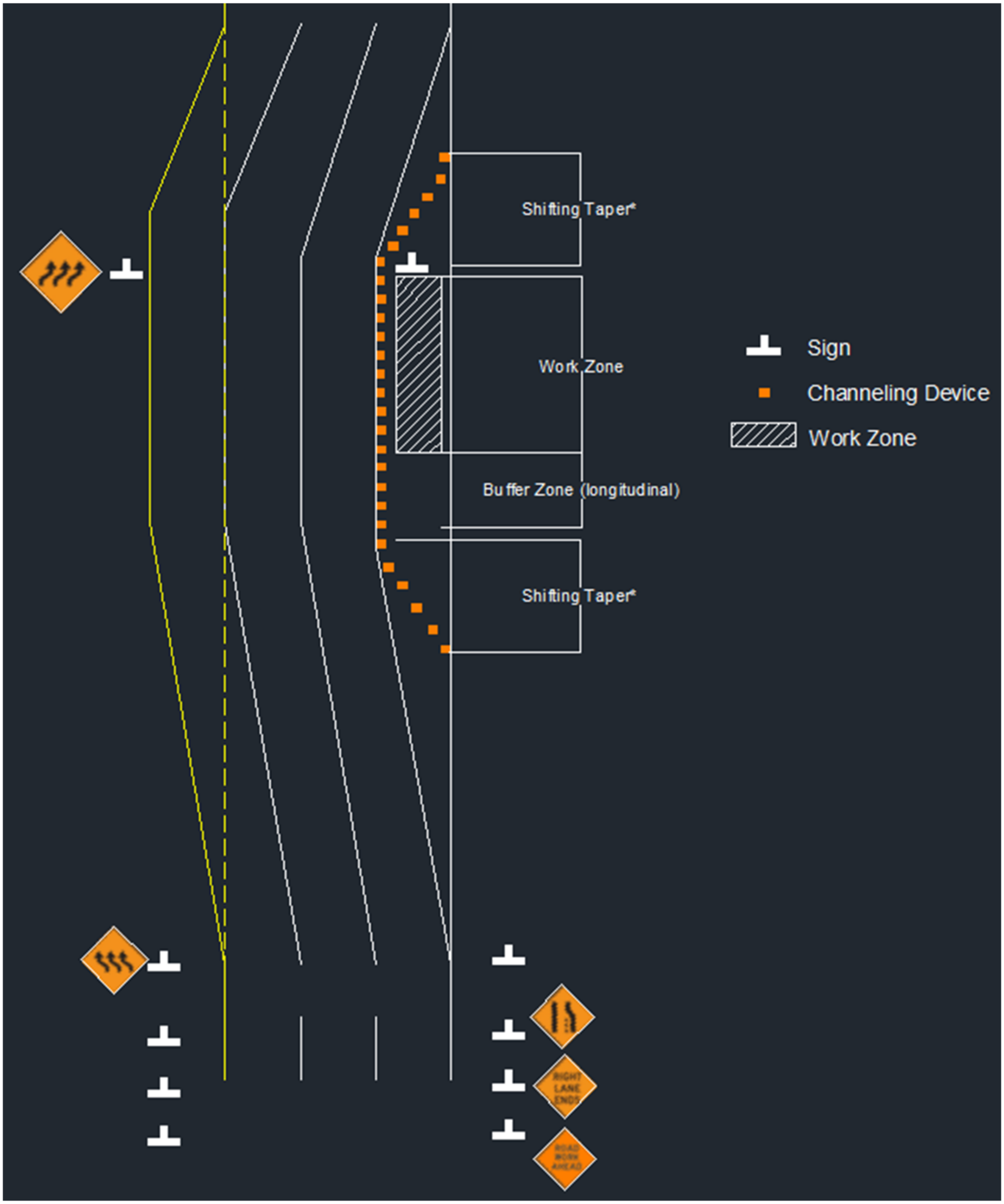

Figure 23. Schematic drawing of highway work zone with shifting lanes

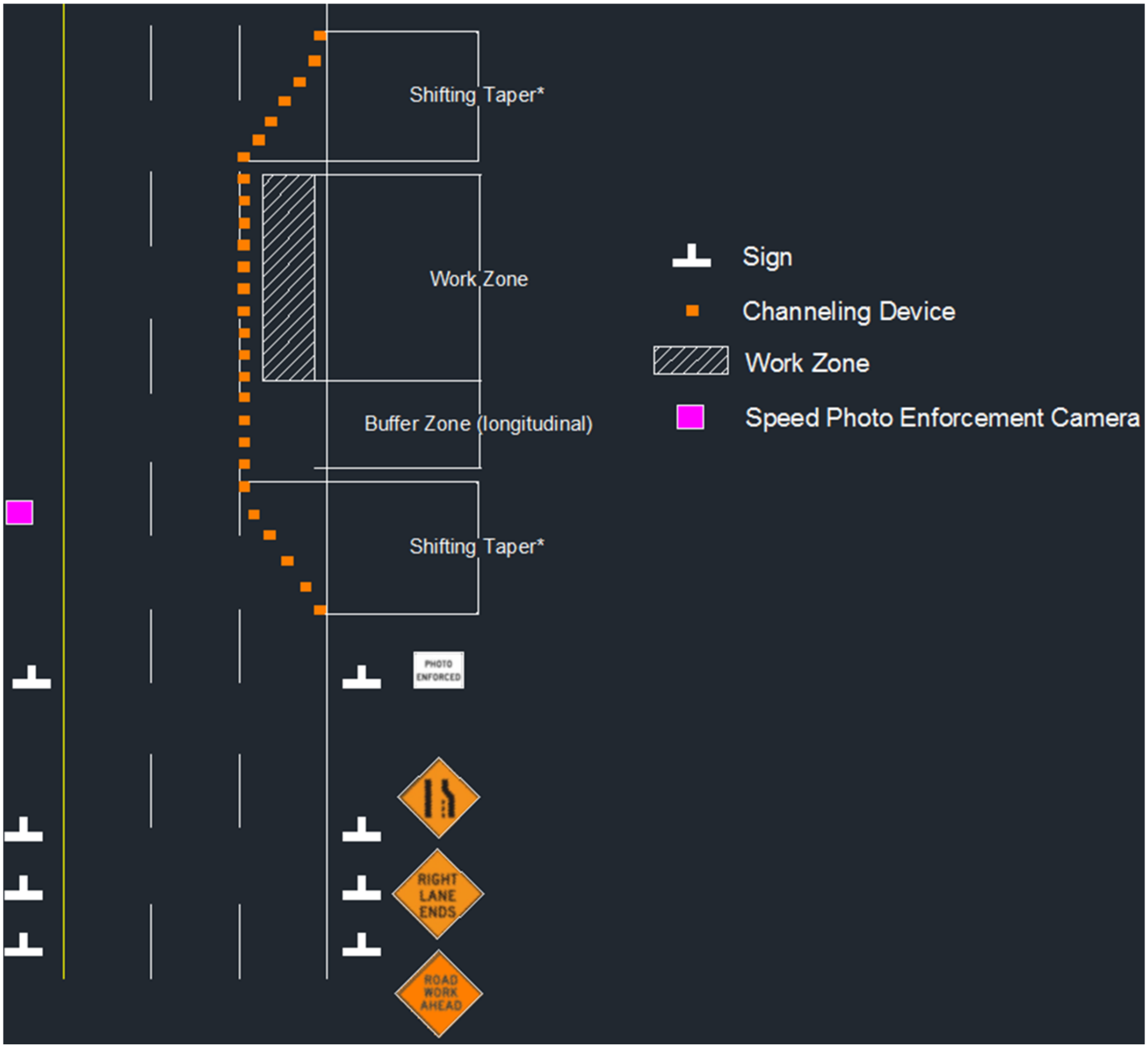

Figure 24. Schematic drawing of highway work zone with speed photo enforcement

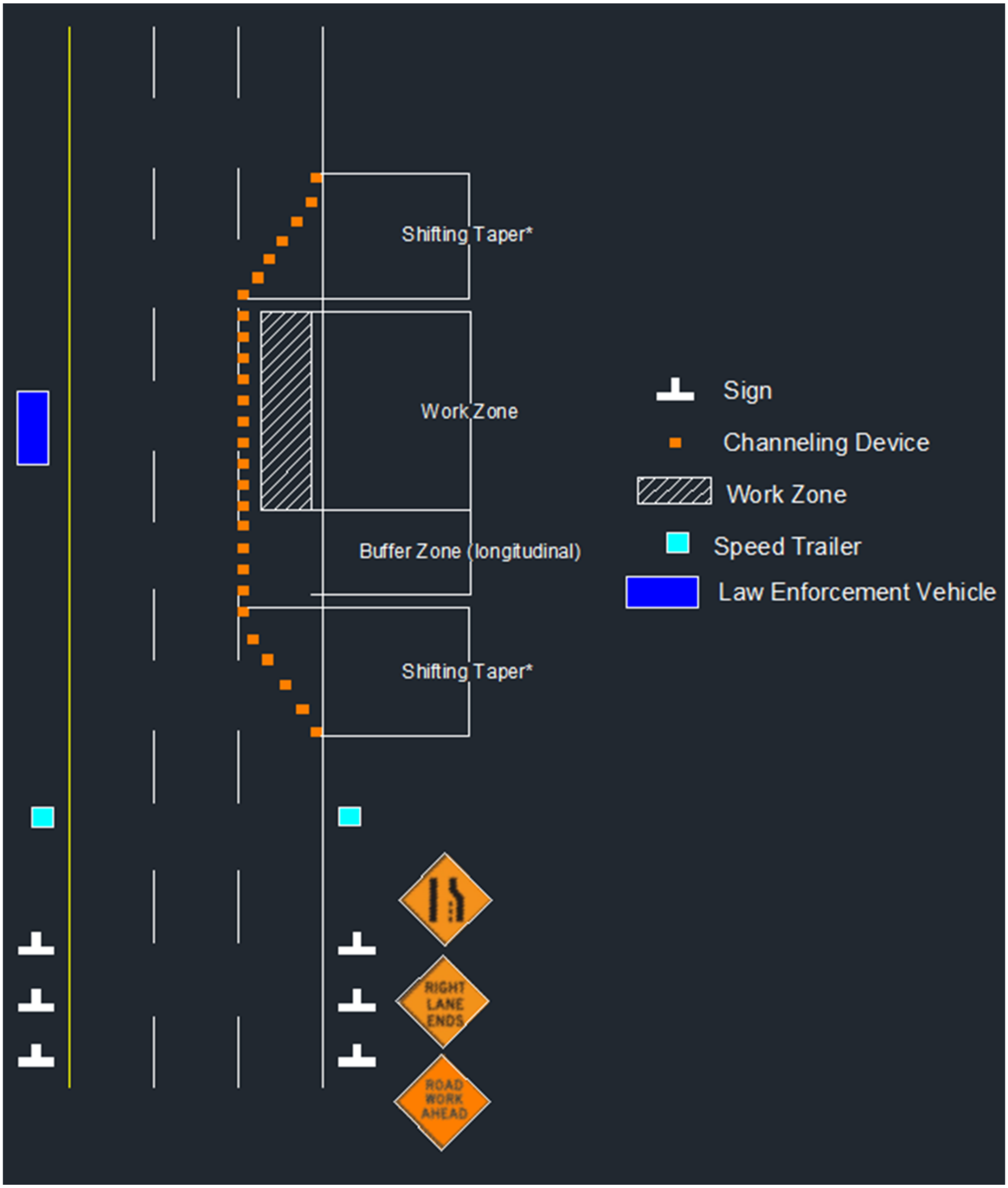

Figure 25. Schematic drawing of highway work zone with speed trailer and law enforcement

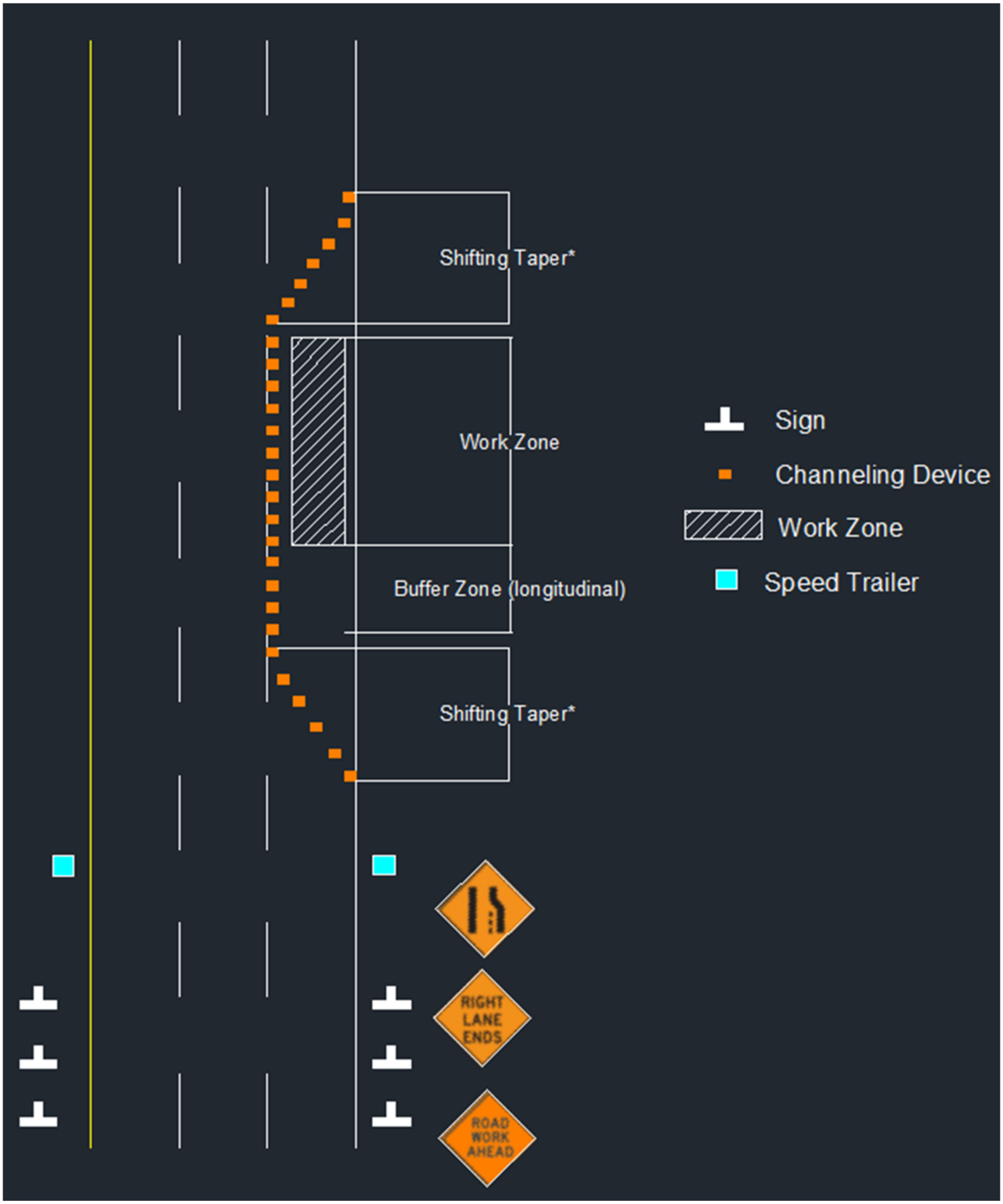

Figure 26. Schematic drawing of highway work zone with speed trailer

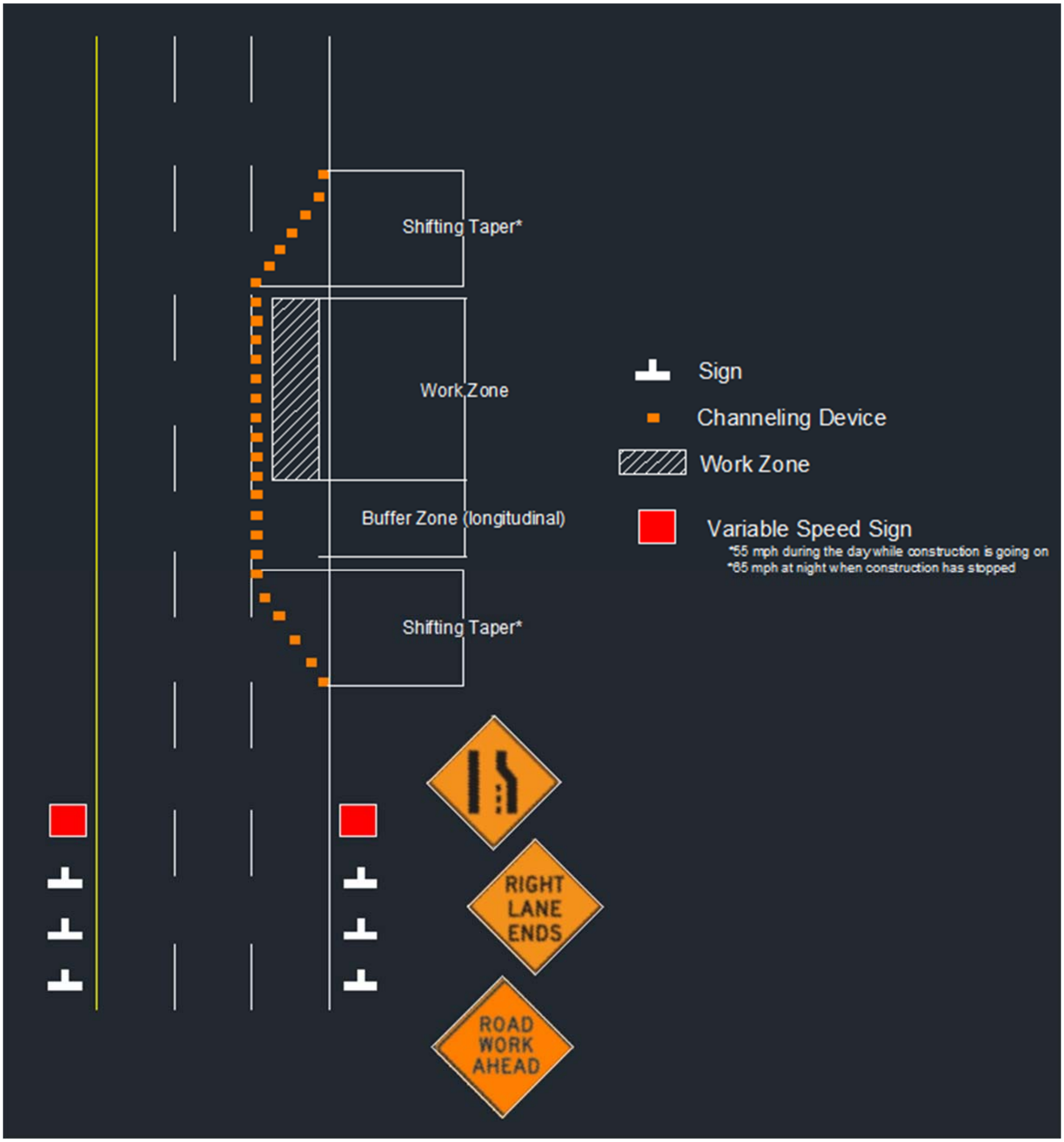

Figure 27. Schematic drawing of highway work zone with variable speed limit signs

4.2 Focus Group Selection

A focus group was selected to drive through the simulator experiment. The focus group was comprised of a sampling of the population of drivers in the state of Ohio, with the specific sample being taken from southeast Ohio drivers. Due to the nature of participant recruitment on a voluntary basis, random sampling for this experiment was not reasonable. As previously discussed, drivers 15-24 years old are the most likely to be involved in a speeding-related fatal crash, with males being involved more often than females [2]. Therefore, participants were recruited to ensure a sample of the most hazardous drivers was represented. Normally, it is desirable to be able to generalize the data and results of a simulator experiment to a population. However, due to research findings of gender and age distributions associated with speeding-related crashes, it was determined that this would not be conducted. Additional data from each participant was collected using a pre-test survey to determine any additional causal relationships. Additional information that was collected centered on the participants driving experience and interaction with work zones while driving. The data included daily commute time, commute time through work zones, work zone crashes, as well as any speeding violations within work zones. Figures 28 through 34 describe the participant sample. In general, the sample included more males with an age grouping mainly between 16 and 25 years old.

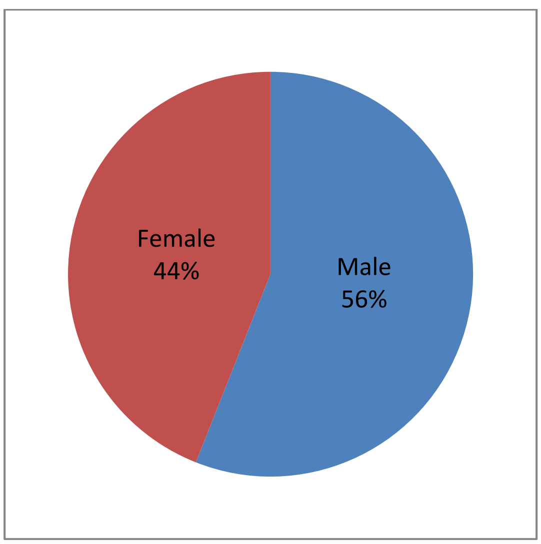

Figure 28. Gender Distribution

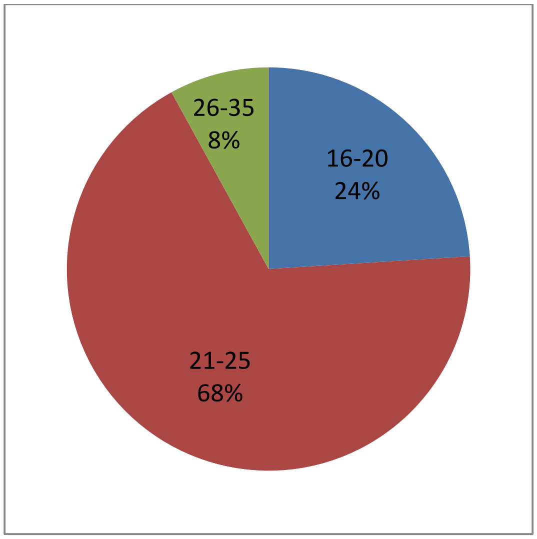

Figure 29. Age Distribution

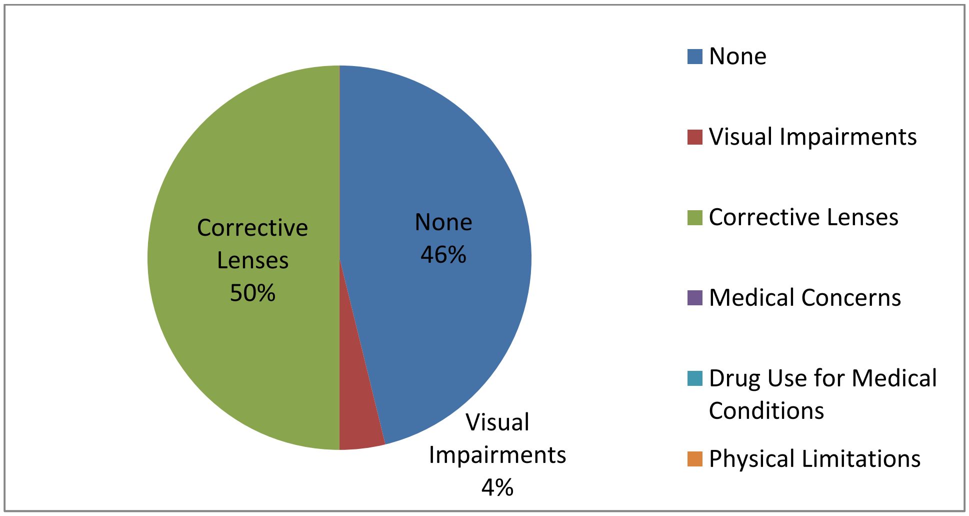

Figure 30. Driving Limitations

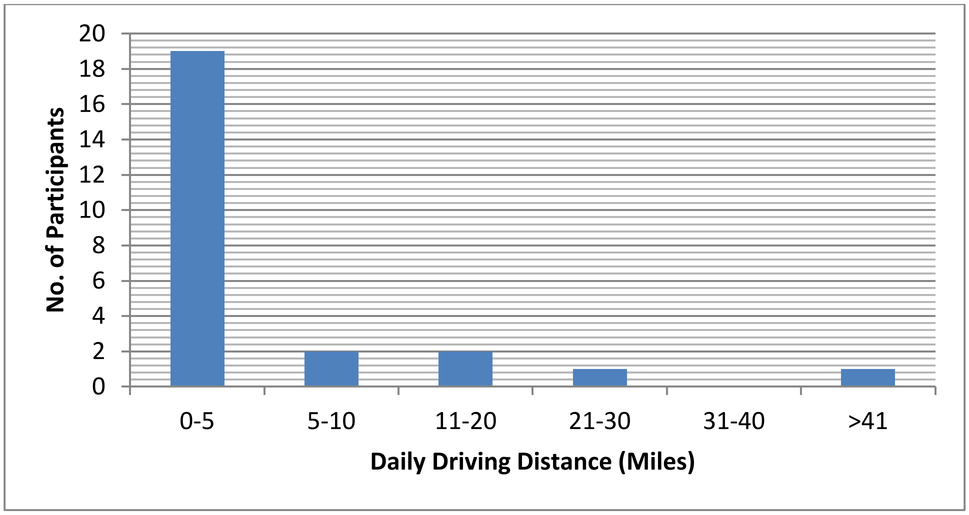

Figure 31. Daily Distance Driven

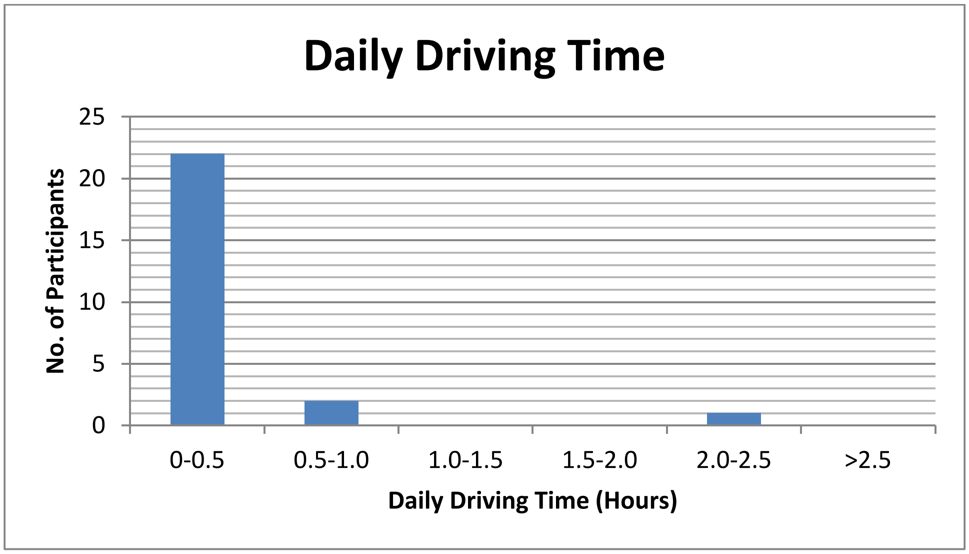

Figure 32. Daily Driving Time

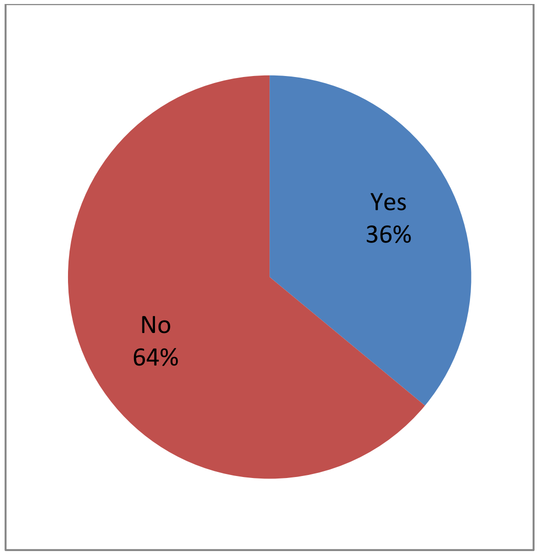

Figure 33. Acknowledged Speeding through Work Zones

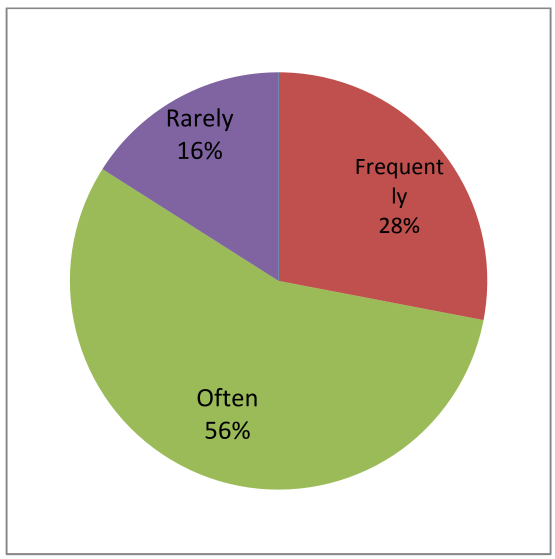

Figure 34. Frequency of Highway Work Zone Encounters

4.3 Simulator Experiment Procedure

A detailed standard test/procedure was developed with standard instructions for each participant to ensure each participant had similar experiences and to reduce bias. Following the pretest questionnaire, each participant was introduced to the simulator and given a brief introduction to the purpose of the driving simulator experiment. The participants were initially familiarized with the vehicle controls and computer generated images of the driving simulator. From there, each participant drove through two simple adaptations scenarios to gain familiarity with the vehicle maneuverability and its control system. The participant was then instructed to drive the simulator vehicle as if they were headed to work or school in their very own vehicle, following the general rules and laws that apply to all Ohio roadways. In order to reduce bias within the data collection, each participant randomly and equally encountered each of the 20 countermeasures in varying random order. To maintain driver awareness and ensure that boredom and/or motion sickness did not occur, the twenty countermeasures were divided into five-10 minute scenarios, each containing four countermeasures.

4.4 Data Collection

The purpose of the simulator experiment was to observe and quantify participant performance while driving through work zones with various countermeasures for speed reduction. The performance of the participants was recorded on the simulator control station. The performance measures included the following: speed, collisions and lateral placement of the vehicle within the travel lane. The data was then compared between each participant throughout each scenario to determine the most effective countermeasure.

The crash data would have been recorded by the simulator and noted anytime a driver came in contact with another object along the roadway; however, collisions did not occur during any of the scenarios. Therefore, crash data could not be utilized for the analysis. Speed data was used as an indicator of perceived risk associated with a given the countermeasure by scenario. The speed data obtained by the simulator was recorded at a speed of 60 Hertz, or approximately 0.034 seconds along the length of the scenario. Each scenario was divided into work zones and non-work zones to allow drivers to return to normal driving habits in between each countermeasure. The speed was analyzed before the work zone and through the work zone to see if there was a variance. The first speed point was taken 500 meters (1640 feet) immediately following the "ROAD WORK 1 MILE." The second speed point varied for each countermeasure. For countermeasures that were a single entity, like a sign or law enforcement vehicle, the average speed was measured at a 500 meter radius around the countermeasure. For other types of countermeasures that spanned the entirety of the work zone, such as presence of highway workers or lane shifts within the work zone, the average speed was measured along the entire work zone. The speed data analyzed was the difference between the first speed point and the second speed point. A positive speed indicated the speeds were higher before encountering the countermeasure, whereas, a negative speed indicated the speeds were higher after encountering the countermeasure. The speed data is shown in Table 2.

Table 2. Speed Data Summary

Scenario	Countermeasure	Mean (mph)	Standard Deviation	Minimum (mph)	Maximum (mph)
A	Variable Speed Limit Sign	10.26	3.87	4.27	20.62
	Sequential Flashing Lights	11.74	4.15	3.21	20.92
	4 sets of 3 Rumble Strips	10.28	3.36	4.21	20.98
	Highway Work Zone Billboard	11.98	3.22	7.68	19.12
B	Speed Trailer	10.60	3.04	1.73	17.03
	Dynamic Message Sign	11.71	3.89	5.23	18.49
	Concrete Barriers	7.98	3.47	0.61	14.69
	Presence of Construction Workers	14.31	4.49	6.28	24.76
C	Law Enforcement	12.78	3.28	7.24	20.78
	Changeable Message Sign	9.23	3.27	2.93	17.49
	Other Channelizing Device	9.14	4.50	0.00	17.69
	Lane Reduction	10.63	4.57	0.27	18.93
D	Speed Trailer with Law Enforcement	10.66	3.01	5.38	15.86
	Monetary Fine	10.44	5.17	0.00	21.44
	3 sets of 3 Rumble Strips	7.81	5.36	0.00	20.96
	Shifting Lanes	12.43	3.69	6.43	21.97
E	Speed Photo Enforcement	12.63	4.40	3.86	26.60
	Emergency Flasher Traffic Control Device	11.39	4.41	2.02	23.03
	Optical Speed Bars	11.68	6.37	2.29	35.87
	Presence of Construction Vehicles	13.50	5.73	0.00	24.17

The last set of data recorded by the simulator was the lateral placement of the vehicle along the roadway. Lane placement or position of a vehicle was quantified in order to assess the ability of the participant to maintain a consistent lane position. The lateral placement is recorded as a relationship to the centerline of the lane, with the centerline having a value of 0.00. If the vehicle travels to the right of the centerline, the value returned is positive and if the vehicle travels to the left of the centerline, the value returned is negative. The lane position was analyzed throughout the entirety of the work zone. The lane placement data is shown in Table 3.

Table 3. Lane Placement Data Summary

Scenario	Countermeasure	Mean (meters)	Standard Deviation	Minimum (meters)	Maximum (meters)
A	Variable Speed Limit Sign	0.42	0.26	-0.05	0.90
	Sequential Flashing Lights	-0.54	0.21	-1.02	-0.03
	4 sets of 3 Rumble Strips	0.31	0.26	-0.06	0.78
	Highway Work Zone Billboard	-0.51	0.20	-0.99	-0.08
B	Speed Trailer	0.33	0.27	-0.11	0.77
	Dynamic Message Sign	-0.51	0.17	-0.84	-0.22
	Concrete Barriers	0.22	0.25	-0.41	0.67
	Presence of Construction Workers	-0.70	0.27	-1.12	0.10
C	Law Enforcement	0.31	0.34	-0.28	0.91
	Changeable Message Sign	-0.52	0.21	-0.85	-0.09
	Other Channelizing Device	0.20	0.27	-0.24	0.85
	Lane Reduction	-0.90	0.27	-1.46	-0.43
D	Speed Trailer with Law Enforcement	0.28	0.31	-0.09	1.16
	Monetary Fine	-0.53	0.21	-0.90	-0.02
	3 sets of 3 Rumble Strips	0.32	0.30	-0.18	0.86
	Shifting Lanes	-0.29	0.15	-0.73	0.03
E	Speed Photo Enforcement	0.31	0.22	-0.12	0.67
	Emergency Flasher Traffic Control Device	-0.57	0.18	-0.85	-0.19
	Optical Speed Bars	0.35	0.29	-0.14	1.08
	Presence of Construction Vehicles	-0.60	0.22	-1.03	-0.17

4.5 Sample Size

In order to determine the detectable difference in speed and lateral lane placement for the statistical analysis while assuring a statistically valid representative sample, the following formula [50] was considered in the estimation of the sample size:

$$n = \frac{Z^2 \times \sigma^2}{\varepsilon^2}$$

Where:

n = estimated sample size

Z = 1.96, the two-tailed value of the standardized normal deviate associated with the desired level of confidence, 95%

σ= standard deviation of the population

ε = acceptable error, or half of the maximum acceptable confidence interval

Unfortunately the above equation only requires knowledge of the standard deviation and the level of confidence or alpha level which corresponds to Type I error. However, the power of the test, 1- β, is not specified nor controlled, which may result in severe reductions in the Type II error rate potentially yielding an irrelevant test result. A second formula for sample size for the comparison of two means, protects for both Type I and Type II errors [51,52,53]. The equation for the comparison of two means, such as mean speeds or lateral lane placement, is as follows:

$$n = \frac{\left(Z_{\beta} - Z_{\alpha/2}\right)^2 \times \sigma^2}{\varepsilon^2}$$

Where:

Z_{β}= critical value corresponding to a given value of β in the upper tail of the standard normal distribution

Z_{α}= critical value corresponding to a given value of $\alpha/2$ in the lower and upper tail of the standard normal distribution

σ= standard deviation of the difference

ε= detectable difference in the means

Based upon the sample sizes collected in the driving simulator study, the detectable difference in means were calculated for the speed data and the lateral lane placement data. The level of confidence was selected at 95 percent or alpha equal to 0.05 and the power was selected at 80 percent or beta equal to 0.20. Given a sample size of 25 participants, a detectable difference of 2.33 miles per hour for speed and 0.13 meters or 0.44 feet for lateral lane placement was possible. Past researchers examined differences in mean speeds ranging between one mph and five mph; one research found statistically significant differences of one mph [54], four found differences of two [54-57] and three mph [58-61], two found differences of four mph [62,63], and three found differences in five mph [64-66]. Therefore, the detectable differences possible for this research were reasonable.

4.6 Statistical Analysis

The statistical significance of the various speed reduction countermeasures was determined through examination of the performance measures of collisions, speed, and lateral lane placement. The statistical analysis was conducted to determine if the differences between the various scenarios were attributable to the countermeasure or chance. In order to compare several means simultaneously in the simulator experiment, a one-way analysis of variance (ANOVA) was utilized to determine if the means were similar. Although a Student's t-test could have been conducted on the same data, several iterations of the t-test would have been required to compare all possible scenarios. However, the Type 1 error rate is greater when multiple t-tests are conducted. On the other hand, the ANOVA determines the level of confidence based upon the number of variable categories that are being compared.

To perform the ANOVA, an F-statistic is calculated which is equal to the mean squares between the groups divided by the mean squares within the groups. If F- calculated was greater than the F-critical obtained in available statistical tables, the difference in the means was statistically significant. When conducting the ANOVA test, the Levene's test for equal variances was performed simultaneously. When the Levene's test indicated that the variances were equal, the ANOVA calculated F-statistic was reported. If the variances were determined not to be equal, the Welch's modification to the ANOVA was conducted and the calculated F value based upon an asymptotically distribution was reported. The equations used to perform this test are as follows [53]:

$$SS_T = \sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2 - \frac{T^2}{N}$$

Where:

SS_T = Total sum of squares

$$\sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2$$ = squared scores summed across all individuals and groups

K = Number of groups

n = Number of observations

T = sum of scores summed across all observations and groups

N = total number of scores

$$SS_B = \sum_{k=1}^{K}\frac{T_k^2}{n_k} - \frac{T^2}{N}$$

Where:

SS_B = Sum of squares between-groups

T_k= sum of observations for k^{th} group

$$SS_W = \sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2 - \sum_{k=1}^{k}\frac{T_k^2}{n_k}$$

Where:

SS_W = Sum of squares within-groups

$$MS_B = \frac{SS_B}{K - 1}$$

$$MS_W = \frac{SS_W}{N - K}$$

$$F_{calc} = \frac{MS_B}{MS_W}$$

Where:

MS_B = Mean sum of squares between-groups

MS_W = Mean sum of squares within-groups

When statistically significant results are obtained in the ANOVA, the only conclusion that can be drawn from the test is that differences exist between the means. However, the determination of which two means are in fact not equal cannot be concluded. Therefore, in order to solve this issue, post-hoc tests can be utilized to assist in specific comparisons among groups.

There are numerous post-hoc tests that have been established for various assumptions or violation of assumptions. Most of the post-hoc tests have been shown in past statistical research to withstand small deviations from normality. The Tukey post hoc test was utilized for the speed data analysis due to the homogeneous variances and equal sample sizes while the Games-Howell post hoc test was utilized for the lane placement data due to the heterogeneous variances.

The statistical tests performed in this research indicated whether the differences in comparisons made were statistically significant. However, a comparison being significantly statistically different indicates only that the probability of the difference between the experimental data and the expected values computed from a given statistical distribution occurring due to chance is less than the significance level, in this research alpha equaled 0.05. Statistical significance is based on the standard error of the sample which can be controlled by sample sized. Large sample sizes lower the standard error and will correspondingly lower the threshold for considering differences to be significant. Conversely, a small sample size can cause a large difference between groups to be statistically insignificant when in reality the difference may be practically significant.

One method provided to consider the practical significance of a result is through the calculation of the effect size. By definition the effect size is the degree to which a phenomenon exists. In this research, the phenomenon would be the diamond grade sheeting caused statistically significant differences in lane placement and traveled speed within work zones when compared to the high intensity sheeting. The effect size calculated is a measure of the number of standard deviations the difference between the groups is from the null hypothesis. The effect size was calculated as follows:

$$r = \sqrt{\frac{SS_B}{SS_T}}$$

Where:

r = effect size
SS_B = sun of squares between groups
SS_T = total sum of squares

Based on standards presented by Cohen, the practical significance, or actual difference of the comparisons made, is as follows:

r = 0.20	Small Effect
r = 0.50	Medium Effect
r = 0.80	Large Effect

5.0 RESULTS

5.1 Speed

The analysis of speed data was used as an indication of a motorist's perceived risk of traveling through a specific area of the work zone given various speed reduction countermeasures. For the comparison of mean speed between the various countermeasures, the mean speeds and standard deviations previously calculated were utilized in statistical tests to determine if the mean speed for each countermeasure was statistically significant. The null hypothesis for the speed analysis was that there was no difference between the mean speed deviations for the 20 speed reduction countermeasures. The ANOVA was utilized to determine the effectiveness of the various speed reduction countermeasures. Based upon the statistical analysis, the null hypothesis was rejected for the speed data. The results of the statistical analysis for speed are shown in Table 4.

Table 4. Speed Statistical Results

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calc.	Test Result; Effect Size
Between Groups	1381.799	19	72.726	4.002	Reject Null ES = 0.37
Within Groups	8723.763	480	18.175		
Total	10105.562	499			

The effect size was calculated as 0.37 indicating a medium effect. Therefore, the mean speeds were statistically and practically significantly different. However, further analysis was required to determine which of the speed reduction countermeasures was indeed effective in reducing speed through work zones. Since all mean speed deviation values were positive values this indicated that the speeds were higher prior to participants encountering the speed reduction countermeasure. This could indicate that all of the speed reduction countermeasures were effective to some degree; however, statistical post hoc analyses explain the statistical significance of such assumptions. Due to the vast results for the post hoc tests, details on the analysis will not be provided; however, results from the test are discussed. The Tukey post hoc tests indicated that the presence of construction workers, presence of construction vehicles, law enforcement, speed photo enforcement and shifting lanes were most effective at reducing speeds in work zones. These findings support previous research indicating construction workers, vehicles and law enforcement are most effective at reducing speeds with average speed reductions over 10 mph. This indicates that the additional findings of the simulator study are generalizable to real world applications. The least effective speed reduction countermeasures included 3 sets of 3 rumble strips, concrete barriers, other channelizing devices and changeable message signs with speed reductions less than 10 mph. The remaining 11 countermeasures were all found to be similar in nature with an approximate 10 mph speed reduction. The countermeasures are shown in Table 5 in order of their effectiveness, with 1 being the most effective.

Table 5. Speed Reduction Countermeasure Effectiveness

Rank	Countermeasure	Mean Speed Reduction (mph)
1	Presence of Workers	14.31
2	Presence of Construction Vehicles	13.50
3	Law Enforcement	12.78
4	Speed Photo Enforcement	12.63
5	Shifting Lanes	12.43
6	Highway Work Zone Billboard	11.98
7	Sequential Flashing Lights	11.74
8	Dynamic Message Signs	11.71
9	Optical Speed Bars	11.68
10	Emergency Flasher Traffic Control Device	11.39
11	Speed Trailer with Law Enforcement	10.66
12	Lane Reduction	10.63
13	Speed Trailer	10.60
14	Monetary Fine	10.44
15	4 sets of 3 Rumble Strips	10.28
16	Variable Speed Limit Sign	10.26
17	Changeable Message Sign	9.23
18	Other Channelizing Devices	9.14
19	Concrete Barriers	7.97
20	3 sets of 3 Rumble Strips	7.81

5.2 Lane Placement

Lane placement data was collected for to assess the ability of the participant to maintain a constant lane position. For the comparison of mean lateral lane placement between the various countermeasures, the mean lateral lane placements and standard deviations previously calculated were utilized in statistical tests to determine if the mean lane placement for each countermeasure was statistically significant. The null hypothesis for the lane placement analysis was that there was no difference between the mean lane placements for the 20 speed reduction countermeasures. The ANOVA was utilized to determine the effectiveness of the various speed reduction countermeasures. The lane placement data was found to have heterogeneous variances which require a modification (Welch) to the analysis. Based upon the statistical analysis, the null hypothesis was rejected for the lateral lane placement data. The results of the statistical analysis for lane placement are shown in Table 6.

Table 6. Lane Placement Statistical Results

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Squares (MS)	F-Calc.	Test Result; Effect Size
Between Groups	100.67	19	5.299	80.003	Reject Null ES = 0.88
Within Groups	29.656	176.742	0.62		
Total	130.330	195.742			

The effect size was calculated as 0.88 indicating a large effect. Therefore, the mean lane placements were statistically and practically significantly different. However, further analysis was required to determine which of the speed reduction countermeasures was indeed. Lateral lane placement data, as previously discussed, describes the distance the participant deviated from the centerline of the lane in which they were traveling. A negative lane placement indicates the motorists were left of center whereas a positive lane placement indicated the participants were right of center. As the lane closures throughout the driving simulator experiment were right lane closures, a placement too far right of center could indicate a potential for work zone intrusion and a placement too far left of center could indicate a potential for sideswipe crashes with vehicles in adjacent travel lanes. Therefore, it is desirable for the speed reduction countermeasure to reduce speeds while allowing the drivers to maintain a position closest to the center of the travel lane. The travel lanes in the simulator were designed as 12 foot lanes. Assuming a 7-foot vehicle width, a distance between the edge of the vehicle and the lane line of 2.5 feet would be available. It was assumed that a clearance of less than one foot would be unacceptable in terms of safety. Therefore, the statistical post hoc analyses were utilized to explain the statistical significance of each countermeasure. Due to the vast results for the post hoc tests, details on the analysis will not be provided; however, results from the test are discussed. The Games Howell post hoc tests with evaluation of mean lane placement data indicated that the countermeasures could be subdivided into six categories; vehicles located 1) 1.1 feet from the lane line nearest the work zone, 2) 1.5 feet from the lane line nearest the work zone, 3) 1.5 feet from the lane line nearest adjacent traffic, 4) 0.82 feet from the lane line nearest adjacent traffic, 5) on the lane line nearest adjacent traffic, and 6) 0.5 feet intrusion into the adjacent lane with traffic . It is important to note that not all speed reduction countermeasures exactly matched the categories outlined above, but values were taken as means representing the groups. Based upon the above discussion, countermeasures identified in groups four through six were considered to increase safety risk through the work zone. The countermeasures are shown in Table 7 by category.

Table 7. Speed Reduction Countermeasure Effectiveness via Lane Placement

Category	Countermeasure	Mean Lane Placement (meters)
1	Variable Speed Limit Sign	0.42
2	Optical Speed Bars	0.35
	Speed Trailer	0.33
	3 sets of 3 Rumble Strips	0.32
	4 sets of 3 Rumble Strips	0.31
	Law Enforcement	0.31
	Speed Photo Enforcement	0.31
	Speed Trailer with Law Enforcement	0.28
	Concrete Barriers	0.22
	Other Channelizing Devices	0.20
3	Shifting Lanes	-0.29
4	Highway Work Zone Billboard	-0.51
	Dynamic Message Signs	-0.51
	Changeable Message Sign	-0.52
	Monetary Fine	-0.53
	Sequential Flashing Lights	-0.54
	Emergency Flasher Traffic Control Device	-0.57
	Presence of Construction Vehicles	-0.60
5	Presence of Workers	-0.70
6	Lane Reduction	-0.90

5.3 Focus Group Post-Test Summary

After the participants completed the scenarios, each person was asked to fill out a post-test questionnaire. The questionnaire asked the participant to choose two of methods that they thought were the most effective at lowering their personal speed throughout the scenarios. As shown by the results of that questionnaire in Table 8, it's again obvious that the consensus remains that the most effective method was the presence of construction workers along with the presence of law enforcement. Speed photo enforcement, which also proved effective in the speed analysis, was also represented in the top three measures as selected by the participants.

Table 8. Results of the participant post-test questionnaire

Countermeasure	Total Responses
Law Enforcement	12
Presence of Construction Workers	10
Speed Photo Enforcement	6
Optical Speed Bars	3
Presence of Construction Vehicles	3
Rumble Strips	2
Speed Trailer	2
Lane Reduction	2
Monetary Fine	2
Shifting Lanes	2
Emergency Flasher Traffic Control Device	2
Variable Speed Limit	1
Dynamic Message Sign	1
Concrete Barrier	1
Speed Trailers	1
Sequential Flashing Lights	0
Highway Work Zone Billboard	0
Changeable Message Sign	0
Other Channelizing Devices	0

6.0 CONCLUSIONS

The main objective of this study was to determine the safest and most effective countermeasure for the reduction of vehicular speeds within construction and maintenance work zone. The goal of this research was to determine driver performance and behavioral changes as a result of the presence of various speed reduction techniques during work zone roadway conditions.

The specific purpose of the simulator experiment was to determine the effectiveness of a 20 countermeasures on the reduction of speed through work zones in a controlled laboratory setting. The literature review identified several past research studies utilizing speed reduction countermeasures in work zones and under normal traffic conditions. From this review, 20 countermeasures were selected for evaluation based upon discussions with ODOT personnel. The simulator experiment research methodology was designed to allow active participation by the subjects in the driving simulator instead of passive participation. The data was also extracted without the presence of the participants making the participants unaware of the measure of performance collected for analysis. Therefore, the participants were able to utilize the driving simulator without knowing the ramifications of their actions. Several countermeasures chosen have been previously researched on different roadway geometrics and configurations. The comparison for this simulator study allowed all of the countermeasures to be conducted on a similar roadway in similar conditions.

Combining the results from the speed and lateral lane placement analysis, each of the 20 speed reduction countermeasures has advantages and disadvantages. Table 9 outlines each countermeasure and conclusions regarding their potential effectiveness.

Table 9. Countermeasure Conclusive Summary

Countermeasure	Speed Reduction (mph)	Lane Placement	Advantages	Disadvantages
Presence of Workers	14.31	On lane line nearest traffic	• Most Effective Countermeasure • Keeps Drivers further away from Work Zone	• May increase potential for sideswipe crashes • Does not reduce speeds when work not present
Presence of Construction Vehicles	13.50	Near traffic lane	• Most Effective Countermeasure • Keeps Drivers further away from Work Zone •	• Impacts driver lane placement • May increase potential for sideswipe crashes • Does not reduce speeds when work not present
Law Enforcement	12.78	Acceptable Position, work zone side	• Very Effective Countermeasure • Does not impact driver lane placement	• Costly to jurisdictions • Coordination required • Potential poor utilization of officers
Speed Photo Enforcement	12.63	Acceptable Position, work zone side	• Very Effective Countermeasure • Does not impact driver lane placement • Financial Generator	• Potential Public Privacy Concerns
Shifting Lanes	12.43	Acceptable Position, traffic lane side	• Very Effective Countermeasure • Keeps Drivers away from Work Zone • Does not impact driver lane placement	• Feasibility Concerns in most projects
Highway Work Zone Billboard	11.98	Near traffic lane	• Keeps Drivers further away from Work Zone	• Impacts driver lane placement • May increase potential for sideswipe crashes
Sequential Flashing Lights	11.74	Near traffic lane	• Keeps Drivers further away from Work Zone	• Impacts driver lane placement • May increase potential for sideswipe crashes
Dynamic Message Signs	11.71	Near traffic lane	• Keeps Drivers further away from Work Zone	• Impacts driver lane placement • May increase potential for sideswipe crashes
Optical Speed Bars	11.68	Acceptable Position, work zone side	• Does not impact driver lane placement	• Potentially confusing pavement markings
Emergency Flasher Traffic Control Device	11.39	Near traffic lane	• Keeps Drivers further away from Work Zone	• Impacts driver lane placement • May increase potential for sideswipe crashes
Speed Trailer with Law Enforcement	10.66	Acceptable Position, work zone side	• Does not impact driver lane placement	• Costly to jurisdictions • Coordination required • Potential poor utilization of officers

Lane Reduction	10.63	Traffic lane intrusion	• Provides additional space for construction work	• Negatively impacts driver lane placement • May increase potential for sideswipe crashes
Speed Trailer	10.60	Acceptable Position, work zone side	• Does not impact driver lane placement	•
Monetary Fine	10.44	Near traffic lane	• Keeps Drivers further away from Work Zone •	• Impacts driver lane placement • May increase potential for sideswipe crashes
4 sets of 3 Rumble Strips	10.28	Acceptable Position, work zone side	• Does not impact driver lane placement	• Disruptive for construction vehicles
Variable Speed Limit Sign	10.26	Acceptable Position, work zone side	• Does not impact driver lane placement	• Potentially confusing to drivers
Changeable Message Sign	9.23	Near traffic lane	• Keeps Drivers further away from Work Zone	• Least Effective Countermeasure • Impacts driver lane placement • May increase potential for sideswipe crashes
Other Channelizing Devices	9.14	Acceptable Position, work zone side	• Does not impact driver lane placement	• Least Effective Countermeasure •
Concrete Barriers	7.97	Acceptable Position, work zone side	• Does not impact driver lane placement	• Least Effective Countermeasure •
3 sets of 3 Rumble Strips	7.81	Acceptable Position, work zone side	• Does not impact driver lane placement	• Least Effective Countermeasure • Disruptive for construction vehicles

7.0 RECOMMENDATION/IMPLEMENTATION

Based upon the results of the simulator study, additional future research should be conducted to field validate the results for specific countermeasures. For instance, the use of speed photo enforcement should be clearly investigated to alleviate the necessity for law enforcement at the work zone for speed reduction. Studies conducted in Maryland have proven that speed photo enforcement has great promise and has proven to generate funds for the transportation agency. Additional countermeasures should be further field investigated to determine if an 11 to 12 mile per hour reduction if possible, particularly the sequential flashing lights, optical speed bars, and emergency flasher traffic control device. If results from a field study verify the simulator study, speed reductions through work zones may be possible with minimal, if any, adjustments to construction project costs and without additional safety risk to drivers or construction workers.

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Appendix A

Ohio University Consent Form

Title of Research: Improving Work Zone Safety through Speed Management

Researchers: Norm Sommers, Undergraduate Research Assistant; Patrick Fry, Graduate Research Assistant; Deborah McAvoy, Ph.D., P.E., P.T.O.E., Assistant Professor

You are being asked to participate in research. For you to be able to decide whether you want to participate in this project, you should understand what the project is about, as well as the possible risks and benefits in order to make an informed decision. This process is known as informed consent. This form describes the purpose, procedures, possible benefits, and risks. It also explains how your personal information will be used and protected. Once you have read this form and your questions about the study are answered, you will be asked to sign it. This will allow your participation in this study. You should receive a copy of this document to take with you.

Explanation of Study

You have volunteered to be in a research study to compare the relative driving performance of drivers in a controlled laboratory environment to understand the impact of various countermeasures for speed reduction in work zones. The driving simulator has been built to represent the interior of a standard size passenger automobile, including dashboard, steering wheel, gas pedal, and brake pedal. As you drive the simulator, operate it as if you were driving an actual automobile. The computer screens are intended to represent the actual images you would encounter while looking through the windshield, door windows, and rear view mirrors. The scenes have been programmed with images to replicate typical features encountered on the roadway, including other vehicles present on the road, pedestrians, lane markings, traffic signs, traffic signals, etc. You will drive through ***three*** *scenarios. The first one is merely to get you acclimated to the vehicle controls and computer-generated images. The first scenario should take about* ***15*** *minutes. Altogether, you will be driving for about* ***45*** *minutes. Your driving performance will be monitored and statistics will be recorded on the computer and quantified.*

Your name will remain confidential in the study and your performance will be identified by a subject number only. Your participation in this study will be greatly appreciated and may be a valuable benefit to society. Through your participation the safety consequences along roadways will be quantified and the results may serve to improve safety campaigns in the State of Ohio as well as across the nation, which ultimately aim to reduce traffic crashes on road and highways as well as reduce taxes.

*We are also requesting that you fill out a questionnaire regarding your demographics and past driving habits. We will use the demographic data to determine if the results from this study can be applied to the nation's population. If the demographic data for the survey participants are significantly different than the nation's demographic data, we may not be able to generalize the results of this project. We are attempting to assure we have an adequate representation so that we can draw significant conclusions from this project. Your total time commitment for this study is approximately **60** minutes; **45** minutes for driving, **10** minutes to answer the pre-test questionnaire and **5** minutes to answer the post-test questionnaire.*

Risks and Discomforts

The risks to which you will be exposed by participating in the experiment are minimal. The risks are as follows:

1. *Simulator sickness due to driving in a simulator; generally less than one percent of participants experience nausea and a headache at the onset of driving or after driving for an hour or more.*
2. *Discomfort while sitting in the simulator for an extended period of time.*

While these risks generally occur in less than one percent of participants, the following *precautions will be taken to ensure minimal risk to you:*

1. *You have the right to withdraw from the experiment at any time.*
2. *You will be allowed to take up to a two-minute break in between driving sessions to alleviate any discomfort you may experience due to sitting for an extended period of time.*
3. *The length of the driving simulation has been kept to one hour.*
4. ***Crackers and water will be available to participants who experience motion sickness.***

Benefits

The current trend in roadway construction is to repair existing infrastructure, thus placing work zone personnel and the driving public at an increased risk. The aim of this research is to determine which speed reduction countermeasure is most affective in adding to work zone safety. These findings will present organizations with a resource they can use when developing their work zone safety public awareness campaigns. Therefore this project will assist in reducing the number of work zone crashes and saving the lives of work zone personnel and the driving public.

Confidentiality and Records

The data collected from the experiment will be identified by a time stamp including date and time of travel run. Your completed questionnaires will be also be linked by a time stamp that will correspond to the collected data. ***Your name will not appear in any document or tape related to this research. Participation in this study is completely confidential.***

Additionally, while every effort will be made to keep your study-related information confidential, there may be circumstances where this information must be shared with:

* Federal agencies, for example the Office of Human Research Protections, whose responsibility is to protect human subjects in research;

* Representatives of Ohio University (OU), including the Institutional Review Board, a committee that oversees the research at OU.

Compensation

No compensation will be provided.

Contact Information

If you have any questions regarding this study, please contact:

Norm Sommers, Undergraduate Research Assistant, By Email ns117608@ohio.edu

Pat Fry, Graduate Research Assistant, By Email: pf376006@ohio.edu

Deborah McAvoy, Ph.D., P.E., P.T.O.E., By Email: mcavoy@ohio.edu

If you have any questions regarding your rights as a research participant, please contact Jo Ellen Sherow, Director of Research Compliance, Ohio University, (740)593-0664.

By signing below, you are agreeing that:

- you have read this consent form (or it has been read to you) and have been given the opportunity to ask questions and have them answered
- you have been informed of potential risks and they have been explained to your satisfaction.
- you understand Ohio University has no funds set aside for any injuries you might receive as a result of participating in this study
- you are 18 years of age or older
- your participation in this research is completely voluntary
- you may leave the study at any time. If you decide to stop participating in the study, there will be no penalty to you and you will not lose any benefits to which you are otherwise entitled.

Signature____ Date__________________

Printed Name____

Version Date: *12/**6/11***

Pre-Test Questionnaire

Date: __________________

1) Gender: ☐ Female ☐ Male

2) Age: ☐ 16-20 ☐ 21-25 ☐ 26-35 ☐ 36-45 ☐ 46-60 ☐ 61-70

3) Do you have any of the following driving limitations? (Check all that apply)
- ☐ Visual impairments (Night time, color blindness, etc.)
- ☐ Corrective lenses
- ☐ Medical concerns
- ☐ Drug use for medical condition(s)
- ☐ Physical Limitations

4) How much **total time** do you spend driving on a typical day on your way to and from work/school?

☐ 0.0-0.5 hours ☐ 0.5-1.0 hours ☐ 1.0-1.5 hours

☐ 1.5-2.0 hours ☐ 2.0-2.5 hours ☐ Over 2.5 hours

5) How many miles do you drive in **one** direction on a typical day to arrive at work/school?

☐ 0-5 miles ☐ 5-10 miles ☐ 11-20 miles

☐ 21-30 miles ☐ 31-40 miles ☐ Over 41 miles

6) I know the rules and regulations for driving in a Construction Work Zone.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

7) How often do you encounter Work Zone when driving during Construction season?

☐ Daily ☐ Frequently ☐ Often ☐ Rarely ☐ Never

8) Do you frequently speed in Work Zones?

☐ Yes ☐ No

If yes, what speed do you travel:

☐ 55 ☐ 65 ☐ 75 ☐ 85+

9) Have you ever received a speeding ticket in a Work Zone?

☐ Yes ☐ No

If yes, how many:

☐ 1 ☐ 2 ☐ 3 ☐ 4+

Post-Test Questionnaire

Date: __________________

1) Which measure do you find most appropriate/effective for speed reduction in Work Zones?

- ☐ Lane Reduction
- ☐ Rumble Strips
- ☐ Changeable Message Signs
- ☐ Variable Speed Limit
- ☐ Different Channeling Barrels
- ☐ Other Channeling Devices
- ☐ Concrete Barriers
- ☐ Flashing Speed Signs
- ☐ Enforcement
- ☐ Presence of Workers
- ☐ Presence of Construction Vehicles
- ☐ Other:

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Participant debriefing text

Sir/Madam,

Thank you for your participation in this research.

There has been a recent shift in transportation projects from new construction of roadways and bridges to the rehabilitation of the existing, aging infrastructure. This shift has increased drivers' exposure to work zones and work zone personnel. This increased exposure increases the risk of crash or injury to both drivers and workers in work zones.

The purpose of this research is to determine if there exists a significant safety difference that results from using different configurations and placements of billboard advertisements. Each year various organizations spend money on advertisement campaigns that focus on improving work zone safety. This study will hope to provide these groups with a basis on which to develop their own advertisements.

This study will utilize the speed data, acceleration, and deceleration data collected from the driving simulator as you progressed through the work zones with the different billboards. This data will be combined with the data collected from the eye-tracking system to determine if there is a difference in driver behavior between each of the different billboards located prior to the work zones. Statistical analysis will be performed to determine if there was a significant difference in travel speed, acceleration, deceleration, and the amount of time you looked at each of the billboards to determine if a significant behavioral difference is present. The results of this study will be made available to government and industry officials to aid in their decision making regarding work zone safety advertisement campaigns.

If you have any further questions pertaining to this research please feel free to email me and I will answer them to the best of my ability.