Effectiveness of Speed Management Methods in Work Zones

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PREPARED BY:

Henry Brown

Praveen Edara

Carlos Sun

Qingzhong Zeng

Zhu Qing

Suzanna Long

Slade Engstrom

Shivraj Patil

University of Missouri-Columbia

PREPARED FOR:

Missouri Department of Transportation

Construction and Materials Division, Research Section

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16. Abstract

Management of speeds is a significant component of any strategy to reduce work zone crashes. The objective of this study is to investigate the effectiveness of speed management countermeasures, such as speed display trailer, speed display trailer with red and blue lights, work vehicle with red and blue lights, and active and passive law enforcement, in managing vehicle speeds in work zones. The research methodology includes a review of the existing literature, field study, simulator study, and driver survey. The field study was conducted at a work zone on I-270 in the St. Louis region. All speed countermeasures tested in the field study achieved speed reductions. Active law enforcement was the most effective speed countermeasure for both daytime and nighttime conditions. Thirteen scenarios were studied using a driving simulator. Combining a speed display trailer and active law enforcement was the most effective countermeasure for daytime conditions. Using a speed display trailer by itself was the most effective for nighttime conditions. While respondents to both the driver and post-simulator surveys generally preferred the speed display trailer, they also admitted that the presence of law enforcement would be the most effective in causing them to slow down. Overall, the results of the study indicate that any of the tested countermeasures would help reduce speeds in a work zone. In some instances, deploying multiple countermeasures at the same site was found to be the most effective speed reduction strategy.

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Principal Investigator
Henry Brown, PE, Research Engineer
University of Missouri-Columbia

Co-Principal Investigators
Praveen Edara, PhD, PE, Professor
Carlos Sun, PhD, PE, Professor
University of Missouri-Columbia

Suzanna Long, Ph.D., PEM., F.ASEM, Dean of College of Engineering
University of Idaho

Slade Engstrom, PE, PTOE, Senior Vice President
Shivraj Patil, PE, PTOE, Civil Engineer
TranSystems

Authors
Henry Brown
Praveen Edara
Carlos Sun
Qingzhong Zeng
Zhu Qing
Suzanna Long
Slade Engstrom
Shivraj Patil

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University of Missouri
Department of Civil and Environmental Engineering
E2509 Lafferre Hall
Columbia, MO 65211

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ABSTRACT

Management of speeds is a significant component of any strategy to reduce work zone crashes. The objective of this study is to investigate the effectiveness of speed management countermeasures, such as speed display trailer, speed display trailer with red and blue lights, work vehicle with red and blue lights, and active and passive law enforcement, in managing vehicle speeds in work zones. The research methodology includes a review of the existing literature, field study, simulator study, and driver survey. The field study was conducted at a work zone on I-270 in the St. Louis region. All speed countermeasures tested in the field study achieved speed reductions. Active law enforcement was the most effective speed countermeasure for both daytime and nighttime conditions. Thirteen scenarios were studied using a driving simulator. Combining a speed display trailer and active law enforcement was the most effective countermeasure for daytime conditions. Using a speed display trailer by itself was the most effective for nighttime conditions. While respondents to both the driver and post-simulator surveys generally preferred the speed display trailer, they also admitted that the presence of law enforcement would be the most effective in causing them to slow down. Overall, the results of the study indicate that any of the tested countermeasures would help reduce speeds in a work zone. In some instances, deploying multiple countermeasures at the same site was found to be the most effective speed reduction strategy.

EXECUTIVE SUMMARY

Management of speeds in work zones is a significant component of any strategy to reduce work zone crashes. The Missouri Department of Transportation (MoDOT) and other state Departments of Transportation (DOTs) utilize various countermeasures to help manage work zone speeds with the goal of reducing speeds to improve compliance with the posted work zone speed limit. The objective of this study is to investigate the effectiveness of speed management countermeasures currently used by MoDOT and other state DOTs. The research methodology to meet this objective includes a review of the existing literature, field study, simulator study, and driver survey. The field study and simulator study focus on the following work zone speed countermeasures: speed display trailer, speed display trailer with red and blue lights, work vehicle with red and blue lights, and active and passive law enforcement.

Results from the literature review indicate that there is limited general guidance available regarding the management of speeds in work zones, including decision tools and suggestions for placement of law enforcement in work zones. Prior research studies have generally found that various countermeasures, such as speed display signs, active or passive law enforcement, speed photo enforcement, lights on work vehicles, variable speed limits (VSL), temporary rumble strips, and graphic aided portable changeable message signs (PCMSs), are effective in reducing vehicle speeds in work zones. Findings from previous research studies on driver behavior indicate that several factors, such as driver age and education, perception of the reasonableness of the posted work zone speed limit, presence of work activity, traffic signs, and time pressures, influence driver speed selection in work zones.

For the field study, approximately four weeks of data from a work zone on I-270 westbound (WB) between the Lindbergh Boulevard interchange and Dunn Road were collected, stored, and analyzed. The field data collection setup included two radar sensors mounted on portable trailers upstream and downstream from the location of the work zone speed countermeasure. Various countermeasures, including no treatment (base), speed trailer, speed trailer with flashing speed when vehicles are speeding, speed trailer with red and blue lights (red and blue lights flashing when above speed limit), passive law enforcement (only police vehicle stationed on the shoulder) active law enforcement (police officers actively pulling violators in addition to a police vehicle stationed along the roadside), and a work vehicle with flashing red and blue lights (nighttime only), were deployed in the work zone during both daytime (6 a.m. to 6 p.m.) and nighttime (6 p.m. to 6 a.m.) during the four-week period. Equipment issues limited the availability of the speed trailer with the red and blue lights.

The field evaluation in the work zone on I-270 found that active law enforcement was the most effective speed countermeasure in reducing vehicle speeds during both daytime and nighttime conditions. The use of the other speed countermeasures also resulted in reductions in vehicle speeds in the work zone. The speed trailer without flashing speed feedback or flashing red and blue lights was associated with lower speed reductions than the other speed countermeasures. In general, the speed countermeasures performed better with respect to speed reductions during nighttime.

The driving simulator study complemented the field study by allowing testing for combinations of strategies in the same work zone scenario, collection of vehicle speeds at several locations, and the use of eye tracking data to assess drivers' responses to countermeasures. The simulator study explored 13 scenarios, including the scenarios conducted in the field study as well as combinations of countermeasures, during daytime and nighttime in a virtual world. The driving simulator used for the study is medium-fidelity built around the half-cab of a sedan. The setup of the work zone in the simulator was based on the field study on I-270. The study protocols and measurement tools were evaluated and approved by the campus Institutional Review Board, and a standard hosting script was used. A total of 50 participants were involved in in the simulator trials. Various types of data, including speed data from simulator log files and eye tracking data extracted from the simulator video recordings, were collected and analyzed.

Results from the simulator study indicate that the use of super law enforcement (the combination of speed trailer and active law enforcement) was the most effective in reducing vehicle speeds during daytime. During daytime, the speed trailer with red and blue lights was more effective than the speed trailer without red and blue lights, and passive law enforcement led to greater speed reductions than active law enforcement. During nighttime, the speed trailer was associated with the lowest speeds, and the speed reductions for both active and passive law enforcement were comparable. Generally, the effect of the speed reduction dissipated more quickly during nighttime than daytime. Results from the eye tracking data show that super law enforcement and speed trailer-related countermeasures had better visibility during daytime and nighttime, respectively.

After participants completed the 13 simulator scenarios, they provided feedback on work zone speed countermeasures by taking a post-simulator survey. The survey contained 17 questions on the following topics: daytime work zone speed countermeasures, nighttime work zone speed countermeasures, driving behavior, driving simulator experience, and demographic data. A 16-question simulator sickness questionnaire (Kennedy et al. 1993), which is frequently used to diagnose the severity of simulator sickness of participants, was administered at the end of the survey.

The post-simulator survey found that the study participants generally thought law enforcement was the most effective strategy for reducing vehicle speeds. However, participants preferred the speed trailers over law enforcement, and some participants suggested that the presence of law enforcement could be distracting. The speed trailer with red and blue lights was perceived to be more effective than the speed trailer without red and blue lights. The work vehicle with red and blue lights was generally viewed by study participants as less effective than most of the other strategies in reducing vehicle speeds in work zones. Participants indicated that visibility and the presence of active work or law enforcement were the factors with the greatest influence on their speed selection in work zones.

In addition to the post-simulator survey, a general driver survey was developed and administered by the research team. Topics covered by the survey included ratings of daytime and nighttime work zone speed control strategies, speed selection in work zones, and demographic information. After review by the project Technical Advisory Committee (TAC), the survey was administered online and distributed using various methods, including the researchers' social media accounts, webpages of larger MoDOT projects, MoDOT project email groups, and an article in the University of Missouri's announcement service (MU Info). During a six-week period, 108 anonymous survey responses were received. The survey responses were then compiled and analyzed.

Findings from the driver survey indicate that the respondents generally preferred the speed display trailers over the presence of law enforcement for both daytime and nighttime. However, respondents also indicated that the presence of law enforcement would most likely cause them to reduce their speed. Respondents generally had a favorable impression of the work vehicle with red and blue lights and rated it between law enforcement and speed display trailers. Survey responses indicate that the presence of active work is the factor that has the greatest effect on drivers' speed selection in work zones.

Overall, the results of the study indicate that an approach that considers multiple strategies to manage vehicle speeds in work zones may be the most effective. The countermeasures evaluated in this study were all associated with speed reductions in the work zone. While law enforcement was generally the most effective strategy in reducing vehicle speeds, it might not be a feasible option at all sites. The selection of speed countermeasures to implement at a specific work zone could be made on a project-by-project basis based on various factors such as traffic volumes, type of work activity, site conditions, availability of law enforcement or equipment, and cost. For some work zones, the implementation of a second speed countermeasure located 250 feet to 500 feet downstream from the first countermeasure could be considered to discourage drivers from accelerating after passing the first countermeasure. Future research could further investigate the effects of a second countermeasure on vehicle speeds. Other strategies could include staggered use of law enforcement during periods of high speeding and the collection of data before the work zone is deployed to help determine the most suitable countermeasures.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ARTBA	American Road and Transportation Builders Association
ATSSA	American Traffic Safety Services Association
DOT	Department of Transportation
EB	Eastbound
FHWA	Federal Highway Administration
MoDOT	Missouri Department of Transportation
mph	Miles per hour
PCMS	Portable changeable message sign
SPE	Speed photo enforcement
TAC	Technical Advisory Committee
VMS	Variable message sign
VSL	Variable speed limits
WB	Westbound

1. INTRODUCTION

Background and Motivation

Improving work zone safety is a major challenge for engineering practitioners. In the United States and Puerto Rico in 2020, there were 857 fatalities and 44,000 estimated injuries due to work zone crashes (ARTBA 2022). Vehicle speeds and speed variance are important factors that play a role in work zone safety (The Roadway Safety Consortium n.d.). A significant component of any strategy to reduce work zone crashes includes managing work zone speeds, with the goal of reducing speeds to improve compliance with the posted work zone speed limit. The need for more guidance for managing speeds in work zones was identified in a survey by the American Association of State Highway and Transportation Officials (AASHTO) (The Roadway Safety Consortium n.d.).

As the Missouri Department of Transportation (MoDOT) shifts its focus to preservation and maintenance of the existing transportation system, the amount of road work being performed continues to increase. MoDOT sometimes uses speed limit reductions to help manage speeds in work zones. According to Section 616.12 of the MoDOT Engineering Policy Guide (EPG), speed reductions of 10 mph are recommended when workers are within 10 feet of the traffic lane or when there is head-to-head traffic on multi-lane highways (MoDOT 2020c). To manage work zone speeds, MoDOT currently utilizes various speed management countermeasures such as signage, speed display trailers (Figure 1-1), work vehicles with red and blue lights (Figure 1-2), and law enforcement presence (Figure 1-3). MoDOT would like to learn more about the effectiveness of these tools and about the practices of other DOTs for managing speeds in work zones.

Figure 1-1. Speed display trailer deployed in work zone on I-270 near Saint Louis, Missouri

Figure 1-2. Work vehicle with flashing red and blue lights in work zone during nighttime road work on I-270 near Saint Louis, Missouri

Figure 1-3. Police car parked on shoulder on work zone on I-270 near Saint Louis, Missouri

Study Objective and Methodology

The objective of this study is to investigate the effectiveness of speed management countermeasures currently used by MoDOT and other state DOTs. The research methodology to meet this objective includes a review of the existing literature, field study, simulator study, post-simulator survey, and driver survey. The field study and simulator study focus on the following work zone speed countermeasures: speed display trailer, speed display trailer with red and blue lights, work vehicle with red and blue lights, and active and passive law enforcement. Attainment of the project objective will help MoDOT focus its efforts on managing work zone speeds and improving work zone safety.

Report Organization

The following chapters of this report are organized as follows:

- Chapter 2 describes the comprehensive literature review of research studies and guidance.
- Chapter 3 presents the methodology and results for the field study.
- Chapter 4 describes the methodology and results for the simulator study.
- Chapter 5 provides information regarding the post-simulator survey.
- Chapter 6 describes the methodology and results for the driver survey.
- Chapter 7 presents the conclusions of the research study.

Table 1-1 lists the supplemental information for the report included in the appendices.

Table 1-1. Report Appendices

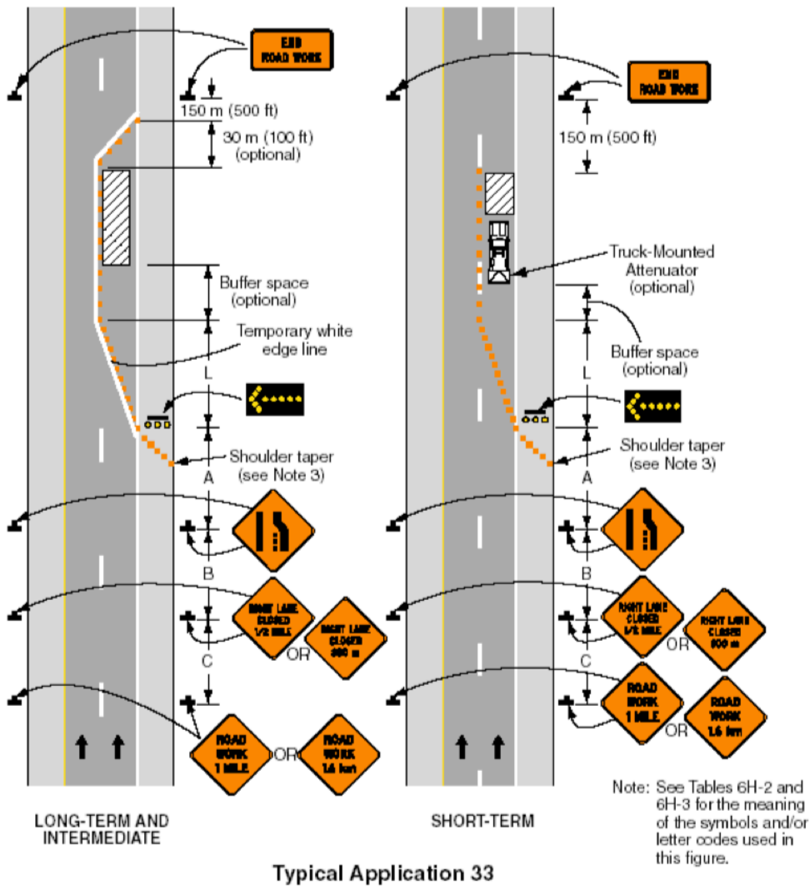
Appendix	Title
A	Summary of Existing Literature for Work Zone Speed Countermeasures
B	Decision Tools for Work Zone Speed Countermeasures
C	Results for Observing Driver Behavior and Vehicle Counts
D	Simulator Results for Speed Profiles
E	Questions for Post-Simulator Survey
F	Questions for Driver Survey
G	Simulator Results for Eye Tracker Data

2. LITERATURE REVIEW

This chapter provides an overview of the existing literature for work zone speed countermeasures, including general guidance; studies of specific countermeasures such as speed display signs, law enforcement, lights on construction vehicles, and variable speed limits; and research on driver behavior and speed selection in work zones. Additional details regarding existing literature may be found in Appendix A.

General Guidance

There is limited general guidance available regarding the management of speeds in work zones. Guidelines on work zone speed management cover topics such as conditions that may require speed reductions in work zones (e.g., worker presence without positive protection, temporary traffic barrier or pavement drop off near traffic, narrow lanes, lane closures, temporary crossovers, and unexpected conditions), the importance of law enforcement, and a decision tool for work zone speed management (The Roadway Safety Consortium n.d.). The decision tool (Appendix B) is flow chart that helps a practitioner determine if speed countermeasures should be implemented based on work zone conditions. A guide on work zone safety from Nevada DOT includes a matrix of work zone countermeasures (Appendix B) (Nevada DOT 2019). In the matrix, each countermeasure is given a score for effectiveness under different work zone conditions, with a required minimum cumulative point value provided for each condition. A publication from the American Traffic Safety Services Association (ATSSA) provides guidance for law enforcement in personnel in work zones on various topics, such as stakeholder roles, tasks, work zone standards, work zone components (advance warning area, transition area, and activity area), a field checklist, and suggested positioning for law enforcement for various typical applications (ATSSA n.d.). For example, the suggested location for law enforcement for a lane closure on a multi-lane highway is on the shoulder between the second and third sign, as shown in Figure 2-1.



Positioning: Consider on the shoulder (or beyond the shoulder if practical) in between the second and third sign. The first advance warning sign will tell drivers to look for you and the work operation.

(ATSSA n.d.)

Figure 2-1. Suggested location for law enforcement for lane closure on multi-lane highway

Work Zone Speed Countermeasures

Speed Display Signs

Several research studies have shown speed trailers to be effective in reducing vehicle speeds and deceleration rates in work zones. For example, field evaluation of a system in Minnesota that displayed downstream speeds on Portable Changeable Message Signs (PCMSs) found that deceleration rates by more than 30 percent were observed when accurate information was shown to drivers (Hourdos et al., 2019). Results from an assessment of radar speed feedback signs on multilane maintenance work zones in Oregon indicated that the use of the signs led to lower vehicle speeds and less speed variation between vehicles (Jafarnejad et al., 2017). Field testing of a speed-activated sign in South Carolina showed an average reduction in mean speed of 3.3 mph on two-lane highways, with similar results on a multilane divided highway and Interstate freeway (Mattox et al., 2007). The results from a field investigation of the effects of dynamic speed feedback signs on vehicle speeds at two work zones in Kansas showed significant speed reductions at both locations (Anderson et al. 2021). In a study by Teng et al. (2009), the effectiveness of speed monitoring displays was assessed at two work zones in Nevada. The study found that the use of larger messages, flashing signs, and multiple speed trailers resulted in higher speed reductions. The extent of the effect varied with vehicle classification, lane usage, and time of day.

Other research studies have shown speed reductions when speed display signs are used in conjunction with other countermeasures. A field assessment of radar speed feedback signs in Arizona (Figure 2-2), which also included an alternating monetary fine message, determined that the use of the alternating messages led to a 50% reduction in the number of vehicles driven 15 mph or more above the speed limit (Roberts and Smaglik, 2014). Commercially available speed data for connected vehicles were used to assess the use of presence lighting and digital speed limit trailers at a work zone (Sakhare et al. 2021). Results showed that median speeds were reduced by 4 to 13 mph during nighttime.

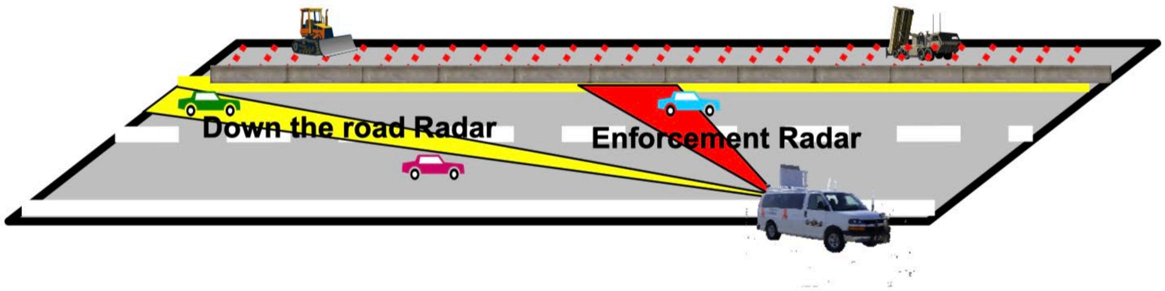
(Roberts and Smaglik 2014)

Figure 2-2. Speed display sign in Arizona study

Law Enforcement

Other research studies have also generally found that the use of active or passive law enforcement in work zones results in lower vehicle speeds. The analysis of speed data from six California work zones showed that any level of police presence reduced the mean and 85th percentile speed (Ravani and Wang, 2018). A field study in Vermont found that the use of targeted police enforcement was less effective in reducing vehicle speeds than radar speed feedback displays or the presence of a Uniform Traffic Officer (Lee et al., 2014). Field data collected from two work zone locations in Illinois indicated that 57 percent of drivers were not speeding at the location of a police patrol car but were exceeding the speed limit at a location 1.5 miles downstream of the law enforcement vehicle (Lodes and Benekohal, 2013). Field studies conducted in four regions in the United States for a project on traffic law enforcement in work zones funded by the National Cooperative Highway Research Program (NCHRP) found that the use of active or passive enforcement practices led to a decrease of 4 mph in vehicle speed immediately downstream of the enforcement vehicle (Ullman et al. 2013). Results from an evaluation of various combinations of stationary police enforcement and complementary variable message signs (VMSs) at six work zones in Indiana showed that distributing enforcement resources among multiple work zones may be more effective than concentrating efforts at fewer work zones and that the VMSs helped to reduce speeds (Chen and Tarko 2013).

Other research studies have compared speed photo enforcement, the presence of police vehicles, and other work zone speed countermeasures. An Illinois study by Benekohal et al. (2010) evaluated the use of speed photo enforcement (Figure 2-3), speed trailers, presence of police vehicles (Figure 2-4), and both speed trailers and police vehicles simultaneously. The results showed that speed photo enforcement lowered the average speed of the general traffic stream by 4.1 mph to 7.9 mph, which improved compliance with the speed limit of 55 mph. Comparable results were obtained with the use of police patrol presence with the emergency lights off. Results from a simulator study of 20 work zone speed countermeasures indicated that presence of workers and construction vehicles, law enforcement, speed photo enforcement, and lane shifts were the most effective methods for reducing vehicle speeds (Sommers and McAvoy 2013). Rumble strips, channelizing devices, and changeable message signs led to the lowest speed reductions.



(Benekohal et al. 2010)

Figure 2-3. Setup for speed photo enforcement van in Illinois study

(Benekohal et al. 2010)

Figure 2-4. Police vehicle parked on the side of the highway

Lights on Work Vehicles

The availability of existing studies regarding the use of flashing lights on work vehicles is limited. In an Oregon study, Ahmed et al. (2021) evaluated the effects of flashing blue lights on paving equipment during nighttime. The results showed that mean vehicle speeds were reduced by 2.7 mph to 16.0 mph at upstream locations when the blue lights were used. The speed reductions were less at locations closer to and downstream from the paver, with increases in mean speed observed in some instances at downstream locations. In follow-up research, three case studies were performed to assess the use of flashing amber and white lights on construction equipment (Figure 2-5) and their impacts on vehicle speeds during nighttime (Hurwitz et al. 2021). The results indicated that speed reductions varied from 1.5 mph to 10.1 mph at two of the locations, with no significant speed reductions observed at the third location. The researchers concluded that the flashing blue lights had a more significant effect on driver behavior than the flashing amber and white lights.

(a)

(b)

(Hurwitz et al. 2021)

Figure 2-5. Use of amber and white flashing lights on construction equipment in Oregon (a) amber lights (b) white lights

Variable Speed Limits

Research studies have shown that the use of variable speed limits (VSL) is effective in reducing vehicle speeds. Microsimulation and field studies were used in Missouri to investigate the effectiveness of a Variable Advisory Speed Limit system (Figure 2-6) (Edara et al. 2013). Results indicated that average speeds decreased and speed compliance increased with the system. The speed variance increased in uncongested urban work zones. A field evaluation of VSL in Indiana using vehicle-matching technology found that mean speed dropped by a maximum of 4.7 mph (Mekker et al. 2016). However, three pairs of signs were required for substantial speed reductions. A portable VSL system was assessed at four locations in Utah (van Jura et al. 2018). Findings indicated that speeds were reduced to 15 to 25 mph below the original posted speed limit with a limited length and duration of the speed reduction.

(Edara et al. 2013)

Figure 2-6. Variable Advisory Speed Limit system used in Missouri study

Other Work Zone Speed Countermeasures

Other work zone speed countermeasures, such as temporary rumble strips and graphic aided PCMSs, have been shown to reduce vehicle speeds in work zones. A research study sponsored by MoDOT included a field evaluation of the effects of both short-term and long-term temporary rumble strips (Figure 2-7) on vehicle speeds (Brown et al. 2022). The results showed reductions in speed violations of 21.2 percent with short-term temporary rumble strips and 18.2 percent with long-term temporary rumble strips. A Kansas study investigated the use of graphic aided PCMSs (Huang and Bai 2019). Vehicle speeds were measured in work zones with different text and graphic aided PCMSs, and a driver survey was conducted. Results indicated that mean vehicle speeds reduced between 13 percent and 17 percent with the graphic aided PCMSs, and drivers also indicated a preference for the graphic aided PCMSs in the survey.

(a)

(b)

(Brown et al. 2022)

Figure 2-7. Temporary rumble strips used by MoDOT (a) short-term temporary rumble strips (b) long-term temporary rumble strips

In a study sponsored by Minnesota DOT, 34 possible countermeasures to reduce vehicle speeds and improve work zone safety were assessed, and 16 countermeasures were recommended for implementation (HDR 2022). Nine of the recommendations, such as speed monitoring equipment, traffic surveillance cameras, increased coordination with construction staff, increased use of speed feedback signs, and greater use of end of queue warning systems, are in the process of being implemented by Minnesota DOT in 2022 and 2023. An evaluation of 20 work zone speed countermeasures in a driving simulator study found that presence of workers and construction vehicles, law enforcement, speed photo enforcement, and lane shifts were associated with the highest speed reductions (Sommers and McAvoy 2013). Findings from a field evaluation of six work zone speed countermeasures in New Brunswick indicated that the following three combinations performed best: Traffic Control Person and Floating Speed Zone (zone of speed reduction that moves with active work area), Fake Police Vehicle and Floating Speed Zone, and Radar Speed Display Board and Floating Speed Zone (Mason 2013). A synthesis on management of work zone speeds from the National Cooperative Highway Research Program (NCHRP) speeds provided general information on 28 work zone speed countermeasures and their effectiveness (Shaw et al. 2015).

Driver Behavior

Several research studies have investigated driver behavior, including factors affecting speed selection, in work zones. In surveys conducted for the NCHRP study by Ullman et al. (2013), drivers indicated that that the type of enforcement used in the work zone did not affect their expected response as much as other factors such as their age, education, and perception of the reasonableness of the posted work zone speed limit. Driver behavior upstream of the work zone was assessed in a naturalistic driving study (Thapa et al. 2019). The study results showed that drivers were most likely to respond at the lane ends, work zone speed limit signs, and speed feedback signs. In addition, drivers were more responsive as they got closer to the start of the work zone. Participants in an online survey in Australia rated worker presence, visible law enforcement presence, and speed feedback display signs as the most influential factors on their speed choice in work zones (Blackman et al. 2014). After viewing videos of work zones under various conditions, drivers in Norway indicated that the presence of roadwork activity had the greatest effect on their preferred speeds in the work zones, followed by traffic signs and time pressures (Steinbakk et al. 2017). In another Norway study, drivers were shown ten pictures of a rural work zone and asked to provide their preferred speed (Steinbakk et al. 2019). The results showed that preferred speeds were higher than the work zone speed limit. In addition, preferred speeds were higher for older drivers and drivers who rated their own driving skills higher.

3. FIELD STUDY

The major approaches of the project are to conduct field and simulator studies to investigate the effectiveness of speed management methods and to study driving behavior. This chapter describes the field test with multiple speed management methods, including speed trailers with and without red and blue lights, law enforcement, and work vehicles with red and blue lights.

Background of I-270 North Work Zone (Lindbergh Boulevard Interchange)

In consultation with MoDOT, the work zone on I-270 westbound (WB) at the Lindbergh Boulevard interchange was chosen as the study location. MoDOT was especially interested in studying the work zone for the I-270 design-build project due to concerns about vehicles speeding through the work zone. In addition, the Lindberg Boulevard interchange work zone had the largest lane shift (approximately 50 feet) on the project with the same lane configuration for the duration of the project. After visiting the site and meeting with the contractor and MoDOT personnel, the research team chose the WB direction for the study. The eastbound (EB) direction was experiencing more speeding and crashes than the westbound direction, and MoDOT had already placed a speed display sign in the EB direction.

I-270 was built in the 1960s, serving as a freight route for commercial vehicles that primarily travelled around the St. Louis area. I-270 is a loop, secondary interstate that connects all the primary interstates that go through St. Louis (for example, I-44, I-55, I-70 and I-64). I-270 also serves as a trailhead for vehicles entering the St. Louis area from the east. I-270 carries over 140,000 vehicles per day (MoDOT 2020a).

The purpose of the I-270 design build project is to address numerous challenges that exist on the corridor, including daily traffic congestion, deteriorating bridges, and lack of pedestrian facilities. The project also includes the improvement of aging infrastructure and the removal of confusing two-way cross-over slip ramps (for example, Dunn Road). The I-270 design-build project starts from McDonald Boulevard and extends to the east limit at the Bellefontaine Road interchange, with a total length of approximately eight miles. The selected work zone in the field test of the research incorporates MoDOT phase 3B of the I-270 design-build project, focusing on the WB section between the Lindbergh Boulevard interchange and the on-ramp from Dunn Road.

Field Setup Plan

Equipment Introduction

The field data collection setup included two Houston Radar SpeedLane® Pro sensors mounted on portable trailers upstream and downstream from the location of the work zone speed countermeasure. The Houston Radar SpeedLane® Pro (Figure 3-1) is capable of detecting lane, speed, and class of individual vehicles across 16 lanes and computing per lane volume, occupancy, gap, average speed, 85th percentile, and headway parameters (Houston Radar 2022). The data are stored in the sensor's internal memory and can be accessed and downloaded online. The sensor also includes a video camera that provides real-time video for use in calibrating the lanes. The Houston Radar SpeedLane® Pro sensors were mounted at the top of the masts of two portable trailers, with four solar panels on each trailer (Figure 3-2).

(© Houston Radar 2022)

Figure 3-1. Houston Radar SpeedLane® Pro sensor

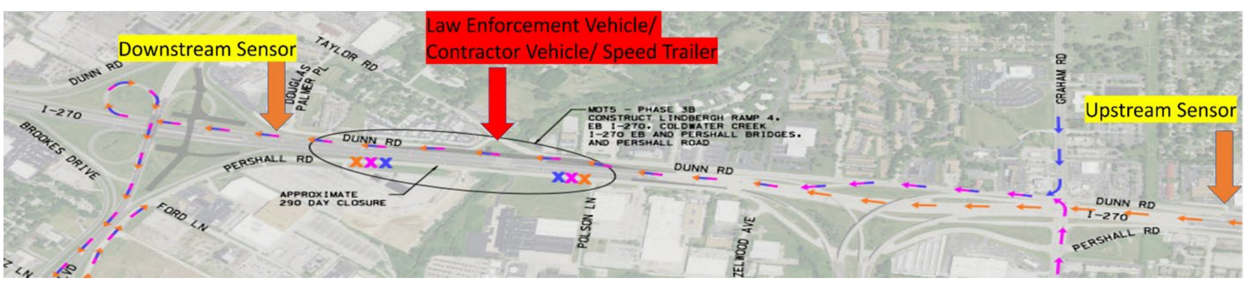
Figure 3-2. Trailer with SpeedLane® Pro sensor

Field Setup Configuration

Two SpeedLane® Pro sensors and two portable trailers were rented for four weeks to conduct the field study. The research team (including personnel from MU and TranSystems) transported the equipment from the vendor lot in Cedar Hill, Missouri to the project site. The sensor and trailers were deployed in the I-270 work zone on August 3, 2021, and removed on August 26, 2021. The sensors were mounted at the top of the trailer mast arm and aimed at the traffic. The upstream sensor (Figure 3-3) was placed adjacent to the outside shoulder near Dunn Road, and the downstream sensor was deployed on the left shoulder of the exit ramp at Lindbergh Boulevard (Figure 3-4) for non-intrusive traffic data collection in all weather and lighting conditions. The approximate locations of the sensors and speed countermeasures are shown in Figure 3-5. The sensors were calibrated in real time in the field with assistance from the vendor, who confirmed the camera view and set up the lane configurations.

Figure 3-3. Field study upstream sensor in work zone

Figure 3-4. Field study downstream sensor in work zone



(MoDOT 2022b

Figure 3-5. Location of sensors and speed management devices

After deployment of the upstream and downstream sensors, frequent maintenance and checking on both of the sensors were necessary. To identify and prevent problems, the research team generally went to the field at least twice a day to check on each sensor. The precise procedures involved three steps. In the first step, researchers recorded the video clips of approximately 5 minutes from the built-in cameras of each sensor for both the upstream and downstream sensors. The research team checked on the sensors, including the stabilizing mast and pillar stands on the four corners of the trailers. The research team verified that the camera was aimed at the traffic and looked for any concerns that could potentially damage the sensors. Usually, the research team could identify any issues from the video footage before going to the field. The third step included driving by the location of the deployed speed countermeasures. The research team also checked on the speed countermeasure devices or briefly talked to the police officers.

These three steps were completed at least twice a day during the dates of data collection for the different scenarios. The checks were completed by approximately 10:30 a.m. and between 3 p.m. and sunset in the afternoon. Additional field visits were arranged, if necessary, at night, such as checking on the scenarios of a work vehicle with red and blue lights and law enforcement at nighttime. The calibration of both sensors was performed on the first day of data collection after the sensors were deployed. Recalibration of the sensors was performed twice after contractors mistakenly moved the upstream sensor. The recalibration process included securing the upstream sensor trailer on the ground and ensuring stability, raising the mast to the appropriate height and aiming the sensor at traffic, and setting up the lane configuration to monitor traffic. The equipment supplier facilitated the process of configuring the lanes remotely.

Types of Speed Management Methods

As shown in Figure 3-6, the area near the Lindbergh Boulevard exit immediately after the lane shift area was used to place traffic control devices or law enforcement vehicles for the different speed countermeasures. A variety of speed countermeasures were set up for this project, including no treatment (base), speed trailer, speed trailer with red and blue lights (red and blue lights flashing when above speed limit), passive law enforcement (only police vehicle stationed on the shoulder), active law enforcement (police officers actively pulling violators in addition to a police vehicle stationed along the roadside), and a work vehicle with flashing red and blue lights (nighttime only). A speed trailer with flashing speed digits when a vehicle was speeding was also used due to limited availability of a speed trailer with red and blue lights. The different work zone speed countermeasures are shown in Figure 3-7 through Figure 3-11. Figure 3-7 and Figure 3-8 show the speed trailer and speed trailer with red and blue lights (red and blue lights flashing when above speed limit), while Figure 3-9 and Figure 3-10 show the passive law enforcement (only police vehicle stationed on the shoulder,) and active law enforcement (police officers actively pulling violators in addition to a police vehicle stationed along the roadside). Figure 3-11 shows the work vehicle with red and blue lights (nighttime only).

Figure 3-6. Location of the speed countermeasures in field study

Figure 3-7. Speed trailer active in field study

Figure 3-8. Speed trailer with red and blue lights in field study

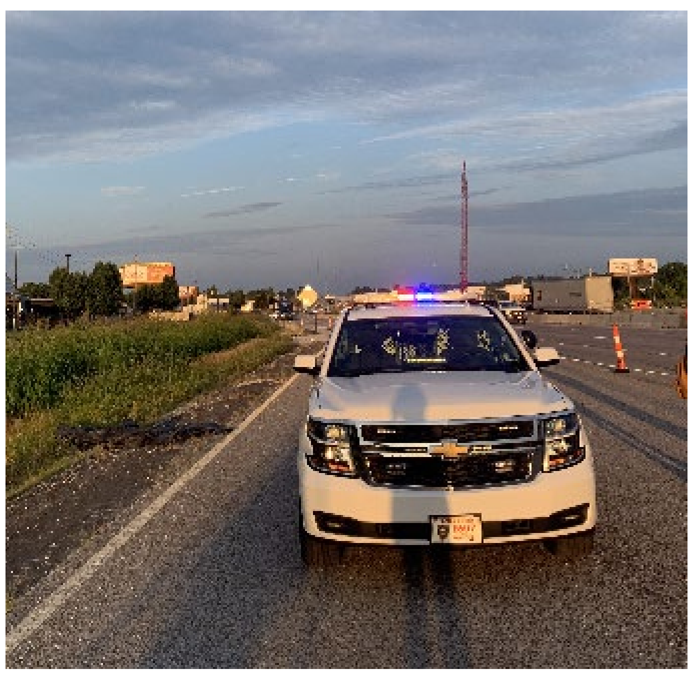


Figure 3-9. Passive law enforcement in field study

(Courtesy St. Louis County Police Department)

Figure 3-10. Active law enforcement

Figure 3-11. Work vehicle with red and blue lights in field study

Field Data Collection

As mentioned previously, collected sensor data was available in the cloud. Thus, researchers were able to download the raw data of individual vehicle speeds in real-time. The field data were collected during a four-week period from August 3, 2021, to August 26, 2021. The original schedule of the field data collection, which includes one to two days of data collection for each countermeasure, is shown in Table 3-1. Due to unforeseen factors, such as the contractor moving equipment, equipment availability, and weather, the original schedule had to be adjusted, and the actual schedule is shown in Table 3-2. A total of 323 hours 40 minutes of data and approximately 778,050 individual vehicle speed data points were collected. The duration of daytime was set from 6 a.m. to 6 p.m., and the duration of nighttime was set from 6 p.m. to 6 a.m. next day.

Table 3-1. Planned schedule of speed management methods in field study

Week	Day	Date	Enforcement	Trailer	Work vehicle Red/Blue Lights	Time periods
1	Tues.	8/3/21	-	-	-	-
1	Wed.	8/4/21	None	No	No	Daytime, Nighttime
1	Thurs.	8/5/21	None	Active	No	Daytime, Nighttime
2	Tues.	8/10/21	None	No	No	Daytime, Nighttime
2	Wed.	8/11/21	None	Active with Red/Blue Lights	No	Daytime, Nighttime
2	Thurs.	8/12/21	None	Active with Red/Blue Lights	No	Daytime, Nighttime
2	Fri.	8/13/21	None	Active	No	Daytime, Nighttime
3	Tues.	8/17/21	Active	No	No	Daytime, Nighttime
3	Wed.	8/18/21	Passive	No	No	Daytime, Nighttime
3	Thurs.	8/19/21	None	Active with Red/Blue Lights	No	Daytime
3	Thurs.	8/19/21	None	No	Yes	Nighttime
4	Tues.	8/24/21	Active	No	No	Daytime, Nighttime
4	Wed.	8/25/21	Passive	No	No	Daytime
4	Wed.	8/25/21	None	No	Yes	Nighttime
4	Thurs.	8/26/21	-	-	-	-

Table 3-2. Actual schedule of speed management methods in field study

Week	Start Date	Start Day	Start Time	End Date	End Day	End Time	Duration (hrs.)	Countermeasure
1	8/3/21	Tues.	15:00	8/5/21	Thurs.	12:00	45 hrs.	No treatment
1	8/5/21	Thurs.	12:00	8/09/21	Mon.	00:00	84 hrs.	Speed trailer
2	8/10/21	Tues.	14:30	8/12/21	Thurs	08:45	43 hrs. 15 min	No treatment
2	8/12/21	Thurs.	8:45	8/12/21	Thurs.	17:00	8hrs15min	Speed trailer (with flashing speed feature)
2	8/13/21	Fri.	5:00	8/14/21	Sat.	00:00	19hrs	Speed trailer
3	8/17/21	Tues.	10:50	8/17/21	Tues.	19:00	8hrs10min	Speed trailer
3	8/17/21	Tues.	19:00	8/18/21	Wed.	07:00	12hrs	Active law enforcement
3	8/18/21	Wed.	7:00	8/18/21	Wed.	13:00	6hrs	Passive law enforcement
3	8/18/21	Wed.	13:00	8/18/21	Wed.	19:00	6hrs	No treatment
3	8/18/21	Wed.	19:00	8/19/21	Thurs.	07:00	12hrs	Passive law enforcement
3	8/19/21	Thurs.	8:00	8/19/21	Thurs.	10:30	2hrs30min	Active law enforcement
3	8/19/21	Thurs.	10:30	8/19/21	Thurs.	18:30	8hrs	No Treatment
3	8/19/21	Thurs.	18:30	8/20/21	Fri.	07:00	12hrs30min	Work vehicle with red and blue lights
4	8/23/21	Mon.	8:00	8/23/21	Mon.	17:00	9hrs	Speed trailer with red and blue lights
4	8/24/21	Tues.	7:00	8/25/21	Wed.	07:00	24hrs	Active law enforcement
4	8/25/21	Wed.	7:00	8/25/21	Wed.	18:00	11hrs	Passive law enforcement
4	8/25/21	Wed.	18:00	8/26/21	Thurs.	07:00	13hrs	Work vehicle with red and blue lights

During the data collection period, the upstream sensor was mistakenly moved twice from its position by the contractor. The first relocation of the upstream sensor happened at the beginning of the second week of field work as shown in Figure 3-12. The upstream sensor was moved from the road shoulder off to the ditch slightly because it was in the path of the contractor's vehicles. The upstream sensor was moved a second time approximately 1972 feet further to the east of previous location due to the construction in the ditch (Figure 3-13). The data collected after the movement of the sensor and before the sensor reconfiguration were considered as outliers and were excluded from the data analysis process.

Figure 3-12. Upstream sensor after first movement

(Imagery © 2022 CNES / Airbus, Maxar Technologies, U.S. Geological Survey, USDA/FPAC/GEO, Map data © 2022 Google)

Figure 3-13. Upstream sensor after second movement (aerial)

Figure 3-14. Upstream sensor after second movement

Field Observations of Driving Behavior

An investigation of drivers' behavior in the field was conducted. The built-in camera in the SpeedLane® Pro sensors allowed the research team to observe vehicles traveling through the work zone via real-time streaming. Although the main purpose of the camera is for sensor calibration, the research team was able to obtain video clips of approximately five minutes. Screenshots from the video clips are shown in Figure 3-15 and Figure 3-16. In general, the clips were captured twice a day, both in daytime due to the low visibility at nighttime. Driver behavior was then inspected through the footage to note any unusual behavior, such as abrupt maneuvers, driving or parking in shoulder, and crashes. Vehicle counts were also collected from the video clips and compared with the sensor counts for verification. Drivers appear to adapt to the speed countermeasures well, and no unusual behavior was observed in the footage that was taken. The vehicle counts observed from the video clips were in close agreement with the sensor vehicle counts. An excerpt from the video clip analysis is shown in Table 3-3, and the full table is shown in Appendix C. In accordance with MoDOT policy, video footage recorded from the sensors was deleted within 48 hours. No video footage was kept, but a few screenshots of the video were saved each time for documentation purposes.

Figure 3-15. Screenshot from upstream sensor camera

Figure 3-16. Screenshot from downstream sensor camera

Table 3-3. Example of driver behavior and vehicle counts from video clips

ID	Sensor Location	Date	Day of week	Recording Start Time	Lane*	Vehicle Counts in Video	Vehicle Counts from sensor	Ratio (Video / Sensor)	Unusual Driver Behavior	Note
1	upstream	08/03/21	Tue.	-	-	-	-	-	-	screen frozen
2	downstream	08/03/21	Tue.	-	-	-	-	-	-	screen frozen
3	upstream	08/04/21	Wed.	8:16:53	2	99	125	0.79	-	includes 1 motorcycle
4	downstream	08/04/21	Wed.	8:29:57	1	60	61	0.98	-	-
5	upstream	08/04/21	Wed.	14:43:26	3	63	67	0.94	-	-
6	downstream	08/04/21	Wed.	14:48:55	3	106	91	1.16	-	-
7	upstream	08/04/21	Wed.	21:20:07	1	dark	-	-	-	-
8	downstream	08/04/21	Wed.	21:31:55	2	49	-	-	-	-
9	upstream	08/05/21	Thu.	7:39:18	3	61	65	0.94	-	-
10	downstream	08/05/21	Thu.	7:46:09	2	109	99	1.10	-	-
11	upstream	08/05/21	Thu.	13:30:46	4	82	81	1.01	-	-
12	downstream	08/05/21	Thu.	13:37:49	3	77	84	0.92	-	-

*for column Lane, lane 1 is the closest to the sensor (outside shoulder) and lane 3 is the farthest from the sensor.

Field data were downloaded every workday and then organized in a spreadsheet by treatment. While being categorized by type of treatment, invalid time periods that were the outliers in this study were excluded. For example, data collected during the time of the unexpected relocation of upstream sensors were considered as outliers and therefore excluded from the study. In addition, some hours of data were excluded due to the changes in traffic conditions. For instance, lane closures near the upstream segment had a significant influence on traffic conditions, such as upstream queuing. The corresponding time periods when a lane closure was in effect due to construction were excluded. For example, there was a right lane closure on August 5, 2021, at I-270 WB and Washington Street/Elizabeth Avenue from 7:30 p.m. to 1 a.m. Thus, the night data for August 5, 2021, was considered as an outlier while analyzing the scenarios of speed trailer active during nighttime.

Overview of Field Data

Approximately four weeks of data were collected, stored, and analyzed for the field study. The following sections present the results for vehicle speeds in both daytime and nighttime. In each section, the effectiveness of different speed management methods is assessed. There are scenarios with no speed countermeasures for both daytime and nighttime which are considered as the base scenario to compare the effectiveness of the different work zone speed countermeasures. The observed speed reduction for the base scenario represents the speed drop between the upstream and downstream average vehicle speed due to the presence of the work zone and lane shift. Typically, this value is positive because downstream speeds were generally lower due to the lane shift. The additional speed reduction is the portion of speed drop that is over the observed speed reduction of the base scenario (5.2 mph for daytime and 4.1 mph for nighttime) for each individual countermeasure. The extent of effectiveness is measured by the additional speed reduction divided by the speed reduction of the corresponding base scenario.

Daytime Results Evaluation

The field results for effectiveness of speed control strategies during daytime are as shown in Table 3-4 to Table 3-6. The duration of daytime was set from 6 a.m. to 6 p.m. of the next day. As shown in Table 3-4, the base scenario with no speed countermeasures experienced a speed reduction of 5.2 mph, with an average upstream speed of 64.5 mph and average downstream speed of 59.3 mph. Table 3-5 shows the speed trailer countermeasure results. Table 3-6 shows the active and passive law enforcement results. The other daytime scenarios are compared with the base scenario. The results indicate that the active law enforcement was the most effective speed management method of all the daytime scenarios in reducing vehicle speeds. The use of active law enforcement resulted in a speed reduction of 9.5 mph between the upstream and downstream locations. The additional speed drop compared to the base scenario is 4.3 mph. During the daytime, the speed trailer with red and blue lights was associated with an additional speed reduction of 2.8 mph, indicating that it was more effective at reducing vehicle speeds than passive law enforcement. Although the speed trailer without red and blue lights was not as effective in reducing vehicle speeds as the other scenarios, it still resulted in an additional speed reduction of 0.5 mph. The speed trailer with the flashing speed display was more effective than the speed trailer without the flashing speed display but not as effective as the speed trailer with the flashing red and blue lights. Effect size complements statistical significance and is the magnitude of the experimental effect (Cohen 1977). It represents the practical usefulness. For example, a very small reduction in speed could still be statistically significant but not very useful in terms of safety improvement. Effect size was presented as Cohen's d value, as effect size greater than 0.2 and less than 0.5 is small, effect size between 0.5 and 0.8 is medium, and effect size greater than 0.8 is large. The effect sizes for most of the speed countermeasures were all larger than 0.8.

Table 3-4. Speed results for no speed countermeasures during daytime

Description	Value
Count (upstream) (vehicles)	256,860
Count (downstream) (vehicles)	161,188
Average speed (upstream) (mph)	64.5
Average speed (downstream) (mph)	59.3
Standard deviation of speed (upstream) (mph)	8.95
Standard deviation of speed (downstream) (mph)	7.40
Observed Speed Reduction (upstream – downstream) (mph)	5.2
Additional speed reduction due to speed countermeasures (mph)	-
Extent of effectiveness	-
Pooled standard deviation	8.39
Cohen's d	0.62

Table 3-5. Speed results for speed trailer countermeasures during daytime

Description	Speed Trailer Active	Speed Trailer with Flashing Speed Feedback	Speed Trailer with Red/Blue lights
Count (upstream) (vehicles)	176,518	33,134	28,615
Count (downstream) (vehicles)	120,249	22,234	24,117
Average speed (upstream) (mph)	64.7	64.6	64.1
Average speed (downstream) (mph)	59.0	58.1	56.1
Standard deviation of speed (upstream) (mph)	8.67	8.65	10.48
Standard deviation of speed (downstream) (mph)	7.31	7.05	8.54
Observed Speed Reduction (upstream – downstream) (mph)	5.7	6.5	8.0
Additional speed reduction due to speed countermeasures (mph)	0.5	1.3	2.8
Extent of effectiveness	9.9%	24.8%	53.5%
Pooled standard deviation	8.15	8.05	9.64
Cohen's d	0.70	0.81	0.83

Table 3-6. Speed results for law enforcement during daytime

Description	Active Law Enforcement	Passive Law Enforcement
Count (upstream) (vehicles)	65,018	25,028
Count (downstream) (vehicles)	54,615	52,255
Average speed (upstream) (mph)	65.1	64.5
Average speed (downstream) (mph)	55.6	56.9
Standard deviation of speed (upstream) (mph)	10.55	9.74
Standard deviation of speed (downstream) (mph)	7.88	6.94
Observed Speed Reduction (upstream – downstream) (mph)	9.5	7.6
Additional speed reduction due to speed countermeasures (mph)	4.3	2.4
Extent of effectiveness	81.7%	46.0%
Pooled standard deviation	9.42	7.96
Cohen's d	1.00	0.96

Nighttime Results Evaluation

The field results for effectiveness of speed control strategies during nighttime are as shown in Table 3-7 to Table 3-10. The duration of nighttime was set from 6 p.m. to 6 a.m. the next day. As shown in Table 3-7, a speed reduction of 4.1 mph between the upstream and downstream sensors was observed for the base scenario with no speed countermeasures. Table 3-8 shows the speed trailer countermeasure results. Table 3-9 shows the active and passive law enforcement results. Similar to daytime, active law enforcement was the most effective speed management method in reducing vehicle speeds. The use of active law enforcement during nighttime was associated with a speed reduction of 9.6 mph and additional speed reduction of 5.5 mph. During nighttime, passive law enforcement was the second most effective countermeasure with an additional speed reduction of 2.8 mph compared to the base scenario. The use of the work vehicle with red and blue lights was found to have a significant effect on vehicle speeds, with an additional speed drop of 2.1 mph. Nighttime scenario for the speed trailer with speed display as shown in Table 3-8 showed an additional speed reduction of 0.9 mph. The effect size of active law enforcement was large. The effect sizes of passive law enforcement and speed trailer with red/blue lights were medium.

Table 3-7. Speed results for no speed countermeasures during nighttime

Description	Value
Count (upstream) (vehicles)	78,353
Count (downstream) (vehicles)	35,509
Average speed (upstream) (mph)	66.1
Average speed (downstream) (mph)	62.0
Standard deviation of speed (upstream) (mph)	8.96
Standard deviation of speed (downstream) (mph)	7.92
Observed Speed Reduction (upstream – downstream) (mph)	4.1
Additional speed reduction due to speed countermeasures (mph)	-
Extent of effectiveness	-
Pooled standard deviation	8.65
Cohen’s d	0.47

Table 3-8. Speed results for speed trailer active during nighttime

Description	Value
Count (upstream) (vehicles)	8,522
Count (downstream) (vehicles)	5,131
Average speed (upstream) (mph)	65.9
Average speed (downstream) (mph)	60.9
Standard deviation of speed (upstream) (mph)	8.68
Standard deviation of speed (downstream) (mph)	6.70
Observed Speed Reduction (upstream – downstream) (mph)	5.0
Additional speed reduction due to speed countermeasures (mph)	0.9
Extent of effectiveness	22.9%
Pooled standard deviation	7.99
Cohen’s d	0.63

Table 3-9. Speed results for law enforcement during nighttime

Description	Active law enforcement	Passive law enforcement
Count (upstream) (vehicles)	23,508	11,670
Count (downstream) (vehicles)	17,698	9,079
Average speed (upstream) (mph)	66.9	65.9
Average speed (downstream) (mph)	57.4	59.0
Standard deviation of speed (upstream) (mph)	10.10	10.18
Standard deviation of speed (downstream) (mph)	7.35	8.05
Observed Speed Reduction (upstream – downstream) (mph)	9.6	6.9
Additional speed reduction due to speed countermeasures (mph)	5.5	2.8
Extent of effectiveness	135.8%	69.7%
Pooled standard deviation	9.02	9.30
Cohen's d	1.06	0.74

Table 3-10. Speed results for work vehicle with red/blue lights during nighttime

Description	Value
Count (upstream) (vehicles)	18,008
Count (downstream) (vehicles)	13,603
Average speed (upstream) (mph)	66.6
Average speed (downstream) (mph)	60.4
Standard deviation of speed (upstream) (mph)	10.26
Standard deviation of speed (downstream) (mph)	7.34
Observed Speed Reduction (upstream – downstream) (mph)	6.2
Additional speed reduction due to speed countermeasures (mph)	2.1
Extent of effectiveness	51.9%
Pooled standard deviation	9.12
Cohen's d	0.68

Summary and Discussion of Field Study Results for Vehicle Speeds

Table 3-11 and Table 3-12 conveniently shows all the speed results together for easy comparison among the speed countermeasures. The observed speed reductions for the daytime and nighttime base scenarios are 5.2 mph and 4.1 mph, respectively. Although the nighttime base scenario reported less speed reduction than the daytime base scenario (possibly due to lower traffic at night), speed countermeasures were generally more effective at night. For example, active law enforcement led to additional speed reductions of 5.5 mph during nighttime and 4.3 mph during daytime. The use of passive law enforcement was associated with an additional speed reduction of 2.8 mph during nighttime and 2.4 mph during daytime. Results for both daytime and nighttime indicate that the use of law enforcement was the most effective in reducing vehicle speeds. Passive law enforcement, the speed trailer with red and blue lights, and the work vehicle with red and blue lights were also relatively effective in reducing vehicle speeds. The use of the speed display trailer without red and blue lights was associated with a smaller speed reduction than the other countermeasures.

Table 3-11. Summary of field study results during daytime

Description	No Speed Countermeasures	Active Law Enforcement	Passive Law Enforcement	Speed Trailer Active	Speed Trailer Active with Red/Blue Lights	Speed Trailer Active with Flashing Speed Feedback
Observed Speed Reduction (upstream – downstream) (mph)	5.2	9.5	7.6	5.7	8.0	6.5
Additional Speed Reduction Due to Speed Countermeasures (mph)	-	4.3	2.4	0.5	2.8	1.3
Extent of Effectiveness	-	81.7%	46.0%	9.9%	53.5%	24.8%

Table 3-12. Summary of field study results during nighttime

Description	No Speed Countermeasures	Active Law Enforcement	Passive Law Enforcement	Speed Trailer Active	Work vehicle with Red/Blue Lights
Observed Speed Reduction (upstream – downstream) (mph)	4.1	9.6	6.9	5.0	6.2
Additional Speed Reduction Due to Speed Countermeasures (mph)	-	5.5	2.8	0.9	2.1
Extent of Effectiveness	-	135.8%	69.7%	22.9%	51.9%

Safety Analysis of Non-compliance and Compliance of Work Zone Speed Limit

Whether drivers comply with the work zone speed limit has been a critical factor for work zone safety. This study analyzed the characteristics of vehicle speeds below or equal to the work zone speed limit ("compliance" hereafter) and the speeds above the limit ("violation" hereafter) to examine the effects of speed countermeasures on work zone safety.

Table 3-13 shows the compliance data for the different speed countermeasures at the upstream and downstream sensors during daytime and nighttime. The speed limit was set at 50 mph in the I-270 WB work zone. The overall speed violation rate was 92.8 percent which means that less than one in ten motorists drove at or below speed limit while passing through I-270 WB work zone. Regarding time of day, daytime was associated with a higher compliance rate (7.8 percent) than nighttime (4.8 percent).

Table 3-13. Characteristics of compliance and non-compliance with work zone speed limit for multiple speed countermeasures

Countermeasure	No. of vehicles	Avg. Speed (mph)	Freq. Above Speed Limit	% Above Speed Limit	Freq. Less than 10 mph Above Speed Limit	% Less than 10 mph Above Speed Limit	Freq. More than 10 mph Above Speed Limit	% More than 10 mph Above Speed Limit	Freq. at or Below Speed Limit	% at or Below Speed Limit
All	**1255591**	-	**1164586**	**92.8%**	**417665**	**33.3%**	**746921**	**59.5%**	**91005**	**7.2%**
Daytime	**1019831**	**-**	**940134**	**92.2%**	**350208**	**34.3%**	**589926**	**57.8%**	**79697**	**7.8%**
No Speed Countermeasures (Upstream*)	256860	64.5	244721	95.3%	56674	22.1%	188047	73.2%	12139	4.7%
No Speed Countermeasures (Downstream*)	161188	59.3	146109	90.6%	61095	37.9%	85014	52.7%	15079	9.4%
Active Law Enforcement (Upstream)	65018	65.1	60385	92.9%	12804	19.7%	47581	73.2%	4633	7.1%
Active Law Enforcement (Downstream)	54615	55.6	43106	78.9%	24473	44.8%	18633	34.1%	11509	21.1%
Passive Law Enforcement (Upstream)	25028	64.5	23519	94.0%	5553	22.2%	17966	71.8%	1509	6.0%
Passive Law Enforcement (Downstream)	52255	56.9	44256	84.7%	24212	46.3%	20044	38.4%	7999	15.3%
Speed Trailer with Speed Display Alone (Upstream)	176518	64.7	172355	97.6%	84280	47.7%	88075	49.9%	4163	2.4%
Speed Trailer with Speed Display Alone (Downstream)	120249	59.0	108466	90.2%	47661	39.6%	60805	50.6%	11783	9.8%

Countermeasure	No. of vehicles	Avg. Speed (mph)	Freq. Above Speed Limit	% Above Speed Limit	Freq. Less than 10 mph Above Speed Limit	% Less than 10 mph Above Speed Limit	Freq. More than 10 mph Above Speed Limit	% More than 10 mph Above Speed Limit	Freq. at or Below Speed Limit	% at or Below Speed Limit
Speed Trailer with Flashing Feedback (Upstream)	33134	64.6	31860	96.2%	7661	23.1%	24199	73.0%	1274	3.8%
Speed Trailer with Flashing Feedback (Downstream)	22234	58.1	19827	89.2%	9710	43.7%	10117	45.5%	2407	10.8%
Speed Trailer Red/Blue (Upstream)	28615	64.1	26258	91.8%	6169	21.6%	20089	70.2%	2357	8.2%
Speed Trailer Red/Blue (Downstream)	24117	56.1	19272	79.9%	9916	41.1%	9356	38.8%	4845	20.1%
Nighttime	**235760**	-	**224452**	**95.2%**	**67457**	**28.6%**	**156995**	**66.6%**	**11308**	**4.8%**
No Speed Countermeasures (Upstream)	78353	66.1	75928	96.9%	14665	18.7%	61263	78.2%	2425	3.1%
No Speed Countermeasures (Downstream)	35509	62.0	33911	95.5%	9994	28.1%	23917	67.4%	1598	4.5%
Active Law Enforcement (Upstream)	23508	66.9	22475	95.6%	3517	15.0%	18958	80.6%	1033	4.4%
Active Law Enforcement (Downstream)	32377	57.4	29945	92.5%	22706	70.1%	7239	22.4%	2432	7.5%
Passive Law Enforcement (Upstream)	11670	65.9	11026	94.5%	2041	17.5%	8985	77.0%	644	5.5%

Countermeasure	No. of vehicles	Avg. Speed (mph)	Freq. Above Speed Limit	% Above Speed Limit	Freq. Less than 10 mph Above Speed Limit	% Less than 10 mph Above Speed Limit	Freq. More than 10 mph Above Speed Limit	% More than 10 mph Above Speed Limit	Freq. at or Below Speed Limit	% at or Below Speed Limit
Passive Law Enforcement (Downstream)	9079	59.0	8070	88.9%	3638	40.1%	4432	48.8%	1009	11.1%
Speed Trailer with Speed Display alone (Upstream)	8522	65.9	8288	97.3%	1619	19.0%	6669	78.3%	234	2.7%
Speed Trailer with Speed Display alone (Downstream)	5131	60.9	4914	95.8%	1704	33.2%	3210	62.6%	217	4.2%
Work vehicle Red/Blue Lights (Upstream)	18008	66.6	17133	95.1%	2852	15.8%	14281	79.3%	875	4.9%
Work vehicle Red/Blue Lights (Downstream)	13603	60.4	12762	93.8%	4721	34.7%	8041	59.1%	841	6.2%

*Upstream sensor is before speed countermeasures versus downstream sensor is after speed countermeasures

The upstream sensor location was far from the location of the deployed speed countermeasures that drivers could not see. The compliance statistics showed here only serve the purpose of comparing between upstream and downstream data to reflect the aggressiveness of the drivers. During daytime, speed compliance was higher at the downstream sensor (9.4 percent) than at the upstream sensor (4.7 percent) for the base scenario with no speed countermeasures. Table 3-13 shows that law enforcement (active law enforcement in particular) had a substantial effect on improving speed limit compliance. In terms of speed compliance, active law enforcement was associated with a compliance rate of 21.1 percent downstream and 7.1 percent upstream. Passive law enforcement was slightly less effective than active law enforcement but still had a significant improvement on speed limit compliance, which was 15.3 downstream and 6.0 percent upstream. Among multiple speed trailers, the speed trailer with red and blue lights was the most effective in obtaining driver compliance, followed by the speed trailer with flashing feedback and speed trailer without flashing feedback.

During nighttime, motorists were less likely to comply with the speed limit at nighttime while passing through the I-270 WB work zone. Speed compliance rates of 4.5 percent (downstream) and 3.1 percent (upstream) were observed when there was no countermeasure present. However, the use of law enforcement (primarily passive law enforcement) was the most effective in discouraging speeding, with observed compliance rates of 11.1 percent downstream and 5.5 percent at the upstream location. Compared to the observed speed limit compliance of active law enforcement (7.5 percent downstream and 4.4 percent upstream), passive law enforcement was found to be more effective at nighttime. The use of the work vehicle with red and blue lights scenario did not result in a significant increase in speed compliance (6.2 percent downstream and 4.9 percent upstream). Minor variation was found in the case of speed trailer with speed display alone (4.2 percent downstream and 2.8 percent upstream) as compared to the scenario with no treatment. Overall, findings indicate that most motorists tend to violate the work zone speed limit irrespective of the speed countermeasures in place.

Missouri has two types of speeding laws: a "basic speeding law" and "absolute limits." The previous section discussed compliance with the posted speed limit, which is absolute limits. According to the Missouri's basic speeding law, motorists must drive at a rate of speed "so as not to endanger the property of another or the life or limb of any person." (Missouri Legislature 1996). However, under specific circumstances, motorists must drive at a safe speed depending on the circumstances which could be much lower than the speed limit. For example, inclement weather could require lower speeds. Thus, an investigation of excessive speeding can also shed some light on motorists' speed behavior under different countermeasures. The results for speeding violations in excess of 10 mph are discussed below.

During daytime, the percentage of drivers exceeding the speed limit by at least 10 mph decreased from 73.2 percent to 52.7 percent between the upstream and downstream locations for the base scenario with no countermeasures, likely due to the presence of the lane shift. The use of law enforcement was effective in reducing excessive vehicle speeding. For active law enforcement, the percentage of drivers exceeding the speed limit by at least 10 mph was 73.2 percent at the upstream sensor and 34.1 percent at the downstream sensor. The results for passive law enforcement were similar, with 71.8 percent and 38.4 percent of drivers exceeding the speed limit by at least 10 mph at the upstream and downstream sensors, respectively. For the speed trailer with only the speed display, excessive speeding was virtually unchanged between the upstream and downstream locations. With the speed trailer with red and blue lights, the percentage of drivers exceeding the speed limit by at least 10 mph decreased being 70.2 percent upstream and 38.8 percent downstream. The speed limit with flashing speed display was also associated with a reduction in excessive speeding.

During nighttime, the percentage of drivers exceeding the speed limit by at least 10 mph was 78.2 percent at the upstream sensor and 67.4 percent at the downstream sensor with no countermeasures. The use of active law enforcement during nighttime was most effective in reducing excessive speeding (80.6 percent upstream and 22.4 percent downstream). With passive law enforcement, the percentage of drivers exceeding the speed limit by at least 10 mph decreased from 77.0 percent upstream to 48.8 percent downstream. The use of the work vehicle with red and blue lights was associated with excessive speeding rates of 79.3 percent upstream and 59.1 percent downstream, indicating that it was less effective at discouraging excessive speeding than law enforcement.

4. SIMULATOR STUDY

After the field study of the speed management methods was completed on I-270 WB in Saint Louis, the simulator study was conducted. The simulator was utilized to examine the effectiveness of different scenarios of speed countermeasures in a virtual world. The simulator study explored the scenarios conducted in the field study as well as combinations of countermeasures, such as a combination of active law enforcement, work vehicle with red and blue lights, and speed trailer. The simulator also provided an opportunity for exploring the details of scenarios of the speed trailer with red and blue lights during nighttime to complement the field study due to weather conditions and equipment availability that precluded the use of the speed trailer with the red and blue lights in the field during nighttime. Another advantage of the simulator study is the provision of a safe environment with less disruptions.

Simulator Study Methodology

ZouSim is the driving simulator lab used for conducting simulator study in the University of Missouri. The simulator is medium-fidelity built around the half-cab of a sedan. Considering the capacity of graphical display, including virtual reality, augmented reality and stereoscopic 3D, the triple 120-inch was chosen as the most compatible display for this study. Such a display environments setup created a 180-degree field-of-view which offered participants an immersive view of the approaching work zone and the relevant peripheral clues for regulating driving speed. Figure 4-1 shows the ZouSim setup for the experiment. The primary virtual camera was the forward windshield view. Three additional virtual cameras imitated the left, right and rear-view mirror perspectives were also incorporated in the simulator scenario set-ups. The active instrumentation in the vehicle includes a force-feedback steering wheel, brake and acceleration pedals, turn signals, and an engine vibration generator.

Figure 4-1. Zousim half-cab sedan driving simulator

Simulator Setup

The study simulated a work zone on I-270 WB in St. Louis, Missouri, with a work zone speed limit of 50 mph and a permanent speed limit of 60 mph. The entire highway was designed without any horizontal or vertical curves in order to eliminate the influence of terrain. Therefore, the simulator scenario is similar but not identical to the field scenario.

The road was created according to AASHTO Green Book standards (AASHTO 2013). Surfaces were textured and/or painted with the appropriate striping and markings that conform to the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA 2009). The work zone plan for the highway is shown in Figure 4-2. The setup of the work zone in the simulator was based on the field study on I-270, and a large lane shift similar to the shift on I-270 was implemented in the simulator scenarios. Upon encountering the first lane shift sign, the lane shift occurred 1000 feet ahead of the first lane shift sign. The work zone configuration, including signage, lane shift angle, and distance between signs, followed the requirements of the I-270 North Standard-Maintenance of Traffic Plan (MoDOT 2020b), MUTCD (FHWA 2009) and MoDOT Engineering Policy Guide (MoDOT 2020c).

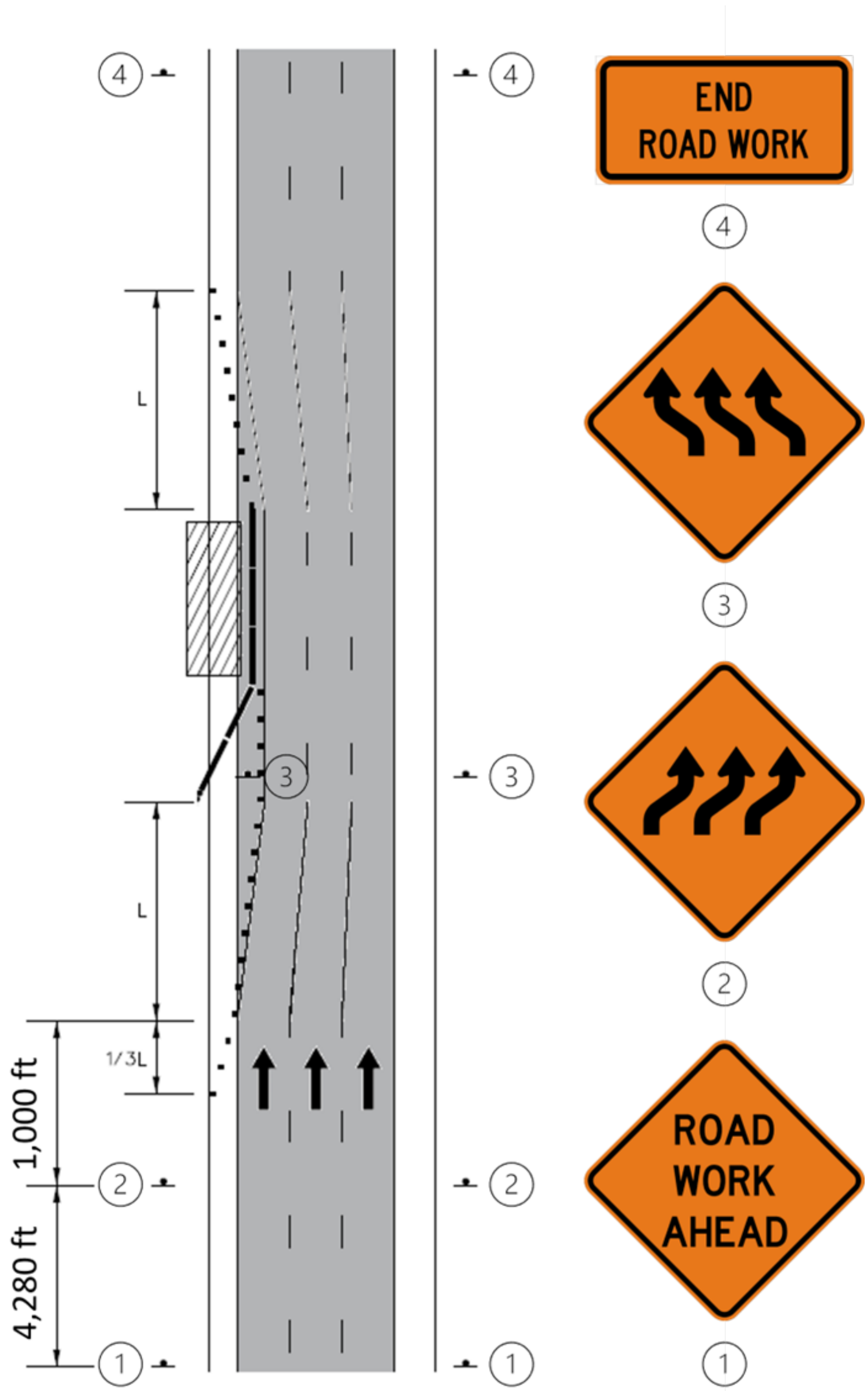


Figure 4-2. Work zone plan for driving simulator study

The following speed countermeasures, individually or in combination, were tested: (1) speed trailer with speed display (flashing when above speed limit), (2) speed trailer with red and blue lights (red and blue lights flashing when above speed limit), (3) passive law enforcement, (4) active law enforcement, and (5) work vehicle with red/blue lights. These countermeasures were tested either in the daytime or nighttime simulation environment, and one or more speed countermeasures could be tested in a scenario. There were 13 scenarios as shown in Table 4-1.

Table 4-1. Driving simulator scenarios

Scenario*	Enforcement	Trailer	Work vehicle Red/Blue Lights	Day/Night
1	None	No	No	Day
2	None	No	No	Night
3	None	Active	No	Day
4	None	Active	No	Night
5	None	Active with Red/Blue Lights	No	Day
6	None	Active with Red/Blue Lights	No	Night
7	None	No	Yes	Night
8	None	Active	Yes	Night
9	Active	No	No	Day
10	Active	No	No	Night
11	Passive	No	No	Day
12	Passive	No	No	Night
13	Active	Active with Red/Blue Lights	No	Day

*Note: Order of scenarios was randomized for each participant

Proper adjustments were made to account for differences between daytime and nighttime simulation environments. Daytime speed countermeasures are shown in Figure 4-3 through Figure 4-6, and nighttime speed countermeasures are shown in Figure 4-7 through Figure 4-11. Figure 4-3 shows the speed display during daytime and Figure 4-4 shows the speed trailer with red and blue lights. Figure 4-5 shows passive law enforcement with a police vehicle parked on the shoulder during daytime. Figure 4-6 shows active law enforcement with a police vehicle pulling over violators during daytime. Figure 4-7 shows the speed trailer during nighttime, and Figure 4-8 shows the speed trailer with red and blue lights. Figure 4-9 shows passive law enforcement with a police vehicle parked on the shoulder during nighttime. Figure 4-10 shows active law enforcement with a police vehicle pulling over violators during nighttime. Figure 4-11 shows the work vehicle with red and blue lights during nighttime.

Figure 4-3. Speed trailer with speed display during daytime (simulator study)

Figure 4-4. Speed trailer with red and blue lights during daytime (simulator study)

Figure 4-5. Passive law enforcement during daytime (simulator study)

Figure 4-6. Active law enforcement during daytime (simulator study)

The speed countermeasures for nighttime are almost the same as the speed countermeasures for daytime except for the introduction of the work vehicle with red and blue lights. The daytime or nighttime countermeasures shared similar configurations, although brightness and color pixel quality might be adjusted if needed.

Figure 4-7. Speed trailer with speed display during nighttime (simulator study)

Figure 4-8. Speed trailer with red and blue lights during nighttime (simulator study)

Figure 4-9. Passive law enforcement during nighttime (simulator study)

Figure 4-10. Active law enforcement during nighttime (simulator study)

Figure 4-11. Work vehicle with red and blue lights during nighttime (simulator study)

Simulator Trials and Measures of Effectiveness (MOEs)

The study protocols and measurement tools were evaluated and approved by the campus Institutional Review Board, and a standard hosting script was used. Participants were recruited regardless of gender, race, occupation, and age. A flyer with brief introduction was sent to participants prior to their human subject trials. First, a participant's informed consent was obtained after the participant was introduced to the simulator and the study purpose. Then, the participant drove through a free-driving warm-up scenario to become familiar with the simulator. Once the participant was comfortable, the actual work zone scenarios were initiated. In each scenario, the participant was asked to drive along an urban three-lane divided highway. While driving, the participant encountered a work zone with different speed management methods, and the participant's vehicle was stopped automatically by the simulator program at the end of the scenario a little beyond the end of the work zone. In total, the participants drove through 13 different scenarios. The order of scenarios was randomized for each participant to prevent sequence bias. After completing the scenarios, participants completed a post simulator survey. A total of 50 participants were involved in in the simulator trials.

The human subject trials, including eye tracking, were all recorded. Effective results were extracted by examining the recorded video clip of eye tracking data. One aspect of the simulator study results involved investigation from the perspective of eye tracking data. Several measures of effectiveness (MOEs) were defined for data reduction.

<u>MOEs for Eye Tracking Data</u>

The simulator study investigated driver behavior. Eye tracking devices and screen recording data focused on the interaction between participants and traffic devices, such as signs and speed countermeasures. Various MOEs for eye tracking were used to help gain insights into driver behavior. These MOEs are described below.

MOE 1: Vehicle speed at first glanced at speed countermeasure (mph). This MOE is the vehicle speed when a participant first glanced at the speed countermeasure placed along the roadside. This speed could help to indicate how much a driver recognized the speed countermeasure and/or how the drivers respond to the speed countermeasures. A lower speed is desired for better effectiveness of the speed countermeasures. An example screenshot is shown in Figure 4-12. The location of the pupil focus is shown as a white circle.

Figure 4-12. Screenshot example for when participant first glanced at speed countermeasure

MOE 2: Distance from first traffic cone when first glanced at speed countermeasure (feet). This MOE is the distance from the first traffic orange cone which marks the beginning of the work zone when the participant first glanced at the speed countermeasure. This MOE could help to indicate where a driver recognized the speed countermeasures. Returning to Figure 4-12, this distance is indicated where the pupil is focused at the speed countermeasure.

MOE 3 Distance from the first traffic cone when first glanced at the lane shift sign in work zone (feet) This MOE is the distance from the first traffic orange cone when participants first glanced at the second lane shift sign when they were approaching the work zone, either about to enter the work zone or already entered the work zone. The first glance at the lane shift sign in work zone can indicate the extent to which motorists acknowledge the upcoming work zone condition, subsequently adapting their driving behavior in the work zone. An example screenshot is shown in Figure 4-13.

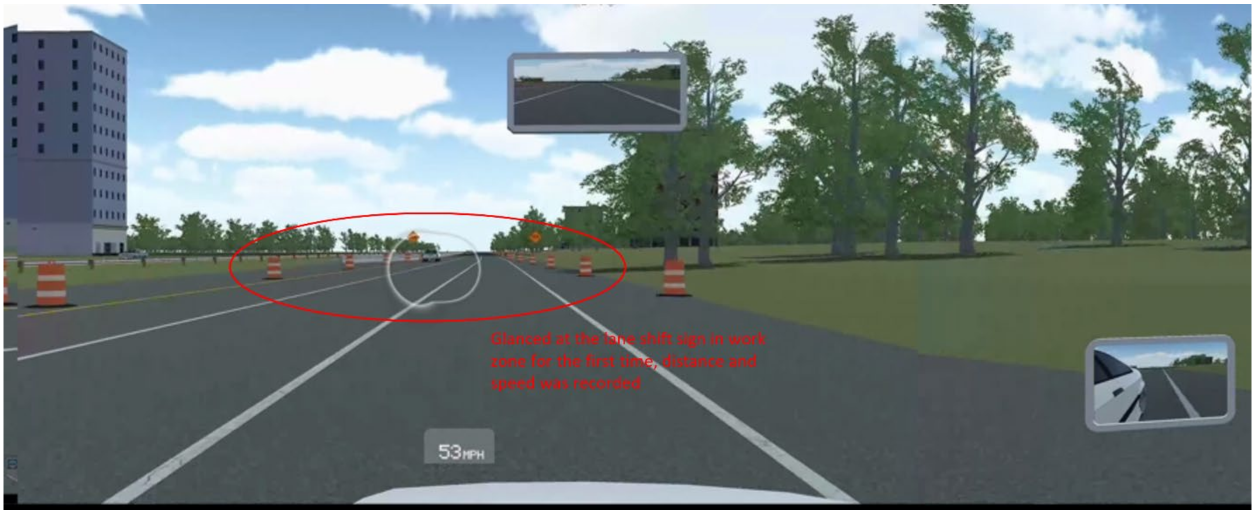


Figure 4-13. Screenshot example for first glance at the lane shift sign in work zone

MOE 4: Vehicle speed when first glanced at the lane shift sign in work zone (mph). This MOE is the vehicle speed when the participant first glanced at the second lane shift sign when they were approaching the work zone, either about to enter the work zone or already slightly entered the work zone. Speed is another common effectiveness measure that is related to safety. An example screenshot is shown in Figure 4-13. These MOEs from the simulator study provided information in terms of perspectives of visibility, speed, distance and drivers' awareness. A few other MOEs are also included in Appendix G for a more thorough discussion.

Verification of Data Accuracy for Unity.log data

A unity.log data file is a file of collection of speeds from different locations in the simulator scenarios, including two locations prior to the work zone, eight locations within the work zone and the downstream sensor location past the work zone. Time and date, speed, and distance from location to work zone were documented in a unity.log file for all 13 scenarios for every single participant. Verification of the accuracy of the data from the unity.log was conducted based on comparing the speed data between the unity.log data and eye tracking recording data as shown in Table 4-2.

Table 4-2. Verification of unity.log speed data

# of Human Subject Trial	Time	Speed Data from unity.log	Speed Data from Recording	Location of the Vehicle Speeds Being Detected	Note
1	4/11/2022 5:31:00 PM	66	66	Beginning of the work zone	
1	4/11/2022 5:26:51 PM	53	53	Beginning of the work zone	
2	4/12/2022 3:34:36 PM	51	51	Upstream sensor	
2	4/12/2022 3:16:56 PM	61	61	Second lane shift sign	
6	4/15/2022 3:09:09 PM	52	52	Downstream sensor	
6	4/15/2022 3:20:37 PM	65	65	Upstream sensor	
18	4/25/2022 3:26:43 PM	75	75	Upstream sensor	
18	4/25/2022 3:36:32 PM	42	42	B point: a location 250 feet downstream from countermeasures	
27	4/28/2022 4:34:32 PM	41	40	End of work zone	Different due to round up
27	4/28/2022 4:47:16 PM	34	34	Speed countermeasures	
32	5/5/2022 4:27:45 PM	53	53	End of work zone	
32	5/5/2022 4:37:29 PM	66	66	Upstream sensor	
40	5/10/2022 2:16:45 PM	60	59	First lane shift sign	Different due to round up
40	5/10/2022 2:25:32 PM	50	50	D point: a location 1,000 feet downstream from countermeasures	
42	5/17/2022 5:32:25 PM	57	57	Beginning of the work zone	
42	5/17/2022 5:42:21 PM	59	59	Beginning of the work zone	
45	5/25/2022 1:59:57 PM	46	46	Second lane shift sign	
45	5/25/2022 2:07:28 PM	76	76	Upstream sensor	

# of Human Subject Trial	Time	Speed Data from unity.log	Speed Data from Recording	Location of the Vehicle Speeds Being Detected	Note
49	6/2/2022 11:13:48 AM	54	54	B point: a location 250 feet downstream from countermeasures	
49	6/2/2022 11:24:28 AM	75	75	D point: a location 1,000 feet downstream from countermeasures	

The results showed that the unity.log data is highly accurate and reliable. Speed data for 18 out of 20 samples matched with each other, and the other two samples are within 1 mph.

Simulator Study Results

Video captures of the simulator trials were recorded for every participant from the beginning through the end of the trial. Eye tracking data, including speed, distance, and some sign glancing data, were extracted from videos recording to measure the results of simulator study. In addition, the video was also used to confirm data accuracy and identify specific potential data issues. Data issues could potentially indicate an unusual driving pattern in this simulator study.

Unity.log was also used in the simulator study to collect primarily speed data, when participants drove pass certain locations. Since these data were collected by the unity system, data for all 50 participants data were collected successfully. Speed differential between two locations and speed profiles were the primary measures used to assess the effectiveness of the speed countermeasures in the simulator study.

Fifty human subjects participated in the simulator tests and completed the trials. However, some eye tracking data were lost due to an internet issue and other technical malfunctions. Distance data for some participants were not obtained because of the technical malfunction. Eye tracking data for 37 participants were collected and analyzed.

The simulator results will be presented from two perspectives: speed data collected from unity.log and eye tracking data extracted from recording. Daytime and nighttime scenarios results will be discussed separately. For both the unity.log data set and eye tracking data set, statistical analysis was performed on the data sets to calculate the significance, confidence level and effect size. Effect sizes can be categorized into small, medium, or large according to Cohen's criteria: small size (0.2 < Cohens'd value <0.5), medium (0.5 < Cohens'd value <0.8), and large (Cohens'd value > 0.8) (Cohen 1977).

Unity.log Data

Speed data for the 50 participants when they passed by certain locations before, within, and after the work zone were collected by unity.log via programming. The same principle for measuring the effectiveness of speed countermeasures for field study applies to the simulator study. Speed differential between two selected locations was the approach used to examine the result in the simulator study. In the field study, the speed differential between the upstream and downstream sensor was examined. In simulator study, these locations were replicated to allow for possible examination of the speed differential between them. In addition, speed profiles were generated in the simulator study. Trends in driving patterns for how participants interacted with the speed countermeasures were also investigated.

<u>Daytime Results for Upstream and Downstream Speeds</u>

The same methodology of examining data from the field study applies to the simulator study, with comparison of the speed differential from the corresponding upstream and downstream sensor locations and downstream sensor location in the simulator scenarios. Figure 4-14 (diagram of work zone) shows the locations where speeds were collected.

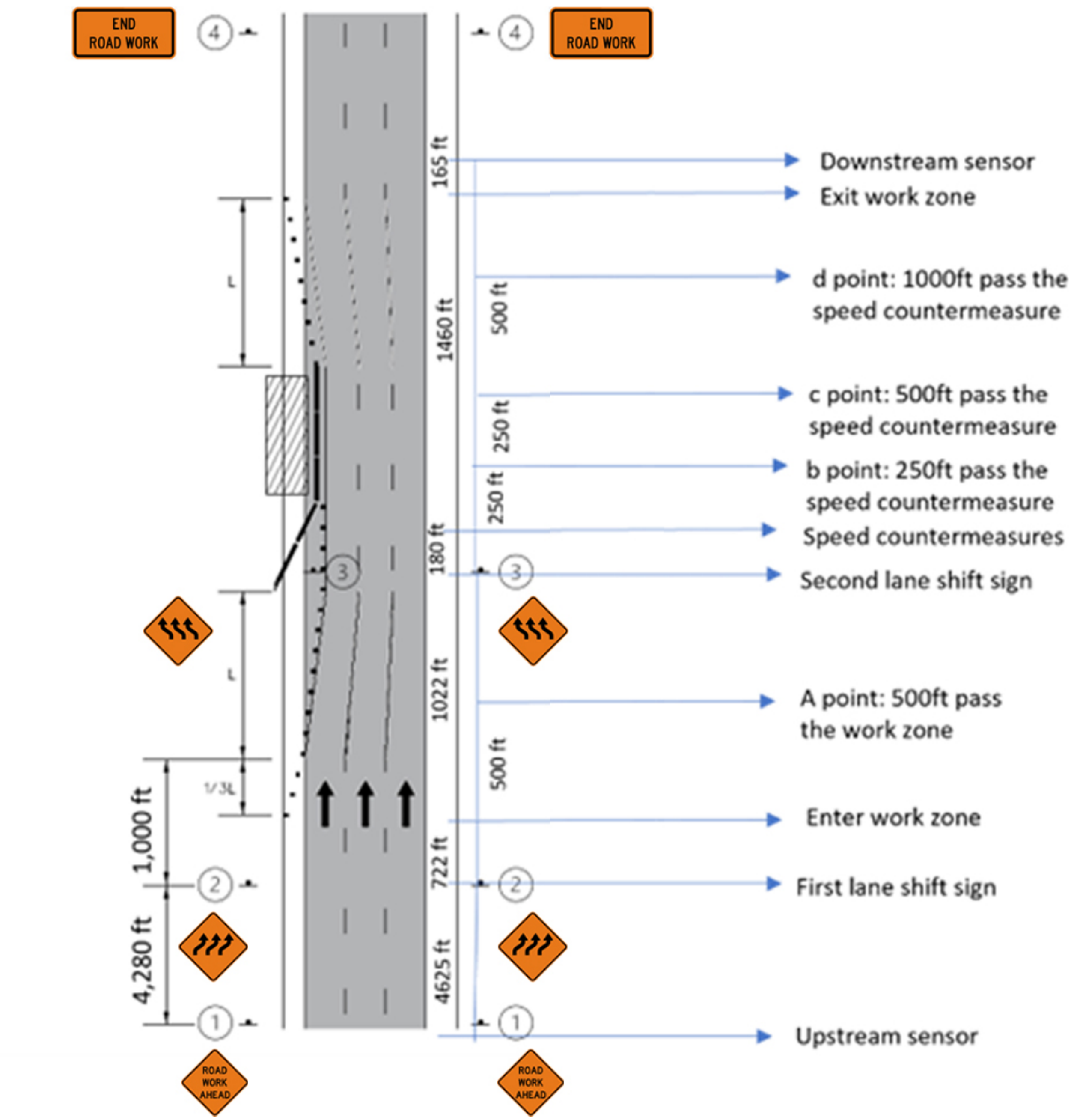


Figure 4-14. Diagram of unity.log location of collecting speed in simulator study

Daytime results for the speed differential between the upstream and downstream sensors are shown in Table 4-3. The baseline, which is the no speed countermeasures scenario, reported an original speed reduction of 3.1 mph at the downstream sensor location. Active law enforcement reported an additional speed reduction at the downstream sensor location of 2.5 mph, corresponding to an effectiveness of 82.7 percent. The daytime results showed that the active law enforcement was the most effective speed countermeasures among all speed countermeasures in the daytime simulator study. These results are consistent with the trends of field study in which active law enforcement was identified as the most effective speed countermeasure during daytime. The speed trailer active resulted in an additional speed reduction of 1.4 mph. Super law enforcement (the combination of speed trailer active and active law enforcement) resulted in effectiveness of 69.4 percentage with the additional speed reduction of 1.1 mph. The speed trailer with red and blue lights scenarios is effective with an additional speed reduction of 0.4 mph. The passive law enforcement, however, did not show any effectiveness.

Table 4-3. Daytime simulator results

Scenario	Speed Differential (mph)	Additional Speed Reduction (mph)	Effectiveness	Standard Deviation (mph)	Confidence Level	Cohens ' d	Effect Size
No speed countermeasure	3.1	Base	Base	8.6	Base	Base	Base
Speed Trailer Active	4.4	1.4	44.9%	7.3	63.4%	0.15	small
Speed Trailer w/ Red/Blue	3.5	0.4	12.6%	8.9	1.1%	0.00	small
Active Law enforcement	5.6	2.5	82.7%	7.2	88.1%	0.32	small
Passive Law enforcement	3.0	-0.1	-2.1%	9.4	16.4%	0.04	small
Super Law enforcement	4.2	1.1	36.2%	13.8	69.4%	0.18	small

Nighttime Results for Upstream and Downstream Speeds

Nighttime results for the speed differential between the upstream and downstream sensors are shown in Table 4-4. For nighttime, the average speed differential between the upstream and downstream sensors for the base scenario with no speed countermeasures was 4.1 mph, which is higher than the value of 3.1 mph observed during daytime. This result can indicate that a higher speed differential for each speed measure scenario is required to reach the same effectiveness as demonstrated for the simulator daytime study. The effectiveness of speed countermeasures based on the methodology of comparison between upstream and downstream locations is not discussed here. The following sections present a more thorough discussion of speeds based on speed profiles.

Table 4-4. Nighttime simulator results

Scenario	Speed Differential (mph)	Additional Speed Reduction (mph)	Effectiveness	Standard Deviation (mph)	Confidence Level	Cohens' d	Effect Size
No speed countermeasure	4.1	Base	Base	9.1	Base	Base	Base
Speed Trailer Active	3.3	-0.7	-17.9%	9.7	6.6%	0.02	small
Speed Trailer w/ Red/Blue	2.9	-1.1	-27.7%	9.9	66.1%	0.15	small
Work vehicle w/ Red/Blue	4.1	0.1	1.9%	9.8	2.5%	0.01	small
Work vehicle+Speed trailer active	1.3	-2.8	-68.1%	10.5	96.1%	0.35	small
Active Law enforcement	4.0	0.0	-0.6%	8.6	2.1%	0.00	small
Passive Law enforcement	1.1	-2.9	-72.0%	10.0	92.6%	0.33	small

Speed Profile Results

A more detailed, specific investigation of speeds was undertaken since speed differential is a single measure that takes into account only two locations. In a field study, the use of differentials is practical since only two detectors were deployed due to cost and other factors. But in a simulator study, virtual detectors can be located anywhere. The speed data of each participant driving through the work zone were collected at 11 locations shown on Figure 4-14 from the beginning to the end of the scenario. The whole process reflected the trends as participants drove past the work zone until the end of the work zone and then reaching the downstream sensor.

Daytime Results for Speed Profiles

Results for speed profiles for daytime speed countermeasures are shown in Figure 4-15 and Figure 4-16. The numerical results are also tabulated in Appendix D. In general, for each speed countermeasure, participants slowed down as they approached the work zone. However, there was variation in the locations and magnitude of the speed reductions.

Figure 4-15 shows the comparison between base and speed trailer related countermeasures during daytime, including the speed trailer with and without red and blue lights. The speed trailer with red and blue lights reported the best performance among speed trailer related countermeasures, with an average speed of 50.2 mph at the location of the deployed speed countermeasure, compared to an average speed of 52.5 mph at this location for the base scenario. The largest speed differential between the speed trailer with red and blue lights and the base scenario (3.3 mph) occurred at a location 250 feet downstream from the speed countermeasure. However, after passing a location 1,000 feet downstream from the speed countermeasures, the speed trailer with red and blue lights had a higher average speed compared to the speed trailer active. The speed trailer active reported lower speeds (51.0 mph) than the base scenario (52.5 mph) at the location of the second lane shift sign. The maximum speed differential between these two scenarios (2.0 mph) was located 250 feet downstream from the speed countermeasure. Figure 4-15 shows the speed curves for both types of speed trailers are under the baseline curve once drivers are near the location of the speed trailer past 1000 ft from the beginning of the work zone.

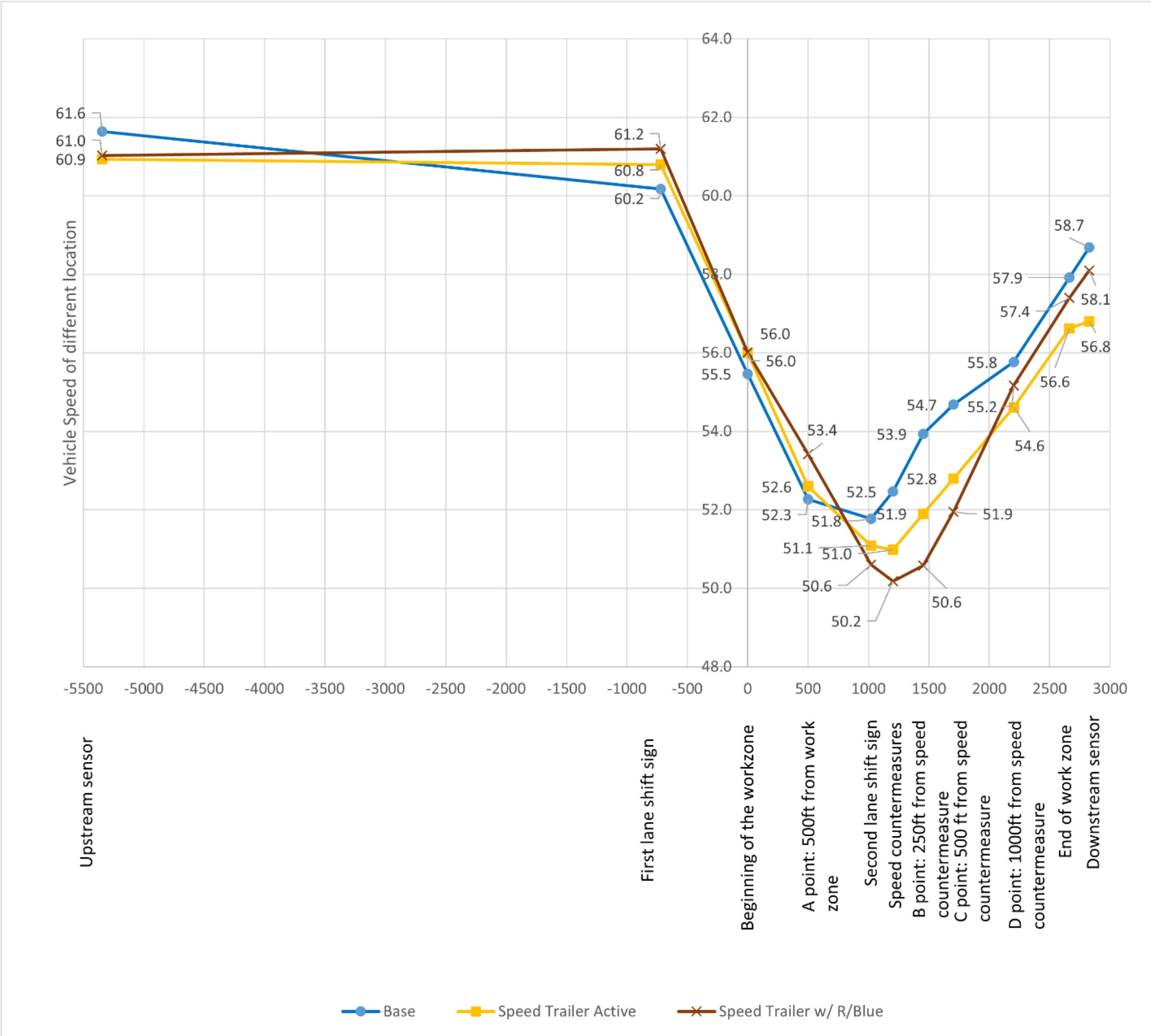


Figure 4-15. Speed profiles for speed trailers during daytime

Figure 4-16 shows the comparison between the base scenario and law enforcement speed countermeasures, including active law enforcement, passive law enforcement and super law enforcement, during daytime. Super law enforcement had the best performance on reducing vehicle speeds from the beginning until the location 1,000 feet downstream from the speed countermeasures. Within this section, the use of super law enforcement led to much lower speeds over the base scenario compared to active and passive law enforcement. Super law enforcement reported an average speed of 50.1 mph while average speed for the base scenario was 52.5 mph at the location of the speed countermeasure. The maximum speed differential of 3.6 mph happened at a location 500 feet downstream from the speed countermeasure. From the second lane shift sign location to a location 500 feet downstream from the speed countermeasures, passive law enforcement had the better performance on reducing vehicle speed. Active law enforcement reported an average speed of 51.9 mph while the average speed for passive law enforcement was 50.5 mph. From a location 1,000 feet downstream from the speed countermeasures until the end, active law enforcement had a better performance on reducing vehicle speeds. The maximum speed differential for active law enforcement and the base scenario of 3.4 mph occurred at a location 1000 feet downstream from the speed countermeasures. Figure 4-16 shows that the speed curves for all types of law enforcement are under the baseline curve once drivers are near the location of law enforcement past 1000 ft from the beginning of the work zone.

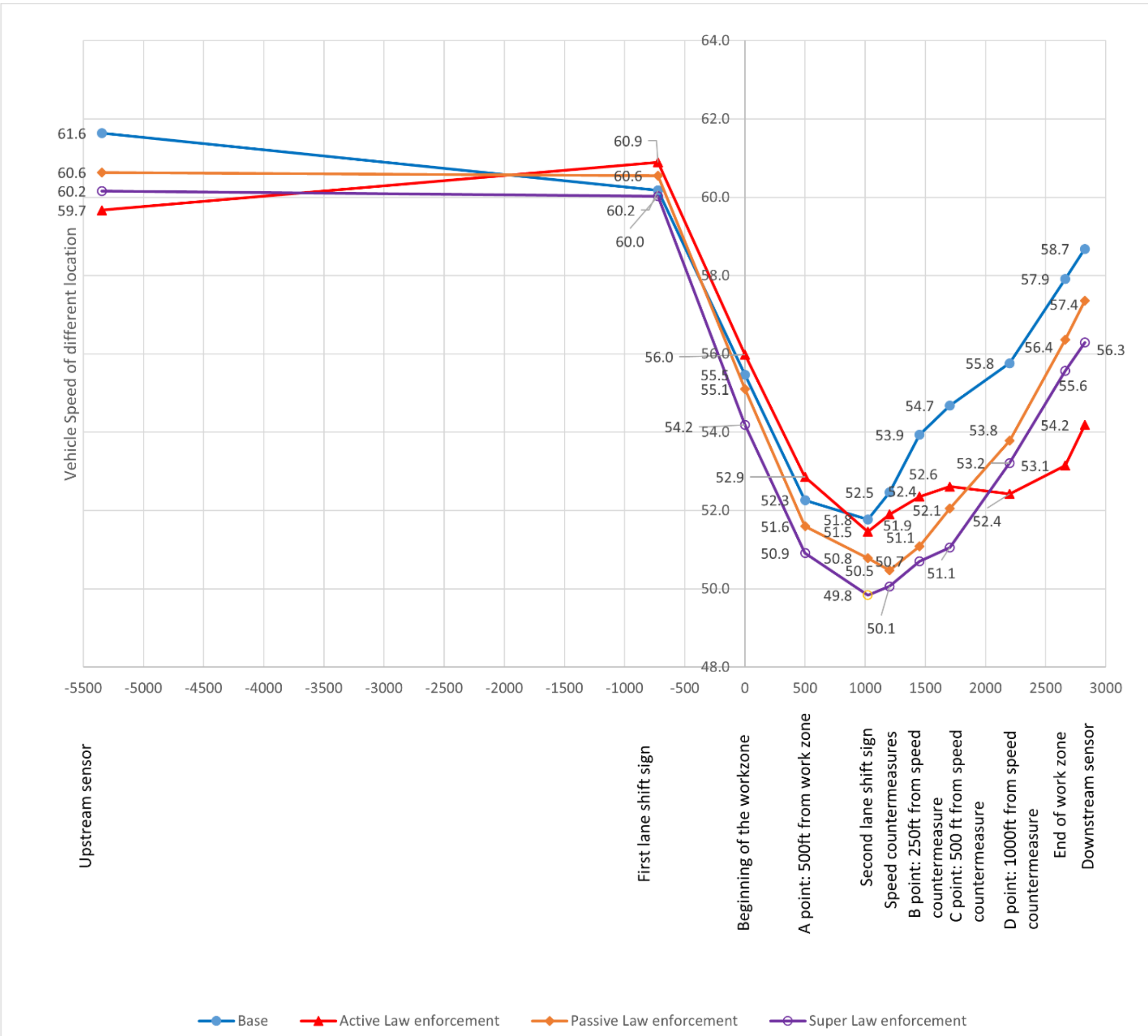


Figure 4-16. Speed profiles for law enforcement during daytime

Nighttime Results for Speed Profiles

Figure 4-17 shows the comparison between the base scenario and law enforcement speed countermeasures, including active law enforcement and passive law enforcement, during nighttime. The results are also tabulated numerically in Appendix D. Active law enforcement resulted in lower speeds at the locations downstream from the upstream sensor location. At the location of the speed countermeasure, active law enforcement reported a speed of 51.4 mph whereas the base was 53.0 mph. The largest speed differential happened at a location 500 feet downstream from the speed countermeasure where the speed differential was 2.6 mph. Passive law enforcement shared a similar trend to active law enforcement with an average speed of 51.5 mph at the countermeasure location compared to 53.0 mph for the base scenario. The largest speed differential between passive law enforcement and the base scenario occurred at a location 500 feet downstream from the speed countermeasures with a speed differential of 2.9 mph. However, a difference between the active and passive law enforcement is that vehicles in the passive law enforcement scenario started to rapidly accelerate after 500 feet downstream from speed countermeasures and then exceeded the base scenario speed from 1000 feet downstream from the speed countermeasures. This acceleration trend continues when vehicles pass the downstream sensor location. Figure 4-17 shows the speed curves for all types of law enforcement are under the baseline curve except for passive law enforcement after passing the location of the countermeasure past 2000 feet from the beginning of the work zone.

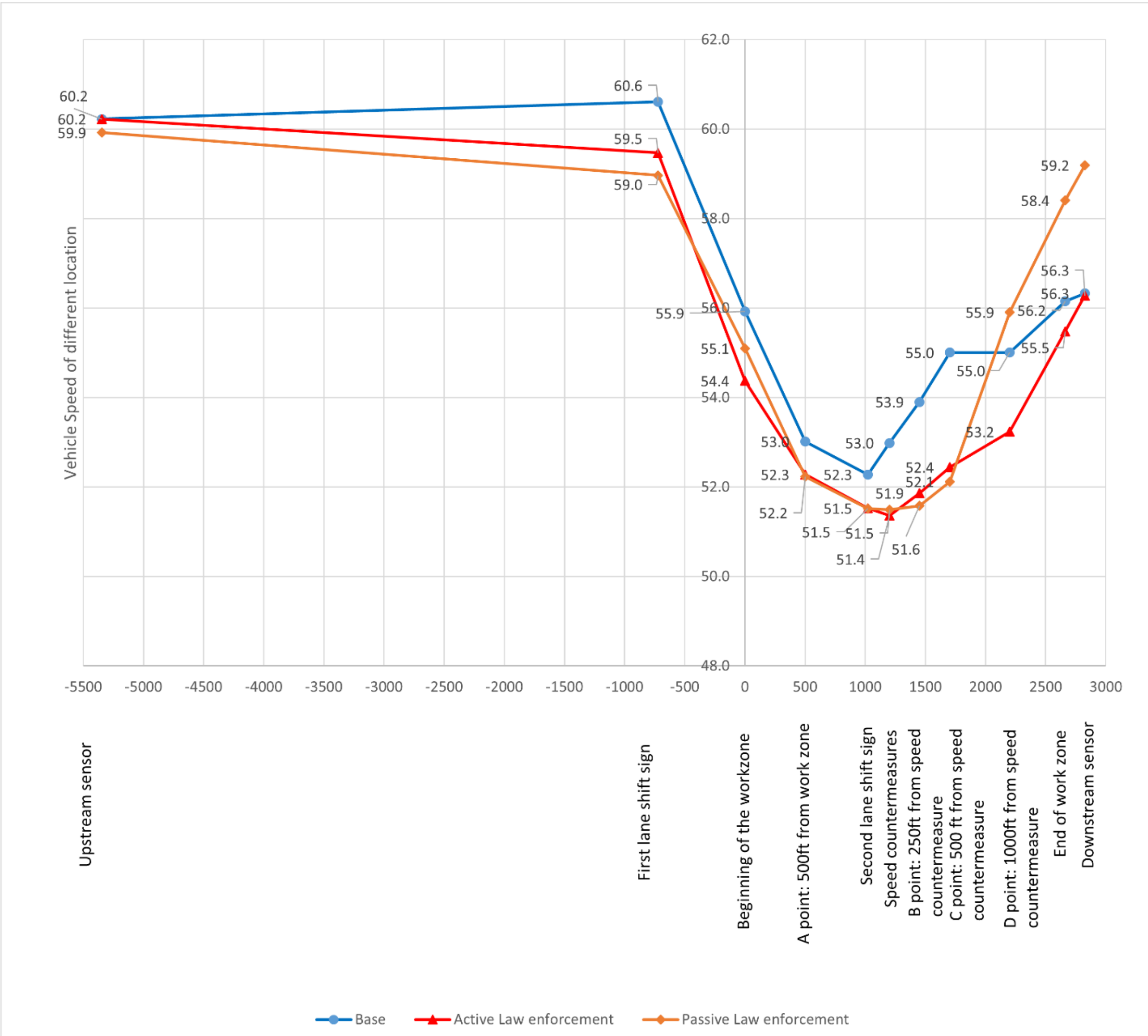


Figure 4-17. Speed profiles for law enforcement countermeasures during nighttime

The results for the comparison between speed trailer active and speed trailer with red and blue lights is shown in Figure 4-18. Speed trailer active generally resulted in lower speeds than the base scenario except at few overlapping locations on the figure, such as near the beginning of the work zone and after the end of the work zone. Compared to the base scenario, participants for speed trailer active started to slow down heavily and started to accelerate rapidly after passing the speed countermeasure. At the moment participants passed the speed countermeasure, speed trailer active reported an average speed of 50.7 mph whereas the base scenario reported a speed of 53.0 mph. However, the maximum speed differential between base and speed trailer of 2.5 mph occurred at a location 250 feet downstream from the speed countermeasures. From entering the work zone until the end of the work zone, the speed trailer active had good performance for reducing vehicle speeds with lower vehicle speeds than the base scenario. The speed trailer with red and blue lights did not result in lower speeds until approaching the speed countermeasures and ended at a location 500 feet downstream from the speed countermeasures. Except for this segment, the speed trailer with red and blue lights showed a higher average speed compared to the base scenario, even at the downstream sensor location. The speed trailer with red and blue lights only showed lower speeds from the speed countermeasure location to a location 500 feet downstream from the speed countermeasure. The speed trailer with red/blue lights showed an average speed of 51.8 mph at the countermeasure location compared to an average speed for the base scenario of 53.0 mph. This speed differential increased to 1.6 mph at the location 250 feet downstream from the speed countermeasures.

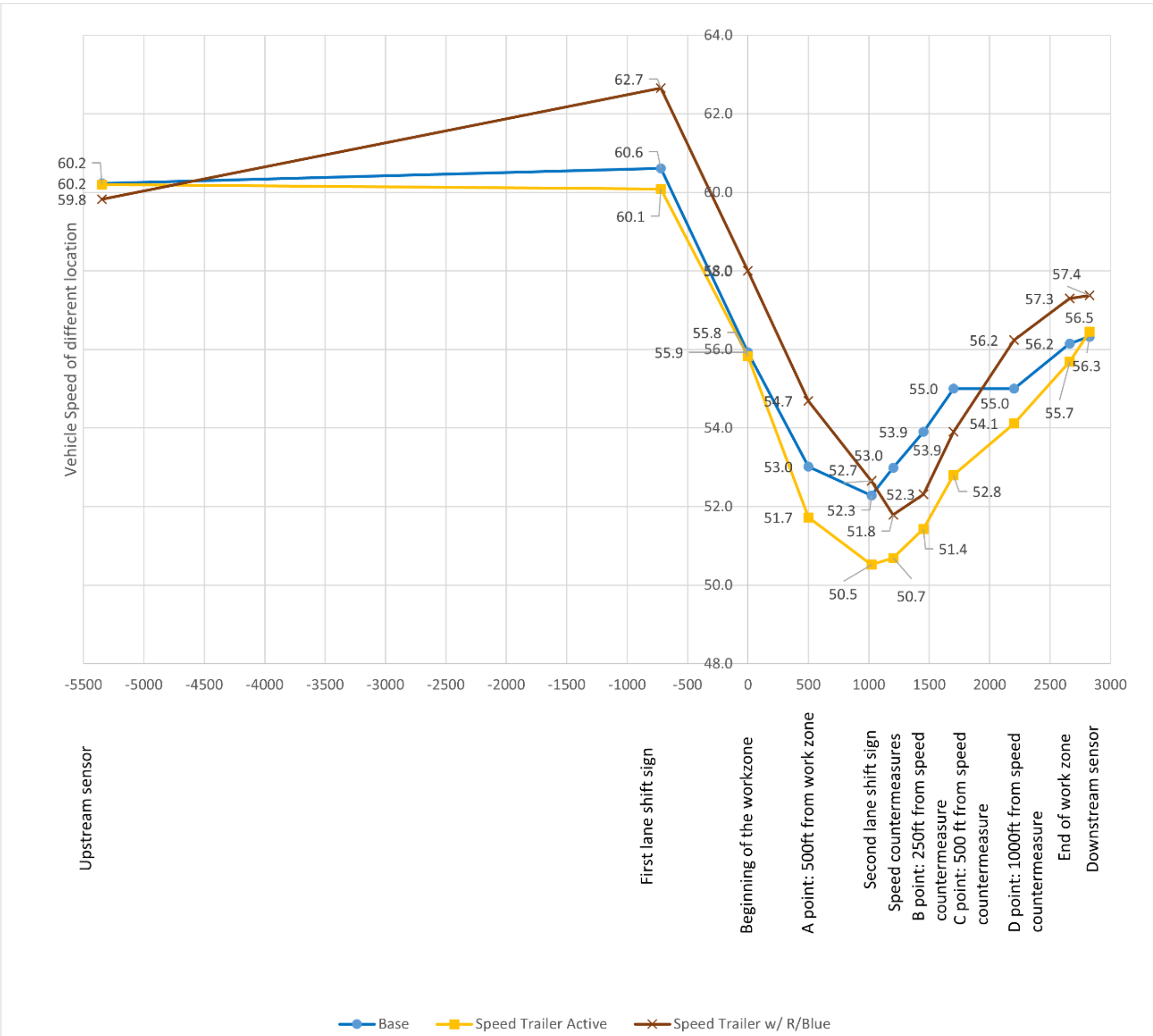


Figure 4-18. Speed profiles for speed trailer related countermeasures during nighttime

The results for the comparison between speed trailer active and work vehicle with red/blue lights are shown in Figure 4-19. The work vehicle with red and blue lights resulted in lower speeds than the base scenario except at the upstream sensor location and after 1000 ft downstream from the speed countermeasures. The work vehicle with red and blue lights reported an average speed of 51.4 mph compared to 53.0 mph at the countermeasure location, which was the maximum speed differential for this countermeasure. The combination of speed trailer active and work vehicle with red and blue lights shared the same trend as the work vehicle with red and blue lights, with an average speed of 51.7 mph at the countermeasure location. The maximum speed differential (2.2 mph) for the combination scenario occurred at a location 500 feet downstream from the speed countermeasures. Between the location of second lane shift sign and the location 500 feet downstream from the speed countermeasures, the combination scenario was relatively more effective in reducing speeds. Thus, the average speed of this segment from the combination scenario was slightly lower than the work vehicle with red and blue lights alone.

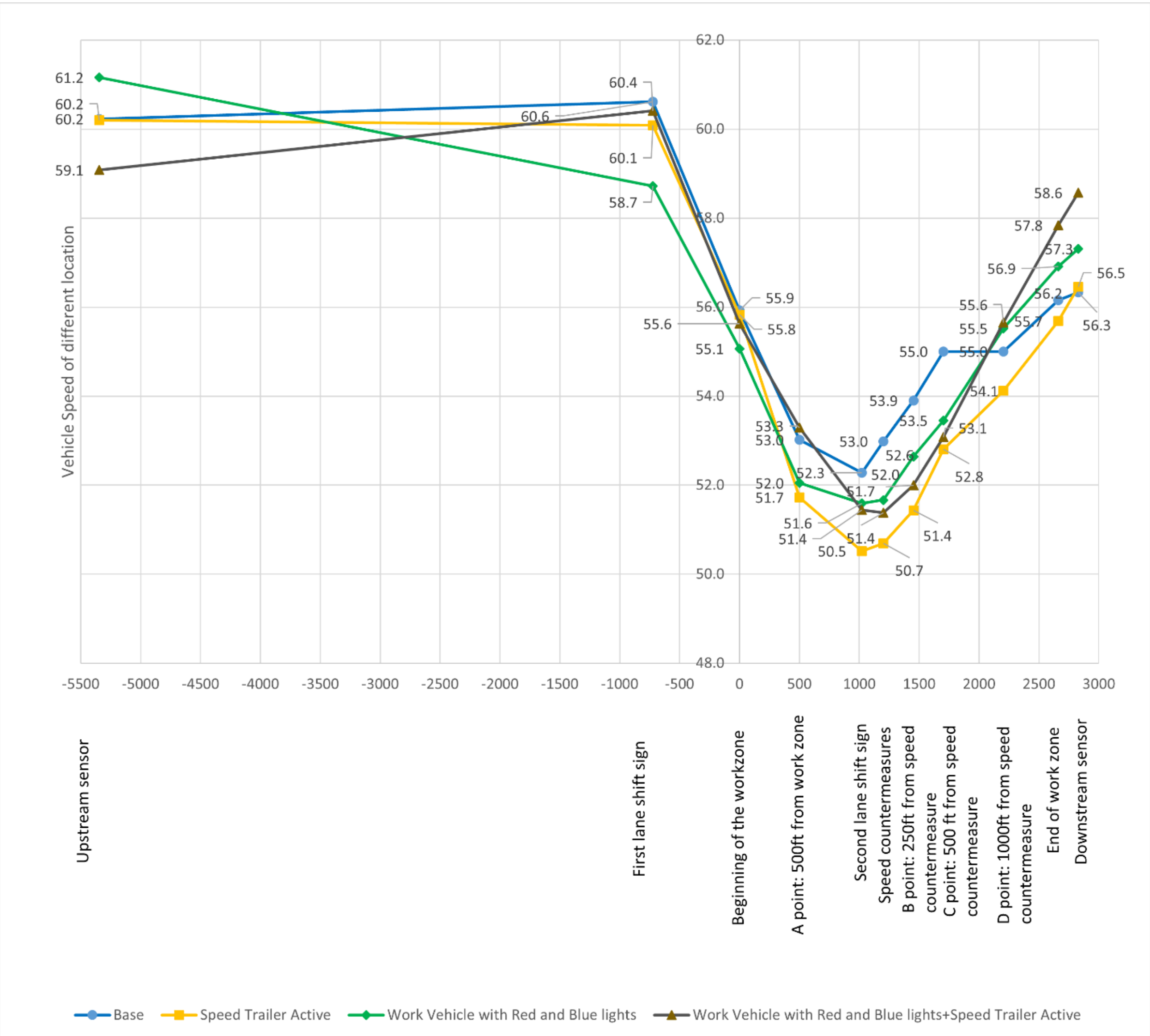


Figure 4-19. Speed profiles for work vehicle with red and blue lights and speed trailer active during nighttime

Eye Tracking Data

Through an investigation of the eye tracking data extracted from the recorded video, driver behavior could be investigated by four MOEs as discussed previously. Detailed results from the eye tracking data are provided in the following sections.

Daytime Results for Eye Tracking

MOE 1 measured the speed of a vehicle when the participant glanced at speed countermeasure for the first time as they drove through the different simulator daytime scenarios. As shown in Table 4-5, law enforcement scenarios were associated with lower average speeds than the speed trailer scenarios. Super law enforcement, which is the combination of the active law enforcement and speed trailer active, resulted in the lowest speed of 50.9 mph while first glancing at the speed countermeasure. Active law enforcement had the second lowest average speed of 51.4 mph while speed trailer active had the highest average speed of 52.8 mph.

Table 4-5. Vehicle speed when participant first glanced at speed countermeasure (daytime)

Scenario	Mean (mph)	Standard Deviation (mph)	Confidence Level
No Speed Countermeasure	Base	Base	Base
Speed Trailer Active	52.8	8.9	16.0%*
Speed Trailer with Red and Blue Lights	52.7	7.8	16.0%*
Active Law Enforcement	51.4	7.2	16.0%*
Passive Law Enforcement	52.0	9.0	16.0%*
Super Law Enforcement	50.9	7.9	16.0%*

* Result is from Anova: single factor analysis.

MOE 2 recorded the distance of the vehicle from the speed countermeasure when the participant glanced at the speed countermeasure for the first time, and the results are shown in Table 4-6. A smaller distance can indicate a better visibility for the speed countermeasure and faster reaction from the perspective of drivers. The super law enforcement, which is the combination of active law enforcement and speed trailer active, had the shortest distance for this MOE of 424.5 ft.

Table 4-6. Distance from first traffic cone when first glanced at speed countermeasure (daytime)

Scenario	Mean (feet)	Standard Deviation (feet)	Confidence Level
Base	Base	Base	Base
Speed Trailer Active	465.1*	452.8	74.4%**
Speed Trailer with Red and Blue Lights	458.1*	501.4	74.4%**
Active Law Enforcement	645.1*	416.5	74.4%**
Passive Law Enforcement	497.9*	328.8	74.4%**
Super Law Enforcement	424.5*	498.9	74.4%**

* This distance is recorded after vehicle passed the first traffic cone in work zone.
** Result is from Anova: single factor analysis.

MOE 3 recorded the distance from the first traffic cone when participants first glanced at the lane shift sign in work zone, and the results are shown in Table 4-7. Shortly before glancing at the speed countermeasures, participants would encounter the lane shift sign as they approached the work zone. This MOE could indicate the acknowledgement of traffic conditions by the participants. Daytime results for all scenarios are very comparable except that the law enforcement had the lowest distance of 115 ft.

Table 4-7. Distance from the first traffic cone when participants first glanced at the lane shift sign in the work zone (daytime)

Scenario	Mean (feet)	Standard Deviation (feet)	Confidence Level
Base	195*	743.5	Base
Speed Trailer Active	181*	701.4	6.1%
Speed Trailer with Red and Blue Lights	201*	839.9	2.4%
Active Law Enforcement	115*	703.7	35.1%
Passive Law Enforcement	187*	750.2	3.2%
Super Law Enforcement	202*	734.1	3.0%

* This distance is recorded before vehicle pass the first traffic cone of work zone.

MOE 4 measures the vehicle speed when participants first glanced at the lane shift sign in the work zone, and the results are shown in Table 4-8. This could indicate how drivers react to the traffic conditions. All of the countermeasures had lower average speeds compared to base scenario, and the speed trailer active had the highest speed among all trials of 55.5 mph.

Table 4-8. Vehicle speed when participants first glanced at lane shift sign in work zone (daytime)

Scenario	Mean (mph)	Standard Deviation (mph)	Confidence Level	Cohens' d	Effect size
Base	56.0	9.1	Base	Base	Base
Speed Trailer Active	55.5	8.2	19.7%	n/a	n/a
Speed Trailer with Red and Blue Lights	54.4	8.4	55.6%	n/a	n/a
Active Law Enforcement	55.4	8.4	23.2%	n/a	n/a
Passive Law Enforcement	53.1	9.3	81.5%	0.32	Small
Super Law Enforcement	53.6	8.7	72.6%	0.27	Small

Nighttime Results for Eye Tracking

MOE 1 measured the speed of a vehicle when the participant first glanced at the speed countermeasure as participants drove through different simulator nighttime scenarios. As shown in Table 4-9, active law enforcement had the lowest speed of 48.8 mph when participants first glanced at the speed countermeasures, followed by passive law enforcement with the second lowest speed of 51.2 mph. These results are consistent with the daytime results. The work vehicle with red and blue lights was associated with an average speed of 51.8 mph for this MOE. However, the speed trailer with red and blue lights had the highest speed of 55.0 mph.

Table 4-9. Vehicle speed when participant first glanced at speed countermeasure (nighttime)

Scenario	Mean (mph)	Standard Deviation (mph)	Confidence Level
No Speed Countermeasure	Base	Base	Base
Speed Trailer Active	53.1	9.9	93.3%*
Speed Trailer with Red and Blue Lights	55.0	7.5	93.3%*
Work vehicle with Red and Blue Lights	51.8	9.5	93.3%*
Work vehicle + Speed Trailer Active	53.0	8.1	93.3%*
Active Law Enforcement	48.8	7.8	93.3%*
Passive Law Enforcement	51.2	7.1	93.3%*

* Result is from Anova: single factor analysis.

MOE 2 recorded the distance of the vehicle from the speed countermeasure when the participant first glanced at the speed countermeasure, and the results are shown in Table 4-10. A smaller distance can indicate a better visibility for the speed countermeasure and faster reaction from the perspective of drivers. The work vehicle with red and blue lights and speed trailer active combination had the lowest distance of 184.8 feet when the participant first glanced at the speed countermeasure. The speed trailer active and speed trailer with red and blue lights both had lower distances at nighttime compared to the daytime results. This result could indicate that speed trailer related countermeasures have better visibility and led to faster driver reactions during nighttime.

Table 4-10. Distance from first traffic cone when participants first glanced at the speed countermeasure (nighttime)

Scenario	Mean (feet)	Standard Deviation (feet)	Confidence Level
Base	Base	Base	Base
Speed Trailer Active	271.3*	681.7	99.97%**
Speed Trailer with Red and Blue Lights	292.1*	550.1	99.97%**
Work vehicle with Red and Blue Lights	253.7*	636.9	99.97%**
Work vehicle + Speed Trailer Active	184.8*	716.7	99.97%**
Active Law Enforcement	746.9*	393.4	99.97%**
Passive Law Enforcement	618.0*	396.3	99.97%**

* This distance is recorded after vehicle passed the first traffic cone in work zone.
** Result is from Anova: single factor analysis.

MOE 3 recorded the distance from the first traffic cone when participants first glanced at the second lane shift sign, and the results are shown in Table 4-11. Shortly before glancing at the speed countermeasures, participants encountered the lane shift sign as they approached the work zone. This could indicate the acknowledgement of traffic conditions by the participants. Speed trailer active had the lowest distance of 30 feet when the participant first glanced the lane shift sign in work zone.

Table 4-11. Distance from the first traffic cone when participants first glanced at the lane shift sign in the work zone (nighttime)

Scenario	Mean (feet)	Standard Deviation (feet)	Confidence Level	Cohens' d	Effect size
Base	158*	693.7	Base	Base	Base
Speed Trailer Active	30**	1123.2	60.1%	0.20	Small
Speed Trailer with Red and Blue Lights	128*	684.4	14.2%	n/a	n/a
Work vehicle with Red and Blue Lights	98*	590.5	29.4%	n/a	n/a
Work vehicle + Speed Trailer Active	155*	698.2	1.5%	n/a	n/a
Active Law Enforcement	60*	644.1	45.9%	n/a	n/a
Passive Law Enforcement	150*	639.9	3.8%	n/a	n/a

*This distance is recorded before vehicle pass the first traffic cone of work zone.
** This distance is recorded after vehicle pass the first traffic cone of work zone.

MOE 4 measured the vehicle speed when participants first glanced at the lane shift sign in the work zone, and the results are shown in Table 4-12. This result could indicate how drivers react to the traffic conditions. The nighttime results are different from the daytime results, with speed trailer active having the second lowest speed of 53.4 mph for this MOE. The work vehicle with red and blue lights was associated with the lowest average speed of 53.2 mph.

Table 4-12. Vehicle speed when participants first glanced at lane shift sign in work zone (nighttime)

Scenario	Mean (mph)	Standard Deviation (mph)	Confidence Level	Cohens' d	Effect size
Base	55.7	8.7	Base	Base	Base
Speed Trailer Active	53.4	9.2	72.8%	0.26	Small
Speed Trailer with Red and Blue Lights	56.8	8.8	39.4%	n/a	n/a
Work vehicle with Red and Blue Lights	53.2	8.6	77.1%	0.29	Small
Work vehicle + Speed trailer active	55.2	7.9	22.5%	n/a	n/a
Active Law Enforcement	53.3	9.0	74.9%	0.27	Small
Passive Law Enforcement	54.2	7.9	55.1%	n/a	n/a

A few other discussions on other MOEs are also included in Appendix G.

5. POST-SIMULATOR SURVEY

This chapter presents the methodology and results for the survey given to simulator study participants after they completed the driving simulator scenarios.

Methodology for Post-Simulator Survey

A post-simulator survey was given to the simulator study participants to obtain their feedback on work zone speed countermeasures. The survey contained 17 questions on the following topics: daytime work zone speed countermeasures, nighttime work zone speed countermeasures, driving behavior, driving simulator experience, and demographic data. A 16-question simulator sickness questionnaire (Kennedy et al. 1993), which is frequently used to diagnose the severity of simulator sickness of participants, was administered at the end of the survey. The complete post-simulator survey is shown in Appendix E.

Results from Post-Simulator Survey

Post-Simulator Survey Results for Daytime Work Zone Speed Countermeasures

The first four questions asked participants about their perceptions of the following daytime work zone speed countermeasures: speed display trailer, speed display trailer with red and blue lights, passive law enforcement, and active law enforcement. The results are shown in Table 5-1 through Table 5-6. As shown in Table 5-1, participants preferred the speed trailers over law enforcement (active and passive). The speed trailer with red and blue lights received the highest rating of 4.20 out of 5, while active law enforcement received the lowest rating of 3.14. In question 2, participants were asked to rate the speed countermeasures with respect to visibility, clarity, and encouraging vehicles to slow down on scale of one to ten. As shown in Table 5-2 through Table 5-5, participants rated the speed display trailer the highest for visibility and clarity, with average ratings of 8.80 and 8.62, respectively. Passive and active law enforcement scored the highest with respect to encouraging drivers to slow down, with average ratings of 9.02 and 9.06, respectively. Participants indicated that passive and active law enforcement would most likely cause them to reduce their speed in work zones, with average ratings (1 to 5) of 4.72 and 4.64, respectively. In the comments (question 4), participants generally indicated that they thought law enforcement was more effective than the speed display trailer in reducing vehicle speeds. However, some participants suggested that the presence of law enforcement could be distracting. One participant thought that law enforcement might be more effective if placed before the work zone. Two participants indicated that they thought the flashing red and blue lights on the speed display trailer were less effective during daytime.

Table 5-1. Overall ratings of daytime strategies (post-simulator survey)

Daytime Work Zone Speed Control Strategy	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Displays your speed	4.16	0.96	1	5	50
Displays your speed and flashes red and blue lights when you are speeding	4.20	1.11	1	5	50
Police car parked on shoulder	3.18	1.41	1	5	50
Police car pulling drivers over	3.14	1.46	1	5	50

*1= lowest, 5 = highest

Table 5-2. Attribute ratings for speed display trailer during daytime (post-simulator survey)

Attribute	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Visibility	8.56	1.66	3	10	50
Clarity	8.50	1.57	4	10	50
Encourages Drivers to Slow Down	7.70	2.02	3	10	50

*1 = lowest, 10 = highest

Table 5-3. Attribute ratings for speed display trailer with red and blue lights during daytime (post-simulator survey)

Attribute	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Visibility	8.80	1.41	3	10	50
Clarity	8.62	1.51	4	10	50
Encourages Drivers to Slow Down	8.28	1.76	3	10	50

*1 = lowest, 10 = highest

Table 5-4. Attribute ratings for passive law enforcement during daytime (post-simulator survey)

Attribute	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Visibility	8.48	1.63	4	10	50
Clarity	8.04	2.18	2	10	50
Encourages Drivers to Slow Down	9.02	1.30	5	10	50

*1 = lowest, 10 = highest

Table 5-5. Attribute ratings for active law enforcement during daytime (post-simulator survey)

Attribute	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Visibility	8.64	1.47	5	10	50
Clarity	8.28	1.97	1	10	50
Encourages Drivers to Slow Down	9.06	1.22	6	10	50

*1 = lowest, 10 = highest

Table 5-6. Likelihood of reducing speed in response to daytime strategies (post-simulator survey)

Daytime Work Zone Speed Control Strategy	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Displays your speed	3.84	0.98	2	5	50
Displays your speed and flashes red and blue lights when you are speeding	4.10	0.97	2	5	50
Police car parked on shoulder	4.72	0.70	1	5	50
Police car pulling drivers over	4.64	0.80	1	5	50

*1= lowest, 5 = highest

Post-Simulator Survey Results for Nighttime Work Zone Speed Countermeasures

Survey questions 5 through 8 sought information from participants regarding their views of the following nighttime work zone speed countermeasures: speed display trailer, speed display trailer with red and blue lights, passive law enforcement, active law enforcement, and work vehicle with red and blue lights. The results are provided in Table 5-7 through Table 5-13. As shown in Table 5-7, participants preferred the speed trailers over law enforcement and the work vehicle with red and blue lights. With respect to attribute ratings (Table 5-8 through Table 5-12), all five countermeasures received an average rating of at least 8 out of 10 for visibility, with the speed display trailer with red and blue lights receiving the highest average rating of 8.88. The speed display trailer with red and blue lights was also rated the highest with respect to clarity, with an average rating of 8.68. Participants indicated that law enforcement would be most likely to encourage drivers to slow down during nighttime, with average ratings of 9.12 and 9.08 for passive and active law enforcement, respectively. Passive and active law enforcement were rated as the most to likely cause participants to reduce their speed in work zones, with average ratings (one to five) of 4.66 and 4.47, respectively. Participants believed that the work vehicle with red and blue lights and speed display trailer without red and blue lights were the least likely to encourage them to slow down. In the comments (question 8), participants generally indicated that the use of law enforcement was the most effective in reducing speeds. They also indicated that the red and blue lights were more effective at nighttime. However, they did not think that the work vehicles were as effective as law enforcement. The survey results from daytime and nighttime were consistent.

Table 5-7. Overall ratings of nighttime strategies (post-simulator survey)

Nighttime Work Zone Speed Control Strategy	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Displays your speed	4.24	0.82	2	5	50
Displays your speed and flashes red and blue lights when you are speeding	4.26	0.96	1	5	50
Police car parked on shoulder	3.84	1.15	1	5	50
Police car pulling drivers over	3.60	1.23	1	5	50
Work vehicle with flashing red and blue lights	3.76	1.06	1	5	50

*1= lowest, 5 = highest

Table 5-8. Attribute ratings for speed display trailer during nighttime (post-simulator survey)

Attribute	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Visibility	8.38	1.83	2	10	50
Clarity	8.50	1.56	3	10	50
Encourages Drivers to Slow Down	7.36	1.98	1	10	50

*1 = lowest, 10 = highest

Table 5-9. Attribute ratings for speed display trailer with red and blue lights during nighttime (post-simulator survey)

Attribute	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Visibility	8.88	1.48	5	10	50
Clarity	8.68	1.38	4	10	50
Encourages Drivers to Slow Down	8.02	1.79	3	10	50

*1 = lowest, 10 = highest

Table 5-10. Attribute ratings for passive law enforcement during nighttime (post-simulator survey)

Attribute	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Visibility	8.42	1.79	2	10	50
Clarity	7.88	2.22	1	10	50
Encourages Drivers to Slow Down	9.12	1.08	6	10	50

*1 = lowest, 10 = highest

Table 5-11. Attribute ratings for active law enforcement during nighttime (post-simulator survey)

Attribute	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Visibility	8.42	1.83	3	10	50
Clarity	7.84	2.25	1	10	50
Encourages Drivers to Slow Down	9.08	1.12	6	10	50

*1 = lowest, 10 = highest

Table 5-12. Attribute ratings for work vehicle with red and blue lights during nighttime (post-simulator survey)

Attribute	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Visibility	8.60	1.65	3	10	50
Clarity	7.64	2.28	1	10	50
Encourages Drivers to Slow Down	7.64	2.16	1	10	50

*1 = lowest, 10 = highest

Table 5-13. Likelihood of reducing speed in response to nighttime strategies (post-simulator survey)

Nighttime Work Zone Speed Control Strategy	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Displays your speed	4.00	0.90	2	5	50
Displays your speed and flashes red and blue lights when you are speeding	4.30	0.79	2	5	50
Police car parked on shoulder	4.66	0.69	2	5	50
Police car pulling drivers over	4.47	0.77	2	5	49
Work vehicle with flashing red and blue lights	4.12	0.92	1	5	50

*1 = lowest, 5 = highest

Post-Simulator Survey Results for Driving Behavior

Question 9 of the post-simulator survey asked participants about the degree to which various factors influence their speed selection in work zones. As shown in Table 5-14, all participants agreed that visibility affects their speed selection, while 90 percent of participants agreed that the presence of active work or law enforcement influenced their choice of driving speed in work zones. Level of traffic and weather were also chosen by at least 80 percent of participants as influential factors. Only 58 percent of participants indicated that time of day affected their speed choice. Other factors mentioned by respondents included the presence of other passengers in the vehicle and the speed of other vehicles.

Table 5-14. Factors affecting speed selection in work zones (post-simulator survey)

Factor	Strongly Agree	Somewhat Agree	Neither Agree nor Disagree	Somewhat Disagree	Strongly Disagree	No Response
Feeling Rushed (e.g., Running Late)	36%	32%	16%	10%	6%	0%
Level of Traffic	32%	48%	14%	4%	2%	0%
Number of Lanes	16%	50%	20%	10%	4%	0%
Presence of Active Work	58%	32%	8%	2%	0%	0%
Presence of Law Enforcement	80%	10%	8%	2%	0%	0%
Roadway Width	30%	42%	20%	8%	0%	0%
Time of Day	22%	36%	22%	16%	4%	0%
Urban or Rural Environment	20%	40%	26%	14%	0%	0%
Visibility	48%	52%	0%	0%	0%	0%
Weather	60%	22%	16%	2%	0%	0%
Work Zone Speed Limit	52%	40%	8%	0%	0%	0%
Other (Please describe)*	6%	0%	2%	0%	0%	92%

* Riding with passengers, the speed of other cars

Post-Simulator Survey Results for Simulator Experience

Survey questions 10 through 12 asked participants about their simulator experience. As shown in Table 5-15, 52 percent of participants believed that they were driving at or below the work zone speed limit. Nearly two-thirds of respondents felt like they were driving on the highway (Table 5-16) with only 10% disagreeing. Half of the respondents felt like they could drive around freely (Table 5-17) with 30% disagreeing.

Table 5-15. Percent of participants who believed that they were driving at or below the work zone speed limit (post-simulator survey)

Level of Agreement	Response
Strongly Agree	20%
Agree	32%
Neutral	26%
Disagree	22%
Strongly Disagree	0%
No Response	0%

Table 5-16. Percent of participants who felt like they were driving on the highway (post-simulator survey)

Level of Agreement	Response
Strongly Agree	12%
Agree	52%
Neutral	26%
Disagree	10%
Strongly Disagree	0%
No Response	0%

Table 5-17. Percent of participants who felt like could drive around freely (post-simulator survey)

Level of Agreement	Response
Strongly Agree	12%
Agree	38%
Neutral	20%
Disagree	30%
Strongly Disagree	0%
No Response	0%

Demographic Data for Post-Simulator Survey

Questions 13 through 16 of the survey sought demographic information, and the results are shown in Table 5-18 through Table 5-21. The participants were well-balanced with respect to gender, while 84 percent of respondents were between 16 and 40 years of age. Passenger car was the regular vehicle type of almost all participants, and 80 percent of the participants were from an urban area.

Table 5-18. Age range of participants (post-simulator survey)

Age Range	Response
16-25	46%
26-40	38%
41-55	8%
56-70	8%
71-95	0%
No Response	0%

Table 5-19. Gender of participants (post-simulator survey)

Gender	Response
Male	50%
Female	48%
No Response	2%

Table 5-20. Participant urban or rural residency (post-simulator survey)

Residency	Response
Urban	80%
Rural	20%
No Response	0%

Table 5-21. Participant regular vehicle type (post-simulator survey)

Vehicle Type	Response
Passenger Car	96%
Vehicle towing trailer	0%
Delivery/Moving Truck	0%
Tractor trailer truck	0%
Bus	2%
No Response	2%

Post Simulator Survey Results for Simulator Sickness Questionnaire

The final section of the post simulator survey involved a simulator sickness questionnaire (Kennedy et al. 1993). The results are shown in Table 5-22. Most participants did not experience severe symptoms after completing the simulator study. The symptoms most commonly reported were fatigue, eye strain, and fatigue. Some degree of fatigue was reported by 48 percent of respondents.

Table 5-22. Results for simulator sickness questionnaire (post-simulator survey)

Symptom	None	Slight	Moderate	Severe	No Response
General discomfort	66%	20%	8%	6%	0%
Fatigue	52%	36%	8%	4%	0%
Headache	76%	14%	4%	6%	0%
Eye strain	64%	18%	14%	4%	0%
Difficult focusing	68%	22%	6%	4%	0%
Salivation increasing	88%	4%	4%	4%	0%
Sweating	74%	14%	4%	8%	0%
Nausea	72%	16%	2%	10%	0%
Difficulty concentrating	70%	18%	6%	6%	0%
Fullness of the Head	76%	12%	6%	6%	0%
Blurred vision	78%	16%	2%	4%	0%
Dizziness with eyes open	78%	14%	4%	4%	0%
Dizziness with eyes closed	82%	6%	6%	6%	0%
Vertigo	82%	8%	2%	8%	0%
Stomach awareness	80%	6%	4%	10%	0%
Burping	90%	2%	2%	6%	0%

Summary of Results from Post-Simulator Survey

The results from the post-simulator survey are summarized below.

- In general, the participants thought law enforcement was the most effective strategy for reducing vehicle speeds. However, participants preferred the speed trailers over law enforcement, and some participants suggested that the presence of law enforcement could be distracting. One participant thought that law enforcement might be more effective if placed before the work zone.
- The speed trailer with red and blue lights was perceived to be more effective than the speed trailer without red and blue lights. The work vehicle with red and blue lights was generally viewed as less effective than most of the other strategies in reducing vehicle speeds in work zones.
- Participants indicated that visibility and the presence of active work or law enforcement were the factors with the greatest influence on their speed selection in work zones.

6. DRIVER SURVEY

This chapter includes information on the driver survey, including methodology and results.

Methodology for Driver Survey

A survey to gauge drivers' perceptions of different work zone speed countermeasures and driving habits in work zones was developed and administered by the research team. Topics covered by the survey included ratings of daytime and nighttime work zone speed control strategies, speed selection in work zones, and demographic information. A copy of the survey is provided in Appendix F. After review by the project Technical Advisory Committee (TAC), the survey was administered online using Qualtrics software (Qualtrics 2022). The survey was distributed using various methods, including the researchers' social media accounts, webpages of larger MoDOT projects, MoDOT project email groups, and an article in the University of Missouri's announcement service (MU Info). During a six-week period, 108 anonymous survey responses were received. The survey responses were then compiled and analyzed.

Results from Driver Survey

Driver Survey Results for Daytime Countermeasures

The first three questions of the survey asked about drivers' perspectives on the following daytime work zone speed control strategies: speed display trailer, speed display trailer with red and blue lights, police car parked on the shoulder (passive law enforcement), and police car pulling drivers over (active law enforcement). Participants were asked to rate each strategy and to indicate how likely they would be to reduce their speed (both on a scale of 1 to 5) after seeing the strategy in a work zone. As shown in Table 6-1, respondents preferred the speed display trailers over law enforcement, and there was a wide range of responses for active law enforcement as indicated by the high standard deviation for that countermeasure. However, drivers indicated that law enforcement presence (both active and passive) is more effective in reducing their speeds during daytime (Table 6-2). The speed display trailer without the red and blue lights was perceived to be the least effective in encouraging drivers to reduce their speeds during daytime. In the comments, temporary rumble strips and signage (for example, "Workers Present" or "This worker is someone's daddy") were also noted as effective strategies to reduce vehicle speeds. These results were consistent with the results from the post-simulator survey.

Table 6-1. Ratings of daytime strategies (driver survey)

Daytime Work Zone Speed Control Strategy	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Displays your speed	4.11	0.98	2	5	108
Displays your speed and flashes red and blue lights when you are speeding	4.25	1.10	1	5	108
Police car parked on shoulder	3.57	1.31	1	5	107
Police car pulling drivers over	3.29	1.58	1	5	107

*1 = lowest, 5 = highest

Table 6-2. Likelihood of reducing speed in response to daytime strategies (driver survey)

Daytime Work Zone Speed Control Strategy	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Displays your speed	3.95	1.20	1	5	107
Displays your speed and flashes red and blue lights when you are speeding	4.24	1.11	1	5	107
Police car parked on shoulder	4.58	0.92	1	5	107
Police car pulling drivers over	4.54	0.93	1	5	107

*1 = lowest, 5 = highest

Driver Survey Results for Nighttime Countermeasures

Drivers were also asked to provide feedback on the following nighttime work zone speed control strategies: speed display trailer, speed display trailer with red and blue lights, police car parked on the shoulder (passive law enforcement), police car pulling drivers over (active law enforcement), and work vehicle with flashing red and blue lights. As shown in Table 6-3, drivers rated the speed display trailers the highest, followed by the work vehicle with flashing red and blue lights and the presence of law enforcement. However, respondents indicated their belief that law enforcement is the most effective countermeasure for reducing their speeds (Table 6-4). These results are consistent with the post-simulator survey where respondents indicated that law enforcement was the most effective even though they preferred the speed display trailer. The work vehicle with red and blue lights was rated as more effective for speed reduction than the speed display trailers. In the comments, respondents noted that flashing lights were effective at getting drivers' attention, but there were concerns about lights from law enforcement being too bright at nighttime.

Table 6-3. Ratings of nighttime strategies (driver survey)

Nighttime Work Zone Speed Control Strategy	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Displays your speed	4.00	1.06	1	5	107
Displays your speed and flashes red and blue lights when you are speeding	4.25	1.08	1	5	107
Police car parked on shoulder	3.64	1.29	1	5	107
Police car pulling drivers over	3.41	1.43	1	5	107
Work vehicle with flashing red and blue lights	3.98	1.23	1	5	106

*1 = lowest, 5 = highest

Table 6-4. Likelihood of reducing speed in response to nighttime strategies (driver survey)

Nighttime Work Zone Speed Control Strategy	Average Rating*	Standard Deviation	Lowest Rating	Highest Rating	Number of Ratings
Displays your speed	4.00	1.12	1	5	107
Displays your speed and flashes red and blue lights when you are speeding	4.22	1.11	1	5	107
Police car parked on shoulder	4.50	0.87	1	5	107
Police car pulling drivers over	4.38	1.06	1	5	107
Work vehicle with flashing red and blue lights	4.27	1.04	1	5	107

*1 = lowest, 5 = highest

Driver Survey Results for Driving Behavior in Work Zones

Questions 7 through 9 sought information regarding driving behavior in work zones, including factors affecting speed selection in work zones, frequency of driving through work zones, and general driving behavior. In question 7, drivers were asked to rank the top three factors that influence their speed selection in work zones. As shown in Table 6-5, the factors ranked the highest were presence of active work, presence of law enforcement, visibility / weather, and work zone speed limit. Seventy percent of respondents ranked presence of active work as one of their top three factors. Several drivers mentioned pressure from tailgating as another factor affecting their speed selection in work zones. With regard to frequency of driving through work zones, approximately half of the respondents indicated that they travel through a work zone daily or once or twice per week (Table 6-6). In response to question 9, 81 percent of respondents indicated that they drive at or below the work zone speed limit or one to five mph over the speed limit in work zones (Table 6-7).

Table 6-5. Ranking of factors affecting speed selection in work zones (driver survey)

Factor	1	2	3	4	5	6	7	8	No response
Feeling Rushed (e.g., Running Late)	7%	9%	7%	2%	4%	4%	6%	5%	56%
Level of Traffic	6%	7%	17%	7%	5%	8%	2%	2%	45%
Presence of Active Work	32%	25%	13%	3%	3%	1%	3%	6%	15%
Presence of Law Enforcement	21%	18%	13%	4%	1%	3%	4%	1%	36%
Time of Day	0%	3%	5%	4%	3%	6%	11%	4%	65%
Visibility / Weather	6%	16%	19%	6%	7%	6%	5%	1%	33%
Work Zone Speed Limit	15%	13%	14%	3%	7%	6%	4%	4%	34%
Other (Please describe)	3%	1%	2%	2%	0%	1%	0%	4%	88%

Table 6-6. Frequency of driving through a work zone (driver survey)

Frequency	Response
Daily	21%
1-2 times per week	30%
1-2 times per month	38%
1-2 times per year	8%
Other (please describe)	3%
No response	0%

Table 6-7. General driving behavior in work zones (driver survey)

Driving Behavior	Response
At or below work zone speed limit	44%
1 to 5 mph over work zone speed limit	37%
6 to 10 mph over work zone speed limit	6%
More than 10 mph over work zone speed limit	0%
Other (please describe)	12%
No response	2%

Demographic Data for Driver Survey

Questions 10 through 14 collected demographic data from the respondents, and the results are shown in Table 6-8 through Table 6-12. Respondents were diverse with respect to age, with 86 percent of respondents between the ages of 26 and 70. Almost two thirds of the respondents were female, with over 90 percent of respondents residing in Missouri and almost 70 percent of respondents living in urban areas. Nearly all respondents indicated that a passenger car is their regular vehicle type.

Table 6-8. Age range of respondents (driver survey)

Age Range	Response
16-25	5%
26-40	26%
41-55	33%
56-70	27%
71-95	8%
No response	1%

Table 6-9. Gender of respondents (driver survey)

Gender	Response
Male	36%
Female	62%
No response	2%

Table 6-10. Missouri residency of respondents (driver survey)

Missouri Resident	Response
Yes	91%
No	6%
No response	3%

Table 6-11. Urban or rural residency of respondents (driver survey)

Residency	Response
Urban	69%
Rural	29%
No response	2%

Table 6-12. Regular vehicle type of respondents (driver survey)

Vehicle Type	Response
Passenger Car	95%
Vehicle towing trailer	4%
Delivery/Moving Truck	0%
Tractor trailer truck	0%
Bus	0%
No response	1%

Summary of Comments Received for Driver Survey

The final question of the survey provided respondents with an opportunity to provide any other comments on the topic. Some noteworthy comments are summarized below:

- Additional law enforcement is needed.
- Temporary rumble strips can also be beneficial in reducing drivers' speeds.
- Some drivers find reduced speed limits in work zones to be frustrating when there are no workers present.
- Contractors need to ensure that work zone speed limit signs are visible.
- Speeds of other vehicles have significant influence on drivers' speeds, and some drivers are concerned for their safety when they are being tailgated.

Summary of Results from Driver Survey

The results from the driver survey are summarized below.

- For both daytime and nighttime, respondents generally preferred the speed display trailers over the presence of law enforcement. However, respondents also indicated that the presence of law enforcement would most likely cause them to reduce their speed.
- Respondents generally had a favorable impression of the work vehicle with red and blue lights and rated it between law enforcement and speed display trailers.
- Survey responses indicate that the presence of active work is the factor that has the greatest effect on drivers' speed selection in work zones.

7. CONCLUSIONS

This chapter presents the overall results conclusions of the research for the literature review, field evaluation, driving simulator study, and post-simulator and driver surveys.

Literature Review

Previous research studies have shown that countermeasures such as speed display trailers, active or passive law enforcement, flashing lights on work vehicles, temporary rumble strips, VSL, and graphic aided PCMSs are associated with speed reductions in work zones. There is a limited number of existing studies regarding the effects of flashing lights on work vehicles on vehicle speeds in work zones.

Field Evaluation

- In this research study, the field evaluation in the work zone on I-270 found that active law enforcement was the most effective speed countermeasure in reducing vehicle speeds during both daytime and nighttime conditions.
- The use of other speed countermeasures evaluated in the field study, including passive law enforcement, speed trailer, speed trailer with flashing speed feedback (daytime only), speed trailer with flashing red and blue lights (daytime only), and work vehicle with flashing red and blue lights (nighttime only), also resulted in reductions in vehicle speeds in the work zones.
- The speed trailer without flashing speed feedback or flashing red and blue lights was associated with lower speed reductions than the other speed countermeasures.
- Generally, the speed countermeasures performed better with respect to speed reductions during nighttime.
- Equipment issues limited the availability of the speed trailer with the red and blue lights.

Driving Simulator Study

- The driving simulator study complemented the field study by allowing testing for combinations of strategies in the same work zone scenario, collection of vehicle speeds at several locations, and the use of eye tracking data to assess drivers' responses to countermeasures.
- During daytime, the use of super law enforcement (the combination of speed trailer and active law enforcement) was the most effective in reducing vehicle speeds.
- During daytime, the speed trailer with red and blue lights was more effective than the speed trailer without red and blue lights, and passive law enforcement led to greater speed reductions than active law enforcement.
- During nighttime, the speed trailer was associated with the lowest speeds, and the speed

reductions for both active and passive law enforcement were comparable.

- In general, the effect of the speed reduction dissipated more quickly during nighttime than daytime.
- Eye tracking results indicate that super law enforcement and speed trailer-related countermeasures had better visibility during daytime and nighttime, respectively.

Post-Simulator and Driver Surveys

- The post-simulator survey and driver survey also obtained feedback from drivers regarding the effectiveness of different speed countermeasures in work zones.
- While drivers generally preferred the speed trailer, they also admitted that law enforcement would be the most effective in causing them to slow down in the work zone.
- Respondents to the driver survey rated the speed trailer with red and blue lights higher than the speed trailer without red and blue lights.
- Survey results regarding the effectiveness of the work vehicle with red and blue lights were mixed, with respondents to the driver survey having a more favorable view of this countermeasure than the simulator study participants.
- Visibility and the presence of active work or law enforcement are the factors with the greatest impact on driver speed selection in work zones.

Summary of Findings

Overall, the results of the study indicate that an approach that considers multiple strategies to manage vehicle speeds in work zones may be the most effective. The countermeasures evaluated in this study were all associated with speed reductions in the work zone. While law enforcement was generally the most effective strategy in reducing vehicle speeds, it might not be a feasible option at all sites. The selection of speed countermeasures to implement at a specific work zone could be made on a project-by-project basis based on various factors such as traffic volumes, type of work activity, site conditions, availability of law enforcement or equipment, and cost. For some work zones, the implementation of a second speed countermeasure located 250 feet to 500 feet downstream from the first countermeasure could be considered to discourage drivers from accelerating after passing the first countermeasure. Future research could further investigate the effects of a second countermeasure on vehicle speeds. Other strategies could include staggered use of law enforcement during periods of high speeding and the collection of data before the work zone is deployed to help determine the most suitable countermeasures.

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APPENDIX A. SUMMARY OF EXISTING LITERATURE FOR WORK ZONE SPEED COUNTERMEASURES

Table A-1. Summary of existing literature for work zone speed countermeasures

State/Country	Topic	Title	Reference	Summary
-	Driver behavior	Why Drivers Speed: The Speeding Perception Inventory	Gabany et al. 1997	This study investigated the factors that predispose, enable, and reinforce drivers' speeding behavior. They found five contributing factors namely: risk-taking, time pressure, inattention, ego gratification, and disdain of driving.
Australia	Driver behavior	Work Zone Items Influencing Driver Speeds at Roadworks: Worker, Driver and Expert Perspectives	Blackman et al. 2014	In an online survey, drivers were asked to rate the extent to which various factors would affect their speed choice in work zones. Participants rated worker presence, visible law enforcement presence, and speed feedback display signs as the most influential factors. “Roadwork speed limits are enforced” and “reduce speed” signs and increased speeding fines in work zones were rated as the least influential factors.
Australia	Driver Behavior	Speeding Through Roadworks: Understanding Driver Speed Profiles and Ways to Reduce Speeding	Debnath et al. 2015	In this study, researchers measured speeds at four points at three long-term work zones. Results indicated that factors contributing to higher speeds included light vehicles, times during late afternoon and early morning, and locations upstream of the work zones.
Norway	Driver behavior	Analysing the Influence of Visible Roadwork Activity on Drivers’ Speed Choice at Work Zones Using a Video-Based Experiment	Steinbakk et al. 2017	Drivers were asked to provide their preferred speeds for work zones under various conditions by viewing videos. Results indicated that the presence of roadwork activity had the greatest effect on vehicle speeds. Traffic signs and pressures of time were also influential factors on vehicle speeds.

State/Country	Topic	Title	Reference	Summary
Norway	Driver behavior	Effects of Roadwork Characteristics and Drivers' Individual Differences on Speed Preferences in a Rural Work Zone	Steinbakk et al. 2019	Drivers were shown ten pictures of a rural work zone and asked to provide their preferred speed. Results showed that preferred speeds were higher than the work zone speed limit. In addition, preferred speeds were higher for older drivers and drivers who rated their own driving skills higher.
United States	Driver behavior	Assessing Driving Behavior Upstream of Work Zones by Detecting Response Points in Speed Profile: A Naturalistic Driving Study	Thapa et al. 2019	Driver behavior upstream of the work zone was assessed in this naturalistic driving study. Results showed that drivers were most likely to respond at the lane ends, work zone speed limit signs, and speed feedback signs. In addition, drivers were more responsive as they got closer to the start of the work zone.
-	General Guidance	Safe Practices for Law Enforcement Personnel Operating in Highway Work Zones: A Pocket Guide	ATSSA n.d.	This booklet provides guidance to help promote safe practices for law enforcement personnel in work zones. Typical applications with suggested locations for law enforcement vehicles are included.
-	General Guidance	Guidelines on Managing Speeds in Work Zones	The Roadway Safety Consortium n.d.	This publication provides guidance regarding the management of vehicle speeds in work zones. A flowchart to facilitate decisions regarding the use of speed reduction strategies in work zones is included.
Minnesota	General guidance	Work Zone Speed Management Study	HDR 2022	In this study, 16 recommendations for strategies to reduce vehicle speeds and improve work zone safety were developed for Minnesota DOT. Nine of the recommendations are in the process of being implemented.

State/Country	Topic	Title	Reference	Summary
Nevada	General guidance	Work Zone Safety and Mobility Implementation Guide	Nevada DOT 2019	These guidelines include an appendix with a matrix of work zone speed countermeasures.
United States	General guidance	Work Zone Speed Management	Federal Highway Administration 2020	The Federal Highway Administration has adopted a variety of methods for work zone traffic management over the years. They include use of automated enforcement, presence of law enforcement, use of speed advisory systems, and implementation of VSL systems.
United States	General guidance	Work Zone Speed Management	Shaw et al. 2015	This NCHRP synthesis covers DOT practices for managing work zone speeds. The synthesis provided general information on 28 work zone speed countermeasures and their effectiveness.
California	Law enforcement	Speeding In Highway Work Zone: An Evaluation of Methods of Speed Control	Ravani and Wang 2018	The authors evaluated the magnitude of the speeding problem and the effectiveness of active or passive police vehicle in improving work zone safety. The results obtained showed that any level of police presence reduced the mean and 85th percentile speed.
Illinois	Law enforcement	Four-Regime Speed–Flow Relationships for Work Zones with Police Patrol and Automated Speed Enforcement	Avrenli et al. 2012	The authors investigated the effects of police presence and speed photo enforcement (SPE) on the speed-flow relationship and capacity. They found that SPE and Police presence caused significant speed reductions in the uncongested branch of the speed-flow curve and a slight capacity drop.
Illinois	Law enforcement	Speed Photo-Radar Enforcement Evaluation in Illinois Work Zones	Benekohal et al. 2010	The study evaluated the use of an automated SPE system on the speed of vehicles in highway work zones. A comparison to other speed management treatments was also carried out. The results showed that SPE lowered the average speed of the general traffic stream below the speed limit. The study showed no significant difference when compared with use of police patrol presence with the emergency lights off.

State/Country	Topic	Title	Reference	Summary
Illinois	Law enforcement	Individual Drivers' Speed Increase in Response to Speed Photo Enforcement and Police Patrol Car	Lodes and Benekohal 2013	Field data collected from two work zone locations in Illinois indicated that 57 percent of drivers were not speeding at the location of a police patrol car but were exceeding the speed limit at a location 1.5 miles downstream of the law enforcement vehicle.
Indiana	Law enforcement	Police Enforcement Strategies and Speed Reduction in Work Zones	Chen and Tarko 2013	This study included an evaluation of various combinations of stationary police enforcement and complementary variable message signs (VMSs) at six work zones. The results showed that distributing enforcement resources among multiple work zones may be more effective than concentrating efforts at fewer work zones. The VMSs also helped to reduce speeds.
Oregon	Law enforcement	Photo Radar Speed Enforcement in a State Highway Work Zone: Yeon Avenue Demonstration project	Joerger 2010	The study evaluated the impact of photo radar on safety in a work zone. The results showed speed reduction of 27.3 percent at the traffic sensor site. For the period of the study, mean and 85th percentile speeds remained quite stable proving the effectiveness of photo radar speed enforcement.
United States	Law enforcement	Traffic Law Enforcement in Work Zones: Phase II Research	Ullman et al. 2013	The study included both field studies and driver surveys to compare passive and active enforcement. The results showed that the use of active or passive enforcement practices led to a decrease of 4 mph in vehicle speed immediately downstream of the enforcement vehicle. In the surveys, drivers indicated that that the type of enforcement used in the work zone did not affect their expected response as much as other factors such as their age, education, and perception of the reasonableness of the posted work zone speed limit.
Ohio	Law enforcement, Lights on work vehicles, other	Improving Work Zone Safety through Speed Management	Sommers and McAvoy 2013	In this study, 20 countermeasures for reducing vehicle speeds were evaluated in a simulator. Presence of workers and construction vehicles, law enforcement, speed photo enforcement, and lane shifts were the most effective strategies for reducing vehicle speeds. Rumble strips, channelizing devices, and changeable message signs led to the lowest speed reductions.

State/Country	Topic	Title	Reference	Summary
Oregon	Lights on work vehicles	Effects of Flashing Blue Lights Mounted on Paving Equipment on Vehicle Speed Behavior in Work Zones	Ahmed et al. 2021	This study evaluated the effects of flashing blue lights on construction vehicles during nighttime. The results showed that mean vehicle speeds were reduced by 2.7 mph to 16.0 mph at upstream locations when the blue lights were used.
Oregon	Lights on work vehicles	Use of Flashing Amber-White Lights on Paving Equipment in Work Zones	Hurwitz et al. 2021	In this study, three case studies were performed to assess the use of flashing amber and white lights on construction equipment and their impacts on vehicle speeds. The results indicated that speed reductions varied from 1.5 mph to 10.1 mph at two of the locations, with no significant speed reductions observed at the third location.
Kansas	Other	Driver Responses to Graphic-Aided Portable Changeable Message Signs in Highway Work Zones	Huang and Bai 2019	Vehicle speeds were measured in work zones with different text and graphic aided portable changeable messages signs (PCMSs), and a driver survey was conducted. Results indicated that mean vehicle speeds reduced between 13 percent and 17 percent with the graphic aided PCMSs, and drivers also indicated a preference for the graphic aided PCMSs in the survey.
Missouri	Other	Effectiveness of Temporary Rumble Strips in Work Zones	Brown et al. 2022	The study included a field evaluation of the effects of temporary rumble strips on vehicle speeds. Results indicated that the use of temporary rumble strips reduced speed violations by 18.2 percent to 21.2 percent.
Arizona	Speed display	Reduction of Speed in Work Zones Using ITS DMS Instant Feedback to Drivers: Vehicle Speed Versus Traffic Fine	Roberts and Smaglik 2014	This research assessed the use of radar speed feedback signs, which also included an alternating monetary fine message. The results showed that the use of the alternating messages led to a 50 percent reduction in the number of speeders driving 15 mph or more above the speed limit.

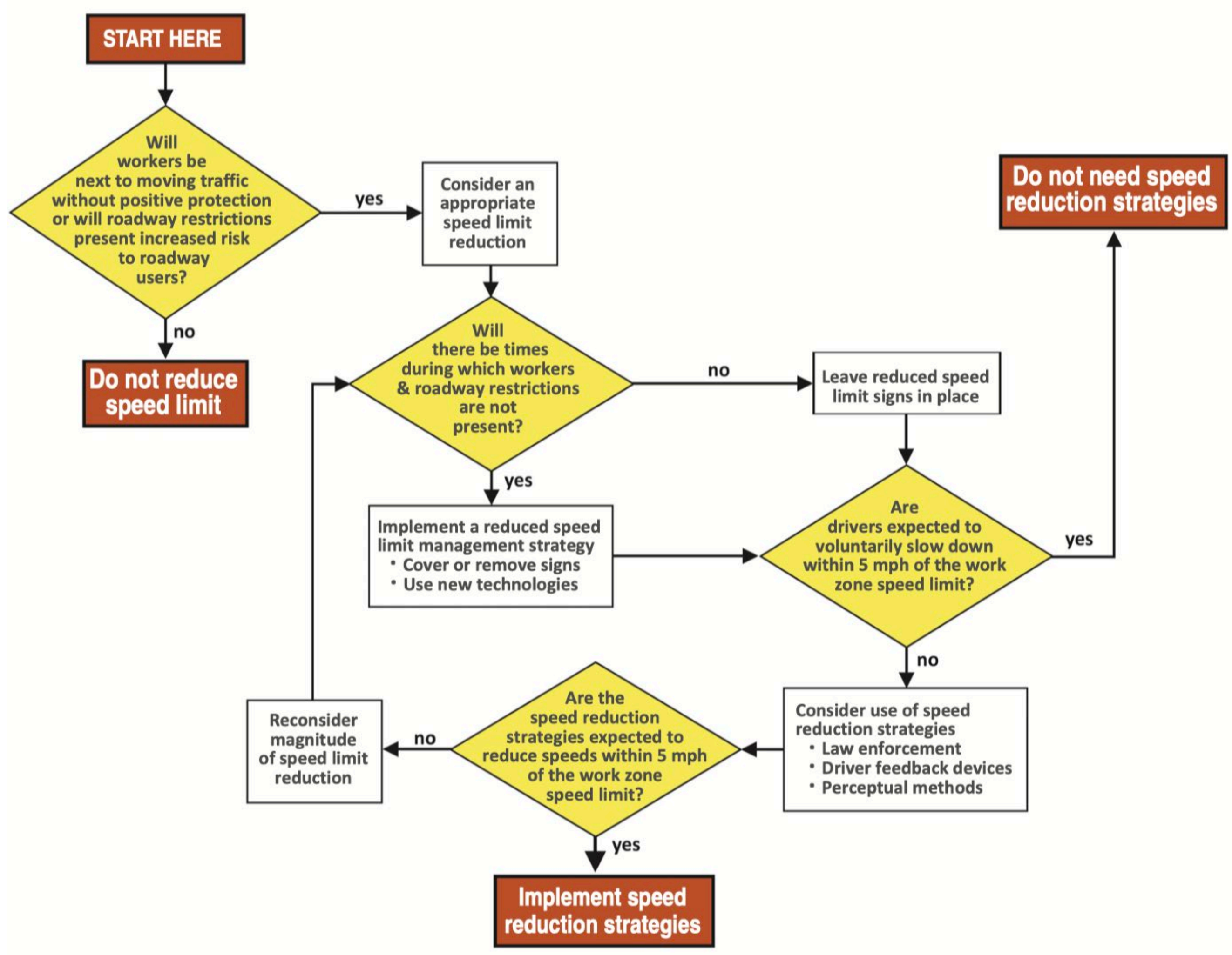
State/Country	Topic	Title	Reference	Summary
Indiana	Speed display	Evaluation of the Impact of Presence Lighting and Digital Speed Limit Trailers on Interstate Speeds in Indiana Work Zones	Sakhare et al. 2021	Commercially available speed data for connected vehicles were used to assess the use of presence lighting and digital speed limit trailers at a work zone. Results showed that median speeds were reduced by 4 to 13 mph during nighttime.
Kansas	Speed display	Evaluation of the Effectiveness of Dynamic Speed Feed Back Signs in Work Zones on High-Speed Kansas Roadways	Anderson et al. 2021	In this study, the effects of dynamic speed feedback signs on vehicle speeds were assessed at two work zones. The results showed significant speed reductions at both locations.
Maryland	Speed display	Use of Portable Changeable Message Signs with Speed Display in Work Zones	Maryland State Highway Administration 2005	Findings from literature review indicate that PCMSs can reduce mean speeds by between 1 to 7 mph and reduce speed variance, although their effectiveness tends to decrease on deployments longer than one or two weeks. Provides PCMSs deployment guidelines for Maryland.
Minnesota	Speed display	Evaluation of the Smart Work Zone Speed Notification System	Hourdos et al. 2019	Their research showed that the PCMS system is noticed by the drivers and can significantly influence driving behavior. It was found that deceleration rates decreased when accurate information was shown to drivers.
Nevada	Speed display	Evaluation of Speed Monitoring Displays for Work Zones in Las Vegas, Nevada	Teng et al. 2009	The effectiveness of speed monitoring displays was assessed at two work zones. Findings showed that the use of larger messages, flashing signs, and multiple speed trailers resulted in higher speed reductions. The extent of the effect varied with vehicle classification, lane usage, and time of day.
Oregon	Speed display	Influence of Truck-Mounted Radar Speed Signs in Controlling Vehicle Speed for Mobile Maintenance Operations: Oregon Case Study	Jafarnejad et al. 2017	The authors conducted a research study to evaluate the influence of truck-mounted radar speed signs on vehicle speed on multilane maintenance work zones in Oregon. The results indicated that the use of the signs led to lower vehicle speeds and less speed variation between vehicles.

State/Country	Topic	Title	Reference	Summary
South Carolina	Speed display	Development and Evaluation of Speed-Activated Sign to Reduce Speeds in Work Zones	Mattox et al. 2007	Field testing of a speed-activated sign on two-lane highways in South Carolina showed an average reduction in mean speed of 3.3 mph on two-lane highways, with similar results on a multilane divided highway and Interstate freeway.
New Brunswick	Speed display, Law enforcement	Evaluation of Traffic Control Countermeasures to Improve Speed Limit Compliance in Work Zones on High-Speed Roadways	Mason 2013	Findings from this field evaluation of six work zone speed countermeasures in New Brunswick indicated that the following three combinations performed best: Traffic Control Person and Floating Speed Zone, Fake Police Vehicle and Floating Speed Zone, and Radar Speed Display Board and Floating Speed Zone
Vermont	Speed display, Law enforcement	Work Zones and Travel Speeds: The Effects of Uniform Traffic Officers and Other Speed Management Measures	Lee et al. 2014	This research assessed the effectiveness of Uniform Traffic Officers and other interventions on maintaining safe travel speeds. It was found that the use of targeted police enforcement was less effective in reducing vehicle speeds than radar speed feedback displays or the presence of a Uniform Traffic Officer.
Illinois	Speed trailer, law enforcement, photo enforcement	Sustained and Halo Effects of Various Speed Reduction Treatments in Highway Work Zones	Hajbabaie et al. 2011	This study evaluated the following work zone speed countermeasures in the field: automated speed photo-radar enforcement, speed feedback trailer, law enforcement (police car), and combination of speed feedback trailer and law enforcement. The results showed that speed reductions with the speed photo enforcement and combination of speed feedback trailer and law enforcement varied from 5 mph to 7 mph.
Illinois	Speed trailer, law enforcement, photo enforcement	Downstream Effects of Speed Photo–Radar Enforcement and Other Speed Reduction Treatments on Work Zones	Medina et al. 2009	The study assessed the effects of automated speed photo-radar enforcement, speed feedback trailer, law enforcement (police car), and combination of speed feedback trailer and law enforcement at a site located 1.5 miles downstream from the treatment. The results indicated that downstream speed was reduced by 1.1 mph to 3.3 mph with the speed photo enforcement.

State/Country	Topic	Title	Reference	Summary
-	Variable speed limits	Fault-Tolerant Control of Variable Speed Limits for Freeway Work Zone Using Likelihood Estimation	Du and Razavi 2020	The authors developed a fault-tolerant VSL control strategy for freeway work zone to handle traffic sensor faults. The system detects and sensor faults and reconfigure the controller accordingly. The system was tested using traffic simulator and results obtained showed it can accurately detect and identify the sensor faults in real time.
-	Variable speed limits	Simulation-Based Evaluation of Using Variable Speed Limit in Traffic Incidents	Farrag et al 2020	A VSL framework was proposed to improve the management of non-recurrent congestion. The study leveraged a connected vehicles environment to identify bottlenecks and adjust the speed limits accordingly. The results proved the feasibility of using this strategy to improve traffic efficiency, safety, and environmental impact during the incidents.
-	Variable speed limits	SPERT: A Speed Limit Strategy for Recurrent Traffic Jams	Frejo and Schutter 2018	Simulation study was conducted to test the performance of a control algorithm for VSL. The algorithm varies speed limit when densities near the congestion reach predefined levels. It was found that the performance was close to the optimal behavior.
-	Variable speed limits	Feedback-Based Integrated Motorway Traffic Flow Control with Delay Balancing	Iordanidou et al. 2017	The study implemented a strategy that took advantage of vehicle-to-vehicle and vehicle-to-infrastructure communication to improve throughput and compliance rates of a VSL control system. The result showed that the strategy significantly reduces the total travel time and decrease the speed variance, thereby improving the safety.
Germany	Variable speed limits	Traffic Management Effects of Variable Speed Limit System on a German Autobahn: Empirical Assessment Before and After System Implementation	Weikl et al. 2013	The study investigated the use of VSL to manage traffic flow on a three-lane German highway. It was found that the VSL system reduced queues and caused flow homogeneity between the lanes. However, there was a reduction in the capacity of the highway.
Indiana	Variable speed limits	Identifying Effects and Applications of Fixed and Variable Speed Limits	Mekker et al. 2016	This study included a field evaluation of VSL using vehicle-matching technology. Results indicated that mean speed dropped by a maximum of 4.7 mph, but three pairs of signs were required for substantial speed reductions.

State/Country	Topic	Title	Reference	Summary
Missouri	Variable speed limits	Evaluation of Variable Advisory Speed Limits in Congested Work Zones	Edara et al. 2013	Microsimulation and field studies were used to investigate the effectiveness of a Variable Advisory Speed Limit system. Results indicated that average speeds decreased and speed compliance increased with the system. The speed variance increased in uncongested urban work zones.
Missouri	Variable speed limits	Driver Perceptions and Sources of User Dissatisfaction in The Implementation of Variable Speed Limit Systems	Long et al. 2012	The authors carried out a survey to assess the reaction of the public and law enforcement to the implementation of VSL system. The results showed a significant dissatisfaction by both groups of stakeholders. The responders stated lack of sufficient public education and difficulty in enforcing speed limits as leading cause of their dissatisfaction. The study proves that traffic management systems could be treated as new products.
Netherlands	Variable speed limits	Dynamic Speed Limit Control to Resolve Shock Waves on Freeways-Field Test Results of the SPECIALIST Algorithm	Hegyi and Hoogendoorn 2013	The authors carried out a field evaluation by using dynamic speed limits on the Dutch A12 Freeway. An algorithm based on shock wave theory was used to implement the dynamic speed limit control. The result showed the approach was capable of sorting out 80 percent of solvable traffic shockwaves.
Utah	Variable speed limits	Use of Portable and Dynamic Variable Speed Limits in Construction Zones	Van Jura et al. 2018	A portable VSL system was assessed at four locations in Utah. Findings indicated that speeds were reduced to 15 to 25 mph below the original posted speed limit with a limited length and duration of the speed reduction.

APPENDIX B. DECISION TOOLS FOR WORK ZONE SPEED COUNTERMEASURES



(The Roadway Safety Consortium n.d.)

Figure B-1. Decision tree for implementation of work zone speed countermeasures

Table B-1. Matrix of work zone speed countermeasures from Nevada DOT (Nevada DOT 2019)

Work Zone Conditions	Changeable Message Sign	Uniform Traffic Control Officer	*Temporary Lighting	Temporary Rumble Strips	Speed Feedback Sign	Lateral Deflection	Lane Narrowing	Flashing Beacon	*Smarter Work Zone System	**Required Cumulative Point Value
Alignment changes designed for speed below the existing posted speed limit	1	1	1	2	1	2	2	1	0	5
Concrete barrier rail less than 2 feet from high speed traffic	1	1	0	2	1	0	2	1	0	3
Insufficient sight distance	1	1	1	2	1	2	2	1	0	4
Pilot Car	1	1	0	2	1	2	2	1	2	6
Ramp Closure	1	1	1	2	1	0	2	1	0	3
Traffic lanes less than 11 feet wide	1	1	0	2	1	2	2	1	0	3
Trucks entering roadway	1	1	1	2	1	0	2	1	2	4
Uneven Lanes/Rough Road	1	1	0	2	1	2	2	1	0	3
Unprotected Work Activities	1	1	0	2	1	2	2	1	0	3
Unusual/Reduced Roadway Geometrics	1	1	1	2	1	2	2	1	0	3
Narrow Shoulders	1	1	1	2	1	2	2	1	0	3
Expected Reduction (mph)	1.4 – 2.8	2 – 6		2.5 – 5.5	2 – 10		3 – 8	3 – 6		

Work Zone Conditions	Changeable Message Sign	Uniform Traffic Control Officer	*Temporary Lighting	Temporary Rumble Strips	Speed Feedback Sign	Lateral Deflection	Lane Narrowing	Flashing Beacon	*Smarter Work Zone System	**Required Cumulative Point Value
Source	Ukkusuri, S. V., Gkriza, K., Qian, X., & Sadri, A. M. (2016)	NCHRP 482 Work Zone Speed Management	NCHRP 476 Guidelines for Design and Operation of Nighttime Traffic Control for Highway Maintenance and Construction	Bai & Li 2009, 2011	FHWA Guidelines on managing speeds in work zones, 2010.		Traffic Control Devices Handbook, ITE, 2013	FHWA Desktop Reference of Potential Effectiveness in Reducing Speed, 2014.		

*These measures do not necessarily decrease operating speeds but are proven safety countermeasures.

**Cumulative point values are determined by aggregating scores of all mitigation strategies implemented in particular work zone.

APPENDIX C. RESULTS FOR OBSERVING DRIVER BEHAVIOR AND VEHICLE COUNTS IN FIELD STUDY

Table C-1. Results for observing driver behavior and vehicle counts from video clips from work zone sensors

ID	Sensor Location	Date	Day of Week	Recording Start Time	Lane*	Vehicle Counts in Video	Vehicle Counts from Sensor	Ratio (Video / Sensor)	Unusual Driver Behavior	Note
1	upstream	08/03/21	Tues.	-	-	-	-	-	-	screen frozen
2	downstream	08/03/21	Tues.	-	-	-	-	-	-	screen frozen
3	upstream	08/04/21	Wed.	8:16:53	2	99	125	0.79	-	includes one motorcycle
4	downstream	08/04/21	Wed.	8:29:57	1	60	61	0.98	-	-
5	upstream	08/04/21	Wed.	14:43:26	3	63	67	0.94	-	-
6	downstream	08/04/21	Wed.	14:48:55	3	106	91	1.16	-	-
7	upstream	08/04/21	Wed.	21:20:07	1	dark	-	-	-	-
8	downstream	08/04/21	Wed.	21:31:55	2	49	-	-	-	-
9	upstream	08/05/21	Thurs.	7:39:18	3	61	65	0.94	-	-
10	downstream	08/05/21	Thurs.	7:46:09	2	109	99	1.10	-	-
11	upstream	08/05/21	Thurs.	13:30:46	4	82	81	1.01	-	-
12	downstream	08/05/21	Thurs.	13:37:49	3	77	84	0.92	-	-
13	upstream	08/05/21	Thurs.	20:58:24	5	dark	-	-	-	unable to identify
14	downstream	08/05/21	Thurs.	21:08:59	1	dark	-	-	-	unable to identify
15	upstream	08/10/21	Tues.	morning	-	-	-	-	-	didn’t record in the morning due to set up upstream sensor

ID	Sensor Location	Date	Day of Week	Recording Start Time	Lane*	Vehicle Counts in Video	Vehicle Counts from Sensor	Ratio (Video / Sensor)	Unusual Driver Behavior	Note
16	downstream	08/10/21	Tues.	morning	-	-	-	-	-	didn't record in the morning due to set up upstream sensor
17	upstream	08/10/21	Tues.	15:53:48	3	61	54	1.13	-	-
18	downstream	08/10/21	Tues.	16:04:21	3	92	78	1.18	-	-
19	upstream	08/10/21	Tues.	21:47:29	-	dark	-	-	-	-
20	downstream	08/10/21	Tues.	21:53:33	-	dark	-	-	-	-
21	upstream	08/11/21	Wed.	7:49:56	4	71	77	0.92	-	-
22	downstream	08/11/21	Wed.	7:56:05	3	105	106	0.99	-	-
23	upstream	08/11/21	Wed.	15:49:17	5	95	87	1.09	-	-
24	downstream	08/11/21	Wed.	15:55:22	2	99	99	1.00	-	-
25	upstream	08/11/21	Wed.	22:00:16	-	dark	-	-	-	-
26	downstream	08/11/21	Wed.	22:06:09	-	dark	-	-	-	-
27	upstream	08/12/21	Thurs.	07:26:21	3	84	87	0.97	-	-
28	downstream	08/12/21	Thurs.	07:40:17	1	100	103	0.97	-	-
29	upstream	08/12/21	Thurs.	13:14:31	2	81	96	0.84	-	-
30	downstream	08/12/21	Thurs.	13:20:01	2	93	98	0.95	-	-
31	upstream	08/12/21	Thurs.	20:54:33	-	-	-	-	-	-
32	downstream	08/12/21	Thurs.	20:59:27	-	-	-	-	-	-
33	upstream	08/13/21	Fri.	08:15:42	4	89	92	0.97	-	-
34	downstream	08/13/21	Fri.	08:21:44	3	78	73	1.07	-	-
35	upstream	08/13/21	Fri.	14:51:36	5	87	86	1.01	-	-
36	downstream	08/13/21	Fri.	14:57:36	2	36	37	0.97	-	two minutes only due to meeting
37	upstream	08/13/21	Fri.	-	-	-	-	-	-	-
38	downstream	08/13/21	Fri.	-	-	-	-	-	-	-

ID	Sensor Location	Date	Day of Week	Recording Start Time	Lane*	Vehicle Counts in Video	Vehicle Counts from Sensor	Ratio (Video / Sensor)	Unusual Driver Behavior	Note
39	upstream	08/17/21	Tues.	14:30:55	3	80	82	0.98	-	-
40	downstream	08/17/21	Tues.	14:37:49	3	96	84	1.14	-	-
41	upstream	08/17/21	Tues.	20:46:32	-	-	-	-	-	-
42	downstream	08/17/21	Tues.	20:54:55	-	-	-	-	-	-
43	upstream	08/18/21	Wed.	09:00:19	4	86	90	0.96	-	-
44	downstream	08/18/21	Wed.	09:06:43	2	89	82	1.09	-	-
45	upstream	08/18/21	Wed.	13:36:04	5	97	104	0.93	-	-
46	downstream	08/18/21	Wed.	13:41:42	3	87	64	1.36	-	-
47	upstream	08/18/21	Wed.	22:07:12	-	-	-	-	-	-
48	downstream	08/18/21	Wed.	22:11:24	-	-	-	-	-	-
49	upstream	08/19/21	Thurs.	8:50:48	3	73	93	0.78	-	
50	downstream	08/19/21	Thurs.	8:56:34	1	11	14	0.79	-	merge ahead sign encouraged drivers to merge rather than stay in Lane 1
51	upstream	08/19/21	Thurs.	14:00:43	4	104	102	1.02	-	-
52	downstream	08/19/21	Thurs.	14:06:19	2	85	77	1.10	-	-
53	upstream	08/19/21	Thurs.	-	-	-	-	-	-	-
54	downstream	08/19/21	Thurs.	-	-	-	-	-	-	-
55	upstream	08/23/21	Mon.	10:46:52	5	61	76	0.80	-	-
56	downstream	08/23/21	Mon.	10:52:33	3	53	51	1.04	-	-
57	upstream	08/23/21	Mon.	15:35:42	4	104	123	0.85	-	-
58	downstream	08/23/21	Mon.	15:41:10	2	116	104	1.12	-	-
59	upstream	08/23/21	Mon.	-	-	-	-	-	-	-
60	downstream	08/23/21	Mon.	-	-	-	-	-	-	-
61	upstream	08/24/21	Tues.	13:14:59	4	92	86	1.07	-	-

ID	Sensor Location	Date	Day of Week	Recording Start Time	Lane*	Vehicle Counts in Video	Vehicle Counts from Sensor	Ratio (Video / Sensor)	Unusual Driver Behavior	Note
62	downstream	08/24/21	Tues.	13:20:33	3	57	66	0.86	-	-
63	upstream	08/24/21	Tues.	15:43:33	4	95	100	0.95	-	-
64	downstream	08/24/21	Tues.	15:49:03	3	96	67	1.43	-	-
65	upstream	08/24/21	Tues.	-	-	-	-	-	-	-
66	downstream	08/24/21	Tues.	-	-	-	-	-	-	-
67	upstream	08/25/21	Wed.	8:45:00	3	114	106	1.08	-	-
68	downstream	08/25/21	Wed.	8:50:47	1	72	71	1.01	-	-
69	upstream	08/25/21	Wed.	14:59:47	3	93	92	1.01	-	-
70	downstream	08/25/21	Wed.	15:05:15	1	89	86	1.03	-	-

APPENDIX D. SIMULATOR RESULTS FOR SPEED PROFILES

Table D-1. Speed profile results for daytime speed countermeasures

Location	Base (mph)	Speed Trailer Active (mph)	Speed Trailer with Red and Blue Lights (mph)	Active Law Enforcement (mph)	Passive Law Enforcement (mph)	Super Law Enforcement (mph)
Upstream sensor	61.6	60.9	61.0	59.7	60.6	60.2
First lane shift sign	60.2	60.8	61.2	60.9	60.6	60.0
Beginning of the work zone	55.5	56.0	56.0	56.0	55.1	54.2
A point: 500ft from work zone	52.3	52.6	53.4	52.9	51.6	50.9
Second lane shift sign	51.8	51.1	50.6	51.5	50.8	49.8
Speed countermeasures	52.5	51.0	50.2	51.9	50.5	50.1
B point: 250ft from speed countermeasure	53.9	51.9	50.6	52.4	51.1	50.7
C point: 500 ft from speed countermeasure	54.7	52.8	51.9	52.6	52.1	51.1
D point: 1000ft from speed countermeasure	55.8	54.6	55.2	52.4	53.8	53.2
End of work zone	57.9	56.6	57.4	53.1	56.4	55.6
Downstream sensor	58.7	56.8	58.1	54.2	57.4	56.3

Table D-2. Speed profile results for nighttime speed countermeasures

Location	Base	Speed Trailer Active (mph)	Speed Trailer with Red and Blue Lights (mph)	Work vehicle with Red and Blue Lights (mph)	Work vehicle + Speed Trailer Active (mph)	Active Law Enforcement (mph)	Passive Law Enforcement (mph)
Upstream sensor	60.2	60.2	59.8	61.2	59.1	60.2	59.9
First lane shift sign	60.6	60.1	62.7	58.7	60.4	59.5	59.0
Beginning of the work zone	55.9	55.8	58.0	55.1	55.6	54.4	55.1
A point: 500ft from work zone	53.0	51.7	54.7	52.0	53.3	52.3	52.2
Second lane shift sign	52.3	50.5	52.7	51.6	51.4	51.5	51.5
Speed countermeasure s	53.0	50.7	51.8	51.7	51.4	51.4	51.5
B point: 250ft from speed countermeasure	53.9	51.4	52.3	52.6	52.0	51.9	51.6
C point: 500 ft from speed countermeasure	55.0	52.8	53.9	53.5	53.1	52.4	52.1
D point: 1000ft from speed countermeasure	55.0	54.1	56.2	55.5	55.6	53.2	55.9
End of work zone	56.2	55.7	57.3	56.9	57.8	55.5	58.4
Downstream sensor	56.3	56.5	57.4	57.3	58.6	56.3	59.2

APPENDIX E. QUESTIONS FOR POST-SIMULATOR SURVEY

Work Zone Speed Study Simulator Survey

Proper management of vehicle speeds in work zones is critical for the safe movement of traffic through work zones. Please tell us your perspective on how to make work zones better. A work zone speed control strategy is something added to the work zone to help drivers slow down in a work zone.

Daytime Work Zone Speed Control Strategies	 Figure 1a (displays your speed)	 Figure 1b (displays your speed and flashes red and blue lights when you are speeding)	 Figure 1c (police car parked on shoulder)	 Figure 1d (police car pulling drivers over)
1.	**Please rate each strategy from [5] Like it very much to [1] Dislike it very much.**			
	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]
2.	**Please rate all strategies from a scale of 10 (highest) to 1 (lowest) with respect to following:**			
Visibility				
Clarity				
Encourages Drivers to Slow Down				
3.	**On a scale of 1 to 5 (5 = very likely, 1 = very unlikely), how likely would you be to reduce your speed after seeing each of the following strategies in a work zone?**			
	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]
4. Comments				

Nighttime Work Zone Speed Control Strategies	 Figure 2a (displays your speed)	 Figure 2b (displays your speed and flashes red and blue lights when you are speeding)	 Figure 2c (police car parked on shoulder)	 Figure 2d (police car pulling drivers over)	 Figure 2e (work vehicle with flashing red and blue lights)
5.	**Please rate each strategy from [5] Like it very much to [1] Dislike it very much.**				
	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]
6.	**Please rate all strategies from a scale of 10 (highest) to 1 (lowest) with respect to following:**				
Visibility					
Clarity					
Encourages Drivers to Slow Down					
7.	**On a scale of 1 to 5 (5 = very likely, 1 = very unlikely), how likely would you be to reduce your speed after seeing each of the following strategies in a work zone?**				
	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]
8. Comments					

9. In general, how strongly do you agree or disagree that the following factors influence the speed you drive in work zones?

Factor	Strongly Agree	Somewhat Agree	Neither Agree nor Disagree	Somewhat Disagree	Strongly Disagree
Feeling Rushed (e.g., Running Late)	☐	☐	☐	☐	☐
Level of Traffic	☐	☐	☐	☐	☐
Number of Lanes	☐	☐	☐	☐	☐
Presence of Active Work	☐	☐	☐	☐	☐
Presence of Law Enforcement	☐	☐	☐	☐	☐
Roadway Width	☐	☐	☐	☐	☐
Time of Day	☐	☐	☐	☐	☐
Urban or Rural Environment	☐	☐	☐	☐	☐
Visibility	☐	☐	☐	☐	☐
Weather	☐	☐	☐	☐	☐
Work Zone Speed Limit	☐	☐	☐	☐	☐
Other (Please describe) _____	☐	☐	☐	☐	☐

Comments:

____

Please answer questions about your simulator experience.

10. I felt like I was driving at or below the work zone speed limit.

[ ] Strongly Agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly Disagree

11. I felt like I was actually there on the highway.

[ ] Strongly Agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly Disagree

12. I felt like I could drive around freely.

[ ] Strongly Agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly Disagree

Please answer the demographic questions below.

13. Age range

[ ] 16-25 [ ] 26-40 [ ] 41-55 [ ] 56-70 [ ] 71-95

14. Gender

[ ] Male [ ] Female

15. My Residency

[ ] Urban [ ] Rural

16. My Regular Vehicle Type

[ ] Passenger Car [ ] Vehicle towing trailer [ ] Delivery/Moving Truck

[ ] Tractor trailer truck [ ] Bus

17. Please enter any additional comments you may have regarding this study.

____

____

____

Please contact Mr. Henry Brown (brownhen@missouri.edu) for additional comments, concerns or information on this survey.

Thank you for completing this survey! We greatly appreciate your time!

Simulator Sickness Questionnaire

Instructions: Circle how much each symptom below is affecting you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficult focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. Fullness of the Head	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

APPENDIX F. QUESTIONS FOR DRIVER SURVEY

DRIVER SURVEY FOR WORK ZONE SPEED STUDY

Introduction

This survey is being conducted by the University of Missouri as part of a research study on management of vehicle speeds in work zones sponsored by the Missouri Department of Transportation (MoDOT). Please complete this survey by June 10, 2022. Your responses are anonymous. The survey includes 15 questions, and we estimate that the survey will take approximately 15 minutes to complete. If you have any questions regarding the survey, please contact Mr. Henry Brown (brownhen@missouri.edu).

Participants must be 18 years of age or older. Your participation is voluntary, and there is no compensation offered for completing the survey.

You may contact the University of Missouri Institutional Review Board (IRB) if you have any questions about your rights as a study participant, want to report any problems or complaints, or feel under any pressure to take part or stay in this study. The IRB is a group of people who review research studies to make sure the rights of participants are protected. You can reach them at 573- 882-3181 or muresearchirb@missouri.edu. The IRB number for this study is 2090129. If you want to talk privately about your rights or any issues related to your participation in this study, you can contact University of Missouri Research Participant Advocacy by calling 888-280-5002 (a free call), or emailing MUResearchRPA@missouri.edu.

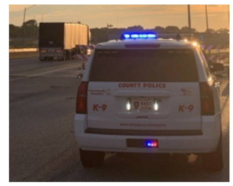
Proper management of vehicle speeds in work zones is critical for the safe movement of traffic through work zones. Please tell us your perspective on how to make work zones better. A work zone speed control strategy is something added to the work zone to help drivers slow down in a work zone.

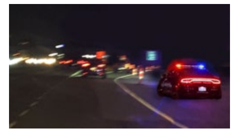
Survey Instructions

1. To begin the survey, click the forward arrow at the bottom of this page.
2. To navigate the survey, select the forward and back arrows at the bottom of each page.
3. To view and print the entire survey for informational purposes, click on this survey link and download and print the document.
4. To view and print your answers after completing the survey, submit the survey by clicking "Submit" on the final page. Download and print the PDF on the following page which contains a summary of your responses.
5. To submit the survey, click on "Submit" on the last page.

Survey Questions

Please refer to the figures below.

Daytime Work Zone Speed Control Strategies	 Figure 1a (displays your speed)	 Figure 1b (displays your speed and flashes red and blue lights when you are speeding)	 Figure 1c (police car parked on shoulder)	 Figure 1d (police car pulling drivers over)*
1.	**Please rate each strategy from [5] Like it very much to [1] Dislike it very much.**			
	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]
2.	**On a scale of 1 to 5 (5 = very likely, 1 = very unlikely), how likely are you to reduce your speed after seeing each of the following strategies in a work zone?**			
	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]
3. Comments				

Nighttime Work Zone Speed Control Strategies	 Figure 2a (displays your speed)	 Figure 2b (displays your speed and flashes red and blue lights when you are speeding)	 Figure 2c (police car parked on shoulder)	 Figure 2d (police car pulling drivers over)**	 Figure 2e (work vehicle with flashing red and blue lights)
4.	**Please rate each strategy from [5] Like it very much to [1] Dislike it very much.**				
	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]
5.	**On a scale of 1 to 5 (5 = very likely, 1 = very unlikely), how likely are you to reduce your speed after seeing each of the following strategies in a work zone?**				
	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]
6. Comments					

7. A list of factors that may influence the speed you drive in work zones is provided below. Please rank the top three factors based on the degree to which they influence the speed you drive in work zones (1 = greatest influence on your speed, 2 = 2nd greatest influence on your speed, 3 = 3rd greatest influence on your speed).

Factor	Ranking
Feeling Rushed (e.g., Running Late)	
Level of Traffic	
Presence of Active Work	
Presence of Law Enforcement	
Time of Day	
Visibility / Weather	
Work Zone Speed Limit	
Other (Please describe ________)	

Driving Behavior

8. How often do you drive through a work zone?

- ☐ Daily
- ☐ 1-2 times per week
- ☐ 1-2 times per month
- ☐ 1-2 times per year
- ☐ Other (please describe) ____________

9. Which of the following best describes your general driving behavior in a work zone?

- ☐ At or below work zone speed limit
- ☐ 1 to 5 mph over work zone speed limit
- ☐ 6 to 10 mph over work zone speed limit
- ☐ More than 10 mph over work zone speed limit
- ☐ Other (please describe) ____________

Demographic Information and Final Comments

Please answer the demographic questions below.

10. Age range

- ☐ 16-25
- ☐ 26-40
- ☐ 41-55
- ☐ 56-70
- ☐ 71-95

11. Gender

- ☐ Male
- ☐ Female

12. Missouri Resident

- ☐ Yes
- ☐ No

13. My Residency

- ☐ Urban
- ☐ Rural

14. My Regular Vehicle Type

- ☐ Passenger Car
- ☐ Vehicle towing trailer
- ☐ Delivery/Moving Truck
- ☐ Tractor trailer truck
- ☐ Bus

15. Please enter any additional comments you may have regarding vehicle speeds in work zones.

Submittal Instructions

To complete the survey and record your answers, please click the "Submit" button.

Please note that once you click the "Submit" button, you will not be able to modify your answers. To review your answers before submitting, please select the forward and back arrows at the bottom of each page.

End of Survey

Thank you for completing this survey! We greatly appreciate your time! For your information, a copy of your responses is provided below. You may download your responses in pdf format using the "Download pdf" link shown below. Please contact Mr. Henry Brown (brownhen@missouri.edu) for additional comments or concerns regarding this survey.

APPENDIX G. SIMULATOR RESULTS FOR EYE TRACKER DATA

Methodology of MOEs

MOE 5: The number of the times glanced at speed countermeasures. This MOE recorded the number of times that participants glanced at the speed countermeasures. Visibility is a common effectiveness measure that is related to safety.

MOE 6: The number of lane changes in work zone after first blinker. This MOE documented how many times participants changed lanes after the first blinker use in work zone. This MOE could help to indicate the extent to which participants acknowledge the speed countermeasures and the road condition. For example, moving over for speed countermeasures could indicate a speed countermeasure was recognized. An example screenshot is shown in Figure G-1in which the vehicle just started to cross a lane marking. In this example, the driver changed lanes even though there was a solid white line.

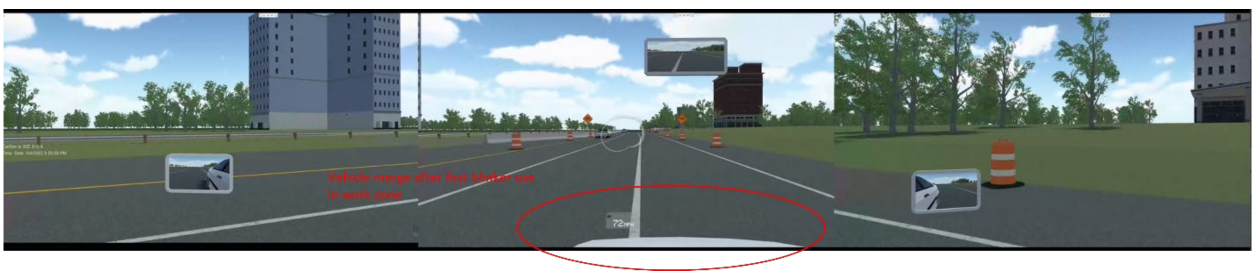


Figure G-1. Screenshot example for vehicle merge after the use of first blinker in work zone

Daytime Results

MOE 5 captured the total number of times that participants glanced at the speed countermeasures out of a sample size of 37, and the daytime results are shown in Table G-1. All five scenarios at daytime had similar results for this MOE.

Table G-1. The total number of the times participants glanced at speed countermeasures (daytime)

Scenario	Total Number of Glances
Base	Base
Speed Trailer Active	33
Speed Trailer with Red and Blue Lights	32
Active Law Enforcement	36
Passive Law Enforcement	34
Super Law Enforcement	34

MOE 6 measured the total number of times participants changed lanes after the first use of blinker in work zone, and the daytime results are shown in Table G-2. This could help indicate how frequently the participant chose to merge when they encountered the speed countermeasure. Although all results from each scenario are comparable, active law enforcement had the highest number of lane changes.

Table G-2. The total number of times participants changed lanes in the work zone after first blinker (daytime)

Scenario	Total Number of lane changes
Base	7
Speed Trailer Active	5
Speed Trailer with Red and Blue	8
Active Law Enforcement	9
Passive Law Enforcement	5

Nighttime Results

MOE 5 captured the total number times the participants glanced at the speed countermeasures during the human subject trials out of a sample size of 37, and the nighttime results are shown in Table G-3. All six scenarios at nighttime had similar results for this MOE.

Table G-3. The total number of the times participants glanced at speed countermeasures (nighttime)

Scenario	Total Number of glances
Base	Base
Speed Trailer Active	34
Speed Trailer with Red and Blue Lights	33
Work vehicle with Red and Blue Lights	33
Work vehicle + Speed Trailer Active	35
Active Law Enforcement	32
Passive Law Enforcement	33

MOE 6 measured the times of participants change the lane after the first use of blinker in work zone, and the nighttime results are shown in Table G-4. This MOE could help indicate how frequently the participants chose to merge when they encountered the speed countermeasure. All of the nighttime results are very comparable, and the work vehicle with red and blue lights had the highest number of lane changes in the work zone after the first use of first blinker.

Table G-4. The total number of times that participants changed lanes in the work zone after first blinker (nighttime)

Scenario	Number of total lane changes
Base	5
Speed Trailer Active	6
Speed Trailer with Red and Blue Lights	5
Work vehicle with Red and Blue Lights	8
Work vehicle + Speed Trailer Active	7
Active Law Enforcement	7
Passive Law Enforcement	7