

SIMULATOR AND FIELD STUDY OF EFFECTIVENESS OF SPEED
MANAGEMENT METHODS IN WORK ZONE IN MISSOURI

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by
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5 METHODS IN WORK ZONE IN MISSOURI

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List of Abbreviations

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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

ABSTRACT

1
2 The objective of this research is to examine the effectiveness of six speed countermeasures in
3 reducing vehicle speeds in work zones. Speed countermeasures such as law enforcement (active
4 and passive), speed trailer displaying speed (with and without flashing speed or red and blue
5 lights when above the speed limit), and work vehicle with red and blue lights were evaluated to
6 assess their effectiveness in reducing vehicle speeds in the field and simulator study. Speed data
7 were captured and analyzed at various westbound I-270 work zone locations in the field and
8 from a simulator study. The simulator study also incorporated eye tracking devices to obtain
9 driver behavior measures. In the 4-week field study, law enforcement speed countermeasures
10 (active and passive) were found to be most effective in reducing vehicle speeds in work zones.
11 The simulator study showed that the super law enforcement (active law enforcement and speed
12 trailer combination) was most effective in reducing vehicle speeds during daytime. Generally,
13 the effect of speed reduction by speed countermeasures dissipated more quickly during nighttime
14 than daytime. The simulator study also found that super law enforcement and speed trailer-
15 related countermeasures had better visibility. Post-simulator and driver survey indicated that law
16 enforcement would be the most effective in causing respondents slow down. Overall, the study
17 showed that all evaluated speed countermeasures were effective in reducing vehicle speeds
18 during daytime and nighttime, however, law enforcement speed countermeasures were found to
19 have the greatest speed reductions.

Chapter 1 Introduction

●2 Motivation and Background

3 Improving work zone safety is needed to mitigate and reduce the work zone crashes and
4 fatalities. In the United States and Puerto Rico in 2020, there were 857 fatalities and 44,000
5 estimated injuries due to work zone crashes (*ARTBA, 2022*). Vehicle speeds and speed variance
6 are important factors that play a role in work zone safety (*Roadway Safety Consortium. n.d.*). A
7 significant component of any strategy to reduce work zone crashes includes managing work zone
8 speeds. The need for more guidance for managing speeds in work zones was identified in a
9 survey by the American Association of State Highway and Transportation Officials (AASHTO)
10 (*Roadway Safety Consortium. n.d.*).

11 The objective of this study is to investigate the effectiveness of speed management
12 countermeasures currently used by the Missouri Department of Transportation (MoDOT) and
13 other state Departments of Transportation (DOTs). The research methodology to meet this
14 objective includes a review of the existing literature, field study, simulator study, post-simulator
15 survey, and driver survey. The field study and simulator study focus on the following work zone
16 speed countermeasures: speed display trailer, speed display trailer with red and blue lights, work
17 vehicle with red and blue lights, and active and passive law enforcement. There is limited
18 existing research on the influence and the comparison of speed control strategies in reducing
19 vehicle speed in work zones, individually or collectively during daytime and nighttime. As
20 DOTs shifts their focus to preservation and maintenance of the existing transportation system,
21 the amount of road work being performed under traffic continues to increase. Attainment of the
22 study objective will help DOTs to focus their efforts on managing work zone speeds and
23 improving work zone safety.

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2 **Methodology**

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Field evaluation and the simulator study completed in this study assisted in investigating the effectiveness of multiple speed management methods by analyzing drivers' behavior in the real world and virtual scenarios. The field study provided data observations for vehicle speeds within a segment of the work zone and a close examination of drivers' behavior. The simulator was utilized to examine the effectiveness of different speed countermeasure scenarios in a virtual environment. Conducting a simulator study enabled the researchers to complete the study in a safe environment with minimal distractions and no crash potential. Post-Simulator Survey and Driver survey were also conducted facing a variety of demographic group. Both surveys investigated the driving behaviors from the human perspective.

Chapter 2 Literature Review

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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, and lane closures), the importance of law enforcement, and a decision tool for work zone speed management (*Roadway Safety Consortium. n.d.*). A publication from the American Traffic Safety Services Association (ATSSA) provides guidance for law enforcement 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.*).

Several studies have also 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, 2018*). Field data collected from two (*Roadway Safety Consortium. n.d.*) work zone locations in Illinois indicated that 57% 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, 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 VMS helped to reduce speeds (*Chen, 2013*).

1 Several research studies have shown that speed trailers are effective in reducing vehicle
2 speeds and deceleration rates in work zones. For example, a field evaluation of a system in
3 Minnesota that displayed downstream speeds on Portable Changeable Message Signs (PCMSs)
4 found that deceleration rates decreased when accurate information was shown to drivers
5 (*Hoursdos, 2019*). Results from an assessment of radar speed feedback signs on multilane
6 maintenance work zones in Oregon indicated that the use of the signs led to lower vehicle speeds
7 and less speed variation between vehicles (*Jafarnejad, 2017*).

8 On the other hand, the availability of existing studies regarding the use of flashing lights on work
9 vehicles is limited. In an Oregon study, Ahmed et al. (*Ahmed, 2021*) evaluated the effects of
10 flashing blue lights on paving equipment during nighttime. The results showed that mean vehicle
11 speeds were reduced by 2.7 mph to 16.0 mph at upstream locations when the blue lights were
12 used.

13 Research studies have also shown that the use of variable speed limits (VSL) is effective in
14 reducing vehicle speeds. Microsimulation and field studies were used in Missouri to investigate
15 the effectiveness of a Variable Advisory Speed Limit system (*Edara, 2013*). Results indicated
16 that average speeds decreased and speed compliance increased with the system. A portable VSL
17 system was assessed at four locations in Utah (*Van Jura, 2018*). Findings indicated that speeds
18 were reduced to 15 to 25 mph below the original posted speed limit with a limited length and
19 duration of the speed reduction.

20 Other work zone speed countermeasures, such as temporary rumble strips and graphic aided
21 portable changeable message signs (PCMSs), have been shown to reduce vehicle speeds in work
22 zones. A research study sponsored by MoDOT included a field evaluation of the effects of both
23 short-term and long-term temporary rumble strips on vehicle speeds (*Brown, 2022*). The results

1 showed reductions in speed violations of 21.2 percent with short-term temporary rumble strips
2 and 18.2 percent with long-term temporary rumble strips.

3 The results from the literature review indicate that there is limited availability of existing studies
4 regarding the use of law enforcement, speed display signs, lights on work vehicles, and variable
5 speed limits, all-in-one intensively in one study. Also, there is no existing study that used both a
6 simulator and field study to explore these speed countermeasures in a work zone at the same
7 time.

8

Chapter 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.

6 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 Lindbergh 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).

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

10 **Field Setup Plan**

11 **Equipment Introduction**

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



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(© Houston Radar 2022)

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Figure 0-1. Houston Radar SpeedLane® Pro sensor



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Figure 0-2. Trailer with SpeedLane® Pro sensor

●1 Field Setup Configuration

2 Two SpeedLane® Pro sensors and two portable trailers were rented for four weeks to conduct
3 the field study. The research team (including personnel from MU and TranSystems) transported
4 the equipment from the vendor lot in Cedar Hill, Missouri to the project site. The sensor and
5 trailers were deployed in the I-270 work zone on August 3, 2021 and removed on August 26,
6 2021. The sensors were mounted at the top of the trailer mast arm and aimed at the traffic. The
7 upstream sensor (Figure 3-3) was placed adjacent to the outside shoulder near Dunn Road, and
8 the downstream sensor was deployed on the left shoulder of the exit ramp at Lindbergh
9 Boulevard (Figure 3-4) for non-intrusive traffic data collection in all weather and lighting
10 conditions. The approximate locations of the sensors and speed countermeasures are shown in
11 Figure 3-5. The sensors were calibrated in real time in the field with assistance from the vendor,
12 who confirmed the camera view and set up the lane configurations.



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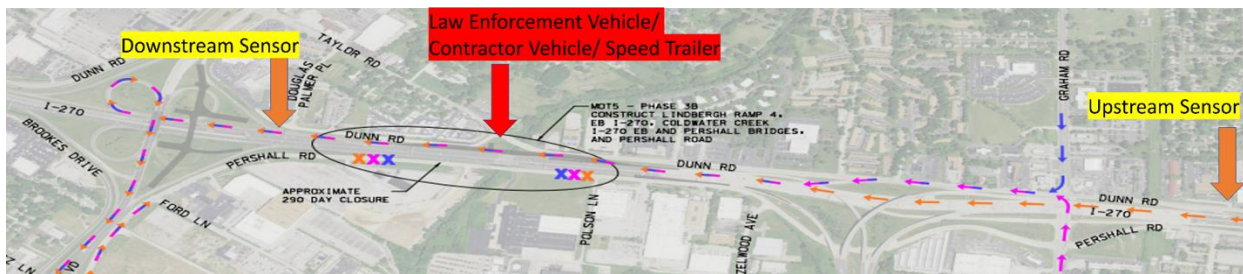
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Figure 0-3. Field study upstream sensor in work zone



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Figure 0-4. Field study downstream sensor in work zone



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(MoDOT 2022b)

Figure 0-5. Location of sensors and speed management devices

6 After deployment of the upstream and downstream sensors, frequent maintenance and checking
 7 on both of the sensors were necessary. To identify and prevent problems, the research team
 8 generally went to the field at least twice a day to check on each sensor. The precise procedures

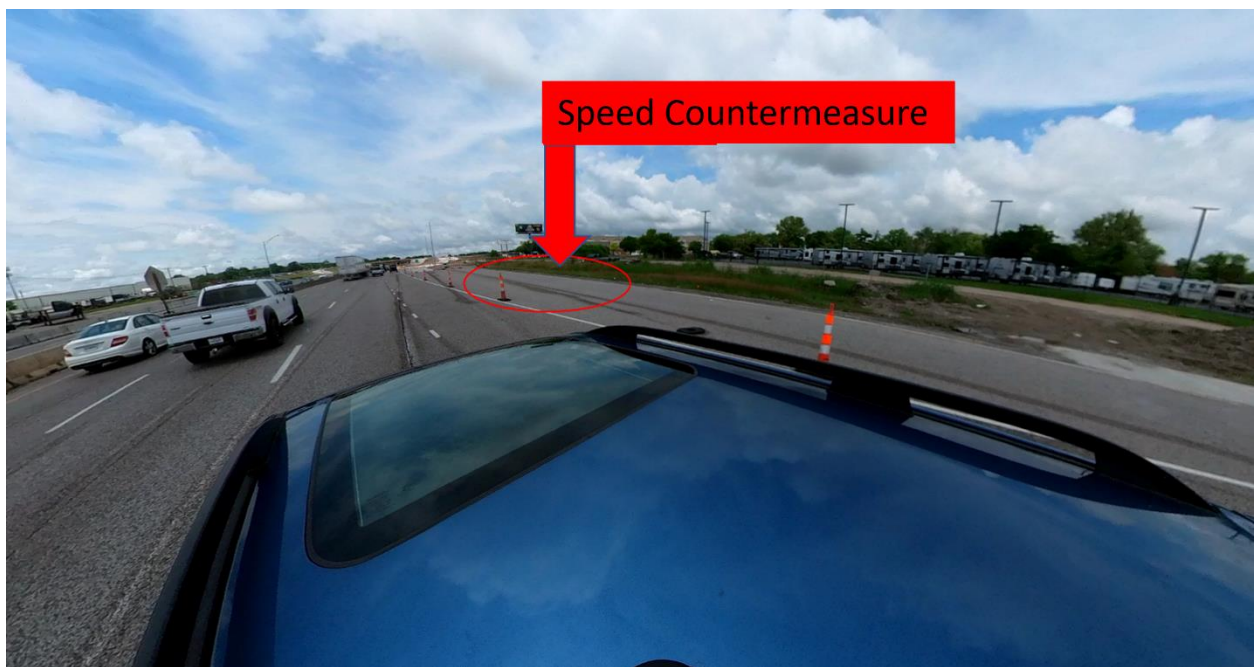
1 involved three steps. In the first step, researchers recorded the video clips of approximately 5
2 minutes from the built-in cameras of each sensor for both the upstream and downstream sensors.
3 The research team checked on the sensors, including the stabilizing mast and pillar stands on the
4 four corners of the trailers. The research team verified that the camera was aimed at the traffic
5 and looked for any concerns that could potentially damage the sensors. Usually, the research
6 team could identify any issues from the video footage before going to the field. The third step
7 included driving by the location of the deployed speed countermeasures. The research team also
8 checked on the speed countermeasure devices or briefly talked to the police officers.

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

19 Types of Speed Management Methods

20 As shown in Figure 3-6, the area near the Lindbergh Boulevard exit immediately after the lane
21 shift area was used to place traffic control devices or law enforcement vehicles for the different
22 speed countermeasures. A variety of speed countermeasures were set up for this project,

1 including no treatment (base), speed trailer, speed trailer with red and blue lights (red and blue
2 lights flashing when above speed limit), passive law enforcement (only police vehicle stationed
3 on the shoulder), active law enforcement (police officers actively pulling violators in addition to
4 a police vehicle stationed along the roadside), and a work vehicle with flashing red and blue
5 lights (nighttime only). A speed trailer with flashing speed digits when a vehicle was speeding
6 was also used due to limited availability of a speed trailer with red and blue lights. The different
7 work zone speed countermeasures are shown in Figure 3-7 through Figure 3-11. Figure 3-7 and
8 Figure 3-8 show the speed trailer and speed trailer with red and blue lights (red and blue lights
9 flashing when above speed limit), while Figure 3-9 and Figure 3-10 show the passive law
10 enforcement (only police vehicle stationed on the shoulder,) and active law enforcement (police
11 officers actively pulling violators in addition to a police vehicle stationed along the roadside).
12 Figure 3-11 shows the work vehicle with red and blue lights (nighttime only).



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Figure 0-6. Location of the speed countermeasures in field study



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Figure 0-7. Speed trailer active in field study



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Figure 0-8. Speed trailer with red and blue lights in field study



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Figure 0-9. Passive law enforcement in field study



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(Courtesy St. Louis County Police Department)

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Figure 0-10. Active law enforcement



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Figure 0-11. Work vehicle with red and blue lights in field study

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●1 **Field Data Collection**

2 As mentioned previously, collected sensor data was available in the cloud. Thus, researchers
 3 were able to download the raw data of individual vehicle speeds in real-time. The field data were
 4 collected during a four-week period from August 3, 2021 to August 26, 2021. The original
 5 schedule of the field data collection, which includes one to two days of data collection for each
 6 countermeasure, is shown in Table 3-1. Due to unforeseen factors, such as the contractor moving
 7 equipment, equipment availability, and weather, the original schedule had to be adjusted, and the
 8 actual schedule is shown in Table 3-2. A total of 323 hours 40 minutes of data and approximately
 9 778,050 individual vehicle speed data points were collected. The duration of daytime was set
 10 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.

11 **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

Week	Day	Date	Enforcement	Trailer	Work vehicle Red/Blue Lights	Time periods
4	Wed.	8/25/21	Passive	No	No	Daytime
4	Wed.	8/25/21	None	No	Yes	Nighttime
4	Thurs.	8/26/21	-	-	-	-

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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

2

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

- 1 movement of the sensor and before the sensor reconfiguration were considered as outliers and
- 2 were excluded from the data analysis process.



3

4

Figure 0-12. Upstream sensor after first movement



1

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

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2022 Google)

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Figure 0-13. Upstream sensor after second movement (aerial)



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Figure 0-14. Upstream sensor after second movement

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4

•1 **Field Observations of Driving Behavior**

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

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Figure 0-15. Screenshot from upstream sensor camera

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Figure 0-16. Screenshot from downstream sensor camera

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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	-	-

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
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	-	-

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

2 Field data were downloaded every workday and then organized in a spreadsheet by treatment.

3 While being categorized by type of treatment, invalid time periods that were the outliers in this

4 study were excluded. For example, data collected during the time of the unexpected relocation of

5 upstream sensors were considered as outliers and therefore excluded from the study. In addition,

6 some hours of data were excluded due to the changes in traffic conditions. For instance, lane

7 closures near the upstream segment had a significant influence on traffic conditions, such as

8 upstream queuing. The corresponding time periods when a lane closure was in effect due to

9 construction were excluded. For example, there was a right lane closure on August 5, 2021 at I-

10 270 WB and Washington Street/Elizabeth Avenue from 7:30 p.m. to 1 a.m. Thus, the night data

11 for August 5, 2021 was considered as a outlier while analyzing the scenarios of speed trailer

12 active during nighttime.

13 Overview of Field Data

14 Approximately four weeks of data were collected, stored, and analyzed for the field study. The

15 following sections present the results for vehicle speeds in both daytime and nighttime. In each

16 section, the effectiveness of different speed management methods is assessed. There are

17 scenarios with no speed countermeasures for both daytime and nighttime which are considered

18 as the base scenario to compare the effectiveness of the different work zone speed

19 countermeasures. The observed speed reduction for the base scenario represents the speed drop

1 between the upstream and downstream average vehicle speed due to the presence of the work
2 zone and lane shift. Typically, this value is positive because downstream speeds were generally
3 lower due to the lane shift. The additional speed reduction is the portion of speed drop that is
4 over the observed speed reduction of the base scenario (5.2 mph for daytime and 4.1 mph for
5 nighttime) for each individual countermeasure. The extent of effectiveness is measured by the
6 additional speed reduction divided by the speed reduction of the corresponding base scenario.

•7 Daytime Results Evaluation

8 The field results for effectiveness of speed control strategies during daytime are as shown in
9 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
10 shown in Table 3-4, the base scenario with no speed countermeasures experienced a speed
11 reduction of 5.2 mph, with an average upstream speed of 64.5 mph and average downstream
12 speed of 59.3 mph. Table 3-5 shows the speed trailer countermeasure results. Table 3-6 shows
13 the active and passive law enforcement results. The other daytime scenarios are compared with
14 the base scenario. The results indicate that the active law enforcement was the most effective
15 speed management method of all the daytime scenarios in reducing vehicle speeds. The use of
16 active law enforcement resulted in a speed reduction of 9.5 mph between the upstream and
17 downstream locations. The additional speed drop compared to the base scenario is 4.3 mph.
18 During the daytime, the speed trailer with red and blue lights was associated with an additional
19 speed reduction of 2.8 mph, indicating that it was more effective at reducing vehicle speeds than
20 passive law enforcement. Although the speed trailer without red and blue lights was not as
21 effective in reducing vehicle speeds as the other scenarios, it still resulted in an additional speed
22 reduction of 0.5 mph. The speed trailer with the flashing speed display was more effective than

1 the speed trailer without the flashing speed display but not as effective as the speed trailer with
 2 the flashing red and blue lights. Effect size complements statistical significance and is the
 3 magnitude of the experimental effect (Cohen 1977). It represents the practical usefulness. For
 4 example, a very small reduction in speed could still be statistically significant but not very useful
 5 in terms of safety improvement. Effect size was presented as Cohen’s d value, as effect size
 6 greater than 0.2 and less than 0.5 is small, effect size between 0.5 and 0.8 is medium, and effect
 7 size greater than 0.8 is large. The effect sizes for most of the speed countermeasures were all
 8 larger than 0.8.

9 **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

10

11 **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

Description	Speed Trailer Active	Speed Trailer with Flashing Speed Feedback	Speed Trailer with Red/Blue lights
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

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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

2

3

●1 **Nighttime Results Evaluation**

2 The field results for effectiveness of speed control strategies during nighttime are as shown in
3 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
4 shown in Table 3-7, a speed reduction of 4.1 mph between the upstream and downstream sensors
5 was observed for the base scenario with no speed countermeasures. Table 3-8 shows the speed
6 trailer countermeasure results. Table 3-9 shows the active and passive law enforcement results.
7 Similar to daytime, active law enforcement was the most effective speed management method in
8 reducing vehicle speeds. The use of active law enforcement during nighttime was associated with
9 a speed reduction of 9.6 mph and additional speed reduction of 5.5 mph. During nighttime,
10 passive law enforcement was the second most effective countermeasure with an additional speed
11 reduction of 2.8 mph compared to the base scenario. The use of the work vehicle with red and
12 blue lights was found to have a significant effect on vehicle speeds, with an additional speed
13 drop of 2.1 mph. Nighttime scenario for the speed trailer with speed display as shown in Table
14 3-8 showed an additional speed reduction of 0.9 mph. The effect size of active law enforcement
15 was large. The effect sizes of passive law enforcement and speed trailer with red/blue lights were
16 medium.

17

1

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

2

3

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

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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

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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

4

5

•1 **Summary and Discussion of Field Study Results for Vehicle Speeds**

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

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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%

2

3

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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%

2

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

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

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

14

1 **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

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2
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1 The upstream sensor location was far from the location of the deployed speed countermeasures
2 that drivers could not see. The compliance statistics showed here only serve the purpose of
3 comparing between upstream and downstream data to reflect the aggressiveness of the drivers.
4 During daytime, speed compliance was higher at the downstream sensor (9.4 percent) than at the
5 upstream sensor (4.7 percent) for the base scenario with no speed countermeasures. Table 3-13
6 shows that law enforcement (active law enforcement in particular) had a substantial effect on
7 improving speed limit compliance. In terms of speed compliance, active law enforcement was
8 associated with a compliance rate of 21.1 percent downstream and 7.1 percent upstream. Passive
9 law enforcement was slightly less effective than active law enforcement but still had a significant
10 improvement on speed limit compliance, which was 15.3 downstream and 6.0 percent upstream.
11 Among multiple speed trailers, the speed trailer with red and blue lights was the most effective in
12 obtaining driver compliance, followed by the speed trailer with flashing feedback and speed
13 trailer without flashing feedback.

14 During nighttime, motorists were less likely to comply with the speed limit at nighttime while
15 passing through the I-270 WB work zone. Speed compliance rates of 4.5 percent (downstream)
16 and 3.1 percent (upstream) were observed when there was no countermeasure present. However,
17 the use of law enforcement (primarily passive law enforcement) was the most effective in
18 discouraging speeding, with observed compliance rates of 11.1 percent downstream and 5.5
19 percent at the upstream location. Compared to the observed speed limit compliance of active law
20 enforcement (7.5 percent downstream and 4.4 percent upstream), passive law enforcement was
21 found to be more effective at nighttime. The use of the work vehicle with red and blue lights
22 scenario did not result in a significant increase in speed compliance (6.2 percent downstream and
23 4.9 percent upstream). Minor variation was found in the case of speed trailer with speed display

1 alone (4.2 percent downstream and 2.8 percent upstream) as compared to the scenario with no
2 treatment. Overall, findings indicate that most motorists tend to violate the work zone speed limit
3 irrespective of the speed countermeasures in place.

4 Missouri has two types of speeding laws: a “basic speeding law” and “absolute limits.” The
5 previous section discussed compliance with the posted speed limit, which is absolute limits.
6 According to the Missouri’s basic speeding law, motorists must drive at a rate of speed “so as not
7 to endanger the property of another or the life or limb of any person.” (Missouri Legislature
8 1996). However, under specific circumstances, motorists must drive at a safe speed depending on
9 the circumstances which could be much lower than the speed limit. For example, inclement
10 weather could require lower speeds. Thus, an investigation of excessive speeding can also shed
11 some light on motorists’ speed behavior under different countermeasures. The results for
12 speeding violations in excess of 10 mph are discussed below.

13 During daytime, the percentage of drivers exceeding the speed limit by at least 10 mph decreased
14 from 73.2 percent to 52.7 percent between the upstream and downstream locations for the base
15 scenario with no countermeasures, likely due to the presence of the lane shift. The use of law
16 enforcement was effective in reducing excessive vehicle speeding. For active law enforcement,
17 the percentage of drivers exceeding the speed limit by at least 10 mph was 73.2 percent at the
18 upstream sensor and 34.1 percent at the downstream sensor. The results for passive law
19 enforcement were similar, with 71.8 percent and 38.4 percent of drivers exceeding the speed
20 limit by at least 10 mph at the upstream and downstream sensors, respectively. For the speed
21 trailer with only the speed display, excessive speeding was virtually unchanged between the
22 upstream and downstream locations. With the speed trailer with red and blue lights, the

1 percentage of drivers exceeding the speed limit by at least 10 mph decreased being 70.2 percent
2 upstream and 38.8 percent downstream. The speed limit with flashing speed display was also
3 associated with a reduction in excessive speeding.

4 During nighttime, the percentage of drivers exceeding the speed limit by at least 10 mph was
5 78.2 percent at the upstream sensor and 67.4 percent at the downstream sensor with no
6 countermeasures. The use of active law enforcement during nighttime was most effective in
7 reducing excessive speeding (80.6 percent upstream and 22.4 percent downstream). With passive
8 law enforcement, the percentage of drivers exceeding the speed limit by at least 10 mph
9 decreased from 77.0 percent upstream to 48.8 percent downstream. The use of the work vehicle
10 with red and blue lights was associated with excessive speeding rates of 79.3 percent upstream
11 and 59.1 percent downstream, indicating that it was less effective at discouraging excessive
12 speeding than law enforcement.

13

Chapter 4. Simulator Study

1
2 After the field study of the speed management methods was completed on I-270 WB in Saint
3 Louis, the simulator study was conducted. The simulator was utilized to examine the
4 effectiveness of different scenarios of speed countermeasures in a virtual world. The simulator
5 study explored the scenarios conducted in the field study as well as combinations of
6 countermeasures, such as a combination of active law enforcement, work vehicle with red and
7 blue lights, and speed trailer. The simulator also provided an opportunity for exploring the details
8 of scenarios of the speed trailer with red and blue lights during nighttime to complement the field
9 study due to weather conditions and equipment availability that precluded the use of the speed
10 trailer with the red and blue lights in the field during nighttime. Another advantage of the
11 simulator study is the provision of a safe environment with less disruptions.

12 Simulator Study Methodology

13 ZouSim is the driving simulator lab used for conducting simulator study in the University of
14 Missouri. The simulator is medium-fidelity built around the half-cab of a sedan. Considering the
15 capacity of graphical display, including virtual reality, augmented reality and stereoscopic 3D,
16 the triple 120-inch was chosen as the most compatible display for this study. Such a display
17 environments setup created a 180-degree field-of-view which offered participants an immersive
18 view of the approaching work zone and the relevant peripheral clues for regulating driving
19 speed. Figure 4-1 shows the ZouSim setup for the experiment. The primary virtual camera was
20 the forward windshield view. Three additional virtual cameras imitated the left, right and rear-
21 view mirror perspectives were also incorporated in the simulator scenario set-ups. The active

- 1 instrumentation in the vehicle includes a force-feedback steering wheel, brake and acceleration
- 2 pedals, turn signals, and an engine vibration generator.



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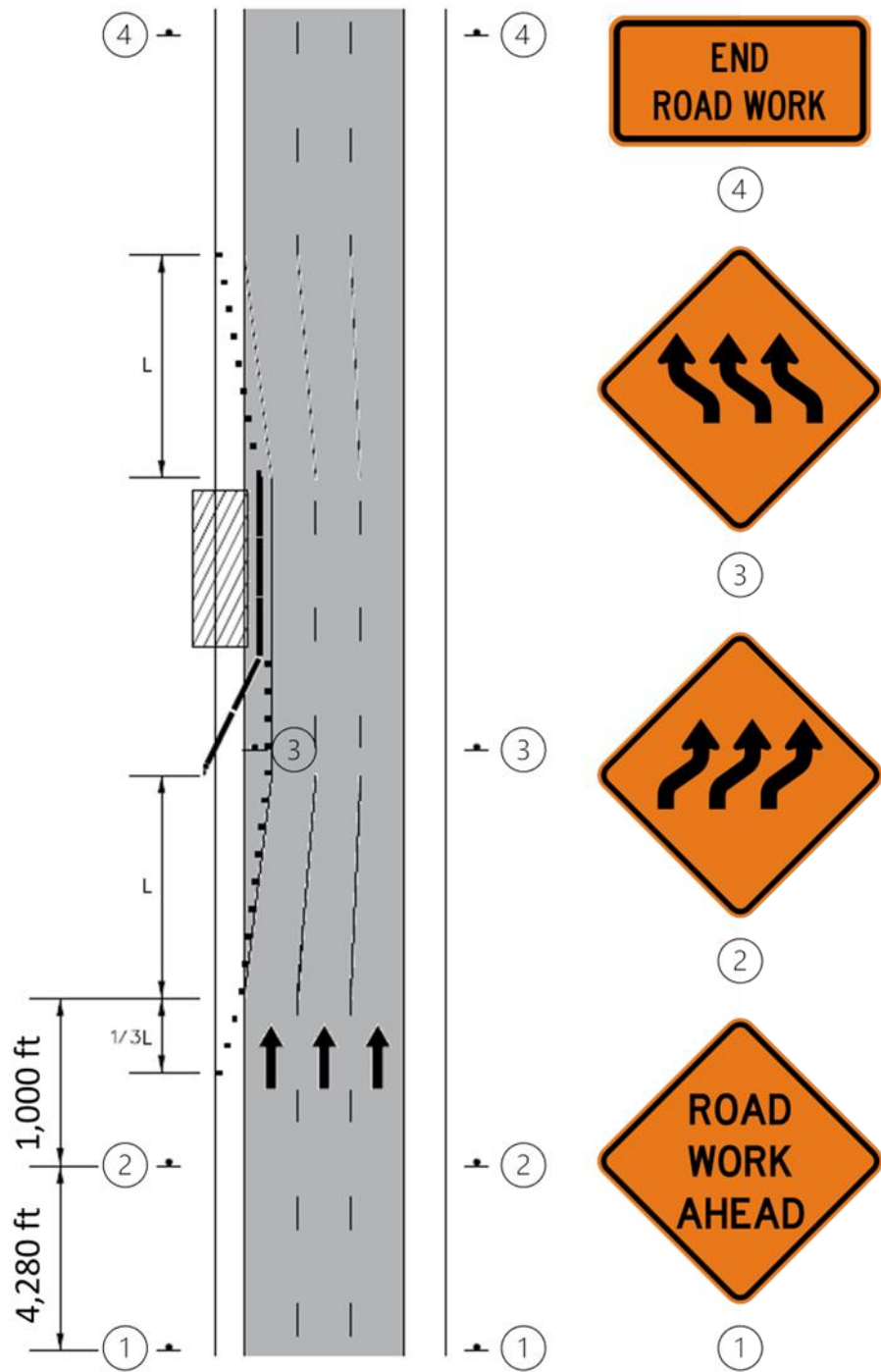
Figure 0-1. Zousim half-cab sedan driving simulator

5 Simulator Setup

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

10 The road was created according to AASHTO Green Book standards (AASHTO 2013). Surfaces
11 were textured and/or painted with the appropriate striping and markings that conform to the

1 Manual on Uniform Traffic Control Devices (MUTCD) (FHWA 2009). The work zone plan for
2 the highway is shown in Figure 4-2. The setup of the work zone in the simulator was based on
3 the field study on I-270, and a large lane shift similar to the shift on I-270 was implemented in
4 the simulator scenarios. Upon encountering the first lane shift sign, the lane shift occurred 1000
5 feet ahead of the first lane shift sign. The work zone configuration, including signage, lane shift
6 angle, and distance between signs, followed the requirements of the I-270 North Standard-
7 Maintenance of Traffic Plan (MoDOT 2020b), MUTCD (FHWA 2009) and MoDOT
8 Engineering Policy Guide (MoDOT 2020c).



1

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Figure 0-2. Work zone plan for driving simulator study

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

7 **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

8 *Note: Order of scenarios was randomized for each participant
 9 Proper adjustments were made to account for differences between daytime and nighttime
 10 simulation environments. Daytime speed countermeasures are shown in Figure 4-3 through
 11 Figure 4-6, and nighttime speed countermeasures are shown in Figure 4-7 through Figure 4-11.
 12 Figure 4-3 shows the speed display during daytime and Figure 4-4 shows the speed trailer with
 13 red and blue lights. Figure 4-5 shows passive law enforcement with a police vehicle parked on

1 the shoulder during daytime. Figure 4-6 shows active law enforcement with a police vehicle
2 pulling over violators during daytime. Figure 4-7 shows the speed trailer during nighttime, and
3 Figure 4-8 shows the speed trailer with red and blue lights. Figure 4-9 shows passive law
4 enforcement with a police vehicle parked on the shoulder during nighttime. Figure 4-10 shows
5 active law enforcement with a police vehicle pulling over violators during nighttime. Figure 4-11
6 shows the work vehicle with red and blue lights during nighttime.

7



8

9 **Figure 0-3. Speed trailer with speed display during daytime (simulator study)**



10

11 **Figure 0-4. Speed trailer with red and blue lights during daytime (simulator study)**



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Figure 0-5. Passive law enforcement during daytime (simulator study)



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4

Figure 0-6. Active law enforcement during daytime (simulator study)

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



1

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Figure 0-7. Speed trailer with speed display during nighttime (simulator study)



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Figure 0-8. Speed trailer with red and blue lights during nighttime (simulator study)



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Figure 0-9. Passive law enforcement during nighttime (simulator study)



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Figure 0-10. Active law enforcement during nighttime (simulator study)



1

2 **Figure 0-11. Work vehicle with red and blue lights during nighttime (simulator study)**

3 **3 Simulator Trials and Measures of Effectiveness (MOEs)**

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

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

5 **MOEs for Eye Tracking Data**

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

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



16

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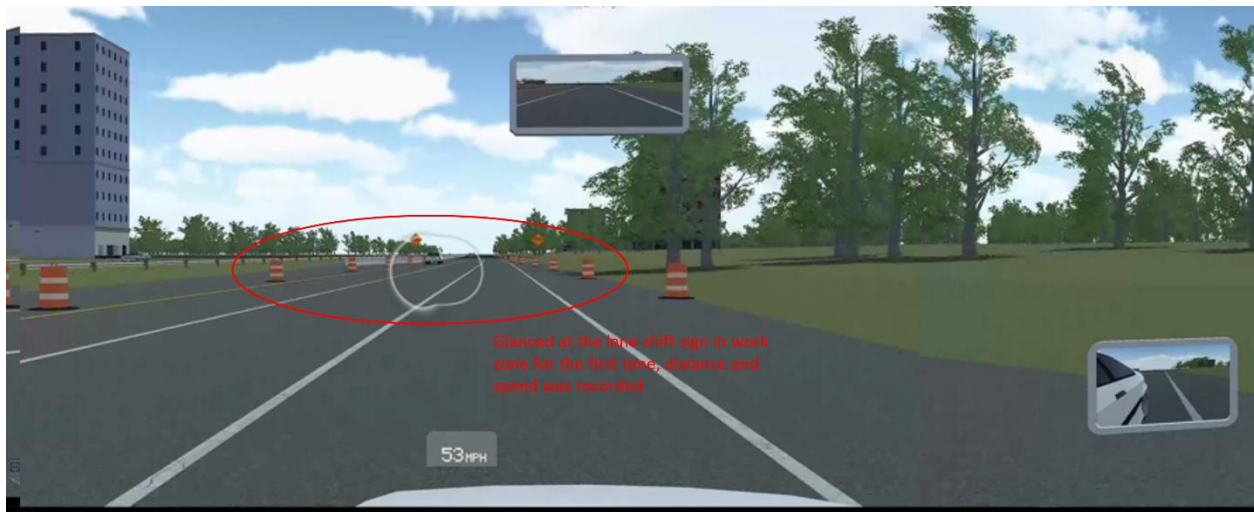
Figure 0-12. Screenshot example for when participant first glanced at speed

18

countermeasure

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

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



13

14 **Figure 0-13. Screenshot example for first glance at the lane shift sign in work zone**

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

•8 Verification of Data Accuracy for Unity.log data

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

16

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	
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	

1

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

•4 Simulator Study Results

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

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

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

19 The simulator results will be presented from two perspectives: speed data collected from
20 unity.log and eye tracking data extracted from recording. Daytime and nighttime scenarios

1 results will be discussed separately. For both the unity.log data set and eye tracking data set,
2 statistical analysis was performed on the data sets to calculate the significance, confidence level
3 and effect size. Effect sizes can be categorized into small, medium, or large according to Cohen's
4 criteria: small size ($0.2 < \text{Cohens'd value} < 0.5$), medium ($0.5 < \text{Cohens'd value} < 0.8$), and large
5 ($\text{Cohens'd value} > 0.8$) (Cohen 1977).

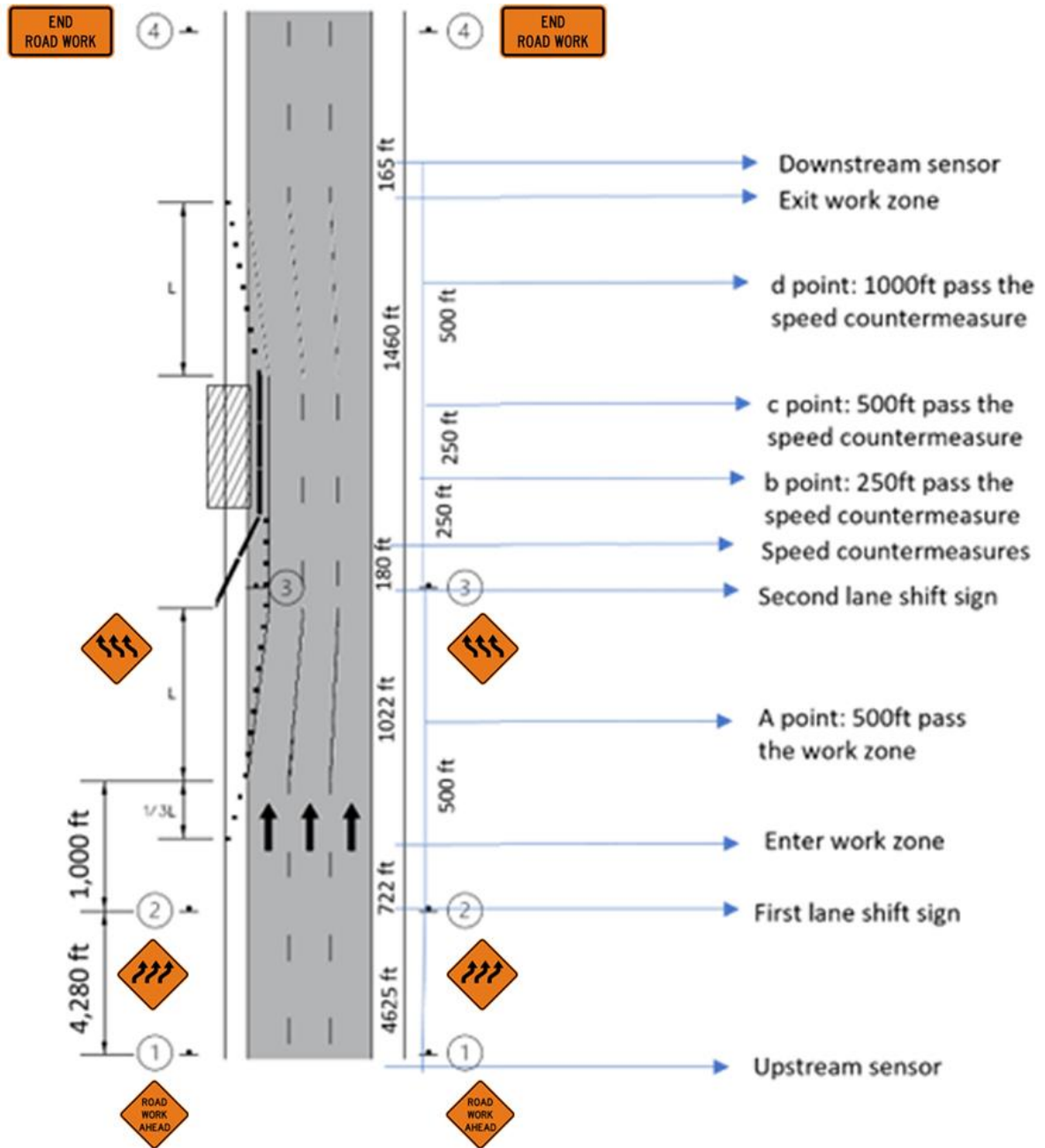
• Unity.log Data

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

• Daytime Results for Upstream and Downstream Speeds

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

1



2

3 **Figure 0-14. Diagram of unity.log location of collecting speed in simulator study**

4 Daytime results for the speed differential between the upstream and downstream sensors are

5 shown in Table 4-3. The baseline, which is the no speed countermeasures scenario, reported an

1 original speed reduction of 3.1 mph at the downstream sensor location. Active law enforcement
 2 reported an additional speed reduction at the downstream sensor location of 2.5 mph,
 3 corresponding to an effectiveness of 82.7 percent. The daytime results showed that the active law
 4 enforcement was the most effective speed countermeasures among all speed countermeasures in
 5 the daytime simulator study. These results are consistent with the trends of field study in which
 6 active law enforcement was identified as the most effective speed countermeasure during
 7 daytime. The speed trailer active resulted in an additional speed reduction of 1.4 mph. Super law
 8 enforcement (the combination of speed trailer active and active law enforcement) resulted in
 9 effectiveness of 69.4 percentage with the additional speed reduction of 1.1 mph. The speed
 10 trailer with red and blue lights scenarios is effective with an additional speed reduction of 0.4
 11 mph. The passive law enforcement, however, did not show any effectiveness.

12

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

13

●1 Nighttime Results for Upstream and Downstream Speeds

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

11 **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

12

●1 Speed Profile Results

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

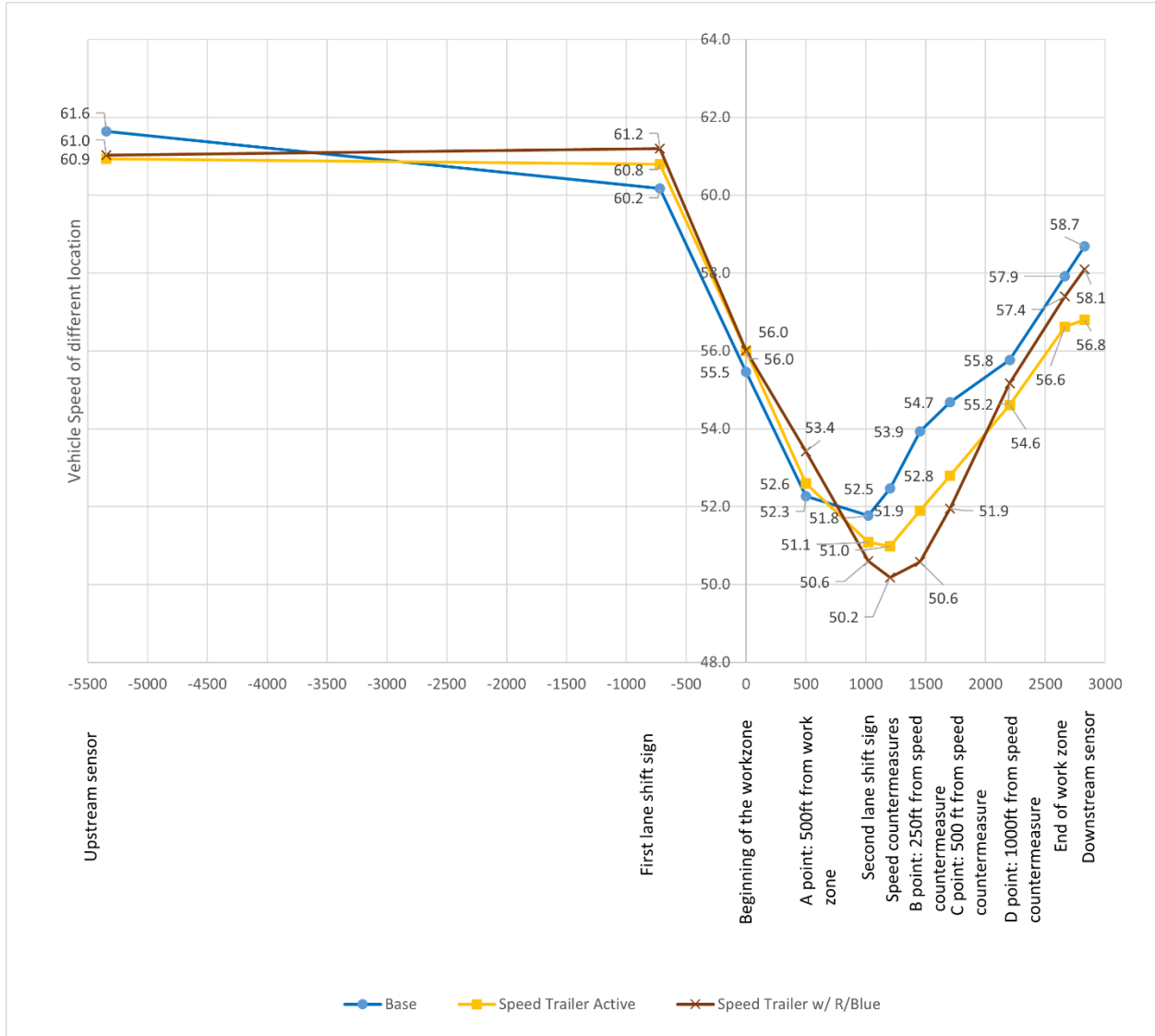
●9 Daytime Results for Speed Profiles

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

14 Figure 4-15 shows the comparison between base and speed trailer related countermeasures
15 during daytime, including the speed trailer with and without red and blue lights. The speed trailer
16 with red and blue lights reported the best performance among speed trailer related
17 countermeasures, with an average speed of 50.2 mph at the location of the deployed speed
18 countermeasure, compared to an average speed of 52.5 mph at this location for the base scenario.
19 The largest speed differential between the speed trailer with red and blue lights and the base
20 scenario (3.3 mph) occurred at a location 250 feet downstream from the speed countermeasure.
21 However, after passing a location 1,000 feet downstream from the speed countermeasures, the

1 speed trailer with red and blue lights had a higher average speed compared to the speed trailer
2 active. The speed trailer active reported lower speeds (51.0 mph) than the base scenario (52.5
3 mph) at the location of the second lane shift sign. The maximum speed differential between these
4 two scenarios (2.0 mph) was located 250 feet downstream from the speed countermeasure.
5 Figure 4-15 shows the speed curves for both types of speed trailers are under the baseline curve
6 once drivers are near the location of the speed trailer past 1000 ft from the beginning of the work
7 zone.

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Figure 0-15. Speed profiles for speed trailers during daytime

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Figure 4-16 shows the comparison between the base scenario and law enforcement speed

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countermeasures, including active law enforcement, passive law enforcement and super law

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enforcement, during daytime. Super law enforcement had the best performance on reducing

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vehicle speeds from the beginning until the location 1,000 feet downstream from the speed

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countermeasures. Within this section, the use of super law enforcement led to much lower speeds

1 over the base scenario compared to active and passive law enforcement. Super law enforcement
2 reported an average speed of 50.1 mph while average speed for the base scenario was 52.5 mph
3 at the location of the speed countermeasure. The maximum speed differential of 3.6 mph
4 happened at a location 500 feet downstream from the speed countermeasure. From the second
5 lane shift sign location to a location 500 feet downstream from the speed countermeasures,
6 passive law enforcement had the better performance on reducing vehicle speed. Active law
7 enforcement reported an average speed of 51.9 mph while the average speed for passive law
8 enforcement was 50.5 mph. From a location 1,000 feet downstream from the speed
9 countermeasures until the end, active law enforcement had a better performance on reducing
10 vehicle speeds. The maximum speed differential for active law enforcement and the base
11 scenario of 3.4 mph occurred at a location 1000 feet downstream from the speed
12 countermeasures. Figure 4-16 shows that the speed curves for all types of law enforcement are
13 under the baseline curve once drivers are near the location of law enforcement past 1000 ft from
14 the beginning of the work zone.



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Figure 0-16. Speed profiles for law enforcement during daytime

3 **Nighttime Results for Speed Profiles**

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Figure 4-17 shows the comparison between the base scenario and law enforcement speed

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countermeasures, including active law enforcement and passive law enforcement, during

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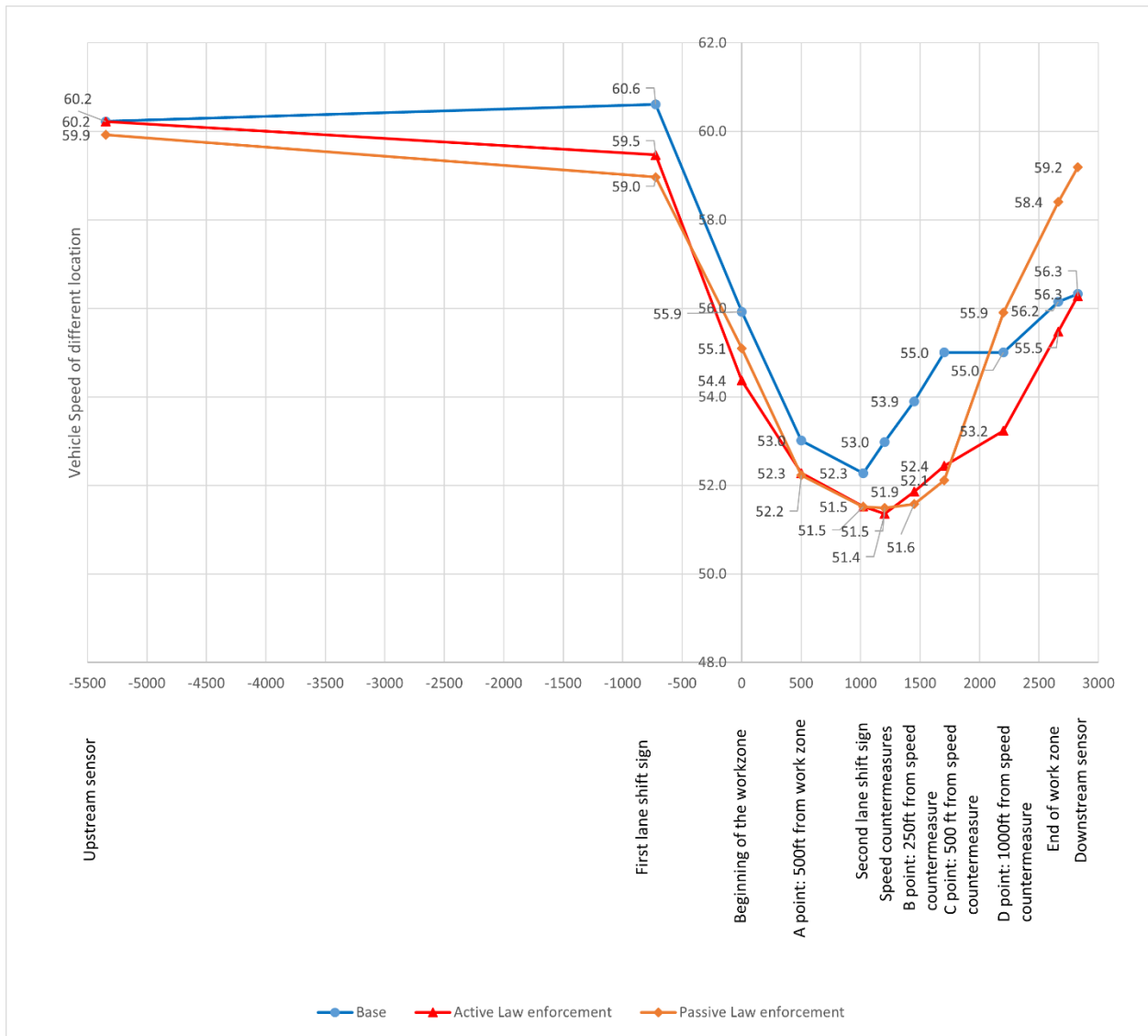
nighttime. The results are also tabulated numerically in Appendix B. Active law enforcement

7

resulted in lower speeds at the locations downstream from the upstream sensor location. At the

1 location of the speed countermeasure, active law enforcement reported a speed of 51.4 mph
2 whereas the base was 53.0 mph. The largest speed differential happened at a location 500 feet
3 downstream from the speed countermeasure where the speed differential was 2.6 mph. Passive
4 law enforcement shared a similar trend to active law enforcement with an average speed of 51.5
5 mph at the countermeasure location compared to 53.0 mph for the base scenario. The largest
6 speed differential between passive law enforcement and the base scenario occurred at a location
7 500 feet downstream from the speed countermeasures with a speed differential of 2.9 mph.
8 However, a difference between the active and passive law enforcement is that vehicles in the
9 passive law enforcement scenario started to rapidly accelerate after 500 feet downstream from
10 speed countermeasures and then exceeded the base scenario speed from 1000 feet downstream
11 from the speed countermeasures. This acceleration trend continues when vehicles pass the
12 downstream sensor location. Figure 4-17 shows the speed curves for all types of law
13 enforcement are under the baseline curve except for passive law enforcement after passing the
14 location of the countermeasure past 2000 feet from the beginning of the work zone.

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Figure 0-17. Speed profiles for law enforcement countermeasures during nighttime

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The results for the comparison between speed trailer active and speed trailer with red and blue

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lights is shown in Figure 4-18. Speed trailer active generally resulted in lower speeds than the

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base scenario except at few overlapping locations on the figure, such as near the beginning of the

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work zone and after the end of the work zone. Compared to the base scenario, participants for

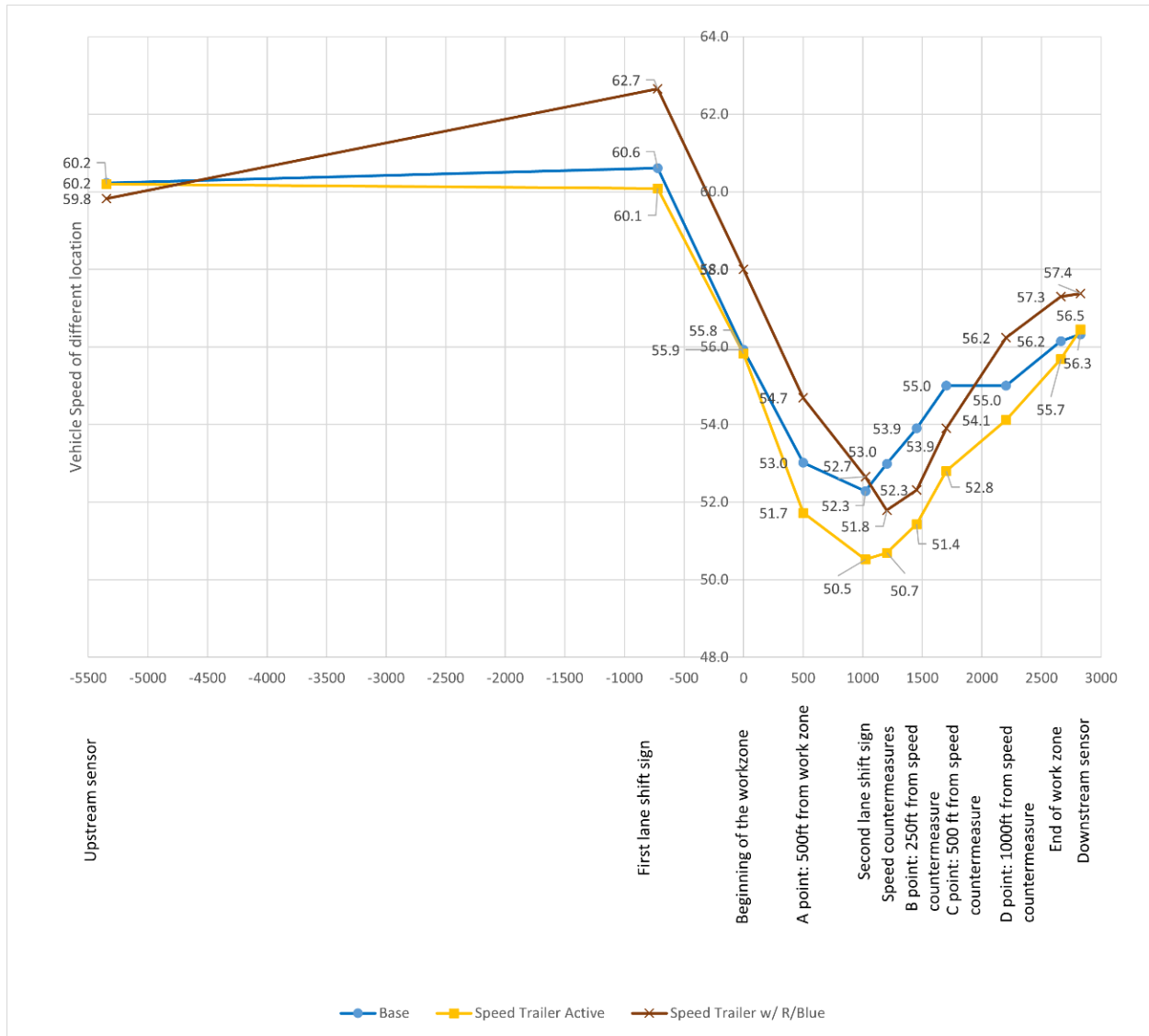
7

speed trailer active started to slow down heavily and started to accelerate rapidly after passing

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the speed countermeasure. At the moment participants passed the speed countermeasure, speed

1 trailer active reported an average speed of 50.7 mph whereas the base scenario reported a speed
2 of 53.0 mph. However, the maximum speed differential between base and speed trailer of 2.5
3 mph occurred at a location 250 feet downstream from the speed countermeasures. From entering
4 the work zone until the end of the work zone, the speed trailer active had good performance for
5 reducing vehicle speeds with lower vehicle speeds than the base scenario. The speed trailer with
6 red and blue lights did not result in lower speeds until approaching the speed countermeasures
7 and ended at a location 500 feet downstream from the speed countermeasures. Except for this
8 segment, the speed trailer with red and blue lights showed a higher average speed compared to
9 the base scenario, even at the downstream sensor location. The speed trailer with red and blue
10 lights only showed lower speeds from the speed countermeasure location to a location 500 feet
11 downstream from the speed countermeasure. The speed trailer with red/blue lights showed an
12 average speed of 51.8 mph at the countermeasure location compared to an average speed for the
13 base scenario of 53.0 mph. This speed differential increased to 1.6 mph at the location 250 feet
14 downstream from the speed countermeasures.



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2 **Figure 0-18. Speed profiles for speed trailer related countermeasures during nighttime**

3 The results for the comparison between speed trailer active and work vehicle with red/blue lights
 4 are shown in Figure 4-19. The work vehicle with red and blue lights resulted in lower speeds
 5 than the base scenario except at the upstream sensor location and after 1000 ft downstream from
 6 the speed countermeasures. The work vehicle with red and blue lights reported an average speed
 7 of 51.4 mph compared to 53.0 mph at the countermeasure location, which was the maximum
 8 speed differential for this countermeasure. The combination of speed trailer active and work

1 vehicle with red and blue lights shared the same trend as the work vehicle with red and blue
2 lights, with an average speed of 51.7 mph at the countermeasure location. The maximum speed
3 differential (2.2 mph) for the combination scenario occurred at a location 500 feet downstream
4 from the speed countermeasures. Between the location of second lane shift sign and the location
5 500 feet downstream from the speed countermeasures, the combination scenario was relatively
6 more effective in reducing speeds. Thus, the average speed of this segment from the combination
7 scenario was slightly lower than the work vehicle with red and blue lights alone.



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Figure 0-19. Speed profiles for work vehicle with red and blue lights and speed trailer

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active during nighttime

4 Eye Tracking Data

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Through an investigation of the eye tracking data extracted from the recorded video, driver

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behavior could be investigated by four MOEs as discussed previously. Detailed results from the

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eye tracking data are provided in the following sections.

•1 Daytime Results for Eye Tracking

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

9 **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%*

10 * Result is from Anova: single factor analysis.

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

16

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

1 traffic conditions. All of the countermeasures had lower average speeds compared to base
2 scenario, and the speed trailer active had the highest speed among all trials of 55.5 mph.

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

5

6 **Nighttime Results for Eye Tracking**

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

14

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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%*

3

* Result is from Anova: single factor analysis.

4

MOE 2 recorded the distance of the vehicle from the speed countermeasure when the participant

5

first glanced at the speed countermeasure, and the results are shown in Table 4-10. A smaller

6

distance can indicate a better visibility for the speed countermeasure and faster reaction from the

7

perspective of drivers. The work vehicle with red and blue lights and speed trailer active

8

combination had the lowest distance of 184.8 feet when the participant first glanced at the speed

9

countermeasure. The speed trailer active and speed trailer with red and blue lights both had lower

10

distances at nighttime compared to the daytime results. This result could indicate that speed

11

trailer related countermeasures have better visibility and led to faster driver reactions during

12

nighttime.

13

14

15

1 **Table 4-10. Distance from first traffic cone when participants first glanced at the speed**
 2 **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%**

3 * This distance is recorded after vehicle passed the first traffic cone in work zone.

4 ** Result is from Anova: single factor analysis.

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

11

1 **Table 4-11. Distance from the first traffic cone when participants first glanced at the lane**
 2 **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

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

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

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

10 **Table 4-12. Vehicle speed when participants first glanced at lane shift sign in work zone**
 11 **(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

12

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

2

Chapter 5. Surveys

This chapter presents the methodology and results for the surveys, including the post-simulator surveys that was given to simulator study participants after they completed the driving simulator scenarios and the other one was the driver survey.

5 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, 1993*), which is frequently used to diagnose the severity of simulator sickness of participants, was administered at the end of the survey.

The daytime results in **Table 5-1** show that participants preferred the speed trailers over law enforcement, and the speed trailer was rated the highest for visibility and clarity. Nevertheless, participants still indicated that active and passive law enforcement would most likely cause them to reduce their speed in work zones. As shown in **Table 5-1**, the nighttime survey results are similar to the daytime survey results. Passive and active law enforcement were rated as the most likely to cause participants to reduce their speed in work zones, with average ratings (one to five) of 4.66 and 4.47, respectively. Another result that is consistent with daytime result is that participants preferred speed trailer with red and blue lights over the law enforcement and work vehicle with red and blue lights. Participants generally commented that the use of law enforcement was the most effective in reducing speeds during nighttime.

1 **Table 5-1 Post-Simulator Survey Results**

	Overall Rating		Likelihood of Reducing Speed in Response to Daytime Strategies		Visibility		Clarity		Encourages Drivers to Slow Down	
	Average Rating	SD	Average Rating	SD	Average Rating	SD	Average Rating	SD	Average Rating	SD
Daytime Work Zone Speed Control Strategy										
Displays your speed	4.16	0.96	3.84	0.98	8.56	1.66	8.5	1.57	7.7	2.02
Displays your speed and flashes red and blue lights when you are speeding	4.2	1.11	4.1	0.97	8.8	1.41	8.62	1.51	8.28	1.76
Police car parked on shoulder	3.18	1.41	4.72	0.7	8.48	1.63	8.04	2.18	9.02	1.3
Police car pulling drivers over	3.14	1.46	4.64	0.8	8.64	1.47	8.28	1.97	9.06	1.22
Nighttime Work Zone Speed Control Strategy										
Displays your speed	4.24	0.82	4	0.9	8.38	1.83	8.5	1.56	7.36	1.98
Displays your speed and flashes red and blue lights when you are speeding	4.26	0.96	4.3	0.79	8.88	1.48	8.68	1.38	8.02	1.79
Police car parked on shoulder	3.84	1.15	4.66	0.69	8.42	1.79	7.88	2.22	9.12	1.08
Police car pulling drivers over	3.6	1.23	4.47	0.77	8.42	1.83	7.84	2.25	9.08	1.12
Work vehicle with flashing red and blue lights	3.76	1.06	4.12	0.92	8.6	1.65	7.64	2.28	7.64	2.16

2

3 Note: 1 = lowest, 5 – highest or (1 = lowest, 10 = highest) for rating

4

•1 Driver Survey Results

2 A survey to gauge drivers' perceptions of different work zone speed countermeasures and
3 driving habits in work zones was developed and administered by the research team. Topics
4 covered by the survey included ratings of daytime and nighttime work zone speed control
5 strategies, speed selection in work zones, and demographic information. After review by the
6 project Technical Advisory Committee (TAC), the survey was administered online using
7 Qualtrics software (*Qualtrics, 2022*). The survey was distributed using various methods,
8 including the researchers' social media accounts, webpages of larger MoDOT projects, MoDOT
9 project email groups, and an article in the University of Missouri's announcement service (MU
10 Info).

11 During a six-week period, 108 anonymous survey responses were received. Both daytime and
12 nighttime results in **Table 5-2** shows that the participants preferred speed display trailers over the
13 law enforcement. However, drivers indicated that law enforcement presence (both active and
14 passive) is more effective in reducing their speeds during both daytime and nighttime. The driver
15 survey results are consistent with the results from the post-simulator surveys. Specifically, the
16 speed display trailer without the red and blue lights was perceived to be the least effective in
17 encouraging drivers to reduce their speeds during daytime. The work vehicle with red and blue
18 lights was rated more effective for speed reduction than the speed display trailer during
19 nighttime.

20

1 **Table 5-2 Driver Survey Results**

	Overall Rating		Likelihood of Reducing Speed in Response to Daytime Strategies	
	Average Rating	SD	Average Rating	SD
Daytime Work Zone Speed Control Strategy				
Displays your speed	4.11	0.98	3.95	1.2
Displays your speed and flashes red and blue lights when you are speeding	4.25	1.1	4.24	1.11
Police car parked on shoulder	3.57	1.31	4.58	0.92
Police car pulling drivers over	3.29	1.58	4.54	0.93
Nighttime Work Zone Speed Control Strategy				
Displays your speed	4	1.06	4	1.12
Displays your speed and flashes red and blue lights when you are speeding	4.25	1.08	4.22	1.11
Police car parked on shoulder	3.64	1.29	4.5	0.87
Police car pulling drivers over	3.41	1.43	4.38	1.06
Work vehicle with flashing red and blue lights	3.98	1.23	4.27	1.04

2

3

CONCLUSION

1
2 In this research study, the field evaluation on I-270 found that active law enforcement was the
3 most effective countermeasure in reducing vehicle speeds in the work zone during both daytime
4 and nighttime conditions. The use of other speed countermeasures evaluated in the field study,
5 including passive law enforcement, speed trailer, speed trailer with flashing speed feedback
6 (daytime only), speed trailer with flashing red and blue lights (daytime only), and work vehicle
7 with flashing red and blue lights (nighttime only), also resulted in reductions in vehicle speeds in
8 the work zones. The speed trailer without flashing speed feedback or flashing red and blue lights
9 was associated with lower speed reductions than the other speed countermeasures. Generally, the
10 speed countermeasures performed better with respect to speed reductions during nighttime.

11 Unfortunately, equipment issues limited the availability of the speed trailer with the red and blue
12 lights.

13
14 The driving simulator study complemented the field study by allowing testing for combinations
15 of strategies in the same scenario, collection of vehicle speeds at several locations, and the use of
16 eye tracking data to assess drivers' responses to countermeasures. During daytime, the use of
17 super law enforcement (active law enforcement and speed trailer combination) was the most
18 effective in reducing vehicle speeds. During daytime, the speed trailer with red and blue lights
19 was more effective than the speed trailer without red and blue lights, and passive law
20 enforcement led to greater speed reductions than active law enforcement. During nighttime, the
21 speed trailer was associated with the lowest speeds, and the speed reductions for both active and
22 passive law enforcement were comparable. In general, the effect of the speed reduction
23 dissipated more quickly during nighttime than during daytime. The maximum speed differential,

1 which indicates the maximum speed reduction over base scenario for each speed control strategy,
2 occurred within the segment from the speed countermeasures to a location 1000 feet downstream
3 from speed countermeasures but not upstream from countermeasures. Eye tracking results
4 indicate that super law enforcement and speed trailer-related countermeasures had better
5 visibility during daytime and nighttime, respectively. The post-simulator survey and driver
6 survey showed that while drivers generally preferred the speed trailer, they also admitted that
7 law enforcement would be the most effective in causing them to slow down in the work zone.
8 Respondents from driver surveys generally had a favorable impression of the construction
9 vehicle with red and blue lights and rated it between law enforcement and speed display trailers.
10
11 Overall, the results of the study indicate that an approach that considers multiple strategies to
12 manage vehicle speeds in work zones may be the most effective. The countermeasures evaluated
13 in this study were all associated with speed reductions in the work zone. While law enforcement
14 was generally the most effective strategy in reducing vehicle speeds, the availability of law
15 enforcement for a specific work zone may be a limitation. Associated with its ability in reducing
16 vehicle speed significantly, the speed trailer with red and blue lights can be an alternative when
17 law enforcement is not available. The selection of speed countermeasures to implement for a
18 specific work zone should be made on a project-by-project basis based on various factors such as
19 traffic volumes, type of work activity, site conditions, availability of law enforcement or
20 equipment, and cost. This research study fills a gap of existing related studies in examining the
21 effectiveness between multiple speed control strategies by using both the simulator and field
22 study. The proper effective and efficient use of the combination of the speed control strategies
23 can help DOTs to improve work zone safety.

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

Table A-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	-	-

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
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.	-	-	-	-	-	-	-
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.	-	-	-	-	-	-	-

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
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	-	-
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	-	-

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1 **APPENDIX B. SIMULATOR RESULTS FOR SPEED PROFILES**

2 **Table B-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

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Table B-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 countermeasures	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

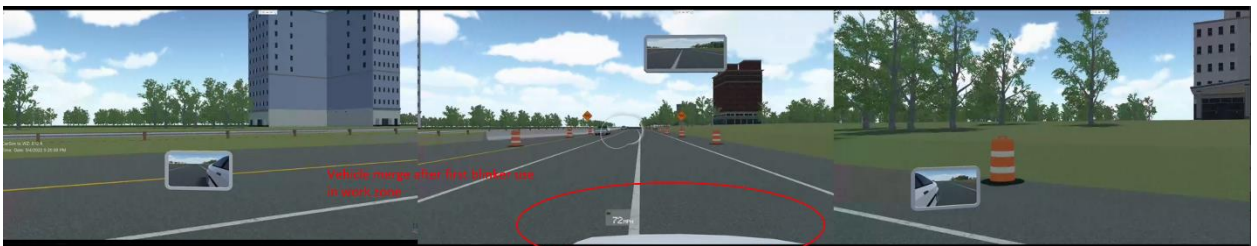
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1 APPENDIX C. SIMULATOR RESULTS FOR EYE TRACKER DATA

2 Methodology of MOEs

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

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



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15 **Figure C-1. Screenshot example for vehicle merge after the use of first blinker in**
16 **work zone**

●1 **Daytime Results**

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

5 **Table C-1. The total number of the times participants glanced at speed**
6 **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

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

12 **Table C-2. The total number of times participants changed lanes in the work zone**
13 **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

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•1 **Nighttime Results**

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

6

7 **Table C-3. The total number of the times participants glanced at speed**
8 **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

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

7 **Table C-4. The total number of times that participants changed lanes in the work**
8 **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

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