Evaluation of Automated Flagger Assistance Devices

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16. Abstract

Automated flagger assistance devices (AFADs) are designed to improve worker safety by replacing flaggers who are typically located near traffic approaching a work zone. In this study, a new AFAD developed by the Missouri Department of Transportation (MoDOT) was evaluated via a combined driving simulator and field study. The MoDOT AFAD configuration conformed to the Manual on Uniform Traffic Control Devices and involved STOP/SLOW paddles, red/yellow lights, and a changeable message sign (CMS). This AFAD was incorporated onto a truck-mounted attenuator for operator protection. Driver behavior measures, including approach speed, initial braking location, full stop distance, reaction time, and intervention rate, were used to measure the effectiveness of AFAD as compared to a human flagger. In the field study, the AFAD induced slower vehicle approach speeds (4.20 mph less), stopped vehicles farther back (11.4 feet), and released traffic quicker (1.3 seconds less) than flaggers. In the driving simulator study, the AFAD and its alternative designs significantly reduced average approach speeds (7.7 to 8.9 mph) and increased the distance at which the approaching vehicles came to a complete stop (24 to 48 feet). Both the field and the simulator study were followed by surveys that captured driver preferences and understanding. The results from both surveys showed that drivers understood AFADs well and preferred AFADs over human flaggers, especially for the MoDOT AFAD configuration. Overall, the AFAD has potential to improve the safety of work zones for both workers and the traveling public.

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A Final Report

presented to

Missouri Department of Transportation

by the University of Missouri-Columbia

by

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EXECUTIVE SUMMARY

Automated flagger assistance devices (AFADs) are designed to improve worker safety by replacing flaggers who are typically located near traffic approaching a work zone. The objective of this project was to evaluate the effectiveness of a new AFAD developed by the Missouri Department of Transportation (MoDOT). The MoDOT AFAD configuration (Figure ES.1), involving STOP/SLOW paddles, Red/Yellow lights, and a changeable message sign (CMS), was incorporated onto a truck-mounted attenuator for operator protection. The scope of this project included three phases: a field test with CMS, a simulator study (both with and without CMS), and a tentative field test without CMS. The third phase was deemed unnecessary as the use of CMS was found to be desirable in the first two phases. The first two phases were each followed by a survey that captured driver preferences and understanding. Detailed quantitative driver behavior measures were used for the first time in this study to compare the effectiveness of human flaggers versus AFADs in the United States.

Figure ES.1 MoDOT AFAD and its CMS Signs

For the field study, video data was collected for two days in a work zone on MO 23 in Knob Noster, Missouri. One direction had a human flagger while the other direction had the MoDOT AFAD. The flagging methods were reversed for the second day. Driver behaviors at both ends of the AFAD and human flagger were recorded by cameras. There were 334 total queues collected, of which 186 were for the AFAD, and 148 were for the flagger. The results of the field data analysis showed that the vehicle approach speed for the AFAD was significantly slower (23.2 mph versus 27.4 mph) than the vehicle approach speed for the flagger. The lower average approaching speed indicates that the AFAD helps to improve work zone safety. The AFAD full stop location was significantly farther than the flagger full stop location (61.07 ft. versus 49.68

ft.). Interventions, or instances of noncompliance, for both the AFAD and human flagger, were also studied. Interventions are instances where drivers do not stop and wait while the STOP paddle is shown and have to be alerted by the AFAD operator or the human flagger. The intervention rate was the total number of interventions divided by the sample size. The intervention rate for AFAD was slightly lower than the intervention rate for the flagger (3/193 vs. 3/155). With the AFAD, the approaching speeds for the 1st following vehicles were significantly slower than without the AFAD (20.63 mph versus 23.09 mph). In summary, the performance measures of vehicle approach speed, stop location, intervention rate, and first vehicle approach speed all favor the AFAD over the flagger. Table ES.1 summarizes the key field test results.

Table ES.1 Summary of Field Results

	Approach Speed (mph)			
	Mean	SD	Diff	Confidence Level
Flagger	27.37	6.53	Baseline	
MoDOT AFAD	23.23	5.87	-4.14	> 99.9%*
	Full Stop Distance (feet)			
	Mean	SD	Diff	Confidence Level
Flagger	49.64	22.75	Baseline	
MoDOT AFAD	61.07	29.26	11.43	> 99.9%*
	Intervention Rate			
	Mean	SD	Diff	Confidence Level
Flagger	0.019 (3/155)	0.14	Baseline	
MoDOT AFAD	0.016 (3/193)	0.12	-0.003	21.30%
	Speed of the 1st Following Vehicle (mph)			
	Mean	SD	Diff	Confidence Level
Flagger	23.09	5.37	Baseline	
MoDOT AFAD	20.63	5.28	-2.46	99.5%*

* indicates significance at 99% confidence level

The reaction time for AFAD was significantly longer than for the flagger (4.41s vs. 1.69s) and may cause extra traffic delay. But the reason for the longer delay is not completely clear. The following are some possible reasons for the difference in reaction time between the AFAD and the flagger. On the AFAD, there was a time lag for turning the slow paddle, thus the paddle and the CMS message were out of synchronization. This delay was corrected after the field test was conducted. The delay may also be due to differences in interpersonal communication with a person as opposed to a device. In addition, drivers who encountered the AFAD may be distracted by their cellphones or other things, while drivers who encountered human flagger may be less distracted with the nearby presence of a construction worker.

For the field survey, the research team distributed 104 hard copies and 182 online links to drivers after they drove through the work zone with the AFAD. A total of 42 responses were received. As shown in Table ES.2, the MoDOT AFAD was preferred over the flagger by almost 80 percent of the participants. Over half of the respondents (54 percent) preferred the AFAD much more than the flagger, and no respondents preferred the flagger much more than AFAD.

Table ES.2 Respondents' Preference between Flagger and MoDOT AFAD

Preference	Count	Percentage	
AFAD much more	22	53.66%	78.05%
AFAD more	10	24.39%	
Neutral	4	9.76%	9.76%
Flagger more	5	12.20%	12.20%
Flagger much more	0	0.00%	

All of the 42 respondents understood AFAD correctly, but two of them misunderstood flagger gestures. Most respondents thought both AFAD and flagger were effective or very effective (88 percent and 93 percent, correspondingly). Although AFAD had a larger percentage of "very effective" (66.7 percent vs. 19 percent), it had a larger percentage of "very ineffective" as well (9.5 percent vs. 4.8 percent). Some drivers may have preferred the ability to communicate with a flagger. Most respondents (90 percent) agreed or strongly agreed that the CMS was helpful. When asked if they had any additional comments regarding the AFAD, respondents stated that the advantages of AFAD included increased visibility, multi-functionality, adaptability to weather conditions, and enhanced safety. Possible reduced visibility of the CMS due to sun glare was mentioned as a concern by two respondents.

After Phase One was completed, the Phase Two simulator study was conducted. In the simulator study, four setups were evaluated as shown in Figure ES.2: human flagger, MoDOT AFAD, AFAD with alternative sign, and AFAD without CMS. There were 32 participants in the study. The age distribution was skewed slightly toward younger drivers: 40 percent of the participants in the 18 to 25 age group, 37 percent in the 26 to 40 age group, 7 percent in the 41 to 55 age group, and the remaining 10 percent in the over 56 age group. Approximately 40 percent were females.

The results for the comparison between flagger and MoDOT AFAD are shown in Table ES.3. The driving simulator results showed that the MoDOT AFAD significantly reduced average approach speeds (8.4 mph), increased full stop distance (44 feet), and increased the first brake location where participants reacted to the stop controls (58 feet) as compared to the human flagger. There were no interventions for the MoDOT AFAD, while the human flagger had an intervention rate of 14 percent. The simulator results indicated that the MoDOT AFAD performed better than the human flagger.

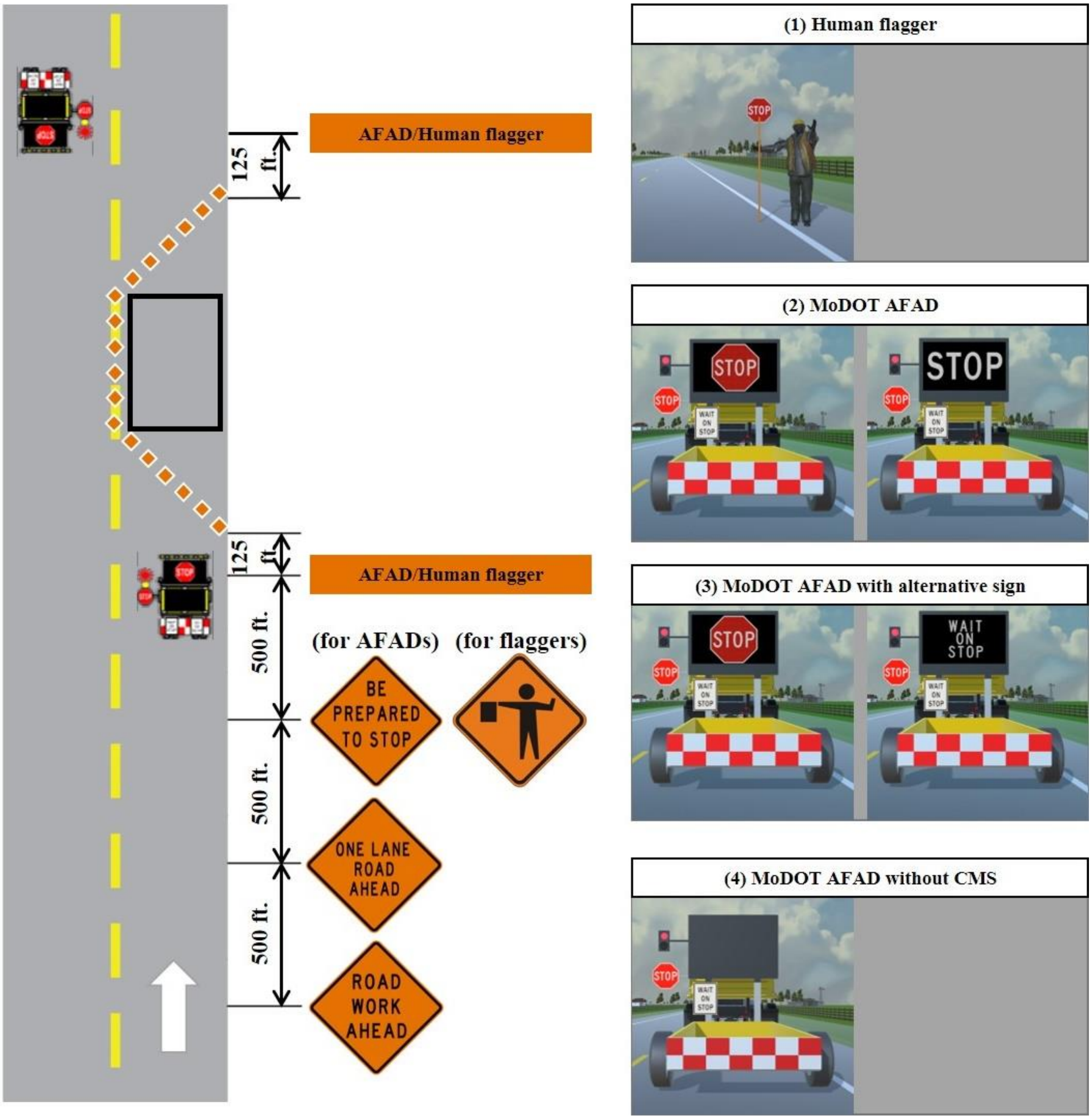

Figure ES.2 The Work Zone Plan and Traffic Control Methods in the Simulator Study

Table ES.3 Simulator Results: Flagger vs. MoDOT AFAD

	Approach Speed (mph)			
	Mean	SD	Diff	Confidence Level
Flagger	34.79	13.83	Baseline	
MoDOT AFAD	26.34	11.63	-8.44	> 99.9%*
	Full Stop Distance (feet)			
	Mean	SD	Diff	Confidence Level
Flagger	53.09	36.03	Baseline	
MoDOT AFAD	97.55	49.93	44.46	> 99.9%*
	Intervention Rate			
	Mean	SD	Diff	Confidence Level
Flagger	0.14 (9/64)	0.35	Baseline	
MoDOT AFAD	0.00 (0/64)	0.00	-0.14	99.8%*
	First Brake Location (feet)			
	Mean	SD	Diff	Confidence Level
Flagger	274.02	120.51	Baseline	
MoDOT AFAD	332.19	108.55	58.17	99.5%*

* indicates significance at 99% confidence level

The average approach speeds for the AFAD with alternative sign and AFAD without CMS were 26.0 mph and 26.9 mph, respectively. The full stop distance locations were 91 feet for the AFAD with alternative sign and 74 feet for the AFAD without CMS. The average approach speeds for the AFAD with alternative sign and AFAD without CMS were comparable to the MoDOT AFAD, while the full stop location was shorter for the AFAD without CMS than for the MoDOT AFAD and AFAD with alternative sign. There were no interventions for the AFAD with alternative sign, while the AFAD without CMS had a 5 percent intervention rate. The reaction times were as follows: 2.05 seconds (flagger), 1.93 seconds (MoDOT AFAD), 1.60 seconds (AFAD with alternative sign, and 1.23 seconds (AFAD without CMS). Thus, participants reacted faster to the AFAD without CMS than the other setups when they were given the instructions to proceed through the work zone.

The post-simulator survey results showed that most drivers understood the flagging devices (93 percent flagger, 90 percent AFAD with alternative sign, 83 percent MoDOT AFAD, and 83 percent AFAD without CMS). Examples of incorrect responses chosen include interpreting the human flagger paddle as a regular STOP sign and AFADs as traffic lights. Although some participants provided wrong answers for the meaning of the MoDOT AFAD and the AFAD with alternative sign in the post-simulator survey, there were no interventions in the simulator trial, indicating that all participants understood these two AFADs correctly. It could be inferred that although AFADs may require some adjustments by drivers due to novelty, they were reasonably understandable and conveyed the desired message effectively.

Overall, the order of average participant rankings, from the most preferred to the least preferred, was: MoDOT AFAD, AFAD with alternative sign, human flagger, and AFAD without CMS. Participants also rated clarity, visibility, safety, and efficiency of each flagging methods. The MoDOT AFAD scored the highest in all four categories, and the AFAD with alternative sign had the second highest scores in all four categories. AFAD without CMS scored the lowest in clarity, and the human flagger had the lowest score in visibility, safety, and efficiency. The results for these ratings for the flagger and MoDOT AFAD are shown in Table ES.4.

Table ES.4 Ratings for Clarity, Visibility, Safety, and Efficiency, MoDOT AFAD vs. Flagger

	Clarity				
	Mean Score	Median	Diff	Diff Range	Confidence Level
MoDOT AFAD	8.94	10	Baseline		
Flagger	6.41	6	-2	(-4, 0)	> 99.9%*
	Visibility				
	Mean Score	Median	Diff	Diff Range	Confidence Level
MoDOT AFAD	9.47	10	Baseline		
Flagger	4.19	4	-5	(-7, -5)	> 99.9%*
	Safety				
	Mean Score	Median	Diff	Diff Range	Confidence Level
MoDOT AFAD	9.19	10	Baseline		
Flagger	4.06	4	-5	(-6, -4)	> 99.9%*
	Efficiency				
	Mean Score	Median	Diff	Diff Range	Confidence Level
MoDOT AFAD	8.74	9	Baseline		
Flagger	5.29	5	-3	(-5, -2)	> 99.9%*

* indicates significance at 99% confidence level

Over half of participants strongly agreed and over a quarter agreed that the CMS was a necessary component of the MoDOT AFAD. With regard to simulator fidelity, most participants (80 percent) agreed or strongly agreed that they felt like they were driving on a real highway, and 83 percent of them agreed or strongly agreed that they felt like they could drive freely.

The Phase Three field test of AFAD without CMS which was tentatively included in the project scope of work was not conducted for several reasons. First, both the field and simulator study clearly indicated that the MoDOT AFAD was a valid and effective replacement of the human flagger. The simulator participants ranked the AFAD without CMS as their lowest preference in the survey. The AFAD project was regarded as complete, and the results provide supporting evidence for potential MoDOT AFAD deployment in future short term work zones.

The simulator, field test, and survey results were consistent in showing that MoDOT AFAD performed better than flaggers using multiple MOEs. One possible explanation for the results is that the TMA truck and CMS increased the visibility of the AFAD, which helped to reduce approach speeds, and increase stopping distances. The combination of STOP/SLOW paddle with the Red/Yellow lights (MUTCD option) also helped drivers understand the device. These results are highly encouraging for any jurisdictions who are interested in pursuing the use of AFADs to improve work zone and worker safety.

These promising results should be interpreted with some issues in mind. Despite the similar trends shown in the simulator and field studies, the absolute magnitudes of MOEs differed. This illustrates the fact the simulator studies are better at establishing relative validity than absolute validity (Kaptein et al.1996). The results were obtained from work zones on a rural highway; results may be different in an urban area. The impacts of other factors, like traffic volume, lane closure length, and speed limit, were not examined in this study. All MOEs were obtained from drivers in Missouri, and all AFAD devices were new to them. Therefore, the results of AFADs on driver behaviors may vary in a different state, and the novelty effect of AFAD designs should be examined in a study of longer duration.

CHAPTER 1: INTRODUCTION

1.1 Background

Flaggers are professionally trained to guide and direct vehicles through work zones, but they are often located closest to the oncoming traffic. As a result, they are exposed to risks associated with errant drivers (Antonucci et al. 2005). Studies have shown that a very high percentage of work-related crashes occurred in the advance warning area where flaggers are located (Ishak et al. 2012; Srinivasan et al. 2007). One study (Ishak et al. 2012) even indicated that the highest percentage occurred in the advanced warning area. Therefore, discovering ways to protect flaggers is an important issue in work zone safety. To reduce exposure to traffic and improve flagger safety, there are several countermeasures applied in work zones, including the use of buffer spaces and barriers (Trout and Ullman 1997). One countermeasure that can be applied when there is a one lane closure on a two-lane road is an Automated Flagger Assistance Device (AFAD). An AFAD removes a worker from having to be near the approaching traffic at a work zone.

A new type of AFAD was developed by the Missouri Department of Transportation (MoDOT) (Figure 1.1.1). This AFAD uses STOP/SLOW paddles and flashing red/yellow lights. In addition, a changeable message sign (CMS) was installed displaying a series of four messages. As shown in Figure 1.1.1, the CMS alternates between an image of a STOP sign and the word "STOP" every two seconds during the stopped interval. The CMS alternates between an image of SLOW and the words "Go on Slow" every two seconds during the go interval. The AFAD was built onto a truck-mounted attenuator (TMA) unit in order to provide protection for the AFAD operator in the truck. The truck integration obviates the need to tow and deploy trailer-mounted AFADs. The MoDOT AFAD was tested in the manual operation mode; the flagger in the truck controlled the signals by observing traffic at the end of work zone and communicating with another flagger at the other end of the work zone by radio.

Figure 1.1.1 AFAD Mounted on TMA

Flaggers have been playing an important role in traffic control for a long time, as they guide and direct vehicles on the highway, and often, through work zones. Flaggers are trained professionally to display uniform gestures for traffic guidance using signaling devices. Richards and Bowman (1981) examined the effectiveness of flagger gestures and signals and found that some signals are more effective than others. They also validated the importance of using flaggers. Flaggers are exposed to safety risks, as they may be hit by oncoming traffic when drivers are not aware of the presence of workers or are not able to come to a full stop when approaching the work zone.

Traffic engineers have proposed different methods to slow down the approaching speed and extend the merge distance of vehicles as they approach work zones. Studies investigating new technology include mobile work zone alarm systems (Brown et al. 2015), alternative merge signs (Zhu et al. 2015), automated traffic light systems (Subramaniam et al. 2010), flashing STOP/SLOW paddles (Pigman et al. 2006), Remote Controlled (RC) Flagman (Jessberger 1999), IntelliStrobe Safety Systems (Missouri Department of Transportation 2006) and other types of AFADs (Cottrell Jr 2006; Finley et al. 2011; Terhaar 2014).

This reports documents the results from a study to evaluate AFADs using four different types of techniques: field monitoring, field survey, driving simulator, and post-simulator survey. Detailed driver behavior measures were used for the first time in this study to compare the effectiveness of human flaggers versus AFADs in the United States.

1.2 Literature Review

AFADs are designed to protect flaggers in work zones by allowing flaggers to control traffic signals remotely instead of standing right next to occupied lanes. According to the *Manual on Uniform Traffic Control Devices* (FHWA 2009), there are two different types of AFADs: STOP/SLOW and red/yellow lens. Both types of AFADs are remotely controlled. In their 2005 technical provision, FHWA (2005a) regulated the maximum distance between two AFAD devices to 1,000 ft. AFADs should not be used for long term work or as regular traffic control signals. According to the FHWA (FHWA 2009), a STOP/SLOW AFAD shall include a sign with STOP and SLOW faces showing alternatively, which could be controlled remotely. A red/yellow lens AFAD shall include a steady circular red lens and a flashing circular yellow lens. A gate arm is required for the red/yellow lens AFAD, which lowers the arm to stop approaching traffic while the red lens is illuminating and raises the arm to release stopped traffic while the yellow lens is illuminating.

Some commercial STOP/SLOW AFADs include the AutoFlagger 76 (AF-76) (Figure 1.2.1) (Safety Technologies 2015a), and J4 Flagger Workstations. Commercial red/yellow lens AFADs include the AutoFlagger 54 (AF-54) (Figure 1.2.2) (Safety Technologies 2015b), RC Flagman RCF 2.4 (Figure 1.2.3) (North America Traffic 2016), Automated Flagger AF-100 (Synergy Technology 2017), and IntelliStrobe W1-AG (Figure 1.2.4) (IntelliStrobe 2017). FHWA also created a policy memorandum (FHWA 2005b) and provided technical provisions (FHWA 2005a) for AFADs. Based on the work and materials from FHWA, American Traffic Safety Services Association (ATSSA 2012) published a guidance document on AFAD usage in 2012.

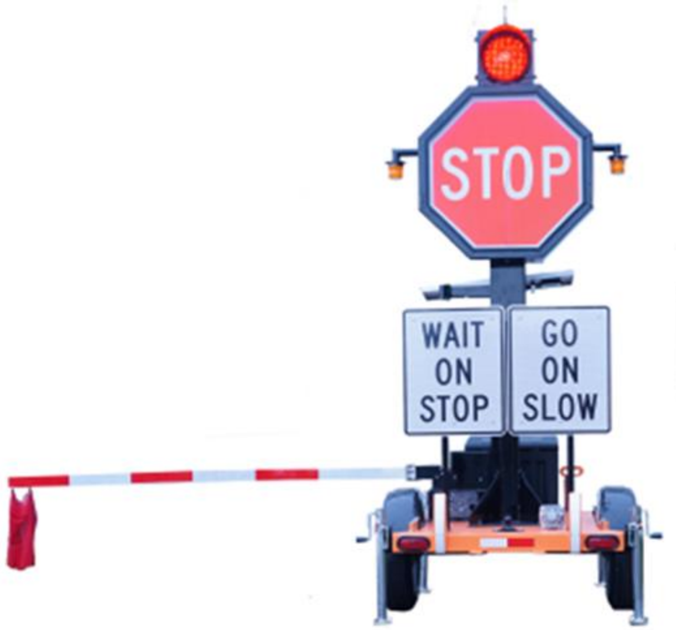

Figure 1.2.1 AutoFlagger 76 (Safety Technologies 2015a)

Figure 1.2.2 AutoFlagger 54 (Safety Technologies 2015b)

Figure 1.2.3 RC Flagman RCF 2.4 (North America Traffic 2016)

Figure 1.2.4 IntelliStrobe W1-AG (IntelliStrobe 2017)

To evaluate the effectiveness of AFADs, research and field studies were performed by the Ohio Department of Transportation (ODOT) (Jessberger 1999), Washington County (Kansas) Public Works (Harris 2002), MoDOT (Missouri Department of Transportation 2006), Minnesota Department of Transportation (MnDOT) (MnDOT 2005; Terhaar 2014), Virginia Transportation Research Council (VTRC) (Cottrell Jr 2006), and Texas A&M Transportation Institute (TTI) (Finley 2013; Finley et al. 2011; Trout et al. 2013). Some of these evaluations are discussed in the following sections.

1.2.1 Evaluation of STOP/SLOW AFADs

MnDOT (MnDOT 2005) tested the AutoFlagger traffic control devices in late 1990s as an enhancement to flagging systems. A human operator controlled the AutoFlagger devices in both directions remotely. Surveys were gathered from drivers and operators on their opinions of the AutoFlagger and the responses were positive.

VTRC and the Virginia Department of Transportation (VDOT) reviewed applications of AFADs in Minnesota (MnDOT 2005) and evaluated AutoFlagger deployments in two areas. VTRC compared AutoFlagger with other AFAD systems (Cottrell Jr 2006). The AutoFlagger deployed in Virginia was a STOP/SLOW paddle device equipped with a horn for warning purposes. The first deployment was located in the Wytheville area. The AutoFlagger was deployed under different types of construction and maintenance projects and was also displayed at a safety day. VDOT used it on roadways with narrow shoulders or no shoulders by putting the device in the lane with a 50-ft taper of cones in front of it. The deployments in Wytheville showed that the "WAIT ON STOP – GO ON SLOW" signs were misunderstood by drivers due to the novelty of AutoFlagger. The second deployment was located in the Beach area. In contrast to the deployment in Wytheville, staff in Beach felt more comfortable using AutoFlagger in long straight areas with wide shoulders and clear sight distance, rather than in areas with narrow shoulders. The crews also suggested that horns should be made louder in order to be heard, and flashing lights should be larger and brighter to enhance visibility. VTRC concluded that although the deployment of AutoFlagger is limited by shoulder conditions, the application of AutoFlagger provides a safe work zone environment, requires less labor, and saves money for the long term. A drawback is that it may be harder for drivers to locate a flagger in order to communicate with him/her.

1.2.2 Evaluation of Red/Yellow Lens AFADs

In the late 1990s, the Ohio Department of Transportation (ODOT) (Jessberger 1999) evaluated the Remote Controlled (RC) Flagman. The RC Flagman device was placed at a two-lane highway location, with one lane closed, and the evaluation involved comments from ODOT employees who operated the devices, public interviews, an assessment of cost effectiveness, and accident statistics. The RC Flagman contains red/yellow signals mounted on a mobile trailer, a remote control unit, a gate arm, and a "STOP HERE ON RED SIGNAL" paddle. During the ODOT field experiment, operators had trouble with short battery life and weak button contact of the remote control units, time delay from the pressing of the button to the changing of the signal light, and slow movement of the gate arm motors. Operators also recommended that the visibility of gate arm be enhanced. Operators indicated that the set up and operation of RC flagman was easy, and they were satisfied with driver reactions. Most of the motorists thought that the device was visible, the STOP message was presented clearly, and the RC Flagman freed one flagger and provided a safer environment for flaggers. Some interviewees were worried about flaggers losing jobs. Although some problems existed, the overall comments from ODOT operators and public regarding the use of RC Flagman were favorable. Based on cost and maintenance history, the study found that using RC Flagman is cost effective. No accidents were reported during the two-year evaluation of RC Flagman. Thus, ODOT concluded that RC Flagman is at least as safe as traditional flaggers. Similar to Ohio, the RC Flagman evaluation in Washington County, Kansas, also found that it is cost-effective, and the visibility of a red light makes it work even better than human flaggers (Harris 2002). According to RC Flagman, no accidents have been reported at RC Flagman sites since this device was produced in 1993 (Harris 2002).

In fall 2005, MoDOT piloted the IntelliStrobe flagging system (IntelliStrobe 2017) in the South Central District. An IntelliStrobe device contains red/yellow signals, two remote control units to be used by one person, and a danger alert. The yellow light flashes continually, and when the red light turns on, the gate arm lowers to stop approaching traffic. In case motorists misunderstand or violate the signal, the danger alert sounds to alert operators. The IntelliStrobe Safety System is suitable for short work zones, and it frees up one flagger because one flagger controls both ends.(Missouri Department of Transportation 2006).

1.2.3 Evaluation of both STOP/SLOW and Red/Yellow Lens

In addition to the evaluation of STOP/SLOW AFADs performed in 2005, MnDOT (Terhaar 2014) held two training sessions for its employees in 2013 to further investigate and evaluate AFADs. These sessions include introduction and demonstration of AFADs, set up, operation, and take down, discussion of impressions and limitations, and field tests. Both AutoFlagger AF-76 (STOP/SLOW) and AutoFlagger AF-54 (red/yellow lens) were evaluated. The outcome of this study indicated that a set of AFADs could be operated by one or two personnel remotely from traffic, and maintenance staff were willing to use AFADs overall. Setting up and taking down an AFAD requires more time and effort than traditional flagging. The result also suggested that AF-76 fits in wide shoulder work zones, while AF-54 fits in narrow shoulder locations, and both AF-76 and AF-54 are recommended for two-lane highways.

The review of the previous AFAD evaluations showed that there was very little use of quantitative performance measures and no applications of statistical methods. The lack of previous scientific AFAD evaluations is a major motivation for the present MoDOT study which uses quantitative performance measures such as speeds, stop locations, wait times, reaction times, and intervention rates in addition to surveys. The present study also uses statistical techniques for analyzing and interpreting quantitative and qualitative performance measures.

CHAPTER 2: FIELD STUDY

Two major tasks of the project are to conduct field and simulator studies to verify AFAD effectiveness and to study driver behavior. The project includes three phases involving the use of an AFAD: a field test with Changeable Message Sign (CMS), a simulator study (both with and without CMS), and a tentative field test without a CMS. This chapter describes the field test with CMS. The third phase was deemed unnecessary as the use of a CMS was found to be desirable by the first two phases.

2.1 Field Set Up Plan

Phase one focused on comparing a MoDOT STOP/SLOW AFAD mounted on a TMA against a human flagging system using field data. Video cameras, speed radar guns and delineators were deployed to collect data measurements. Driver performance and driving behavior at both AFAD and human flagger sides were recorded. These driver performance measures included vehicle approach speed, full stop location, reaction time and other unusual driving behaviors.

The field study plan is shown in Figure 2.1.1. The camera was placed on the right side of road, to avoid influencing opposite traffic. To measure the vehicle approach speed, the speed radar was set in front of the video camera without blocking the view of vehicles, delineators, and the AFAD or the flagger. The delineators were placed every 50 feet along the road. There were a total of seven delineators from the stop control on each side of the road. In addition to the driver reaction measures, the camera also recorded traffic information on the road, such as traffic volume, waiting time, and queue length.

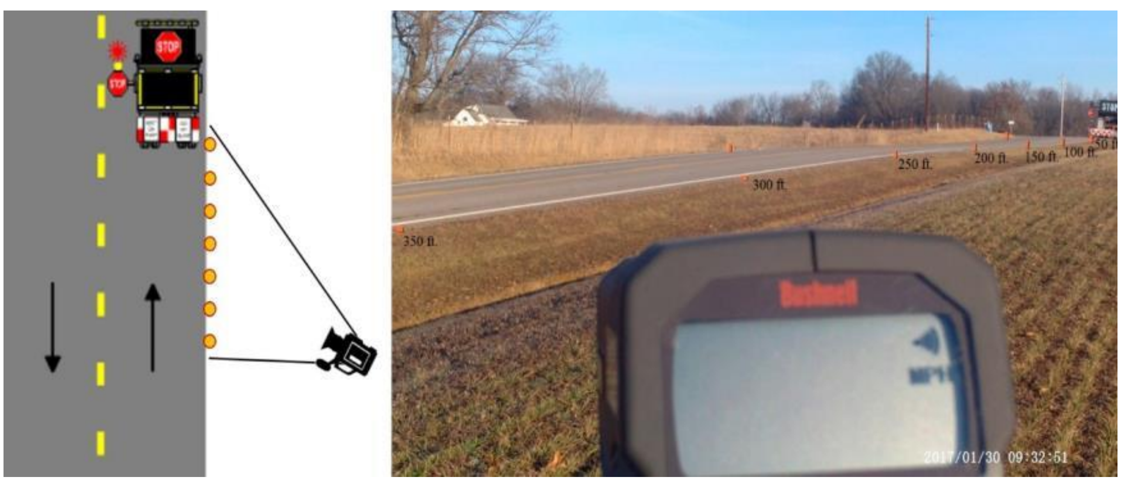

Figure 2.1.1 Field Study Plan of Cameras, Radar Speed Gun, and Delineators

Two field data sessions were conducted to collect field data. The first one was on December 20th, 2016, on MO150 in Lone Jack, Missouri. The second one was conducted on January 30th and 31st, 2017, on MO-23 Highway in Knob Noster, Missouri.

2.2 First Field Data Collection

The first field data collection was on December 20th, 2016, on MO-150 in Lone Jack, Missouri. MO-150 was a two-lane highway, and the work zone was 2,200 feet long from the AFAD on one end to the flagger at the other end. The annual average daily traffic (AADT) on the road segment was 1,028 vehicles per day, according to the MoDOT Transportation Management Systems (TMS). The work zone layout and descriptions are shown in Figure 2.2.1 and Table 2.2.1.

Figure 2.2.1 Map of MO-150 Work Zone (Google Maps 2017)

Table 2.2.1 MO-150 Field Data Collection Information

Location:	MO-150 in Lone Jack, MO
	Two-lane highway
	Speed Limit 45 mph/55 mph
AADT:	1,028 vpd (directional 514)
Length:	2,200 ft. (from the flagger to AFAD)
Duration:	12/20/2016 10:30 AM - 11:45 AM

In the field, one camera, one radar speed gun, and a set of delineators were placed at each work zone end. The field settings and the field views of the cameras are shown in Figure 2.2.2. The west end camera recorded traffic and driver reaction to the flagger, and the east end camera recorded activities at the AFAD.

Figure 2.2.2 Field Settings on MO-150 Highway Work Zone (Google Maps 2017)

The data collection was conducted from 10:30 AM to 11:45 AM. As the testing was underway, it was discovered that the AFAD was not functioning properly. Therefore, the data collection was aborted. Subsequently, MoDOT changed the AFAD controller from wireless to wired to enhance reliability, and a second field survey was scheduled.

2.3 Second Field Data Collection

The second field data collection was conducted on January 30th and 31st, 2017, on MO-23 Highway in Knob Noster, Missouri. The work zone was 2,400 ft. long and the AADT value on the road was 2,610 vehicles per day. The work zone layout and information of work zone are shown in Figure 2.3.1 and Table 2.3.1.

Figure 2.3.1 Map of MO-23 Work Zone (Google Maps 2017)

Table 2.3.1 MO-23 Field Data Collection Information

Location:	MO-23 Hwy, Knob Noster, MO
	Two-lane highway
	Speed limit 55 mph
AADT:	2,610 vpd (directional 1,305)
Length:	2,400 ft. (from the flagger to AFAD)
Duration:	01/30/2017 09:17 AM – 04:47 PM
	01/31/2017 09:57 AM – 04:29 PM

2.3.1 Data Collection

The data collection deployment on MO-23 Highway is shown in Figure 2.3.2. The difference between the deployment and the field study plan was that the north side camera was placed on the left side of road due to topographic constraints. This change had minimal impact because the small volume of opposing traffic did not occlude the camera. On one end of the work zone, there was an AFAD mounted on a truck-mounted attenuator (TMA) truck (Figure 1.1.1) with an operator sitting inside the TMA vehicle to control the AFAD remotely. On the other end, there was a human flagger standing next to the traffic lane to show STOP/SLOW paddles (Figure 2.3.3). Speed guns and cameras were set up at each side to record approaching speeds of vehicles. On the first day, the AFAD was located on the south side of the work zone, and the flagger was on the north side. On the second day, the locations of the AFAD and flagger were reversed. Thus each type of flagging was deployed at both directions.

(a) MO-23 Work Zone (Google Maps 2017)

(b) South end, first day (AFAD)

(c) North end, first day (Flagger)

(d) South end, second day (Flagger)

(e) North end, second day (AFAD)

Figure 2.3.2 Field Settings on MO-23 Work Zone

Figure 2.3.3 Flagger

2.3.2 Data Processing

Field videos were reviewed and performance data were obtained. Only vehicles that encountered the STOP message were processed; those vehicles that encountered the SLOW display and drove through directly were not processed. The reason for focusing on stopped vehicles was to assess the safety impacts of flagging systems. The number of samples is shown in Table 2.3.2. The sample size collected was 334 total, of which 186 was for AFAD and 148 for flagger.

Table 2.3.2 Summary of Field Data Collected

Field Data	Traffic Control Types		Total
Location	AFAD	Flagger	
South End	102 (First Day)	82 (Second Day)	184
North End	84 (Second Day)	66 (First Day)	150
Total	186	148	334

After the field data was collected, the research team reviewed the videos, and conducted the data reduction process. Seven Measures of Effectiveness (MOEs) were defined for data reduction as described below.

- MOE 1: speed of the leading vehicle at 250 ft. from the AFAD/Flagger (Figure 2.3.4). The speed was read from the speed gun. However, the speed gun did not display any speeds lower than 10 mph, so researchers estimated speeds less than 10 mph using the speed from the last reading.

Figure 2.3.4 MOE 1 Example: Speed of the Leading Vehicle at 250 ft. from AFAD/Flagger

- MOE 2: full stop location (Figure 2.3.5). Location of vehicle's front end when the vehicle came to a full stop. The location was the distance from the AFAD or flagger. The distance was determined from the video based on the delineator cones that were placed.

Figure 2.3.5 MOE 2 Example: Full Stop Location

- MOE 3: waiting time (Figure 2.3.6). Waiting time was measured as the time gap between the time when the vehicle came to a full stop and when the vehicle started to move again after receiving the SLOW indication from the flagger or AFAD.

Figure 2.3.6 MOE 3 Example: Waiting Time

- MOE 4: reaction time (flagger/AFAD CMS) (Figure 2.3.7). Reaction time was measured as the time between when STOP changes to SLOW (paddle for flagger and CMS for AFAD) and when the vehicle restarts. At the time of the field experiment, the SLOW paddle on AFAD and the messages on CMS were not fully synchronized. When the message on the CMS changed from STOP to SLOW, the paddle started to turn, and it took four seconds to finish turning. Drivers appeared to react based on the message shown on CMS. The time lag between the paddle and CMS on the AFAD was corrected after the field work. For the AFAD, reaction time was measured based on the CMS and not the paddle since drivers appeared to react to the CMS.

Figure 2.3.7 MOE 4: Reaction Time

- MOE 5: Intervention rate (Figure 2.3.8). Intervention refers to when a vehicle ignored the STOP sign and was stopped by the AFAD or flagger. If a vehicle came too close to the AFAD or tried to go through, then the AFAD truck would sound its horn. If a vehicle came too close to the flagger, then the flagger stopped the vehicle via gestures. In either case, it was regarded as one intervention. Intervention rate equals the ratio of interventions over the sample size.

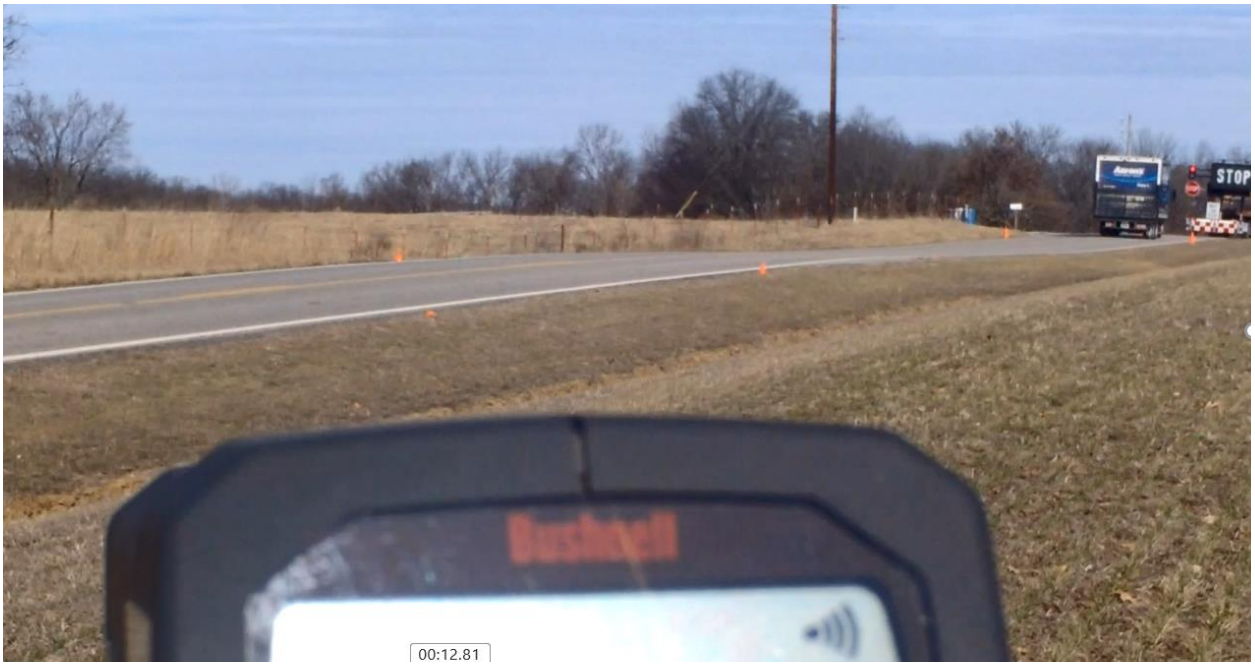

Figure 2.3.8 MOE 5: Intervention Rate

- MOE 6: speed of the 1st following vehicle at 250 ft. from AFAD/Flagger. Similar to MOE 1, the speed was again captured at 250 ft.

Figure 2.3.9 MOE 6: Speed of the 1st Following Vehicle at 250 ft. from AFAD/Flagger

- MOE 7: queue length (Figure 2.3.10). The number of vehicles in a queue.

The seven MOEs were extracted and data were grouped by direction (southbound/northbound), flagging type (AFAD/Flagger), and vehicle type (sedan, pickup, commercial vehicle). Since the height of vehicles impacts sight distance, taller passenger vehicles such as SUVs, pickups, and minivans were differentiated and labeled as the pickup category.

Figure 2.3.10 MOE 7: Queue Length

2.3.3 Field Data Results

All of the MOEs were recorded and extracted from videos. Differences between MOEs were calculated to compare AFAD and flagger performance. Confidence level was indicated by the t-test result, and the effect size was indicated by Cohen’s d. Cohen's d indicates the standardized difference between two means. Cohen’s d equals the ratio of the difference over the standard deviation.

MOE 1 measured the speed of the leading vehicle at 250 ft. from the AFAD/Flagger. As shown in Table 2.3.3, the average approaching speed of vehicles that encountered AFAD was 23.2 mph, and the approaching speed of vehicles that encountered the human flagger was 27.4 mph. Approach speeds for vehicles that traveled through the AFAD were significantly lower than for the human flagger with a confidence level higher than 99.9 percent. Cohen's d indicated that the standardized mean of AFAD speed was 0.667 standard deviations lower than the mean of flagger.

Table 2.3.3 Speed of the Leading Vehicle at 250 ft. from the AFAD/Flagger

	Speed at 250 ft. (mph)
AFAD	23.23
Flagger	27.37
Confidence Level	> 99.9%*
Difference	-4.14
Cohen's d	-0.667

* indicates significance at 99% confidence level

MOE 2 measured the full stop location of vehicles that encountered STOP message/paddle. As shown in Table 2.3.4, the average full stop location of vehicles that encountered AFAD was 61.07 ft. behind the AFAD, and the average full stop location of vehicles that encountered human flagger was 49.64 ft. behind the flagger. The full stop location for AFAD was significantly farther away than the flagger with the confidence level being higher than 99.9 percent. Cohen's d indicated the mean of AFAD full stop location was 0.436 units of standard deviation farther than flagger.

Table 2.3.4 Full Stop Location

	Full Stop Location (ft.)
AFAD	61.07
Flagger	49.64
Confidence Level	> 99.9%*
Difference	11.43
Cohen's d	0.436

* indicates significance at 99% confidence level

MOE 3 measured the waiting time of the first vehicle in the queue, and MOE 7 measured the queue length in the stopped queue. MOEs 3 and 7 are shown in Table 2.3.5. These two MOEs were not related to safety but efficiency. Waiting time was defined as the time gap between vehicle restart and full stop. The waiting time for the AFAD was approximately 33 seconds less than the waiting time for the flagger. In some instances, the AFAD waiting time was increased because the AFAD showed "SLOW" on the CMS and the STOP paddle while vehicles were still clearing the work zone, thus requiring vehicles to wait for the opposing traffic to clear. An example of this situation is shown in Figure 2.3.11. One contributing factor to this situation was a synchronization delay between the STOP/SLOW paddle and the CMS. Although the synchronization issue has since been corrected, it is recommended that the AFAD operator ensures that all traffic has passed the end of the TMA (rather than the location of the AFAD operator) before switching the paddle and CMS from "STOP" to "SLOW".

Figure 2.3.11 Delay due to Opposing Traffic Not Clearing

Table 2.3.5 Waiting Time and Queue Length

	Waiting Time (s)	Queue Length (veh)
AFAD	72.25	1.70
Flagger	105.52	2.08
Confidence Level	99.8%*	99.4%*
Difference	-33.26	-0.39
Cohen's d	-0.389	-0.301

* indicates significance at 99% confidence level

MOE 4 measured the reaction time of the first vehicle in the queue. It was calculated as the time gap between the first appearance of SLOW message (AFAD) or paddle (flagger) and when the vehicle started to move again. As previously discussed, the reaction time based on the AFAD CMS was ultimately used instead of the AFAD paddle. As shown in Table 2.3.6, the average reaction time for the AFAD was 4.41 s, and for the flagger was 1.69 s. The reaction time for the AFAD was significantly longer than for the flagger. This result may be due to the differences in interpersonal communication with a person as opposed to interaction with a device. Another reason for the significant longer reaction time for drivers who encountered AFAD may be that some drivers were looking at their cellphones or were otherwise distracted, but the drivers that passed through the flagger may have been less distracted due to the presence of a live human flagger standing by the side. Also, as previously discussed, the lag between the CMS display and the paddle turning could also have been a factor. Cohen’s d (effect size) indicated that the mean reaction to AFAD was 2.921 units of standard deviation longer than reaction time to flagger.

Table 2.3.6 Reaction Time (AFAD based on CMS, flagger based on paddle)

	Reaction Time (CMS) (s) Based on AFAD CMS	Reaction Time (CMS) (s) Based on AFAD Paddle
AFAD	4.41	0.412
Flagger	1.69	1.690
Confidence Level	> 99.9%*	> 99.9%*
Difference	2.72	-1.279
Cohen's d	2.921	-0.530

* indicates significance at 99% confidence level

MOE 5 measured the intervention rate, which could be an indication of driver misunderstanding of the AFAD or flagger. Intervention refers to when a vehicle ignored the STOP sign, thus requiring the AFAD to honk its horn or the flagger to stop the vehicle using gestures. In some instances, the vehicle backed up to the proper position after the intervention. The intervention rate for AFAD was slightly lower than flagger, as shown in Table 2.3.7. However, the difference was not statistically significant. A previous MnDOT (2005) evaluation reported an intervention rate of 0.0096 (5/313). This is a similar low but non-negligible intervention rate.

Table 2.3.7 Intervention Rate

	Intervention Rate
AFAD	0.016 (3/193)
Flagger	0.019 (3/155)
Confidence Level	21.3%
Difference	-0.004
Cohen's d	-0.029

MOE 6 measured the approaching speed of the second vehicle in the queue. As shown in Table 2.3.8, the average speed of the second vehicle in the AFAD queue at 250 ft. was 20.6 mph, and in the flagger queue was 23.1 mph. The difference was significant at the 99.5 percent confidence level. This result indicates that the second vehicle approached the AFAD at a lower speed than vehicles approaching the flagger.

Table 2.3.8 1st Following vehicle Speed at 250 ft.

	1st Following Vehicle Speed at 250 ft. (mph)
AFAD	20.63
Flagger	23.09
Confidence Level	99.5%*
Difference	-2.46
Cohen's d	-0.460

* indicates significance at 99% confidence level

During the field collection process, unusual driving behavior was observed. Types of unusual driving behaviors include high approaching speed and extra-long reaction time. Two instances of high speeds at the flagger end were a pickup going 47 mph and an SUV going 55 mph (Figure 2.3.11). These two vehicles had approaching speeds which were much higher than the other vehicles since the average approaching speed was 27.4 mph. For long reaction times (Figure 2.3.12), one leading vehicle at the AFAD end had a reaction time of 20 seconds, while the average reaction time for AFAD was 4.41 s. After the CMS showed the SLOW sign, the leading vehicle did not realize the change of message on CMS, and the AFAD honked twice to get the vehicle’s attention.

Figure 2.3.12 Vehicle Approaching Flagger at High Speed

Figure 2.3.13 Vehicle Long Reaction Time to SLOW Indication on AFAD

Interventions at the south side of the work zone were less frequent than interventions at the north side of the work zone. One reason why the intervention rate at the north side was higher (Table A-2.2 and A-3.2, Appendix A) may be the difference in grades at the two ends. In the field study, the north end was at the top of a steep hill while the approach to the south end was more level. Some drivers may have wanted to know what was going on behind the stop control. At the south side, they could see more of the work zone as they approached, but at the north side, their view was more limited.

CHAPTER 3: FIELD SURVEY

3.1 Survey Methodology

A driver intercept survey was administered for vehicles that traveled through the AFAD end of the work zone. Vehicles were stopped in the work zone after they went through the AFAD and given a short survey. There were two survey formats: hard copies with stamped envelopes and an index card with a link (including QR code) to an online version of the survey. In some cases, drivers were given a choice of which survey format they preferred. In other instances, to reduce vehicle delay, drivers were assigned a survey format based on the researcher's judgment of the survey format preference. For example, drivers who had their cell phones readily available or were texting on their phones were typically given the online version of the survey. The research team distributed 104 hard copies and 182 online links (Table 3.1.1). A total of 42 responses were received, and the response rate was 14.7 percent. This response rate is relatively low but is similar to some of the mail surveys discussed in Hager et al. (2003).

Table 3.1.1 Survey Numbers

Survey	Hard Copy	Online	Total
Sent Out	104	182	286
Response Received	30	12	42

The survey consisted of four parts. Parts 1 and 2 asked questions about drivers' understanding of the AFAD signage and human flagger gesture, their perceptions regarding the effectiveness of the two different stop controls, their opinion regarding whether the CMS was helpful, and any additional comments. Part 3 asked for their preference between the AFAD and flagger. Part 4 asked for their demographic information and regular vehicle type. The complete field survey is attached in Appendix B.

Survey responses included two types: hard copies and online. To ensure consistency in survey data processing, hard copy entries were entered into the online survey system. Results were extracted directly from the online survey system.

3.2 Survey Results

Two multiple choice questions involved the meaning of the AFAD signage and human flagger gesture, respectively. Among the 42 respondents, all of them understood the AFAD meaning correctly, but two of them chose the wrong answer for the meaning of the flagger gesture. The results implied that the AFAD was more understandable than the flagger.

The survey responses indicate that most of the respondents thought both AFAD and flagger were effective. Although 88.1 percent of respondents thought AFAD was effective or very effective and 92.86 percent of respondents thought flagger was effective or very effective, the proportion of respondents who thought AFAD was very effective was more than the proportion who thought that the flagger was very effective. However, there were more respondents who thought that

AFAD was ineffective or very ineffective, as shown in Table 3.2.1. This result may due to the novelty of the AFAD as these drivers had not previously encountered the AFAD. Some drivers may have preferred the interpersonal communication with the flagger.

Table 3.2.1 Survey Responses Regarding Effectiveness

Effectiveness	STOP/SLOW AFAD			Flagger		
	Count	Percentage		Count	Percentage	
Very Effective	28	66.67%	88.10%	8	19.05%	92.86%
Effective	9	21.43%		31	73.81%	
Neutral	1	2.38%	2.38%	1	2.38%	2.38%
Ineffective	1	2.38%	9.52%	1	2.38%	4.76%
Very Ineffective	3	7.14%		1	2.38%	
Total	42	100.00%		42	100.00%	

Respondents were asked about the reasons for their effectiveness ratings for the AFAD and flagger. Five factors were provided as possible answers: clarity, visibility, safety, efficiency, and other. Among the four factors, visibility ranked number one, in both AFAD and flagger situations as shown in Table 3.2.2. Clarity and safety were also both considered as important reasons for the effectiveness ratings.

Table 3.2.2 Reason of Effectiveness Rating

Factor	Count		
	AFAD	Flagger	Total
Clarity	21	31	52
Visibility	23	36	59
Safety	20	30	50
Efficiency	13	20	33
Other	5	5	10

As shown in Table 3.2.3, 90.48 percent of the respondents thought that the CMS was helpful, with 57.14 percent of the respondents strongly in agreement. Only one respondent (2.38 percent) disagreed or strongly disagreed that the CMS was helpful. Most of the respondents thought that the CMS improved the visibility of stop control and could help them to understand signage. One respondent felt that the CMS was redundant and unnecessary since the STOP/SLOW paddle was present and was informative enough.

Table 3.2.3 Summary of Responses to Survey Question Regarding Helpfulness of CMS

CMS helpfulness	Count	Percentage	
Strongly Agree	24	57.14%	90.48%
Agree	14	33.33%	
Neutral	3	7.14%	7.14%
Disagree	0	0.00%	2.38%
Strongly Disagree	1	2.38%	
Total	42	100.00%	

The survey asked if the drivers had encountered the two types of stop controls before. Although the respondents had just driven through the AFAD, less than half of them responded that they had encountered an AFAD before, while all of them had previously encountered a flagger (Table 3.2.4).

Table 3.2.4 Summary of Responses to Question about Previous Experience with AFAD and Flagger

Encountered Before?	AFAD		Flagger	
	Count	Percentage	Count	Percentage
Yes	19	45.24%	41	100%
No	23	54.76%	0	0%
Total	42	100.00%	41	100%

When drivers were asked for their preference between AFAD and flagger, no respondents preferred the flagger much more than AFAD, and only 12.2 percent of the respondents preferred the flagger more. Although the percentage of respondents who thought that the flagger was effective or very effective was higher than the percentage who thought that the AFAD was effective or very effective, respondents preferred the AFAD more than the flagger. As shown in Table 3.2.5, 53.66 percent respondents preferred the AFAD much more than flagger, and 24.39 percent preferred the AFAD more than flagger.

Table 3.2.5 Respondents' Preference for AFAD or Flagger

Preference	Count	Percentage	
AFAD much more	22	53.66%	78.05%
AFAD more	10	24.39%	
Neutral	4	9.76%	9.76%
Flagger more	5	12.20%	12.20%
Flagger much more	0	0.00%	
Total	41	100.00%	

Demographic information was collected, and the results are shown in Tables 3.2.6 and 3.2.7. Among the survey respondents, gender distributions were even, with the number of female drivers slightly less than the number of male drivers. Older drivers were more prevalent than younger drivers, and over 64 percent of the respondents were over 55 years old. The field work was performed in a rural area, and 83.33 percent of respondents were rural residents. Most of the respondents drove passenger cars as their regular vehicle type. Different responses by age, gender, and residency are attached in Appendix C.

Table 3.2.6 Demographic Information

Gender		**Age**				
Male	Female	16-25	26-40	41-55	56-70	71-95
22	19	1	5	8	14	13
52.38%	45.24%	2.38%	11.90%	19.05%	33.33%	30.95%

Table 3.2.7 Residency and Vehicle Information

Residency		**Regular Vehicle Type**	
Urban	Rural	Passenger car	Other
3	35	37	4
7.14%	83.33%	88.10%	9.52%

Respondents provided written comments on the advantages and disadvantages of AFAD. They thought the advantages of AFAD included increased visibility, multi-functionality, adaptability to weather conditions, and enhanced safety, as a human flagger means a worker is standing near traffic. Some concerns raised by some respondents about the AFAD included:

- Sun glare reduced visibility
- Potential confusion in case of its malfunction
- AFAD may not be respected as well as a live human flagger
- It may be easier to communicate with human flaggers than the AFAD

Some additional comments include:

- The higher cost of AFAD was worthwhile due to its benefits
- A warning noise for violations would help to alert both drivers and workers in the work zone
- Advanced signage for TMA instructions would be beneficial

CHAPTER 4: SIMULATOR STUDY

After Phase One, field study of the MoDOT AFAD and human flagger, was completed, Phase Two, simulator study, was conducted. The simulator was utilized to examine various details of the AFAD design in a cost-efficient manner since AFAD variations were implemented in a virtual world. This simulator study explored three different AFAD configurations, including one without the use of a CMS. The simulator offered a highly controlled environment, thus limiting extraneous causal factors. The simulator also provided safe experiment conditions to allow for different options to be tested.

4.1 Simulator Study Methodology

ZouSim, the University of Missouri's driving simulator, was used for conducting the AFAD simulator study. ZouSim is a medium-fidelity simulator built around the half-cab of a sedan. Even though ZouSim has a wide range of graphical display capabilities, including virtual reality, augmented reality, and stereoscopic 3D, the triple 120-inch screen was chosen as the most appropriate display for the AFAD study. This display setup provided a 180-degree field-of-view which offered an excellent view of the approaching work zone and the relevant peripheral clues for regulating driving speed. Figure 4.1.1 shows the ZouSim setup for the AFAD experiment. The primary virtual camera was the forward windshield view. Three additional virtual cameras presented the left, right and rear view mirrors perspectives. The active instrumentation in the vehicle includes a force-feedback steering wheel, brake and acceleration pedals, turn signals, and an engine vibration generator.

Figure 4.1.1 AFAD Experiment Using ZouSim

4.1.1 Simulator Setup

The study simulated work zones on a rural highway in Missouri with a speed limit of 55 mph. The entire highway was designed without any horizontal or vertical curves in order to eliminate the influence of terrain. The road was created according to AASHTO Green Book standards (AASHTO 2013). Surfaces were textured and/or painted with the appropriate striping and markings that conform to the MUTCD (FHWA 2009). The work zone plan on the highway is shown in Figure 4.1.2. In the work zone, one lane is closed for road work while traffic movements in the open lane are controlled by a pair of flaggers or AFADs. The work zone configuration, including signage, distance between signs, and location of flagger/AFAD, followed the requirements of MUTCD (FHWA 2009) and MoDOT Engineering Policy Guide (MoDOT 2009).

As shown in Figure 4.1.2, the following four flagging methods, one flagger and three AFAD designs, were tested: (1) human flagger, (2) MoDOT AFAD, (3) variation on method (2) with an alternative sign, and (4) variation on method (2) with the CMS turned off. There was no other traffic in the direction that the participant is traveling, so the participant was always the leading vehicle. When arriving at a work zone, participants always encountered the STOP interval and had to wait for the opposite traffic to pass first before given the SLOW sign.

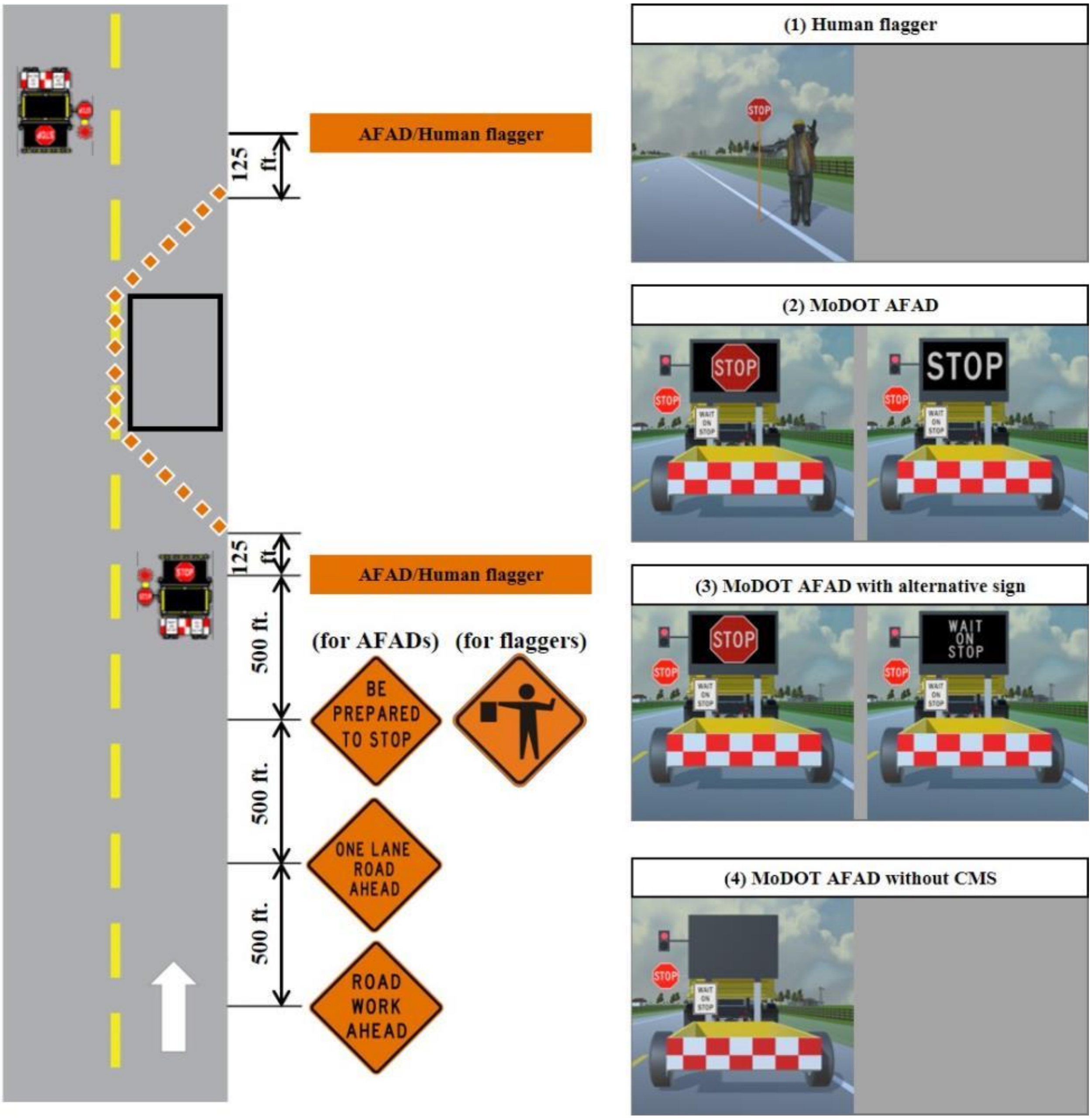

Figure 4.1.2 Work Zone Plan and Traffic Control Methods in the Simulator Study

The human flagger was the baseline for this experiment. A human flagger manually operated a STOP/SLOW paddle. The size of paddle was an 18-inch hexagon conforming to the MUTCD (FHWA 2009). There were two faces of the paddle: one face showed STOP in a red hexagon and the other one showed SLOW in an orange rhombus. During the STOP phase, the human flagger stopped traffic according to the MUTCD flagger guidance (FHWA 2009) while the flagger waved his arm to guide traffic during the SLOW phase as shown in Figure 4.1.3.

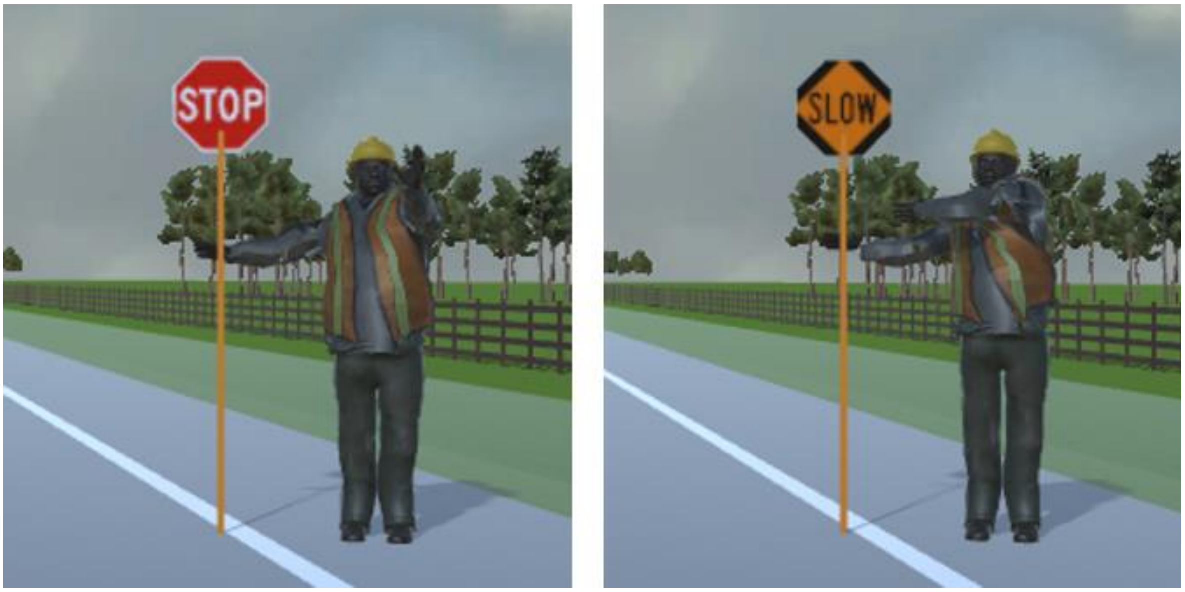

Figure 4.1.3 Human Flagger Configuration

The AFAD was the simulation of the MoDOT AFAD deployed in field tests. The AFAD was mounted on a TMA with a beacon, a STOP/SLOW paddle, and a CMS. There were two phases: STOP and SLOW. During the STOP phase, the beacon was static red, the paddle showed the STOP face, and the message on the CMS alternated between a STOP sign and the word "STOP", as shown in Figure 4.1.4. During the SLOW phase, the message on the CMS alternated between a SLOW sign and the phrase "GO ON SLOW."

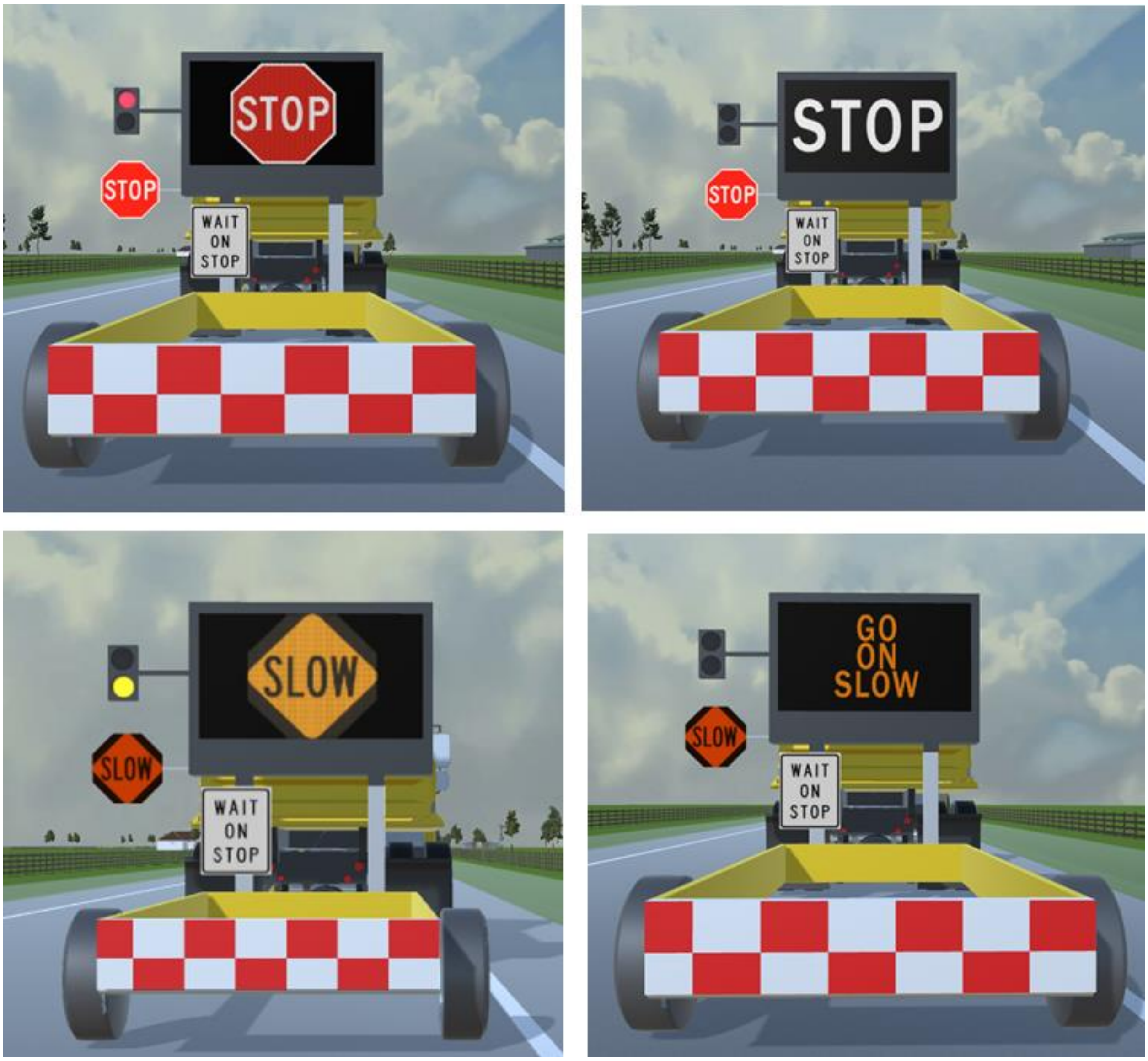

Figure 4.1.4 MoDOT AFAD Configuration

The AFAD with the alternative sign was similar to MoDOT AFAD. The only variation was the STOP phase with "WAIT ON STOP" being displayed on the CMS instead of the word "STOP", after the STOP sign was shown on the CMS. The configuration of the AFAD with the alternative sign is shown in Figure 4.1.5.

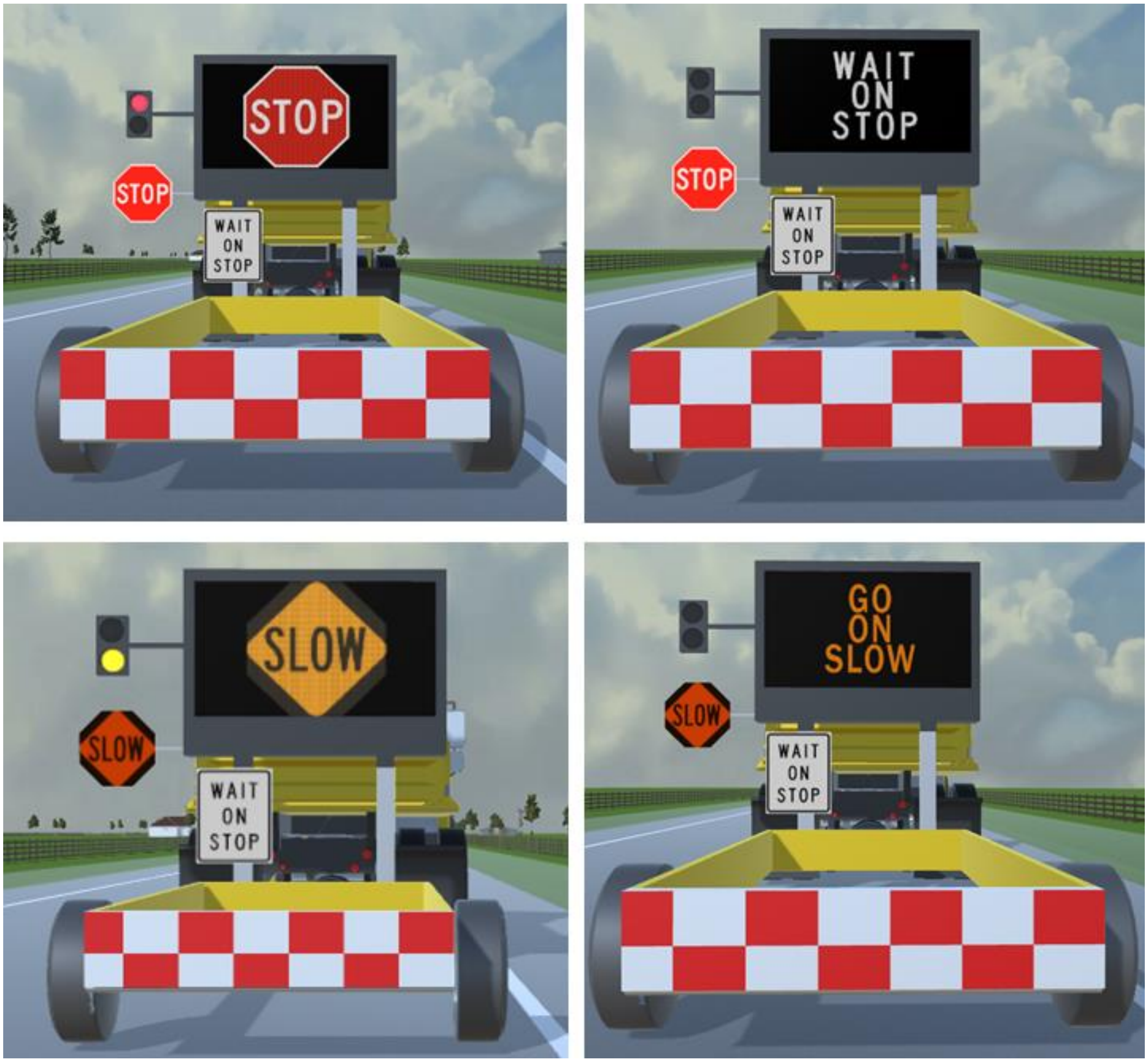

Figure 4.1.5 AFAD with Alternative Sign Configuration

The AFAD without a CMS was a simplified version of the MoDOT AFAD with the CMS turned off, as shown in Figure 4.1.6. The CMS was not removed for AFAD without CMS as per MoDOT request in order to replicate an AFAD with a CMS-style arrow board. Thus, a MoDOT AFAD would not have the CMS space unoccupied without an arrow board. This arrow board was not turned on for the simulator experiment as per MoDOT request.

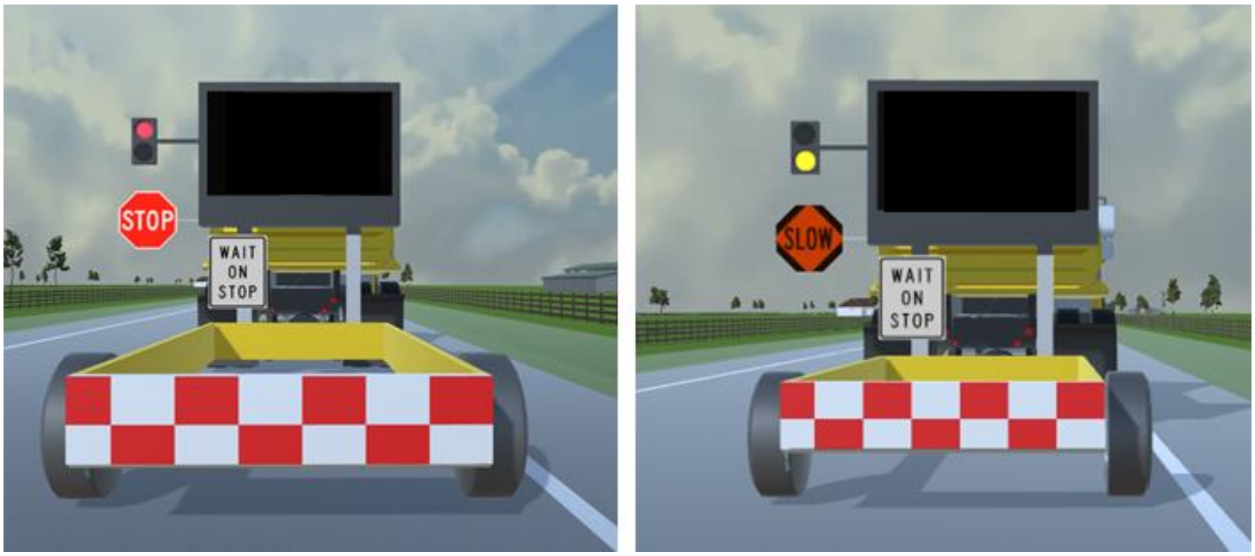

Figure 4.1.6 AFAD without CMS Configuration

In any simulator study, there is a possible sequence bias or order effect because the first flagging operation that a participant encounters can act as an anchor, affecting subsequent encounters (Perreault 1975). One way to control for this bias is to randomize the test order. Therefore, with four different flagging methods, 24 different test orders were generated, and each participant was randomly assigned to one of 24 test orders to minimize sequence bias effects. Each of the four flagging methods was tested twice to obtain more data. The waiting time was varied, either 30 seconds or 40 seconds, to prevent participants from recognizing a pattern in waiting times.

4.1.2 Simulator Trials and MOEs

The study protocols and measurement tools were evaluated and approved by the campus institutional review board, and a standard hosting script was used. First, a participant's informed consent was obtained after being introduced to the simulator and the experiment purpose. Then, the participant drove a free-driving warm-up scenario to become familiar with the specific vehicle. Once the participant was comfortable, the actual work zone scenarios were initiated. The participant was asked to drive along a rural two-lane, two-way highway to arrive at a clinic. On the way, the participant encountered eight work zones involving the four flagging methods.

After the simulator data was collected, the research team reviewed the videos, and conducted the data reduction process. Five Measure of Effectiveness (MOEs) were defined for data reduction as described below.

- MOE 1 - Approach Speed (mph) is the speed when a vehicle is 250 feet from the flagger/AFAD. This is the same distance at which field speed data was collected. At this location, drivers can see the AFAD/flagger clearly. A lower approach speed is desirable. The approach speed was echoed on the screen as shown in Figure 4.1.7. Figure 4.1.7 also shows that the vehicle was at 250 ft. from the flagger/AFAD.

Figure 4.1.7 MOE 1 Example: Approach Speed (mph)

- MOE 2 - Full Stop Distance (feet) is the distance to the human flagger or AFAD when the vehicle fully stops. A larger distance means more separation from the flagger/AFAD. This is the same MOE recorded in the field. MOE 2 was echoed on the screen as shown in Figure 4.1.8.

Figure 4.1.8 MOE 2 Example: Full Stop Distance (feet)

- MOE 3 - Reaction Time (seconds) is the time between when "SLOW" sign is shown and when the vehicle restarts. A faster reaction may indicate that the driver has a better understanding of when to go. An example of MOE 3 is shown in Figure 4.1.9.

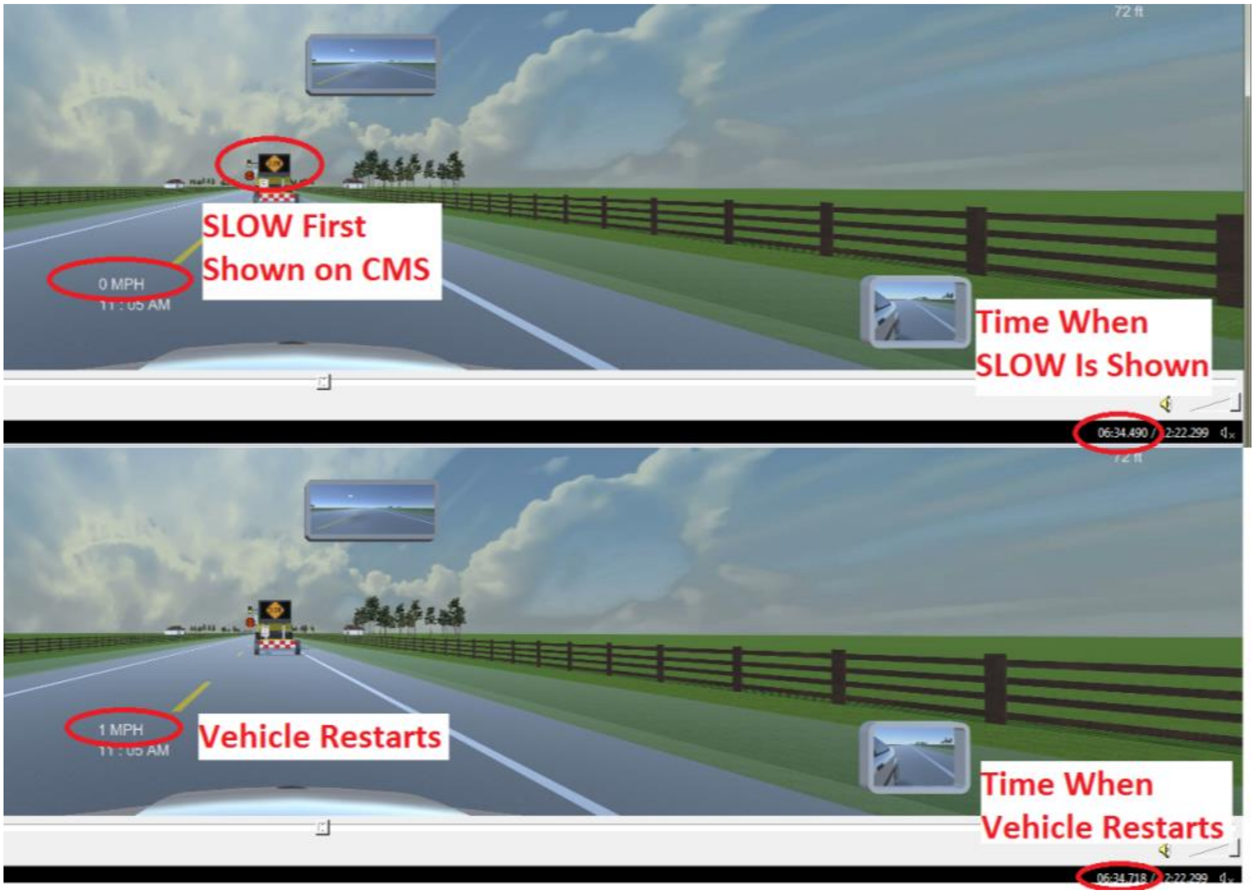

Figure 4.1.9 MOE 3 Example: Reaction Time (seconds)

- MOE 4 - Intervention Rate is the percentage of drivers not obeying the flagging instructions as indicated by a driver not stopping or stopping after the location of the flagger/AFAD. A lower intervention rate is desired. An example of a driver trying to bypass the AFAD is shown in Figure 4.1.10.

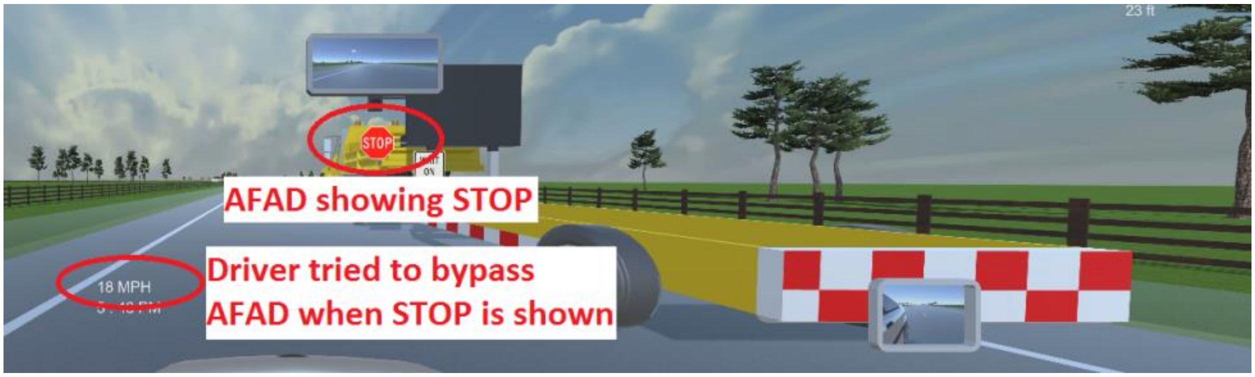

Figure 4.1.10 MOE 4 Example: Intervention Rate

- MOE 5 - First Brake Location (feet) is the location at which the driver first pressed the decelerator pedal in reaction to the flagger/AFAD. This location could indicate where a driver recognized and understood the flagging instruction. MOE 5 is illustrated in the screen output as shown in Figure 4.1.11.

Figure 4.1.11 MOE 5 - First Brake Location (feet)

4.2 Simulator Study Results

The video of each participant trial was recorded and all of the MOEs were extracted from videos and presented. The MOEs were purposely extracted from video instead of an automated data file since visual confirmation is often helpful for identifying data issues. To compare MOEs between the flagger and AFAD alternatives, differences between them were calculated. Statistical analysis was performed to calculate significance, confidence level, and effect size. Confidence level higher than 95 percent was regarded as significant in this study. Effect size was presented as Cohen's d value, and significant difference is defined to be small, medium, and large (Cohen 1977), as effect size < 0.5 is small, effect size between 0.5 and 0.8 was medium, and effect size > 0.8 was large.

To clarify comparisons and provide guidance to decision makers, the results were divided into two parts. The first part is the comparison between human flagger and MoDOT AFAD, with the flagger as the baseline. The second part is the comparison among the three AFAD scenarios, with the MoDOT AFAD as the baseline. The test result in its totality is attached in Appendix D.

4.2.1 Simulator Results: MoDOT AFAD vs. Human Flagger

MOE 1 measured the speed of the vehicle at 250 ft. from the MoDOT AFAD/flagger. As shown in Table 4.2.1, the average speed of vehicles approaching the MoDOT AFAD was 26.3 mph, and the speed of vehicles approaching the human flagger was 34.8 mph. Approach speeds for vehicles that traveled through the MoDOT AFAD were significantly lower than for the human flagger with a confidence level higher than 99.9 percent. Cohen's d indicated that the standardized mean of AFAD speed was 0.66 units of standard deviation lower than the mean for flagger, and this difference was considered a medium effect size. The results show that MoDOT AFAD was more visible and safer than a human flagger.

Table 4.2.1 Approach Speed MoDOT, AFAD vs. Human Flagger

	Approach Speed (mph)
MoDOT AFAD	26.34
Flagger	34.79
Difference	-8.44
Confidence Level	> 99.9%*
Cohen’s d	-0.66 (Medium)

* indicates significance at 99% confidence level

MOE 2 measured the full stop location of vehicles that encountered STOP message/paddle. As shown in Table 4.2.2, the average full stop location of vehicles that encountered AFAD was 97.55 ft. in front of the AFAD, and the average full stop location of vehicles that encountered human flagger was 53.09 ft. in front of the flagger. The full stop location for AFAD was significantly farther away than the flagger with the confidence level being higher than 99.9 percent. Cohen’s d indicated the mean of AFAD full stop location was 1.02 units of standard deviation farther than flagger, which was a large effect size difference. Therefore, MoDOT AFAD improves work zone safety by encouraging drivers to stop farther away.

Table 4.2.2 Full Stop Location, MoDOT AFAD vs. Human Flagger

	Full Stop Location (ft.)
MoDOT AFAD	97.55
Flagger	53.09
Confidence Level	> 99.9%*
Difference	44.46
Cohen's d	1.02 (Large)

* indicates significance at 99% confidence level

MOE 3 measured the reaction time of the driver. It was calculated as the time gap between the first appearance of the SLOW paddle for both flagger and AFAD, and when the vehicle started to move again. As shown in Table 4.2.3, the average reaction time for the AFAD was 1.93 s, and for the flagger was 2.05 s. The difference was not significant. It indicated that drivers reacted similarly when the SLOW indication was presented either by the MoDOT AFAD or the human flagger.

Table 4.2.3 Reaction Time, MoDOT AFAD vs. Human Flagger

	Reaction Time (s)
MoDOT AFAD	1.93
Flagger	2.05
Confidence Level	70.3%
Difference	-0.12
Cohen's d	-0.03

MOE 4 measured the intervention rate, which is an indication of a driver's misunderstanding of the AFAD or flagger. Intervention refers to when STOP is indicated, and the driver bypassed the AFAD or flagger without fully stopping. Among the 64 iterations from 32 participants (each participant went through each scenario twice), no intervention events happened with the MoDOT AFAD, and nine interventions occurred for the human flagger, as shown in Table 4.2.4. The intervention rate indicated that the MoDOT AFAD was more understandable and communicated information to drivers more effectively.

Table 4.2.4 Intervention Rate, MoDOT AFAD vs. Human Flagger

	Intervention Rate
MoDOT AFAD	0.00 (0/64)
Flagger	0.14 (9/64)
Confidence Level	99.8%*
Difference	-0.14
Cohen's d	N.A

* indicates significance at 99% confidence level

MOE 5 measured the first brake location where the driver first hit the brake pedal in reaction to the flagger/AFAD. This measure could indicate where a driver first recognized and understood the flagging instruction. The results in Table 4.2.5 showed that the first brake location for MoDOT AFAD was significantly farther away, and the difference was a medium effect size. This measure indicated that the MoDOT AFAD was more visible than the human flagger, and the MoDOT AFAD clearly conveyed the STOP message to drivers.

Table 4.2.5 First Brake Location, MoDOT AFAD vs. Human Flagger

	First Brake Location (ft.)
MoDOT AFAD	332.19
Flagger	274.02
Confidence Level	99.5%*
Difference	58.17
Cohen's d	0.51 (Medium)

* indicates significance at 99% confidence level

Overall, the comparison between the MoDOT AFAD and human flagger showed that MoDOT AFAD performed significantly better than human flagger with respect to approach speed, full stop distance, intervention rate, and first brake location. The results imply that the MoDOT AFAD may improve work zone safety and can be a valid and effective replacement for the human flagger.

4.2.2 Simulator Results: MoDOT AFAD vs. other AFADs

MOE 1 measured the speed of the vehicle at 250 ft. from AFADs. As shown in Table 4.2.6, the average speeds of vehicles approaching AFADs were similar for all three AFAD configurations, and the differences were not significant.

Table 4.2.6 Approach Speed, MoDOT AFAD vs. other AFADs

	MOE 1 Approach Speed (mph)			
	Mean	Diff	Cohen's d	Confidence Level
MoDOT AFAD	26.34	Baseline		
AFAD with alternative sign	25.98	-0.36	0.03	28.2%
AFAD without CMS	26.87	0.53	0.05	33.7%

MOE 2 measured the full stop location of vehicles from AFADs, as shown in Table 4.2.7. The average full stop distances for the MoDOT AFAD and the AFAD with alternative sign were similar. However, vehicles that encountered the AFAD without CMS stopped 23.35 ft. closer to the AFAD than vehicles that encountered the MoDOT AFAD, which was a medium effect size. This result indicates that the CMS may be needed to better communicate STOP instructions to drivers.

Table 4.2.7 Full Stop Location, MoDOT AFAD vs. other AFADs

	MOE 2 Full Stop Distance (feet)			
	Mean	Diff	Cohen's d	Confidence Level
MoDOT AFAD	97.55	Baseline		
AFAD with alternative sign	90.67	-6.88	-0.14	89.7%
AFAD without CMS	74.20	-23.35	-0.58 (Medium)	> 99.9%*

* indicates significance at 99% confidence level

MOE 3 measured the reaction time of the driver. Drivers reacted to the AFAD with alternative sign and the AFAD without CMS faster than the MoDOT AFAD as shown in Table 4.2.8. The difference between MoDOT AFAD and the AFAD with alternative sign was not significant. However, the reaction time to the AFAD without CMS was significantly shorter than the MoDOT AFAD. This result indicates that the presence of the CMS may have required more processing time for drivers after the SLOW indication was presented.

Table 4.2.8 Reaction Time, MoDOT AFAD vs. other AFADs

	MOE 3 Reaction Time (seconds)			
	Mean	Diff	Cohen's d	Confidence Level
MoDOT AFAD	1.93	Baseline		
AFAD with alternative sign	1.60	-0.32	-0.13	82.8%
AFAD without CMS	1.23	-0.70	-0.42	98.8%**

** indicates significance at 95% confidence level

MOE 4 measured the intervention rate, which is an indication of a driver's understanding of AFADs. Among the 64 iterations from 32 participants (each participant went through each scenario twice), no interventions occurred when drivers encountered the MoDOT AFAD or the AFAD with alternative sign, and three interventions occurred for the AFAD without CMS, as shown in Figure 4.2.9. Differences in intervention rates were not significant among all three AFAD configurations.

Table 4.2.9 Intervention Rate, MoDOT AFAD vs. other AFADs

	MOE 4 Intervention Rate			
	Mean	Diff	Cohen's d	Confidence Level
MoDOT AFAD	0.00	Baseline		
AFAD with alternative sign	0.00	0.00	n/a	n/a
AFAD without CMS	0.05 (3/64)	0.05	n/a	91.7%

MOE 5 measured the first brake location where the driver first applied the brake pedal in reaction to AFADs, which indicates where a driver recognized and understood the flagging instruction. The results in Table 4.2.10 show that the first brake location for all three AFAD configurations were similar and the differences were not significant.

Table 4.2.10 First Brake Location, MoDOT AFAD vs. other AFADs

	MOE 5 First Brake Location (feet)			
	Mean	Diff	Cohen's d	Confidence Level
MoDOT AFAD	332.19	Baseline		
AFAD with alternative sign	334.95	2.77	-0.03	13.9%
AFAD without CMS	320.30	-11.89	-0.11	46.6%

Overall, the comparison of the three AFAD configurations showed that the performance of AFAD with the alternative CMS message was similar to the performance of the MoDOT AFAD, and no significant differences occurred due to the replacement of the "STOP" message with "WAIT ON STOP". The AFAD without CMS resulted in a significant closer full stop distance than the MoDOT AFAD which may indicate that it was less visible and drivers approached closer to see the STOP/SLOW paddle more clearly. In addition, the reaction time for AFAD without CMS was significantly shorter than MoDOT AFAD which may indicate that the CMS required additional processing time for drivers when changing to the SLOW indication. Although the difference in intervention rate was not significant, the AFAD without CMS experienced threeinterventions while the MoDOT AFAD had no interventions. The results indicate that the AFAD without CMS did not communicate information to drivers as effectively as the MoDOT AFAD.

CHAPTER 5: POST-SIMULATOR SURVEY

5.1 Simulator Survey Methodology

A post-experiment survey was administered to obtain stated preferences and qualitative feedback from the simulator study participants. The 15-question survey consisted of four parts. Part 1 asked questions about participants' understanding of the AFAD signage and human flagger gestures. Part 2 asked participants to indicate their preferences and rate the clarity, visibility, safety, and efficiency properties of designs, as well as the necessity of the CMS. Part 3 of the survey asked about the fidelity of the driving simulator while demographic information of the participants was collected in Part 4. A 16-question simulator sickness questionnaire (SSQ) was provided at the end, which is widely used in diagnosing the simulator sickness severity of participants (Kennedy et al. 1993). The complete simulator survey is shown in Appendix E.

During the participant recruitment process, an effort was made to align to the demographic distribution of the field study to the extent possible. However, due to differences in demographics between the locations of the field and simulator studies, the demographics were not fully matched. Balance in the distribution of age and gender also was sought. The total number of participants was 32, and demographic information is shown in Tables 5.1.1 and 5.1.2. Approximately 78 percent of participants were between the ages of 18 and 40, and 62.5 percent of the participants were male. Because the experiment was conducted in an urban area, over 96 percent of participants were from an urban area, and only one participant was a rural resident. Over 90 percent drove passenger cars as their regular vehicle, and less than 10 percent of them drove other vehicles, such as a truck or bus.

Table 5.1.1 Age and Gender Distribution

	Age					Gender	
	18-25	26-40	41-55	56-70	71-95	Male	Female
Count	12	13	4	2	1	20	12
Percentage	37.50%	40.63%	12.50%	6.25%	3.13%	62.50%	37.50%

Table 5.1.2 Residency and Regular Vehicle Type

	Residency		Regular Vehicle Type	
	Urban	Rural	Passenger Car	Other
Count	31	1	29	3
Percentage	96.88%	3.13%	90.63%	9.38%

5.2 Simulator Survey Results

5.2.1 Survey Question Results

Part 1 of the survey asked for participants' understanding of the flagger and three AFAD configurations. From the results of Question 1 to 4 (Table 5.2.1), the human flagger had the best comprehension with a rate of understanding of 94 percent, followed by the AFAD with alternative sign (91 percent). The MoDOT AFAD had an understanding rate of 84 percent, and the AFAD without CMS was understood by 81 percent of participants. Both participants who misunderstood the human flagger regarded it as a regular STOP sign, and all the participants who misunderstood the AFADs thought they were traffic lights.

Table 5.2.1 Drivers' Understanding of AFADs/Flagger

Drivers' Understanding	Sample Size	Answered Correctly	Correct Rate
Flagger	32	30	93.75%
MoDOT AFAD	32	27	84.38%
AFAD with Alternative Sign	32	29	90.63%
AFAD without CMS	32	26	81.25%

Part 2 of the survey asked participants to rank and rate the AFADs and flagger and assess the necessity of the CMS. In Question 5, participants were asked to rank their preference of the four different setups with "1" representing the most preferred, and "4" representing the least preferred. The results from this question are summarized in Table 5.2.2. The MoDOT AFAD had the highest average ranking of 1.53 while the AFAD without CMS had the lowest average ranking of 3.47. These results demonstrate that the MoDOT AFAD was the most preferred setup followed by the AFAD with alternative sign and the human flagger. The AFAD without CMS was the least preferred setup.

Table 5.2.2 Preference Ranking

Preference	Average Score	Ranking
Flagger	3.07	3
MoDOT AFAD	1.53	1
AFAD with Alternative CMS Message	1.90	2
AFAD without CMS	3.47	4

To better understand how participants ranked their preference and see if there were any correlations between the rankings, one way ANOVA tests were conducted. The plots of these results are shown in Figures 5.2.1, 5.2.2, and 5.2.3. The plots show the distribution of scores with a line connecting the mean scores. From Figure 5.2.1, it can be seen that the majority of participants who preferred the MoDOT AFAD the most, preferred the human flagger the least. The preferences for the MoDOT AFAD and the AFAD with alternative sign were similar, and their rankings were close to each other as shown in Figure 5.2.2. The AFAD without CMS was not preferred by participants who were in favor of the MoDOT AFAD, as shown in Figure 5.2.3.

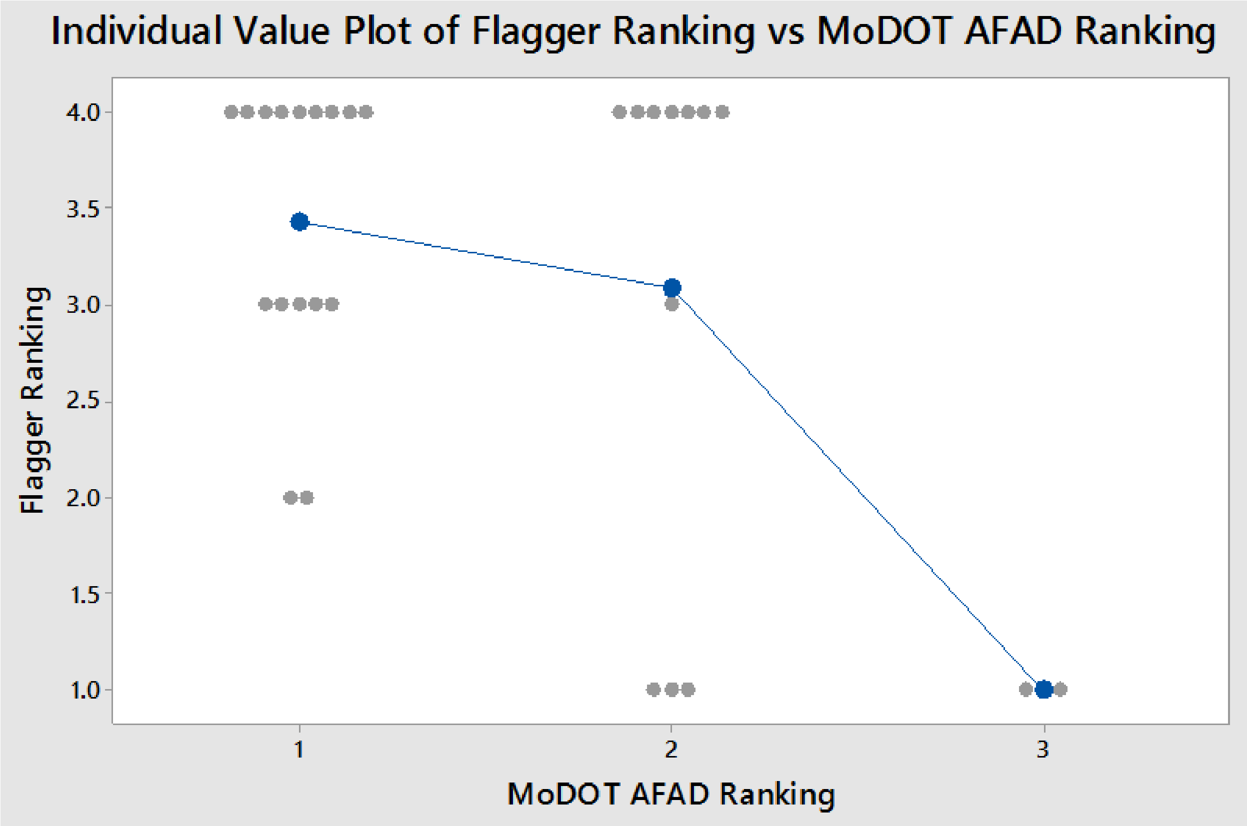

Figure 5.2.1 Ranking: MoDOT AFAD vs. Flagger

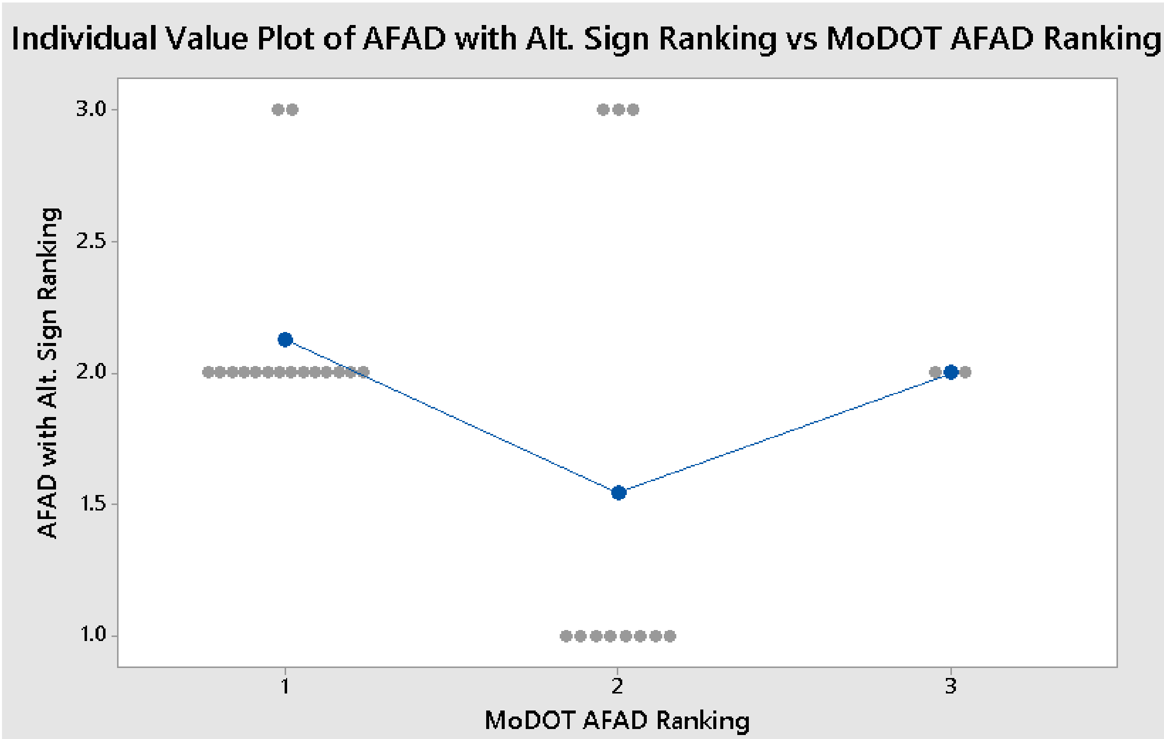

Figure 5.2.2 Ranking: MoDOT AFAD vs. AFAD with Alternative Sign

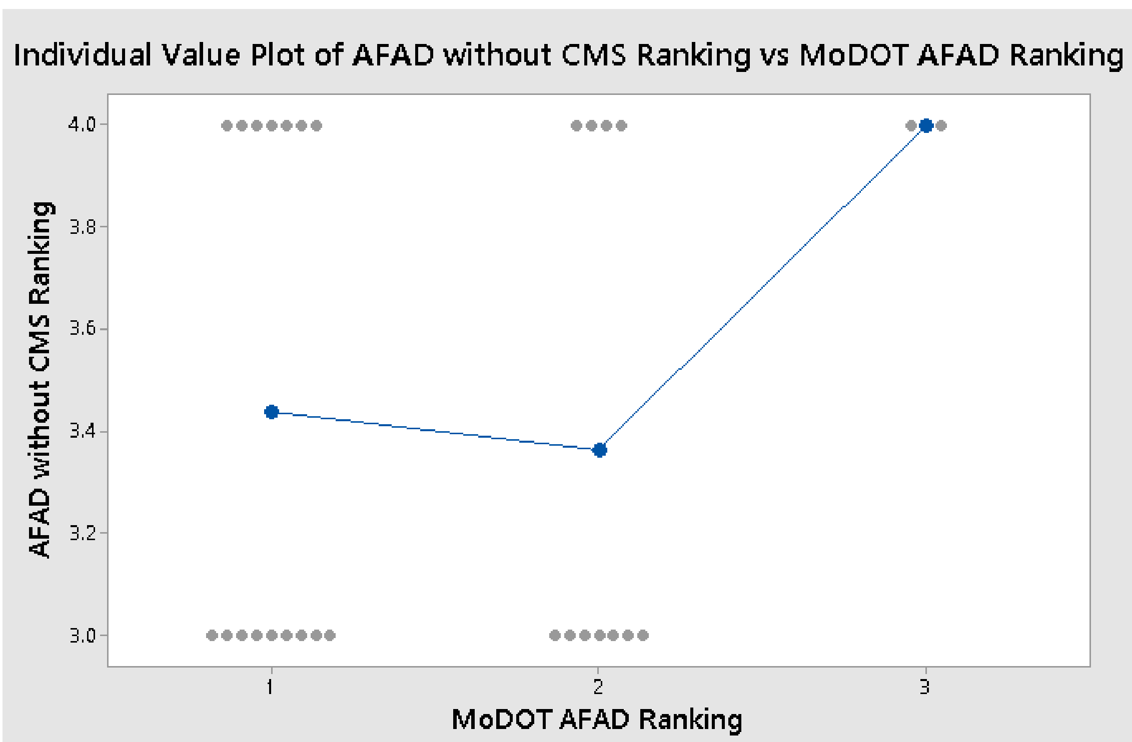

Figure 5.2.3 Ranking: MoDOT AFAD vs. AFAD without CMS

The survey also asked participants to rate different attributes of the human flagger and AFAD configurations in Question 6. These attributes included clarity, visibility, safety, and efficiency. The average score across the four attributes for each setup was consistent, as shown in Table 5.2.3. The MoDOT AFAD scored the highest in all four attributes, and the AFAD with alternative sign scored the second highest in all categories. The AFAD without CMS scored the lowest in clarity but was higher than the human flagger for the other three attributes. The human flagger had the lowest scores in visibility, safety, and efficiency. Since these ratings were subjective discrete ordinal data, a nonparametric Mann-Whitney test was conducted to assess the statistical significance of the ranked data. The Mann-Whitney test is used to assess ordinal data that is not normally distributed by calculating average score differences and determining if difference between the data sets is significant (De Winter and Dodou 2010). The confidence level for the range of differences was set to be 95 percent in this study. The results from this test showed that the AFAD without CMS and the human flagger had significantly lower scores than the MoDOT AFAD for all four attributes, and the AFAD with alternative CMS message scored significantly lower in visibility and safety than the MoDOT AFAD. One way ANOVA results are attached in Appendix F.

Table 5.2.3 Ratings for Clarity, Visibility, Safety, and Efficiency

	Clarity				
	Mean Score	Median	Diff	Diff Range	Confidence Level
MoDOT AFAD	8.94	10	Baseline		
AFAD with Alternative Sign	8.56	9	0	(-1, 0)	79.80%
AFAD without CMS	6.13	6	-3	(-4, -2)	> 99.9%*
Flagger	6.41	6	-2	(-4, 0)	> 99.9%*
	Visibility				
	Mean Score	Median	Diff	Diff Range	Confidence Level
MoDOT AFAD	9.47	10	Baseline		
AFAD with Alternative Sign	8.44	9	-1	(-2, 0)	99.9%*
AFAD without CMS	6.41	6	-3	(-4, -2)	> 99.9%*
Flagger	4.19	4	-5	(-7, -5)	> 99.9%*
	Safety				
	Mean Score	Median	Diff	Diff Range	Confidence Level
MoDOT AFAD	9.19	10	Baseline		
AFAD with Alternative Sign	8.5	8.5	-1	(-1, 0)	98.6%**
AFAD without CMS	6.28	6.5	-3	(-4, -2)	> 99.9%*
Flagger	4.06	4	-5	(-6, -4)	> 99.9%*
	Efficiency				
	Mean Score	Median	Diff	Diff Range	Confidence Level
MoDOT AFAD	8.74	9	Baseline		
AFAD with Alternative Sign	8.48	9	0	(-1, 0)	86.40%
AFAD without CMS	6.58	6	-2	(-3, -1)	> 99.9%*
Flagger	5.29	5	-3	(-5, -2)	> 99.9%*

* indicates significance at 99% confidence level
** indicates significance at 95% confidence level

In response to Question 7 regarding the necessity of the CMS (Table 5.2.4), 78 percent of participants agreed or strongly agreed that the CMS was necessary for the AFAD as shown in Table 5.2.4. Half of the participants strongly agreed that the CMS was necessary while only 10 percent of participants disagreed or strongly disagreed that the CMS was necessary. The results from this question support the use of the CMS in conjunction with the AFAD.

Table 5.2.4 Survey Results for Necessity of CMS

CMS Necessary?	Count	Percentage	
Strongly Agree	16	50.00%	78.13%
Agree	9	28.13%	
Neutral	4	12.50%	12.50%
Disagree	1	3.13%	9.38%
Strongly Disagree	2	6.25%	

Questions 8 and 9 in Part 3 of the survey evaluated the fidelity of the simulator, and the results are shown in Table 5.2.5. Among the participants, 75 percent of them agreed or strongly agreed that they felt like they were driving on a real highway, and 81 percent of them agreed or strongly agreed that they felt like they could drive freely. Approximately 6 percent of participants disagreed or strongly disagreed with the highway fidelity of the simulator, and less than 10 percent of participants disagreed with the feeling of driving freely.

Table 5.2.5 Survey Results for Simulator Fidelity

	Fidelity of Highway			Drive Freely		
	Count	Percentage		Count	Percentage	
Strongly Agree	12	37.50%	75.00%	11	34.38%	81.25%
Agree	12	37.50%		15	46.88%	
Neutral	6	18.75%	18.75%	3	9.38%	9.38%
Disagree	1	3.13%	6.25%	3	9.38%	9.38%
Strongly Disagree	1	3.13%		0	0.00%	

Participants provided written comments on the different designs and the overall simulation experience. Some thought the human flagger was unsafe (five participants) and the flagger was less visible than AFADs (eight participants). Two participants said that they would be more careful when seeing a human flagger, and three thought that it was easy to understand a flagger. Participants commented that MoDOT AFAD was highly visible (six participants), safe (one participant), clear (three participants), and love it (three participants). Although one participant commented that the MoDOT AFAD was easy to understand, two thought that the MoDOT AFAD would be confused with a STOP sign. Some said the AFAD with alternative sign was safe (one participant), and provided clearer instructions (one participant), but the letters on the CMS was too small (four participants). Two participants were confused by it. Seven participants commented that the AFAD without CMS was confusing, of which three thought that the blank

CMS board was more confusing. Three of them thought its visibility was not high enough. Two participants thought the simulator was great.

Other comments and suggestions included:

- Add more road signs before the human flagger.
- Put more flash lights on AFADs to distinguish it from cars.
- AFADs consumed more energy, solar powered may be more efficient.
- The white sign showing "WAIT ON STOP" was hard to read from far distance. It was confusing and should be removed.
- Add night time scenarios for the test.

5.2.2 SSQ Results

The simulator experiment was followed by a 16-question SSQ, asking if participants felt sick during or after the simulator experiment. The results are shown in Table 5.2.6, and the percentages are presented in Appendix G. Most participants felt no or slight discomfort, and only three out of 32 participants had moderate or worst symptoms.

Among the three participants with moderate or severe symptoms, one participant felt moderate general discomfort, dizziness with eyes open, stomach awareness, and severe nausea. The second one felt moderate eye strain, difficulty focusing, and fullness of the head. The last one felt moderate nausea and stomach awareness.

Table 5.2.6 SSQ Results

	General discomfort	Fatigue	Headache	Eye strain
None	25	31	24	23
Slight	6	1	8	8
Moderate	1	0	0	1
Severe	0	0	0	0
	Difficulty focusing	Salivation increasing	Sweating	Nausea
None	27	31	30	26
Slight	4	1	2	4
Moderate	1	0	0	1
Severe	0	0	0	1
	Difficulty concentrating	Fullness of the Head	Blurred vision	Dizziness with eyes open
None	31	27	28	27
Slight	1	3	3	4
Moderate	0	1	0	1
Severe	0	0	0	0
	Dizziness with eye closed	Vertigo	Stomach awareness	Burping
None	30	31	27	30
Slight	2	1	3	2
Moderate	0	0	2	0
Severe	0	0	0	0

CHAPTER 6: CONCLUSIONS

The field test, simulator study, and multiple survey results were consistent in showing that the MoDOT AFAD performed better than human flaggers using multiple MOEs. The results indicated that the AFAD may enhance safety over the human flagger based on a reduced vehicle approach speed, farther full stop location, and lower intervention rate. The public had a favorable impression of the AFAD and generally preferred it over the human flagger. Among all AFADs, the MoDOT AFAD had the most outstanding performance and was preferred the most.

One possible explanation for the results is that the TMA truck and CMS increased the visibility of the AFAD, which helped to reduce approach speeds and increase stopping distances. The combination of the STOP/SLOW paddle with the red/yellow lights (MUTCD option) also helped drivers better understand the device. These results are highly encouraging for any jurisdictions who are interested in pursuing the use of AFADs to improve work zone and worker safety.

These promising results should be interpreted with some issues in mind. Despite the similar trends shown in field and simulator studies, the absolute magnitudes of MOEs differed. This illustrates the fact the simulator studies are better at establishing relative validity than absolute validity (Kaptein et al. 1996). The results were obtained from work zones on a rural highway; results may be different in urban area. The impacts of other factors, like traffic volume, lane closure length, and speed limit, were not examined in this study. All MOEs were obtained from drivers in Missouri, and all AFADs device were new to them. Therefore, the results of AFADs on driver behaviors may vary in a different state, and the novelty effect of AFAD designs should be examined in a study of longer duration.

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APPENDIX A: DATA COLLECTION RESULTS FOR ALL TYPES OF VEHICLES (FIELD STUDY)

A.1 Total Data Statistics (Field Survey)

Table A.1.1 Total Data Statistics, MOE 1 – MOE 4 (Field Study)

MOE 1 – MOE 4		Total							
		AFAD				Flagger			
		Sedan	Pickup	CV	Total	Sedan	Pickup	CV	Total
Speed at 250 ft. (mi/hr)	Sample Size	57	123	13	193	55	91	9	155
	Mean	23.947	23.211	20.231	23.228	28.273	27.198	23.556	27.368
	SD	6.323	5.553	6.260	5.871	6.404	6.684	4.275	6.527
	Max	39	38	32	39	43	58	30	58
	Min	10	10	10	10	11	16	18	11
	T-test					0.000	0.000	0.183	0.000
Full Stop Location (ft.)	Sample Size	52	102	9	163	49	85	7	141
	Mean	58.942	62.059	62.222	61.074	50.735	49.212	47.143	49.638
	SD	35.207	25.817	31.236	29.259	31.944	15.784	20.178	22.752
	Max	170	170	100	170	220	100	65	220
	Min	10	25	0	0	10	25	10	10
	T-test					0.224	0.000	0.287	0.000
Waiting Time (s)	Sample Size	44	83	7	134	38	71	7	116
	Mean	84.584	62.364	111.991	72.253	98.911	111.602	79.629	105.515
	SD	71.607	74.660	184.048	82.565	79.927	96.231	34.484	88.500
	Max	290.791	548.765	518.518	548.765	367.474	464.508	124.515	464.508
	Min	1.418	2.002	2.976	1.418	2.555	4.721	24.950	2.555
	T-test					0.395	0.000	0.656	0.002
Reaction Time (s) (Based on CMS)	Sample Size	43	83	7	133	38	69	6	113
	Mean	4.500	4.398	4.024	4.412	1.492	1.758	2.171	1.690
	SD	3.179	3.477	1.376	3.290	0.955	0.860	1.008	0.908
	Max	17.491	27.161	6.072	27.161	4.332	4.725	3.433	4.725
	Min	1.193	0.804	2.457	0.804	0.204	0.177	0.612	0.177
	T-test					0.000	0.000	0.020	0.000

Table A.1.2 Total Data Statistics, MOE 5 – MOE 7 (Field Study)

MOE 5 – MOE 7		Total							
		AFAD				Flagger			
		Sedan	Pickup	CV	Total	Sedan	Pickup	CV	Total
Intervention	Sample Size	57	123	13	193	55	91	9	155
	Abs Number	1	1	1	3	2	1	0	3
	Mean	0.018	0.008	0.077	0.016	0.036	0.011	0.000	0.019
	T-test					0.542	0.831	0.419	0.787
1st Following Vehicle Speed at 250 ft. (mph)	Sample Size	25	41	5	71	24	52	6	82
	Mean	22.160	20.195	16.600	20.634	22.667	23.308	22.833	23.085
	SD	5.498	5.105	3.130	5.284	5.639	5.319	5.565	5.371
	Max	31	31	20	31	37	33	30	37
	Min	10	10	14	10	13	13	17	13
	T-test					0.752	0.005	0.054	0.005
Queue Length (veh)	Sample Size	57	123	13	193	55	90	9	154
	Mean	1.825	1.610	2.000	1.699	1.927	2.178	2.111	2.084
	SD	1.167	1.185	2.236	1.272	1.245	1.346	0.928	1.288
	Max	6	8	9	9	6	6	3	6
	Min	1	1	1	1	1	1	1	1
	T-test					0.653	0.001	0.890	0.006

A.2 South Bound Data Statistics (Field Study)

Table A.2.1 South Bound Data Statistics, MOE 1 – MOE 4 (Field Study)

MOE 1 – MOE 4		South							
		AFAD				Flagger			
		Sedan	Pickup	CV	Total	Sedan	Pickup	CV	Total
Speed at 250 ft. (mph)	Sample Size	32	57	8	97	30	47	4	81
	Mean	23.094	22.053	21.875	22.381	26.800	25.149	20.500	25.531
	SD	6.130	4.673	6.978	5.355	5.804	7.587	1.732	6.883
	Max	34	35	32	35	38	58	22	58
	Min	10	13	10	10	17	16	18	16
	T-test					0.018	0.012	0.712	0.001
Full Stop Location (ft.)	Sample Size	32	57	7	96	29	46	3	78
	Mean	58.906	64.912	63.571	62.813	49.862	50.609	31.667	49.603
	SD	41.673	30.713	35.674	34.799	23.760	19.797	22.546	21.464
	Max	170	170	100	170	120	100	55	120
	Min	10	25	0	0	10	25	10	10
	T-test					0.309	0.007	0.197	0.004
Waiting Time (s)	Sample Size	25	41	5	71	21	39	3	63
	Mean	68.055	59.420	30.060	60.393	97.956	129.182	93.266	117.063
	SD	50.508	57.821	33.187	54.178	83.763	117.410	31.777	104.825
	Max	184.962	237.783	85.632	237.783	367.474	464.508	124.515	464.508
	Min	4.010	2.879	2.976	2.879	2.555	4.721	60.987	2.555
	T-test					0.143	0.001	0.038	0.000
Reaction Time (s) (Based on CMS)	Sample Size	25	42	5	72	21	39	2	61
	Mean	4.565	3.821	3.902	4.085	1.491	1.566	1.850	1.551
	SD	4.078	2.865	1.596	3.260	0.765	0.582	0.078	0.636
	Max	17.491	14.932	6.072	17.491	4.194	2.987	1.906	4.194
	Min	1.193	0.804	2.457	0.804	0.365	0.177	1.795	0.177
	T-test					0.001	0.000	0.146	0.000

Table A.2.2 South Bound Data Statistics, MOE 5 – MOE 7 (Field Study)

MOE 5 – MOE 7		South							
		AFAD				Flagger			
		Sedan	Pickup	CV	Total	Sedan	Pickup	CV	Total
Intervention	Sample Size	32	57	8	97	30	47	4	81
	Abs Number	0	0	1	0	0	0	0	0
	Mean	0.000	0.000	0.125	0.010	0.000	0.000	0.000	0.000
	T-test					\	\	0.506	0.356
1st Following Vehicle Speed at 250 ft. (mph)	Sample Size	12	17	2	31	14	31	3	48
	Mean	20.833	17.412	20.000	18.903	20.714	22.290	22.333	21.833
	SD	3.538	5.432	0.000	4.812	3.451	5.503	6.807	5.012
	Max	27	25	20	27	28	33	30	33
	Min	15	10	20	10	16	13	17	13
	T-test					0.932	0.005	0.677	0.012
Queue Length (veh)	Sample Size	32	57	8	97	30	47	4	81
	Mean	1.719	1.509	1.250	1.557	1.967	2.319	2.250	2.185
	SD	1.170	0.966	0.707	1.020	1.299	1.337	0.957	1.305
	Max	6	5	3	6	6	6	3	6
	Min	1	1	1	1	1	1	1	1
	T-test					0.432	0.001	0.066	0.000

A.3: North Bound Data Statistics (Field Study)

Table A.3.1 North Bound Data Statistics, MOE 1 – MOE 4

MOE 1 – MOE 4		North							
		AFAD				Flagger			
		Sedan	Pickup	CV	Total	Sedan	Pickup	CV	Total
Speed at 250 ft. (mile/hr)	Sample Size	25	66	5	96	25	44	5	74
	Mean	25.040	24.212	17.600	24.083	30.040	29.386	26.000	29.378
	SD	6.522	6.073	4.278	6.262	6.755	4.736	4.183	5.486
	Max	39	38	23	39	43	38	30	43
	Min	15	10	12	10	11	18	20	11
	T-test					0.011	0.000	0.014	0.000
Full Stop Location (ft.)	Sample Size	20	45	2	67	20	39	4	63
	Mean	59.000	58.444	57.500	58.582	52.000	47.564	58.750	49.683
	SD	22.219	17.478	10.607	18.644	41.751	9.023	7.500	24.427
	Max	120	120	65	120	220	70	65	220
	Min	35	40	50	35	30	25	50	25
	T-test					0.512	0.001	0.872	0.021
Waiting Time (s)	Sample Size	19	42	2	63	17	32	4	53
	Mean	106.334	65.238	316.817	85.619	100.090	90.177	69.401	91.789
	SD	89.269	88.710	285.249	104.724	77.460	56.122	37.144	62.179
	Max	290.791	548.765	518.518	548.765	297.378	229.726	110.055	297.378
	Min	1.418	2.002	115.115	1.418	5.024	5.393	24.950	5.024
	T-test					0.825	0.168	0.122	0.707
Reaction Time (s) (Based on CMS)	Sample Size	18	41	2	61	18	30	4	52
	Mean	4.410	4.990	4.330	4.797	1.493	2.007	2.332	1.854
	SD	1.214	3.958	0.955	3.310	1.154	1.085	1.260	1.133
	Max	7.691	27.161	5.005	27.161	4.332	4.725	3.433	4.725
	Min	2.520	1.718	3.654	1.718	0.204	0.734	0.612	0.204
	T-test					0.000	0.000	0.125	0.000

Table A.3.2 North Bound Data Statistics, MOE 5 – MOE 7 (Field Study)

MOE 5 – MOE 7		North							
		AFAD				Flagger			
		Sedan	Pickup	CV	Total	Sedan	Pickup	CV	Total
Intervention	Sample Size	25	66	5	96	25	44	5	74
	Abs Number	1	1	0	2	2	1	0	3
	Mean	0.040	0.015	0.000	0.021	0.080	0.023	0.000	0.041
	T-test					0.561	0.773	\	0.454
1st Following Vehicle Speed at 250 ft. (mph)	Sample Size	13	24	3	40	10	21	3	34
	Mean	23.385	22.167	14.333	21.975	25.400	24.810	23.333	24.853
	SD	6.752	3.875	0.577	5.299	7.058	4.771	5.508	5.434
	Max	31	31	15	31	37	33	27	37
	Min	10	14	14	10	13	18	17	13
	T-test					0.494	0.047	0.048	0.024
Queue Length (veh)	Sample Size	25	66	5	96	25	43	5	73
	Mean	1.960	1.697	3.200	1.844	1.880	2.023	2.000	1.973
	SD	1.172	1.347	3.347	1.475	1.201	1.354	1.000	1.269
	Max	5	8	9	9	4	5	3	5
	Min	1	1	1	1	1	1	1	1
	T-test					0.813	0.220	0.464	0.551

APPENDIX B: FIELD SURVEY QUESTIONS

Date _______________________

Work Zone Signage Survey

Note: To complete this survey online using a computer or mobile device, please visit https://goo.gl/BM40Ju or scan the QR code below.

Proper communication of work zone information is critical for the safe movement of traffic through work zones. Please provide us with your perspective on the following communication alternatives.

Please refer to the device shown below in Figure 1.

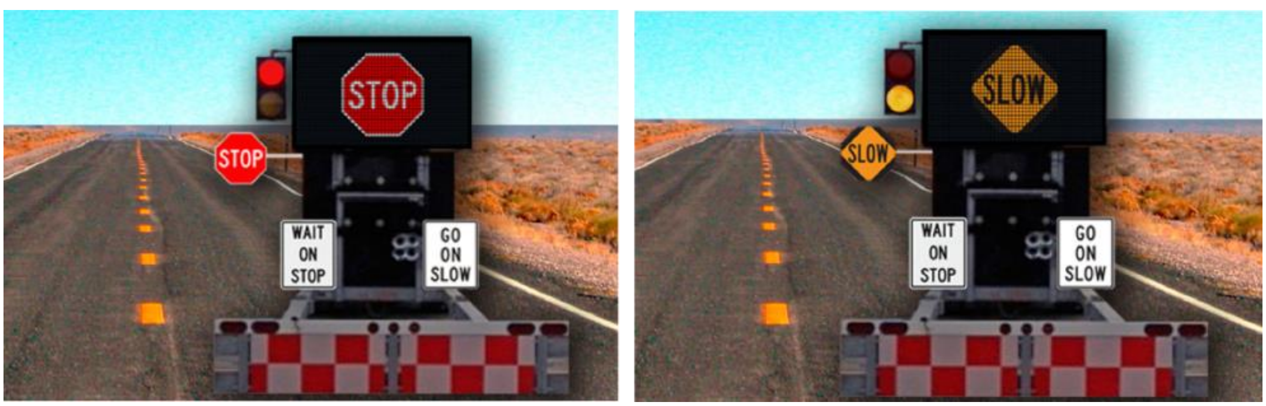


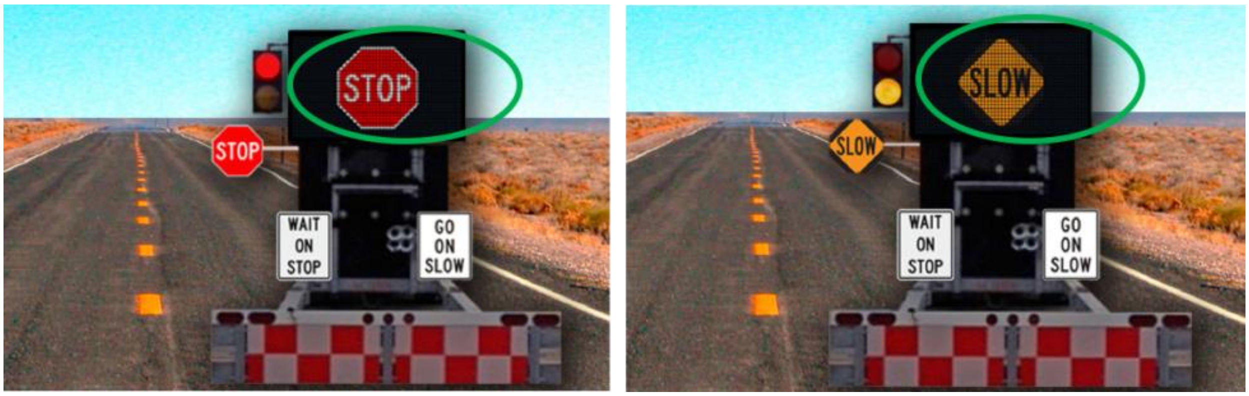
Figure 1

1. **What is the meaning of the device shown in Figure 1?**
   a. Narrow lanes ahead – reduce speed.
   b. Wait if “stop” indicated, proceed if “slow” indicated.
   c. The device makes no sense.

2. **Please rate the effectiveness of the device shown in Figure 1.**
   [ ] Very Effective [ ] Effective [ ] Neutral [ ] Ineffective [ ] Very Ineffective

3. **Please check any reasons for your rating on the device shown in Figure 1.**
   [ ] Clarity [ ] Visibility [ ] Safety [ ] Efficiency

[ ] Other



4. **The message board on the device in Figure 1 (circled in green) was helpful in complementing the instructions provided by the stop/slow paddle.**
   [ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

5. **I have encountered the device shown in Figure 1 before.**
   [ ] Yes [ ] No [ ]

6. **Please enter any additional comments you may have regarding the device shown in Figure 1.**

____
____
____

Figure 2

7. What is the meaning of the signage shown in Figure 2?
   a. Narrow lanes ahead – reduce speed.
   b. Wait if "stop" indicated, proceed if "slow" indicated.
   c. The signage makes no sense.

8. Please rate the effectiveness of the signage shown in Figure 2.
[ ] Very Effective [ ] Effective [ ] Neutral [ ] Ineffective [ ] Very Ineffective

9. Please check any reasons for your rating on the signage shown in Figure 2.
[ ] Clarity [ ] Visibility [ ] Safety [ ] Efficiency
[ ] Other

____
_

10. I have encountered the signage shown in Figure 2 before.
[ ] Yes [ ] No

11. Please enter any additional comments you may have regarding the signage shown in Figure 2.

____
____
____

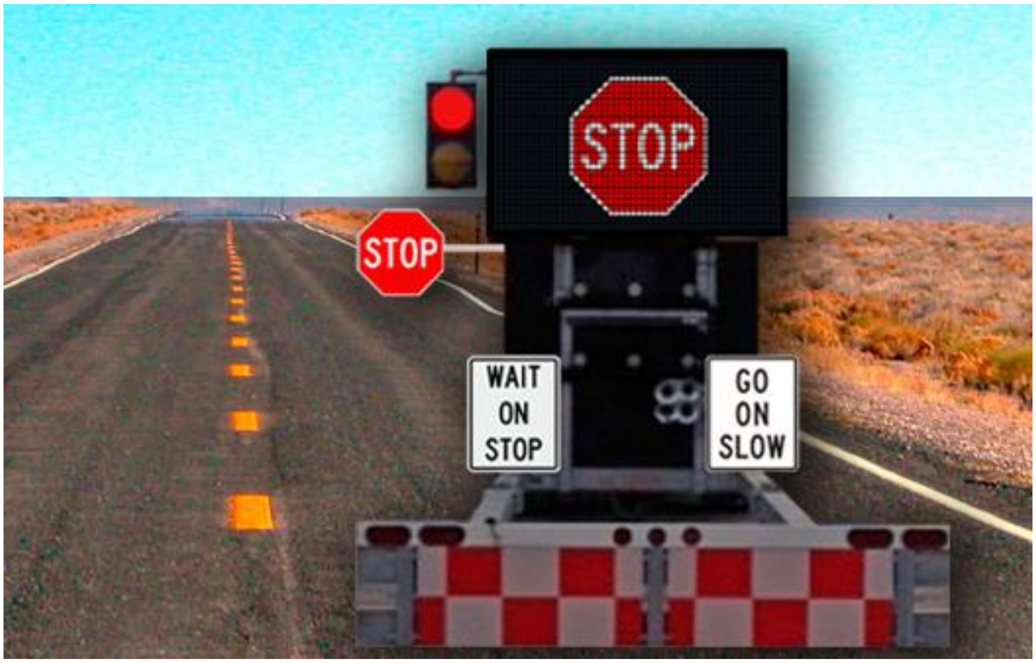


Figure 1

Figure 2

12. Please indicate your preference.

[ ] Figure 1 much more [ ] Figure 1 more [ ] Neutral [ ] Figure 2 more [ ] Figure 2 much more

Please answer the demographic questions below.

13. Age range
[ ] 16-25 [ ] 26-40 [ ] 41-55 [ ] 56-70 [ ] 71-95

14. Gender
[ ] Male [ ] Female

15. My Residency
[ ] Urban [ ] Rural

16. My Regular Vehicle Type
[ ] Passenger Car [ ] Vehicle towing trailer [ ] Delivery/Moving Truck
[ ] Tractor trailer truck [ ] Bus

Please contact Mr. Henry Brown (**brownhen@missouri.edu**) for additional comments, concerns or information on this survey. Thank you for completing this survey! We greatly appreciate your time!

APPENDIX C: FIELD SURVEY RESULTS BY DIFFERENT GROUPS

C.1 Results by Age (Field Survey)

Table C.1.1 Age Range vs. Effectiveness of AFAD (Figure 1 in Field Survey)

Age Ranges	Effectiveness	Count
16-25	Very Effective	1
26-40	Very Effective	3
	Effective	1
41-55	Very Effective	4
	Effective	3
	Neutral	1
56-70	Very Effective	9
	Effective	2
	Ineffective	1
	Very Ineffective	2
71-95	Very Effective	9
	Effective	3
	Very Ineffective	1

Table C.1.2 Age Range vs. Reasons of Rating (Field Survey)

Age Ranges	Factor	Count
16-25	Clarity	1
	Visibility	1
	Safety	1
	Efficiency	1
	Other	0
26-40	Clarity	4
	Visibility	5
	Safety	5
	Efficiency	3
	Other	2
41-55	Clarity	5
	Visibility	7
	Safety	6
	Efficiency	3
	Other	3
56-70	Clarity	12
	Visibility	11
	Safety	10
	Efficiency	7
	Other	0
71-95	Clarity	9
	Visibility	12
	Safety	10
	Efficiency	6
	Other	0

Table C.1.3 Age Range vs. Helpfulness of CMS (Figure 1 in Field Survey)

Age Ranges	Categories	Count
16-25	Strongly Agree	1
26-40	Strongly Agree	3
	Agree	2
41-55	Strongly Agree	5
	Agree	1
	Neutral	1
	Strongly Disagree	1
56-70	Strongly Agree	9
	Agree	3
	Neutral	2
71-95	Strongly Agree	5
	Agree	8

Table C.1.4 Age Range vs. Encountered Signage Before (Field Survey)

Age Ranges	Yes or No	Count
16-25	Yes	1
	No	0
26-40	Yes	4
	No	1
41-55	Yes	4
	No	4
56-70	Yes	4
	No	10
71-95	Yes	6
	No	7

Table C.1.5 Age Range vs. Effectiveness of Flagger (Figure 2 in Field Survey)

Age Ranges	Effectiveness	Count
16-25	Very Effective	1
26-40	Effective	5
41-55	Effective	8
56-70	Very Effective	3
	Effective	9
	Ineffective	1
	Very Ineffective	1
71-95	Very Effective	3
	Effective	9
	Neutral	1

Table C.1.6 Age Range vs. Reasons of Rating (Field Survey)

Age Ranges	Factor	Count
16-25	Clarity	1
	Visibility	1
	Safety	1
	Efficiency	1
	Other	0
26-40	Clarity	2
	Visibility	3
	Safety	2
	Efficiency	2
	Other	0
41-55	Clarity	4
	Visibility	3
	Safety	1
	Efficiency	3
	Other	2
56-70	Clarity	7
	Visibility	6
	Safety	8
	Efficiency	2
	Other	1
71-95	Clarity	9
	Visibility	8
	Safety	10
	Efficiency	6
	Other	1

Table C.1.7 Age Range vs. Preference (Field Survey)

Age Ranges	Preference	Count
16-25	Neutral	1
26-40	AFAD Much More	3
	AFAD More	2
41-55	AFAD Much More	6
	AFAD More	1
	Flagger More	1
56-70	AFAD Much More	8
	AFAD More	2
	Neutral	1
	Flagger More	2
71-95	AFAD Much More	4
	AFAD More	5
	Neutral	2
	Flagger More	2

C.2 Results by Gender (Field Survey)

Table C.2.1 Gender vs. Effectiveness of AFAD

Gender	Effectiveness	Count
Male	Very Effective	16
	Effective	3
	Neutral	1
	Ineffective	1
	Very Ineffective	1
Female	Very Effective	11
	Effective	6
	Ineffective	0
	Very Ineffective	2

Table C.2.2 Gender vs. Reasons of Rating (Field Survey)

Gender	Factor	Count
Male	Clarity	14
	Visibility	19
	Safety	15
	Efficiency	10
	Other	2
Female	Clarity	17
	Visibility	17
	Safety	15
	Efficiency	10
	Other	3

Table C.2.3 Gender vs. Helpfulness of CMS (Field Survey)

Gender	Category	Count
Male	Strongly Agree	12
	Agree	8
	Neutral	1
	Strongly Disagree	1
Female	Strongly Agree	11
	Agree	6
	Neutral	2

Table C.2.4 Gender vs. Encountered Stop Control Before (Field Survey)

Gender	Yes or No	Count
Male	Yes	10
	No	12
Female	Yes	9
	No	10

Table C.2.5 Gender vs. Effectiveness of Flagger (Field Survey)

Gender	Effectiveness	Count
Male	Very effective	4
	Effective	17
	Ineffective	1
Female	Very effective	3
	Effective	14
	Neutral	1
	Very Ineffective	1

Table C.2.6 Gender vs. Reasons of Rating (Field Survey)

Gender	Factor	Count
Male	Clarity	10
	Visibility	12
	Safety	11
	Efficiency	9
	Other	1
Female	Clarity	11
	Visibility	11
	Safety	9
	Efficiency	4
	Other	4

Table C.2.7 Gender vs. Preference (Field Survey)

Gender	Preference	Count
Male	AFAD Much More	12
	AFAD More	4
	Neutral	2
	Flagger More	4
Female	AFAD Much More	9
	AFAD More	6
	Neutral	2
	Flagger More	1

C.3 Survey Results by Residency (Field Survey)

Table C.3.1 Residency vs. Effectiveness of AFAD (Field Survey)

Residency	Effectiveness	Count
Urban	Very Effective	4
	Effective	1
	Very Ineffective	1
Rural	Very Effective	23
	Effective	8
	Neutral	1
	Ineffective	1
	Very Ineffective	2

Table C.3.2 Residency vs. Reasons of Rating (Field Survey)

Residency	Factor	Count
Urban	Clarity	6
	Visibility	4
	Safety	4
	Efficiency	3
	Other	0
Rural	Clarity	25
	Visibility	32
	Safety	26
	Efficiency	17
	Other	5

Table C.3.3 Residency vs. Helpfulness of CMS (Field Survey)

Residency	Categories	Count
Urban	Strongly Agree	3
	Agree	3
Rural	Strongly Agree	20
	Agree	11
	Neutral	3
	Strongly Disagree	1

Table C.3.4 Residency vs. Encountered Stop Control Before (Field Survey)

Residency	Yes or No	Count
Urban	Yes	3
	No	3
Rural	Yes	16
	No	19

Table C.3.5 Residency vs. Effectiveness of Flagger (Field Survey)

Residency	Effectiveness	Count
Urban	Very Effective	2
	Effective	3
	Ineffective	1
Rural	Very Effective	5
	Effective	28
	Neutral	1
	Very Ineffective	1

Table C.3.6 Residency vs. Reasons of Rating (Field Survey)

Age Ranges	Factor	Count
Urban	Clarity	3
	Visibility	6
	Safety	3
	Efficiency	2
	Other	0
Rural	Clarity	18
	Visibility	17
	Safety	17
	Efficiency	11
	Other	5

Table C.3.7 Residency vs. Preference (Field Survey)

Residency	Preference	Count
Urban	AFAD Much More	2
	AFAD More	2
	Neutral	2
Rural	AFAD Much More	19
	AFAD More	8
	Neutral	2
	Flagger More	5

APPENDIX D: SIMULATOR RESULTS

Table D.1.1 Simulator Results

	MOE 1 Approach Speed (mph)							
	Mean	SD	Diff	Cohen's d	Confidence Level	Diff	Cohen's d	Confidence Level
Flagger	34.79	13.83	Baseline			n/a		
MoDOT AFAD	26.34	11.63	-8.44	-0.66	> 99.9%*	Baseline		
AFAD with alternative sign	25.98	10.30	-8.80	-0.72	> 99.9%*	-0.36	0.03	28.2%
AFAD without CMS	26.87	11.07	-7.91	-0.63	> 99.9%*	0.53	0.05	33.7%
	MOE 2 Full Stop Distance (feet)							
	Mean	SD	Diff	Cohen's d	Confidence Level	Diff	Cohen's d	Confidence Level
Flagger	53.09	36.03	Baseline			n/a		
MoDOT AFAD	97.55	49.93	44.46	1.02	> 99.9%*	Baseline		
AFAD with alternative sign	90.67	48.69	37.58	0.88	> 99.9%*	-6.88	-0.14	89.6%
AFAD without CMS	74.20	28.20	21.11	0.65	> 99.9%*	-23.35	-0.58	> 99.9%*
	MOE 3 Reaction Time (seconds)							
	Mean	SD	Diff	Cohen's d	Confidence Level	Diff	Cohen's d	Confidence Level
Flagger	2.05	1.14	Baseline			n/a		
MoDOT AFAD	1.93	1.99	-0.12	-0.03	70.3%	Baseline		
AFAD with alternative sign	1.60	1.86	-0.45	-0.20	94.5%	-0.32	-0.13	82.9%
AFAD without CMS	1.23	1.84	-0.82	-0.56	99.8%*	-0.70	-0.42	98.8%*
	MOE 4 Intervention Rate							
	Mean	SD	Diff	Cohen's d	Confidence Level	Diff	Cohen's d	Confidence Level
Flagger	0.14	0.35	Baseline			n/a		
MoDOT AFAD	0.00	0.00	-0.14	N. A	99.8%*	Baseline		
AFAD with alternative sign	0.00	0.00	-0.14	N. A	99.8%*	0.00	n/a	n/a
AFAD without CMS	0.05	0.21	-0.09	-0.32	94.3%	0.05	n/a	91.7%

* indicates significance at 99% confidence level

	MOE 5 First Brake Location (feet)							
	Mean	SD	Diff	Cohen's d	Confidence Level	Diff	Cohen's d	Confidence Level
Flagger	274.02	120.51	Baseline			n/a		
MoDOT AFAD	332.19	108.55	58.17	0.51	99.5%*	Baseline		
AFAD with alternative sign	334.95	112.08	60.94	0.52	99.5%*	2.77	-0.03	13.9%
AFAD without CMS	320.30	106.09	46.29	0.41	99.5%*	-11.89	-0.11	46.6%

* indicates significance at 99% confidence level

APPENDIX E: SIMULATOR SURVEY QUESTIONS

Date ______________________

AFAD Simulator Survey

Proper communication of work zone information is critical for the safe movement of traffic through work zones.

Please answer the following questions.

Figure 1a

1. **What is the meaning of Figure 1a?**
   a. Wait if STOP sign indicated.
   b. A regular STOP sign, make a full stop and go.
   c. The device makes no sense.

Figure 1b

2. **What is the meaning of Figure 1b?**
   a. Wait if STOP sign indicated.
   b. A regular STOP sign, make a full stop and go.
   c. This is a traffic signal, stop on the red light.
   d. The device makes no sense.

Figure 1c

3. **What is the meaning of Figure 1c?**

    a. Wait if STOP sign indicated.
    b. A regular STOP sign, make a full stop and go.
    c. This is a traffic signal, stop on the red light.
    d. The device makes no sense.

Figure 1d

4. **What is the meaning of Figure 1d?**

    a. Wait if STOP sign indicated.
    b. A regular STOP sign, make a full stop and go.
    c. This is a traffic signal, stop on the red light.
    d. The device makes no sense.

Figure 1a

Figure 1b

Figure 1c

Figure 1d

5. **Please rank your preference from [1] being most preferred to [4] being least preferred.**

[ ] Figure 1a [ ] Figure 1b [ ] Figure 1c [ ] Figure 1d

6. **Please rate all designs from a scale of 1 (lowest) to 10 (highest) with respect to the following attributes:**

	Figure 1a 	**Figure 1b** 	**Figure 1c** 	**Figure 1d** 
Clarity				
Visibility				
Safety				
Efficiency				
Comments				

Figure 2

7. **To what extent do you believe the message board in Figure 2, as circled in green, is necessary?**

[ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

8. **I felt like I was actually there on the highway.**

[ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

9. **I felt like I could drive around freely.**

[ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

10. Did any issues arise during the use of the Automated Flagger Assistance Devices (AFAD) simulator?

[ ] Yes [ ] No

If yes, please explain the issue(s) that you experienced:
____
____
____

Please answer the demographic questions below.

11. Age range

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

12. Gender

[ ] Male [ ] Female

13. My Residency

[ ] Urban [ ] Rural

14. My Regular Vehicle Type

[ ] Passenger Car [ ] Vehicle towing trailer [ ] Delivery/Moving Truck
[ ] Tractor trailer truck [ ] Bus

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

____
____
____

Please contact Mr. Henry Brown (brownhen@missouri.edu) for additional comments, concerns or information on this survey. Thank you for completing this survey! We greatly appreciate your time!

APPENDIX F: ONE WAY ANOVA RESULTS FOR CLARITY, VISIBILITY, SAFETY, AND EFFICIENCY (SIMULATOR SURVEY)

This appendix shows the one way ANOVA test results of clarity, visibility, safety and efficiency rated by simulator participants. MoDOT AFAD was regarded as the base factor, and human flagger, AFAD with alternative sign, and AFAD without CMS were the alternatives. The grey dots plotted in the figures represent the original individual ratings while the blue dots indicate the mean value of the same corresponding factor. For example, for clarity of flagger vs. MoDOT AFAD (Figure F.1.1), Point (10, 1) means a participant rated "10" for MoDOT AFAD clarity, and rate "1" for human flagger clarity. Each point represented one paired score rated by one participant.

F.1 Clarity

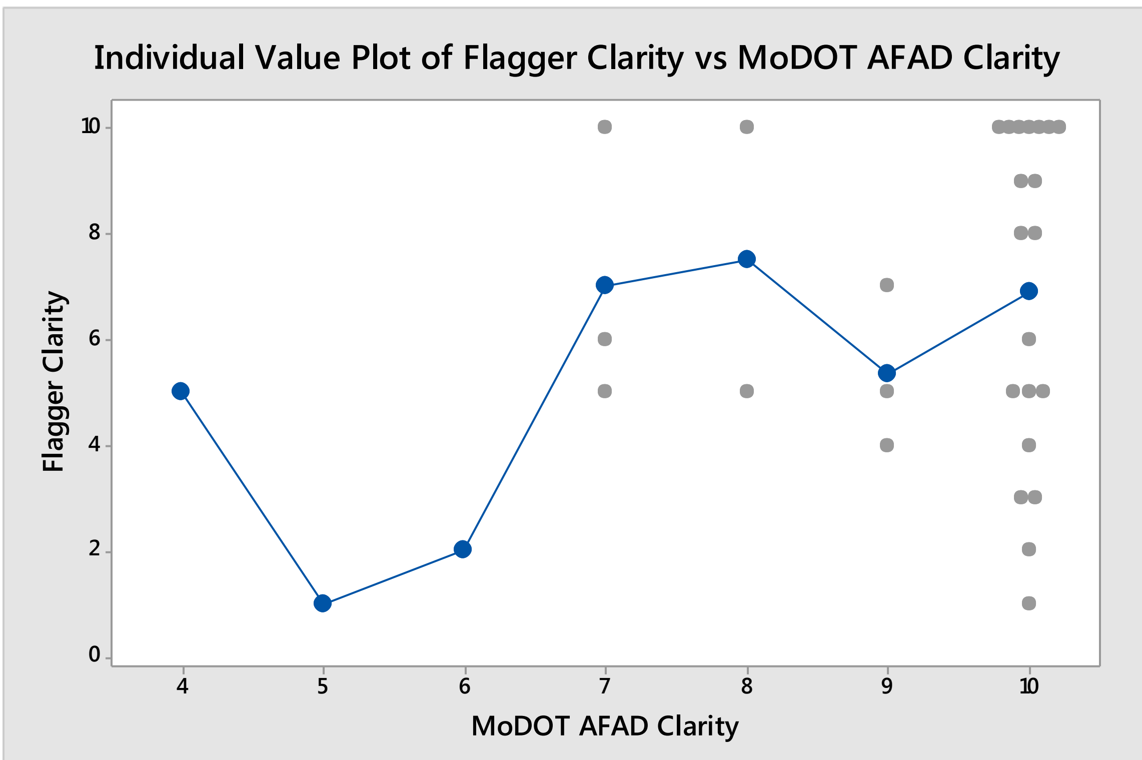


Figure F.1.1 Clarity: Flagger vs. MoDOT AFAD

MoDOT AFAD Clarity	N	Mean	StDev	95% CI
4	1	5.000	*	(-1.095, 11.095)
5	1	1.000	*	(-5.095, 7.095)
6	1	2.000	*	(-4.095, 8.095)
7	4	7.00	2.16	(3.95, 10.05)
8	2	7.50	3.54	(3.19, 11.81)
9	3	5.333	1.528	(1.814, 8.852)
10	20	6.900	3.144	(5.537, 8.263)

Pooled StDev = 2.95950

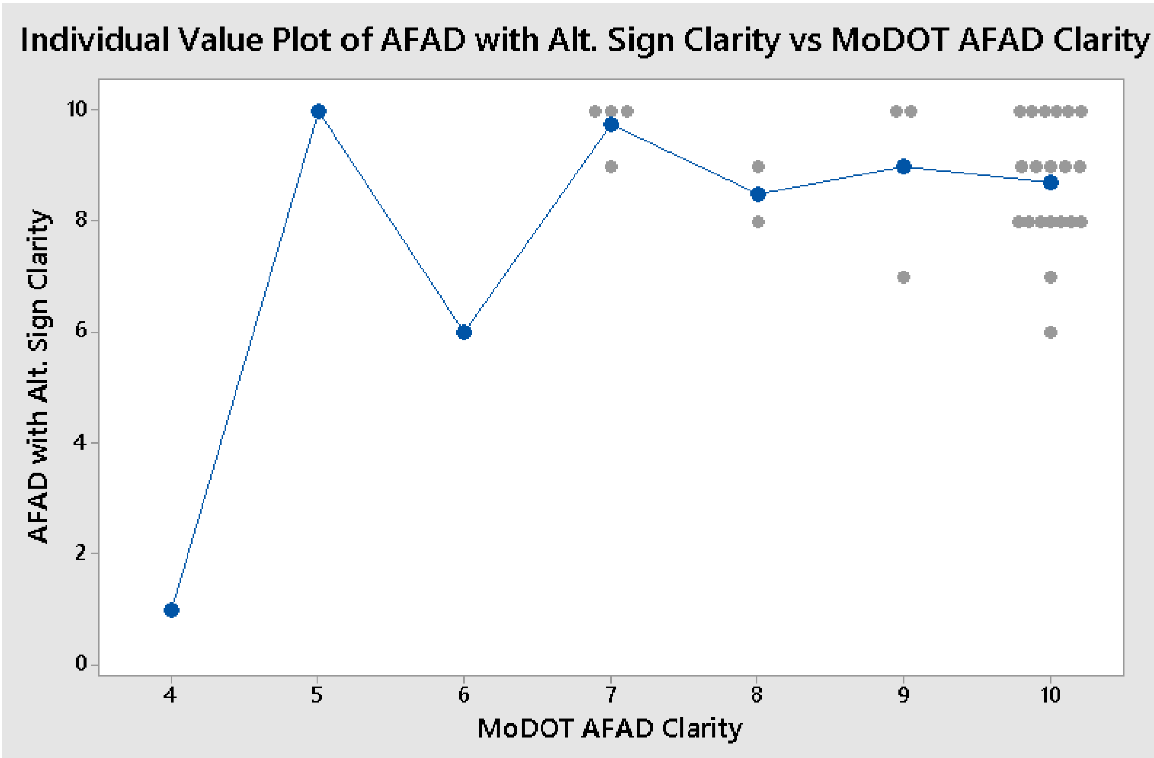


Figure F.1.2 Clarity: AFAD with Alternative Sign vs. MoDOT AFAD

MoDOT AFAD Clarity	N	Mean	StDev	95% CI
4	1	1.000	*	(-1.310, 3.310)
5	1	10.00	*	(7.69, 12.31)
6	1	6.000	*	(3.690, 8.310)
7	4	9.750	0.500	(8.595, 10.905)
8	2	8.500	0.707	(6.867, 10.133)
9	3	9.00	1.73	(7.67, 10.33)
10	20	8.700	1.129	(8.183, 9.217)

Pooled StDev = 1.12161

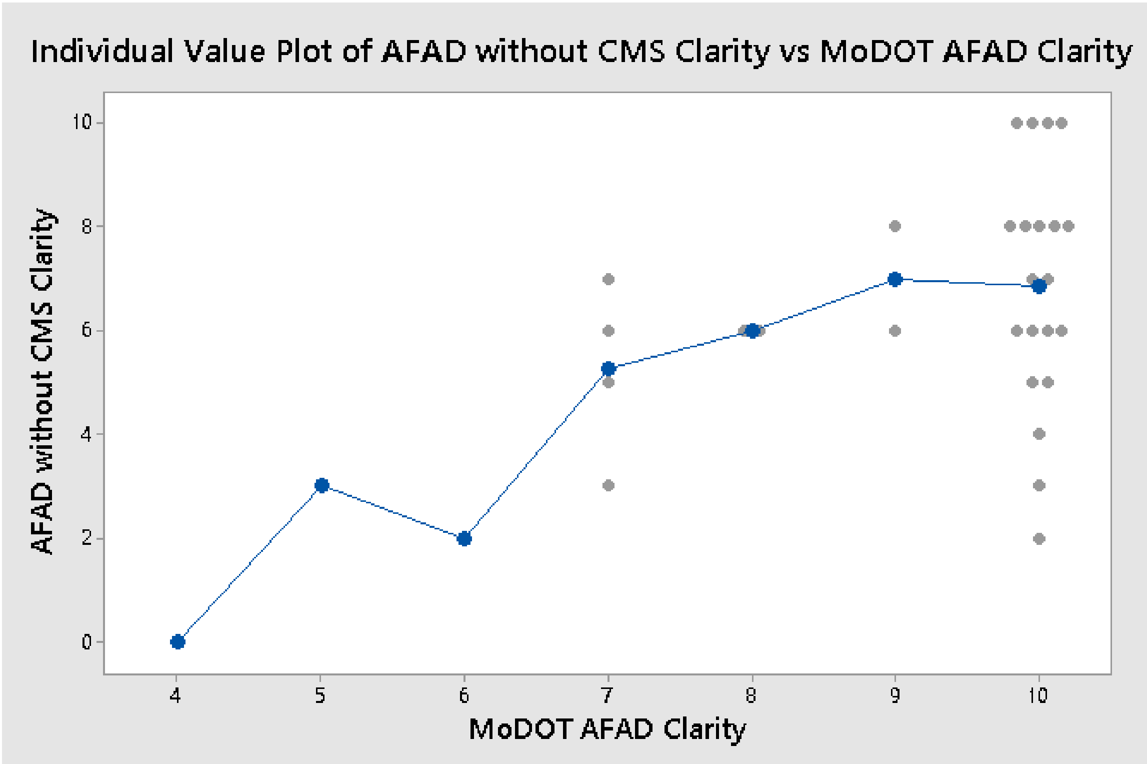


Figure F.1.3 Clarity: AFAD without CMS vs. MoDOT AFAD

MoDOT AFAD Clarity	N	Mean	StDev	95% CI
4	1	0.000000	*	(-4.384448, 4.384448)
5	1	3.000	*	(-1.384, 7.384)
6	1	2.000	*	(-2.384, 6.384)
7	4	5.250	1.708	(3.058, 7.442)
8	2	6.000	0.000	(2.900, 9.100)
9	3	7.000	1.000	(4.469, 9.531)
10	20	6.850	2.323	(5.870, 7.830)

Pooled StDev = 2.12885

F.2 Visibility

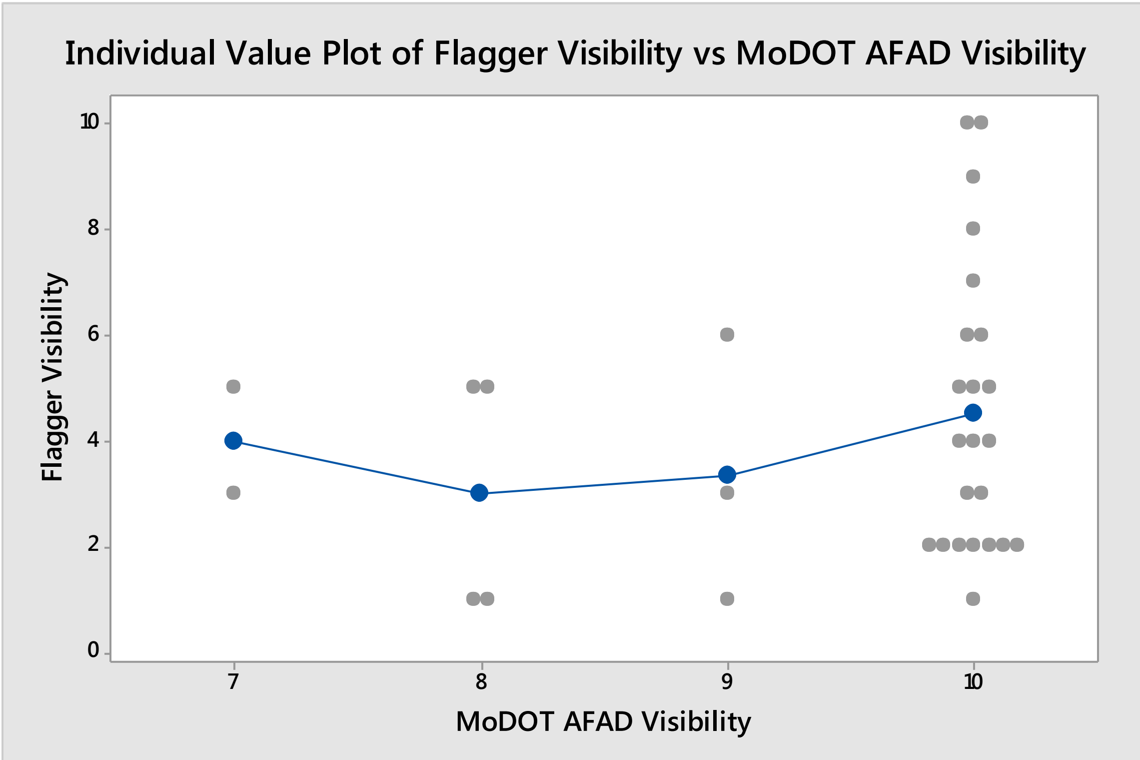


Figure F.2.1 Visibility: Flagger vs. MoDOT AFAD

MoDOT AFAD Visibility	N	Mean	StDev	95% CI
7	2	4.00	1.41	(0.16, 7.84)
8	4	3.00	2.31	(0.29, 5.71)
9	3	3.33	2.52	(0.20, 6.47)
10	23	4.522	2.745	(3.391, 5.653)

Pooled StDev = 2.64849

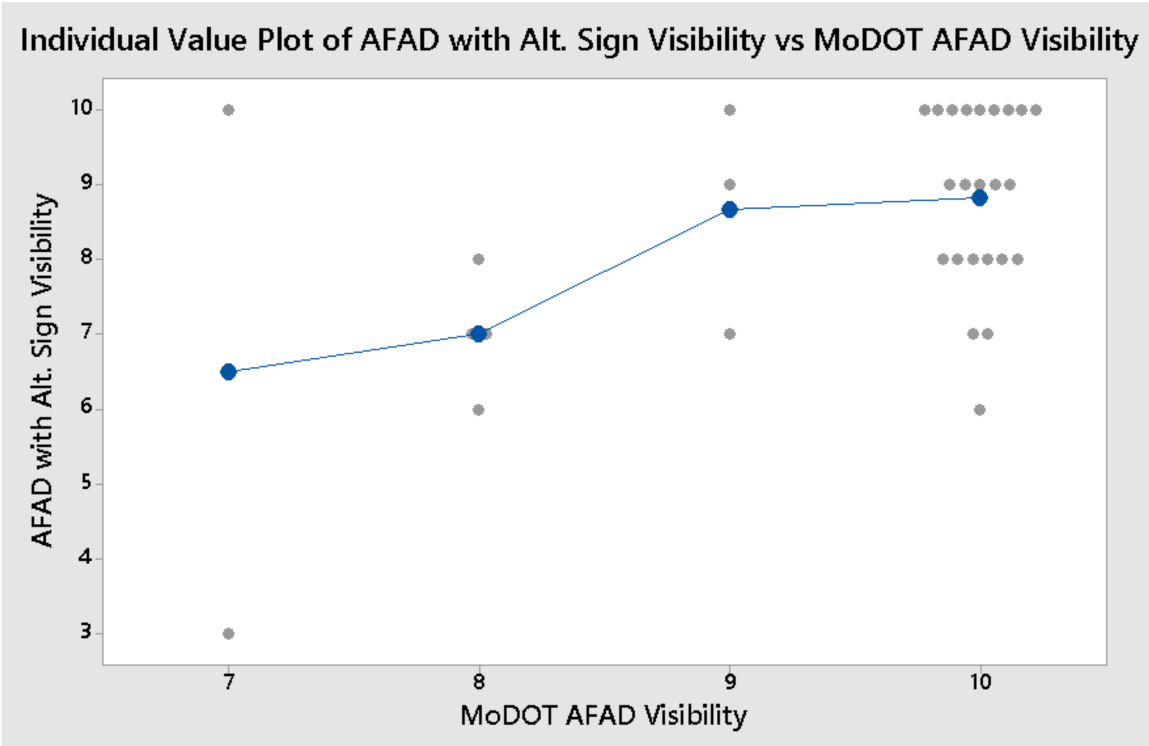


Figure F.2.2 Visibility: AFAD with Alternative Sign vs. MoDOT AFAD

```
MoDOT AFAD
Visibility    N   Mean  StDev       95% CI
7             2   6.50   4.95  ( 4.34,   8.66)
8             4  7.000  0.816  (5.470,   8.530)
9             3  8.667  1.528  (6.900, 10.433)
10           23  8.826  1.193  (8.188,   9.464)

Pooled StDev = 1.49369
```

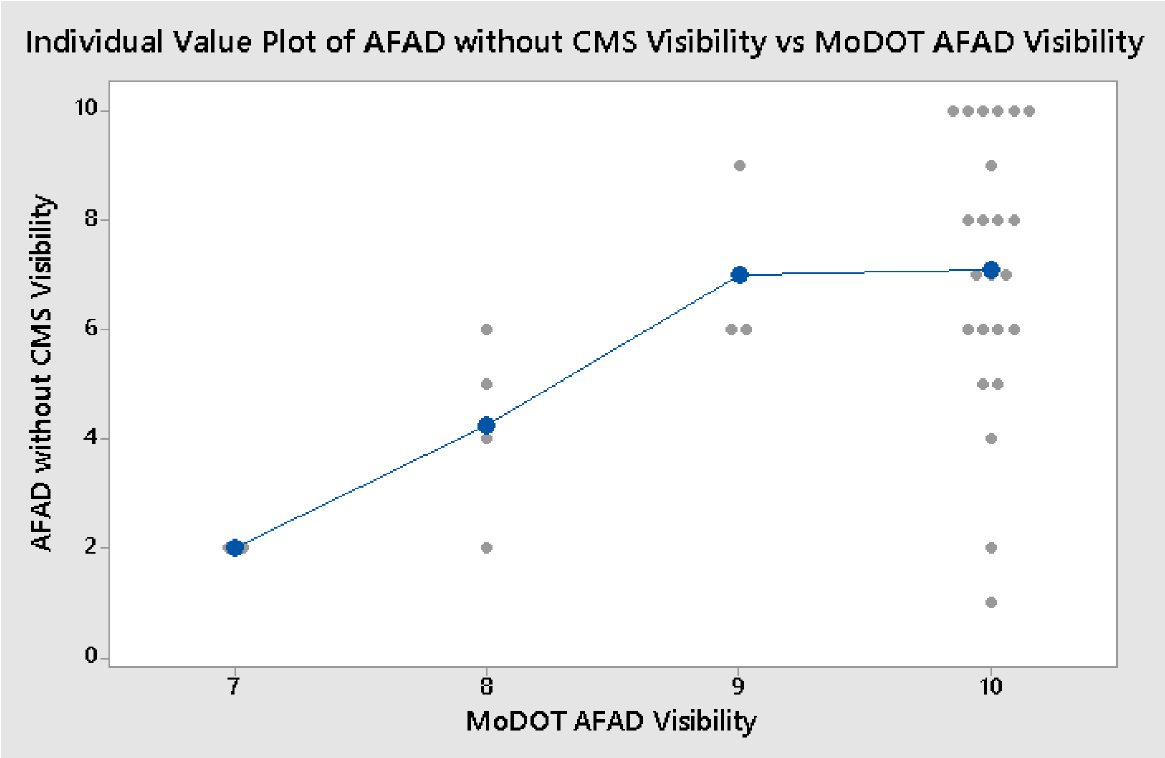


Figure F.2.3 Visibility: AFAD without CMS vs. MoDOT AFAD

MoDOT AFAD Visibility	N	Mean	StDev	95% CI
7	2	2.000	0.000	(-1.447, 5.447)
8	4	4.250	1.708	(1.813, 6.687)
9	3	7.00	1.73	(4.19, 9.81)
10	23	7.087	2.557	(6.070, 8.103)

Pooled StDev = 2.37980

F.3 Safety

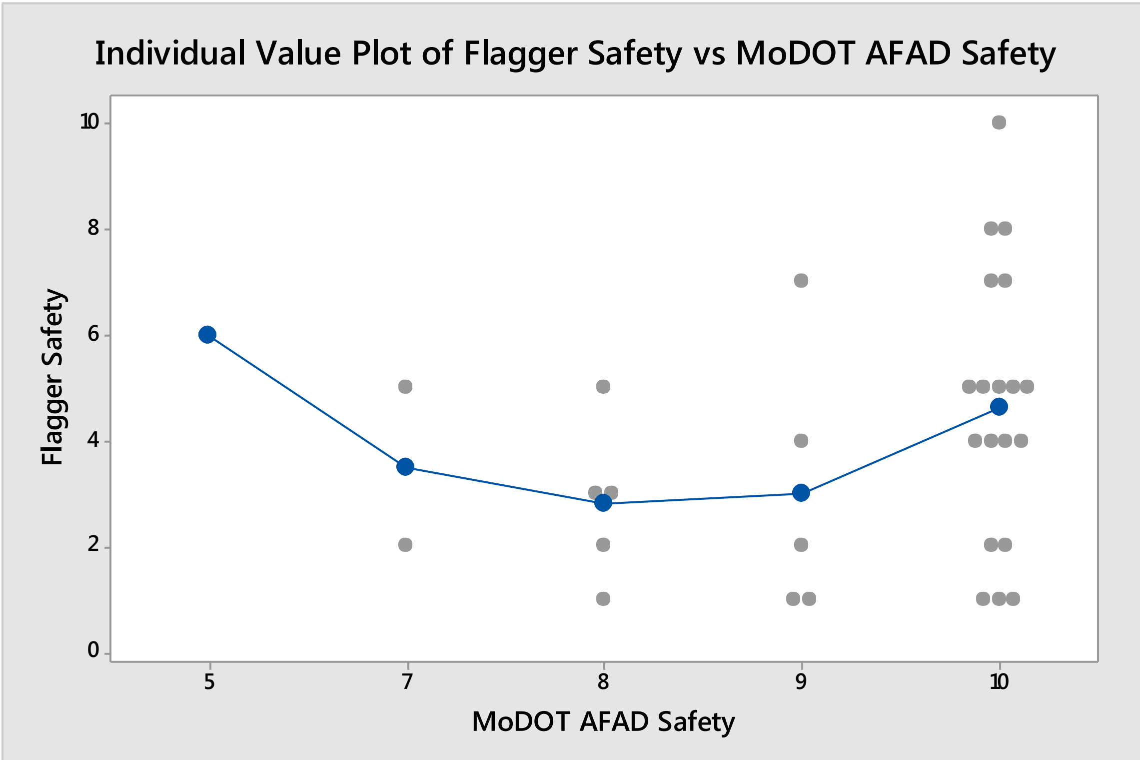


Figure F.3.1 Safety: Flagger vs. MoDOT AFAD

MoDOT AFAD Safety	N	Mean	StDev	95% CI
5	1	6.000	*	(1.041, 10.959)
7	2	3.50	2.12	(-0.01, 7.01)
8	5	2.800	1.483	(0.582, 5.018)
9	5	3.00	2.55	(0.78, 5.22)
10	19	4.632	2.565	(3.494, 5.769)

Pooled StDev = 2.41692

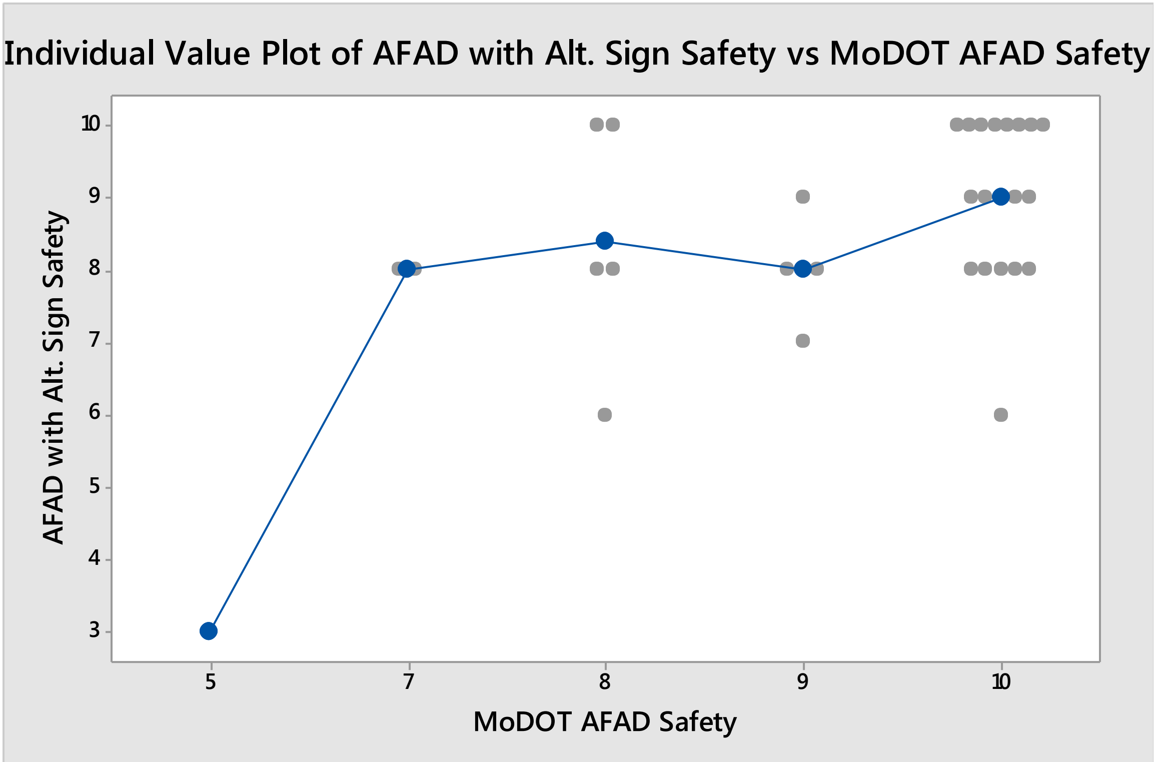


Figure F.3.2 Safety: AFAD with Alternative Sign vs. MoDOT AFAD

MoDOT AFAD Safety	N	Mean	StDev	95% CI
5	1	3.000	*	(0.657, 5.343)
7	2	8.000	0.000	(6.343, 9.657)
8	5	8.400	1.673	(7.352, 9.448)
9	5	8.000	0.707	(6.952, 9.048)
10	19	9.000	1.106	(8.463, 9.537)

Pooled StDev = 1.14180

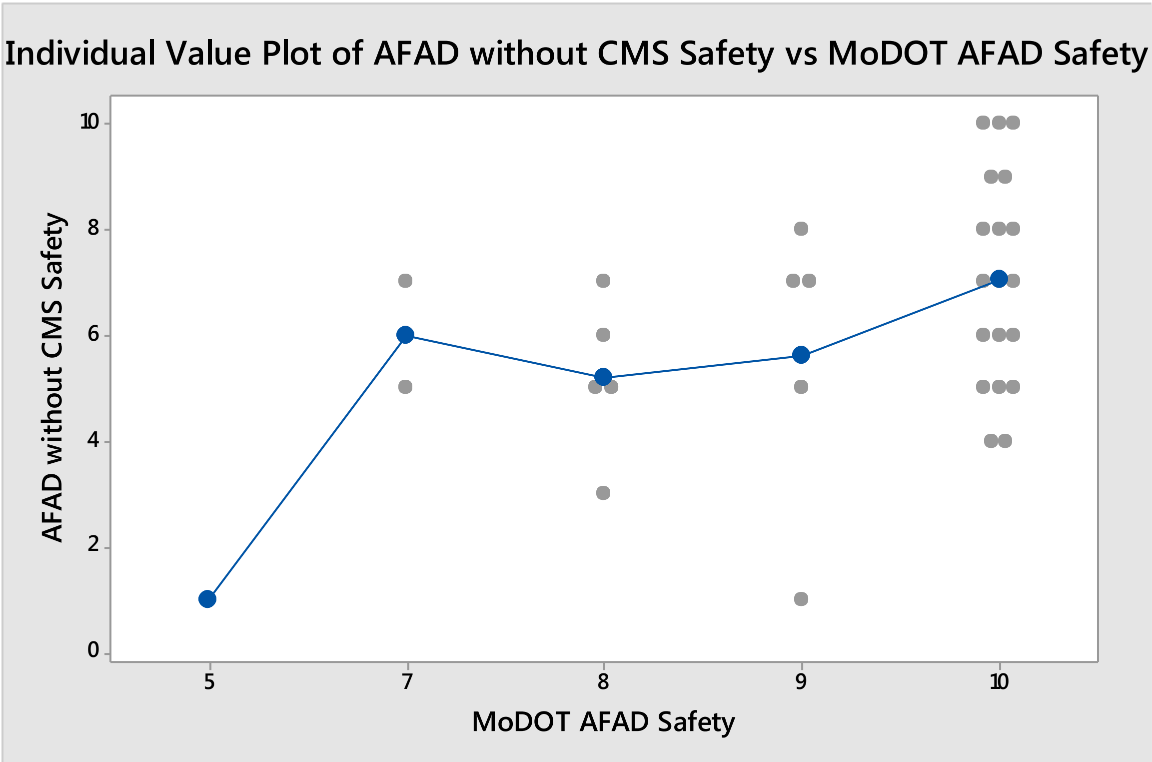


Figure F.3.3 Safety: AFAD without CMS vs. MoDOT AFAD

```
MoDOT
AFAD
Safety     N    Mean  StDev        95% CI
5          1   1.000      *   (-3.197, 5.197)
7          2    6.00   1.41   (  3.03,   8.97)
8          5   5.200  1.483   ( 3.323, 7.077)
9          5    5.60   2.79   (  3.72,   7.48)
10        19   7.053  1.985   ( 6.090, 8.015)

Pooled StDev = 2.04530
```

F.4 Efficiency

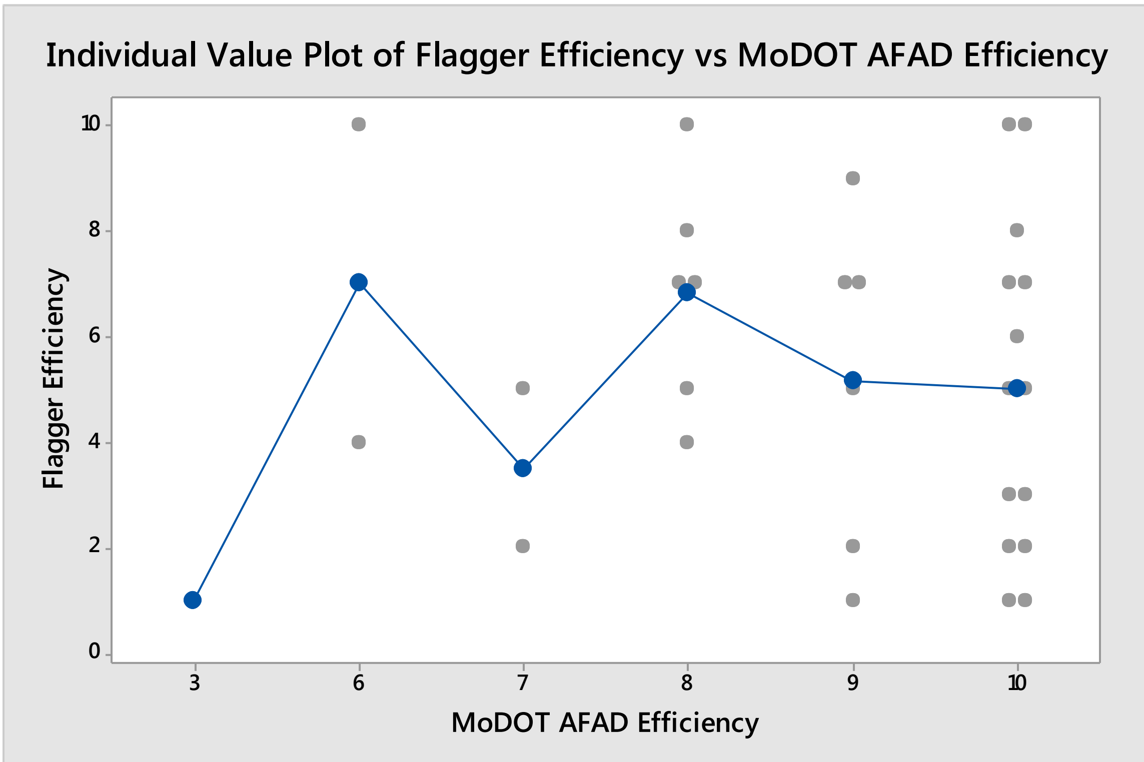


Figure F.4.1 Efficiency: Flagger vs. MoDOT AFAD

MoDOT AFAD Efficiency	N	Mean	StDev	95% CI
3	1	1.000	*	(-5.112, 7.112)
6	2	7.00	4.24	(2.68, 11.32)
7	2	3.50	2.12	(-0.82, 7.82)
8	6	6.833	2.137	(4.338, 9.329)
9	6	5.17	3.13	(2.67, 7.66)
10	14	5.000	3.113	(3.367, 6.633)

Pooled StDev = 2.96760

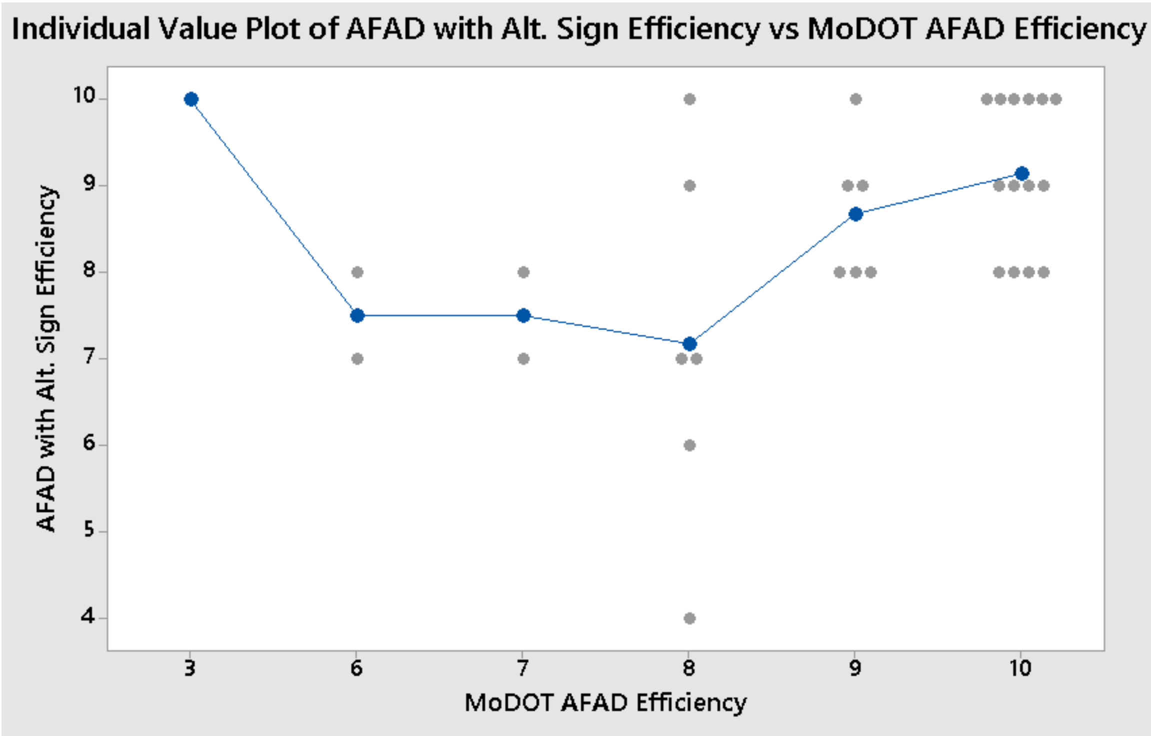


Figure F.4.2 Efficiency: AFAD with Alternative Sign vs. MoDOT AFAD

MoDOT AFAD Efficiency	N	Mean	StDev	95% CI
3	1	10.00	*	(7.50, 12.50)
6	2	7.500	0.707	(5.731, 9.269)
7	2	7.500	0.707	(5.731, 9.269)
8	6	7.167	2.137	(6.145, 8.188)
9	6	8.667	0.816	(7.645, 9.688)
10	14	9.143	0.864	(8.474, 9.811)

Pooled StDev = 1.21459

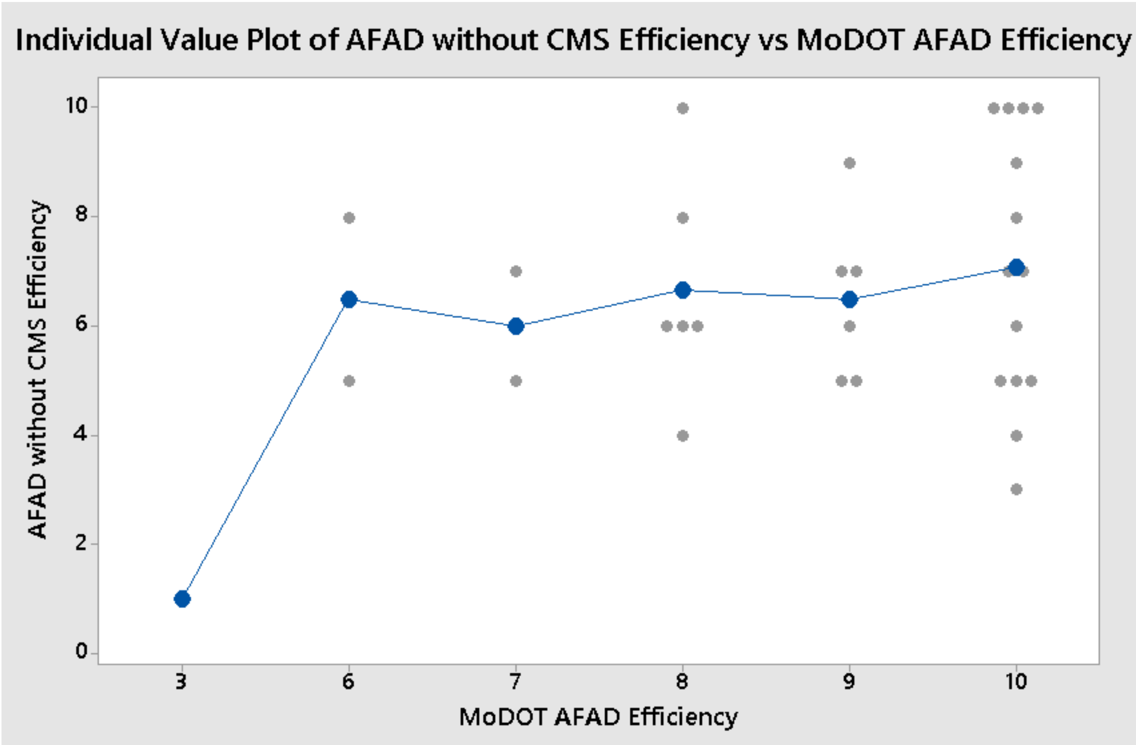


Figure F.4.3 Efficiency: AFAD without CMS vs. MoDOT AFAD

MoDOT AFAD Efficiency	N	Mean	StDev	95% CI
3	1	1.000	*	(-5.112, 7.112)
6	2	7.00	4.24	(2.68, 11.32)
7	2	3.50	2.12	(-0.82, 7.82)
8	6	6.833	2.137	(4.338, 9.329)
9	6	5.17	3.13	(2.67, 7.66)
10	14	5.000	3.113	(3.367, 6.633)

Pooled StDev = 2.96760

APPENDIX G: SSQ RESULTS IN PERCENTAGE

Table G.1.1 SSQ Results

	General discomfort	Fatigue	Headache	Eye strain
None	78.13%	96.88%	75.00%	71.88%
Slight	18.75%	3.13%	25.00%	25.00%
Moderate	3.13%	0.00%	0.00%	3.13%
Severe	0.00%	0.00%	0.00%	0.00%
	Difficulty focusing	Salivation increasing	Sweating	Nausea
None	84.38%	96.88%	93.75%	81.25%
Slight	12.50%	3.13%	6.25%	12.50%
Moderate	3.13%	0.00%	0.00%	3.13%
Severe	0.00%	0.00%	0.00%	3.13%
	Difficulty concentrating	Fullness of the Head	Blurred vision	Dizziness with eyes open
None	96.88%	87.10%	90.32%	84.38%
Slight	3.13%	9.68%	9.68%	12.50%
Moderate	0.00%	3.23%	0.00%	3.13%
Severe	0.00%	0.00%	0.00%	0.00%
	Dizziness with eye closed	Vertigo	Stomach awareness	Burping
None	93.75%	96.88%	84.38%	93.75%
Slight	6.25%	3.13%	9.38%	6.25%
Moderate	0.00%	0.00%	6.25%	0.00%
Severe	0.00%	0.00%	0.00%	0.00%