Evaluation of Green Lights on TMAs

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16. Abstract
The use of green versus traditional amber lights on Truck Mounted Attenuators (TMAs) was investigated to see if their use could help to improve safety in mobile work zones. Four light color configurations were evaluated via a combination of simulator and field study: amber/white, green only, green/white, and green/amber. The TMAs were used as shadow vehicles representing mobile work zones and were equipped with flashing light bars, an arrow board, and a checkerboard sign with steady light bulbs. Driver behavior measures, including first blinker distance and speed, merge distance and speed, work zone and arrow direction recognition distance, and disability glare were captured in simulator tests. Vehicle speeds as they passed TMAs were recorded in both the simulator and field studies. The simulator study results indicated that the amber/white combination had the highest visibility of work zone but created the highest level of concern with disability glare. The green only configuration yielded the least disability glare but also low overall visibility. The study findings implied an inverse relationship between visibility (awareness of work zone) and arrow board recognition (easy on eyes). The green/amber TMA light configuration performed roughly between the two aforementioned configurations and was the configuration preferred by the participants in a post simulator survey. The field study found that the green only TMA slowed drivers down when they passed the mobile work zone, and lower TMA speeds led to lower vehicle speeds. The results did not point in a single direction for both the simulator and field tests, and all four configurations appear to be viable.

17. Key Words
Color; Driver performance; Drivers; Green; Lighting; Truck mounted attenuators; Work zone safety; Work zone traffic control; Mobile work zone; Green lights

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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

Truck-mounted attenuators (TMAs) are designed to improve mobile work zone safety by shadowing the working truck, enhancing visibility of a work zone, and catching drivers' attention early to slow them down when driving through a mobile work zone. Despite the use of the TMAs and other precautions such as shadow vehicles, arrow boards, and signs to warn drivers that they are approaching a mobile work zone, some drivers do not respond to warnings and collide with the TMA. The goal of this research project was to help improve safety in mobile work zones. The objective of this project was to evaluate the effectiveness of green lights on TMAs and determine the best TMA light bar configuration. The scope of the project included two phases: a simulator test with four configurations and a field test with two configurations. The simulator testing phase examined amber/white ("MoDOT typical"), green only ("MoDOT preferred"), green/amber ("MoDOT alternative"), and green/white (Design alternative) configurations. In the field test, only amber/white and green only configurations were evaluated. The simulator testing phase was composed of three elements: the regular simulator scenario followed by a post-simulator survey, a disability glare test utilizing an eye tracker, and a visibility test. Detailed quantitative measures were used for the first time in this study to evaluate green lights on TMAs in the United States.

An example of the TMA configuration is shown in Figure ES.1. The TMA was equipped with a flashing light bar on top of the arrow board and lights on top of the checkerboard to enhance visibility. This project mainly focused on the evaluation of the light colors on the top light bar.

Figure ES.1 Example of green only TMA

In Phase One of the simulator test, four configurations were evaluated for both daytime and nighttime, as shown in Figure ES.2. In this section, first blinker distance and speed, merge distance and speed, and work zone and arrow direction recognition distance were captured for both daytime and nighttime. In addition, the test assessed disability glare which results from high intensity of light, making things around hard to see. Disability glare was measured at nighttime by using a water bottle rolling right next to the rear advanced TMA and an eye tracker. There were 30 participants in the regular simulator trials and the post-simulator survey. Eye tracker data were recorded for 18 of these participants. There were 20 participants for the visibility tests, including some participants from the simulator trials and some newly recruited participants. The age distribution represented drivers from a wide range of ages: 40 percent of the participants in the 18 to 25 age group, 43 percent in the 26 to 40 age group, 13 percent in the 41 to 55 age group, and the remaining 3 percent in the over 56 age group. Approximately 43 percent were females. A brief summary of the simulator results is presented in Table ES.1. Based on the safety measures, "#1" represents the most preferred, and "#4" represents the least preferred.

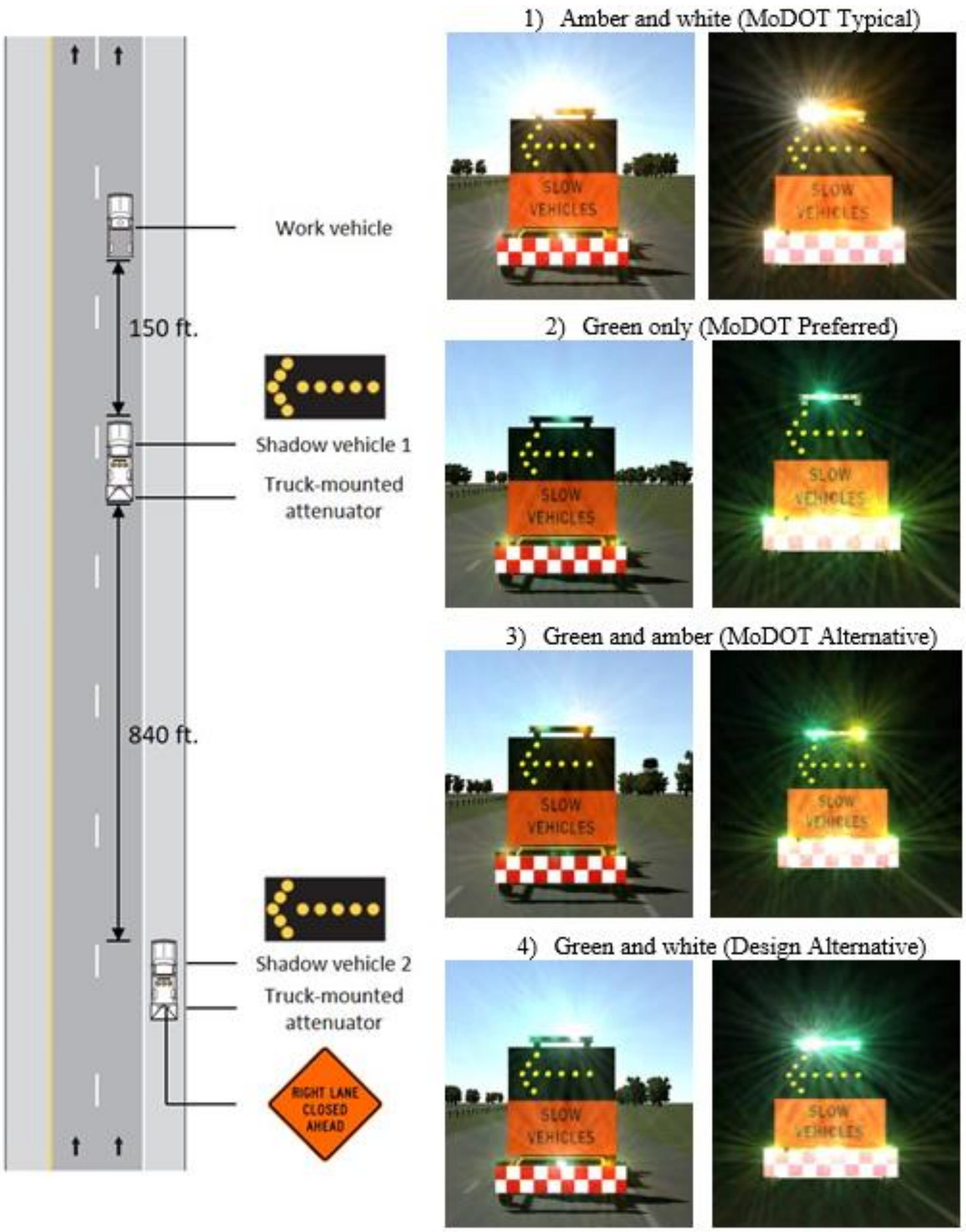


Figure ES.2 TMA configurations in the simulator testing

Table ES.1 Brief summary of simulator results

		First blinker distance	Merge distance	Work zone recognition	Arrow direction recognition	Disability glare
Day	#1	amber/white	amber/white	amber/white	green only	n/a
	#4	green/white	green only	green only	amber/white	
Night	#1	amber/white	amber/white	amber/white	green only	green/white
	#4	green only	green only	green only	green/white	amber/white

The daytime results for the simulator tests are shown in Table ES.2. The results show that drivers reacted to amber/white TMA the quickest, with the farthest first blinker and merge distances and earliest work zone recognition. However, the amber/white configuration resulted in the closest arrow direction recognition distance. The green only TMA had significantly closer first blinker, merge, and work zone recognition distances than the amber/white TMA. But drivers recognized the arrow direction for green only the earliest among the four configurations. These results indicate that the visibility of the work zone and the visibility of arrow direction are counterbalancing, meaning an increase in one decreases the other. The green/amber TMA had the second farthest first blinker and merge distances and second farthest arrow recognition distance, therefore it sits in between the amber/white and green only options. The speeds at first blinker and merging locations for the amber/white TMA were significantly higher than for the other configurations which may be due to the speed measured farther away from the work zone. The vehicle speeds passing TMAs for green only TMA were slightly higher than the other configurations, but the difference was not statistically significant.

Table ES.2 Daytime simulator results

	Mean daytime distances (ft.)			
	First blinker	Merge	Work zone recognition	Arrow direction recognition
Amber/white	1039.1	971.0	1554.2	569.7
Green only	813.8*	649.0*	1166.2*	663.0
Green/amber	973.1	814.5	1292.8	644.6
Green/white	788.4*	750.1*	1382.6	578.6
	Mean daytime speeds (mph)			
	First blinker	**Merge**	**Passing shoulder TMA**	**Passing rear advance TMA**
Amber/white	57.8	57.4	52.3	51.0
Green only	55.7*	53.7*	53.2	52.1
Green/amber	54.8*	53.5*	52.1	50.8
Green/white	54.8*	53.0*	50.5	50.6

Amber/white was baseline, and * indicates statistical significance at 90%.

The nighttime simulator results are shown in Table ES.3. The nighttime results were similar to the daytime results, and the amber/white TMA had the farthest first blinker distance and merge distance and earliest work zone recognition. The green/white TMA had the closest arrow direction recognition distance, followed by the amber/white TMA. Again, the green only TMA had significantly closer first blinker, merge, and work zone recognition distances than the amber/white TMA, and the farthest arrow direction distance. As was also found in the daytime results, the green/amber TMA had the second farthest first blinker and merge distance and the second farthest arrow recognition distance. The speed measurements for nighttime were not significantly different, except for the passing speed for the green/amber shoulder TMA.

Table ES.3 Nighttime simulator results

	Mean nighttime distances (ft.)			
	First blinker	**Merge**	**Work zone recognition**	**Arrow direction recognition**
Amber/white	1577.6	1309.5	1388.7	530.9
Green only	869.1*	706.5*	976.5*	555.1
Green/amber	1483.0	1288.7	1162.5	546.9
Green/white	887.3*	851.9*	1296.0	519.5
	Mean nighttime speeds (mph)			
	First blinker	**Merge**	**Passing shoulder TMA**	**Passing rear advance TMA**
Amber/white	58.3	57.3	51.8	48.6
Green only	57.4	56.0	50.9	49.3
Green/amber	59.5	57.9	48.6*	47.7
Green/white	59.6	58.2	51.1	48.2

Amber/white was baseline, and * indicates statistical significance at 90%.

Disability glare issue was measured by placing a water bottle right next to the rear advance TMA and using an eye tracker to determine if participants recognized the water bottle. In Table ES.4, the disability glare issue results are presented. Most participants recognized the water bottle when encountering green/white TMA, followed by the green only TMA, both around 92%. Therefore, the disability glare was the least for these two configurations. Only 71% of participants recognized the water bottle for the amber/white TMA, indicating that the glare issue may be a concern for this configuration.

Table ES.4 Water bottle recognition

	Water bottle recognition (For nighttime only)		
	Sample size	**Recognized**	**Percentage**
Amber/white	14	10	71.4%
Green only	12	11	91.7%
Green/amber	13	11	84.6%
Green/white	13	12	92.3%

After participants completed the simulator trials, a post-simulator survey was administered to collect their preferences. The post-simulator survey summary is shown in Table ES.5. The results again show that there may be an inverse relationship between visibility/awareness of work zone and arrow board recognition/easy on eyes.

Table ES.5 Summary of post-simulator survey results

<table>
<tr><th colspan="2"></th><th>Ranking</th><th>Visibility of work zone</th><th>Awareness of work zone</th><th>Clear arrow direction</th><th>Easy on eyes</th></tr>
<tr><td rowspan="2">Day</td><td>#1</td><td>green/amber</td><td>amber/white</td><td>amber/white</td><td>green only</td><td>green only</td></tr>
<tr><td>#4</td><td>green only</td><td>green only</td><td>green only</td><td>amber/white, green/white, tied</td><td>amber/white</td></tr>
<tr><td rowspan="2">Night</td><td>#1</td><td>green/amber</td><td>amber/white</td><td>amber/white</td><td>green only</td><td>green only</td></tr>
<tr><td>#4</td><td>amber/white</td><td>green only</td><td>green only</td><td>amber/white</td><td>amber/white</td></tr>
</table>

The post-simulator survey results show that green/amber TMA was the most preferred option, as it was ranked as the number one preference in both daytime and nighttime. As shown in Table ES.6, drivers preferred green/amber the most and green only the least for daytime, and drivers preferred green/amber the most and amber/white the least for nighttime, with 66 percent agreeing that the lights were too bright.

Table ES.6 Preference ranking and light intensity

	Rank		Lights too bright at night?		
	Day	Night	Agree	Neutral	Disagree
Amber/white	2	4	19 (66%)	5 (17%)	5 (17%)
Green only	4	3	5 (17%)	3 (10%)	21 (72%)
Green/amber	1	1	8 (28%)	11 (38%)	10 (34%)
Green/white	3	2	10 (34%)	14 (48%)	5 (17%)

Participants also rated the attributes of visibility of work zone, awareness of work zone, clear recognition of arrow direction, and easiness on the eyes on a scale of 1 to 10. These results are shown in Table ES.7. The amber/white TMA scored the highest in visibility and awareness of work zone but lowest in arrow recognition and ease of eyes. The scores of the green/amber TMA was the second for all four attributes.

Table ES.7 Ratings of features

	Visibility of work zone		Awareness of work zones		Clear recognition of arrow direction		Easiness on eyes	
	Day	Night	Day	Night	Day	Night	Day	Night
Amber/white	8.3	8.7	8.9	9.1	7.1	6.5	5.6	4.8
Green only	7.2	8.1	7.8	8.2	8.0	8.0	8.6	8.1
Green/amber	8.0	8.6	8.5	8.7	8.0	7.6	8.1	7.5
Green/white	7.7	8.0	8.1	8.4	7.1	7.0	6.1	6.2

After the completion of the Phase One simulator study, the Phase Two field study was conducted. Video data were collected for two days in a mobile work zone on US 50 in the Kansas City area. The mobile work zone consisted of a green only rear advance TMA and an amber/white shoulder TMA for the first day and two amber/white TMAs for the second day. A LiDAR detector was mounted to measure vehicle distance from the rear advance TMA. A camera was mounted on the TMA to record traffic behavior and LED readings for post video image processing. A total of 4,966 vehicles were captured in the field data, with 2,589 platoon leaders and 2,756 distances measured by a LiDAR detector. Platoon leaders were especially important because such vehicles reacted only to the mobile work zone and not to other traffic. Vehicle passing speeds were calculated by counting dash lines to measure distance and dividing the distance by the travel time. Rear advance TMA speeds were sampled and calculated using the same method. The results indicate that lower TMA speeds result in lower vehicle passing speeds (Table ES.8). It is reasonable to extrapolate that if the TMA speeds were the same, the green only TMA would result in lower vehicle passing speeds (Table ES.9). Another finding was that vehicle speeds were generally lower during nighttime (Table ES.10).

Table ES.8 Impact of TMA speeds on vehicle passing speeds

Daytime speeds (amber/white)			
TMA speed (mph)		**Vehicle speed (mph)**	
Morning	Afternoon	Morning	Afternoon
20.3	9.8*	64.5	61.9*

Morning result was baseline, and * indicates statistical significance at 90%.

Table ES.9 Field study results: green only vs. amber/white

	TMA speed (mph)		**Vehicle speed (mph)**	
	Green	**amber/white**	**Green**	**amber/white**
Day	19.0*	12.6	62.5	62.6
Night	22.2*	12.6	52.1*	52.9

Amber/white result was baseline, and * indicates statistical significance at 90%.

Table ES.10 Field study results: Day vs. night

	TMA speed (mph)		**Vehicle speed (mph)**	
	Day	**Night**	**Day**	**Night**
Green	19.0	22.2*	62.5	52.1*
amber/white	12.6	12.6*	62.6	52.9*

Daytime result was baseline, and * indicates statistical significance at 90%.

Even though the simulator and field tests were not identical, the tests produced complementary data. The results indicated that tradeoffs between visibility/awareness of the work zone and arrow board recognition/easy on eyes need to be considered. All four configurations appeared to be viable, but none was clearly superior.

Although the results are not pointing to a clear direction, this is the first quantitative study of green lights on TMAs in the United States. Configurations were tested not only in field but also a driving simulator. The use of a simulator allowed for assessment of additional scenarios in a safe, efficient and cost-effective way. The utilization of an eye tracker allowed accurate tracking of the movement of drivers' eyes as they approached the TMA. In the field study, vehicle speeds were measured, providing important information on how drivers reacted to the presence of mobile work zones. An inverse relationship of overall visibility and disability glare was indicated in the study, which is consistent with previous literature, such as a NCHRP study (Gibbons 2008).

There were multiple challenges during the course of this project. During the field data collection for the green light TMA, the shoulder TMA still used the standard amber/white lighting; it is possible that the drivers may have reacted to the shoulder TMA instead of the rear advance TMA. In the field study, the TMA were not always driven at the same speed, thus possibly influencing passing vehicle speeds differently. Ideally, it would have been good to obtain the distance at which vehicles merged from the TMA lane into the passing lane. However, most of the vehicles did not merge near the TMAs, and only 8 out of 4,966 vehicles merged into the passing lane after bypassing the shoulder TMA. Because green lights indicate "go" in traffic signals, drivers may be unclear about its meaning in a freeway setting. The results could potentially be influenced by the novelty effect of green light TMAs. All MOEs were obtained from drivers in Missouri, and green light TMAs were new to them. The novelty effect of green lights could be examined in a study of longer duration.

CHAPTER 1: INTRODUCTION

1.1 TMA Incidents

Mobile work zones for various types of moving operations such as striping, sweeping, and pothole filling are an important component of maintaining highways. The Manual on Uniform Traffic Control Devices (MUTCD) (FHWA 2009) provides guidance for the layout for mobile work zones, using shadow vehicles, arrow boards, and signs to warn drivers that they are approaching a mobile work zone. In addition, a Truck-Mounted Attenuator (TMA) attached to a construction vehicle helps to mitigate the impact of a collision from a highway vehicle that fails to recognize the mobile work zone. Amber/white lights are typically used on the TMA to help draw motorists' attention to the moving work zone. Despite these precautions, some drivers do not respond to warnings and collide with the TMA. Distracted driving may be a contributing factor in these collisions.

Research was conducted by the Virginia Transportation Research Council (VTRC) on TMA crashes in work zones in Virginia (Cottrell Jr 2015). The goals of the VTRC research were to find trends in TMA crashes over a period of three to five years and find out the biggest causes of TMA crashes in work zones. From 2011-2014, the number of TMA crashes had increased in contractor work zones, and the Virginia DOT work zones experienced approximately the same level of TMA crashes per year. The study found that some of the leading contributing factors to TMA crashes in work zones were distracted driving, sight distance issues, and improper placement of the TMA in work zones.

There were 139 TMA crashes reported in Missouri from 2012 to 2017. Thus, there was a TMA hit approximately every 15 days. The major reason for drivers to hit a TMA was distracted driving (44 percent), as shown in Table 1.1.1. Among all TMA crashes, 97 were related to mobile work zones (70 percent), 20 were stationary work zones, and the others unknown. Some TMA operations had a higher risk of crash, such as pothole patching, striping, and sweeping, as shown in Table 1.1.2. This result could be due to higher exposure, or because these specific operations were more risky.

Table 1.1.1 Reasons for TMA crashes in Missouri

	Distracted driving	Late merging	Speeding	Others	Not reported
Count	61	21	7	7	43
Percentage	43.9%	15.1%	5.0%	5.0%	30.9%

Table 1.1.2 Mobile work activity when TMAs were struck in Missouri

Operation	Count	Percentage
Pothole patching	31	22.3%
Striping	20	14.4%
Sweeping	18	12.9%
Maintenance (not specified)	13	9.4%
Bridge	9	6.5%
Mowing	8	5.8%
Cleaning dirt	8	5.8%
Signage	7	5.0%
Spraying weeds	3	2.2%
Rolling	2	1.4%
Other	9	6.5%
Unknown	11	7.9%

The aforementioned data in Tables 1.1.1 and 1.1.2 show that vehicles crashing into a TMA at a mobile work zone is a real concern. By testing different combinations of light colors, the objective of this project was to improve mobile work zone safety and evaluate the performance of green lights on TMAs. This project consisted of two phases: Phase One involved simulator testing, with four different configurations followed by post-simulator surveys; Phase Two involved a field study to compare the performance of green only and amber/white color lights on TMAs.

1.2 Literature review

This review of the existing literature on the use of green lights on construction vehicles includes aspects of light colors, light positions, and other light factors which are described in the following sections. Light color is one important factor in TMA light bar configuration, as the sensitivity of human vision varies across colors. Several research studies on service vehicle warning lights have been conducted. One such study was performed by the American Association of State and Highway Transportation Officials (AASHTO 2009). AASHTO investigated and defined the best practices for selecting warning lights on roadway operations equipment. They considered safety and lighting issues, along with defining lighting selection. The study found that an asynchronous flashing pattern was the most effective. Amber/white colored lights were also proven to be more effective than blue and red lights. There was no observed difference between different types of light sources, such as LED or strobe. The study also recommended that lights be placed with a portion of the vehicle behind them. Finally, lights with a higher effective intensity obtained better drivers' attention. However, safety and time of day should also be considered. The glare of high-intensity lights may affect driver vision. This effect can be mitigated by adjusting the level of lighting and by establishing a difference between daytime and nighttime lighting configurations.

A National Cooperative Highway Research Program (NCHRP) study was conducted to evaluate the effectiveness of warning lights on roadway maintenance vehicles and their impacts on motorist awareness (Gibbons 2008). Photometric characterization, static screening, and performance experiments were used in order to review current practices and further investigate different warning light systems. The study determined that drivers noticed flashing lights more quickly than steady lights. Furthermore, flashing lights with an asynchronous pattern were proven to be more effective than flashing lights with a synchronous pattern. An asynchronous flashing pattern using amber and white lights was found to be the most effective, as it was better recognized by drivers than red and blue ones. In addition to color, the type of light made an impact on obtaining the attention of the driver. The study found that, for halogen and strobe lights, increasing the intensity helped drivers on the road to recognize them much more readily. In addition, lane change distances for LED warning lights were much farther than lane change distances for warning beacons mounted high or low on highway maintenance vehicles. The report recommended that the warning light system should also have a higher effective intensity in the daytime, compared to nighttime, and the light should be laid out on a controlled background. It was additionally determined that lights with a higher effective intensity are necessary in adverse weather conditions but result in increased glare. Overall, lighting characteristics and layout along with environmental conditions are all factors to consider while designing a lighting system. Furthermore, it is important to evaluate the measurement techniques used for lighting systems and to standardize them across different manufacturers. This report pointed out that during daytime, green light had the shortest detection time, but it did not perform well with respect to disability glare and discomfort glare. The balance between conspicuity and distraction of warning beacons needed to be maintained, as well as the balance between high effective light intensity and disability glare issues. The report recommended placing light bars at a higher position to reduce the glare issue, and recommended the amber/white combination for maintenance vehicles to avoid confusion.

Internationally, a research study was performed in the United Kingdom regarding warning beacons (Cook et al. 2000). Researchers investigated the conspicuity of warning beacons with lights consisting of different flash types, flash rates, and flash intensities. Through laboratory and field trials, the study found that strobe lights yielded a greater sense of urgency for drivers. Also, flash rates of 4 Hz were found to be ideal in getting driver’s attention. Finally, high flash intensities were determined to minimize detection time of the warning beacon.

1.3 DOT practices

The Texas Department of Transportation (TxDOT) (Ullman and Lewis 1998) performed research evaluating the vehicle fleet warning lights in order to determine if using different colored warning lights on fleet vehicles, other than the standard flashing yellow lights, provided greater safety in highway work zones. This study found out that 12 states used colors other than yellow-only on some equipment. The combinations of colored lights tested were yellow/blue and yellow/blue/red. The results showed that drivers perceived flashing yellow lights to convey a less hazardous situation, which may not be the correct hazardous level, compared with flashing yellow/blue or yellow/blue/red combinations.

The Kentucky Transportation Center (KTC) surveyed state DOTs on warning light color options for work vehicles and their effectiveness (Howell et al. 2015) and received 16 responses. The survey indicated that four states used blue lights on their maintenance vehicles and five different states used red lights on their work vehicles. The study reviewed warning light practices at other state DOTs nationwide as well as other relevant factors, such as light source, light color, and layout of lights. This review served to gather information on the current state of affairs on work vehicle warning lights and allow for Kentucky Transportation Cabinet (KYTC) to improve their work vehicle lighting systems. All state DOTs surveyed had policies and regulations covering their work vehicle lighting programs. They all reported using amber colored lights and LED lights on their work vehicles. Other commonly used light colors were white, and red and blue for emergency vehicles. The DOTs also reported using different lighting intensities at day and night, along with varying light colors by highway vehicle type. A strong preference for roof-top mounted lighting was also indicated. The summary of light usage for selected states is shown in Table 1.3.1. This research found that most of the agencies that participated in the survey strongly preferred putting warning lights on top of the roof of highway maintenance vehicles. The study also found that when drivers encountered red and blue warning lights on highway work vehicles, they linked the red and blue lights with other emergency vehicles. The KYTC plans to use this knowledge to place appropriate lighting on their emergency and public safety vehicles. KYTC attempted to use amber and green combination, however they were not available from manufacturers.

Table 1.3.1 Color usage on emergency and warning vehicles by state

State	Maintenance	Emergency vehicles	Note
Alaska	amber, blue	n/a	use different colors for maintenance vs. emergency
Illinois	n/a	amber	prevent glare
Indiana	amber	n/a	tested range of weather and lighting conditions
Iowa	amber	n/a	can use white, blue, red to complement amber
Maine	amber	n/a	amber for maintenance
Massachusetts	amber, white	red	use different colors for maintenance vs. emergency
Michigan	amber	n/a	amber for maintenance
Minnesota	amber, blue	n/a	to promote safety
Missouri	amber, white	red, blue	use different colors for maintenance vs. emergency
New Hampshire	amber	n/a	amber for maintenance
Ohio	green, white, amber	n/a	to improve truck visibility
Oklahoma	amber, blue, red, white	n/a	4 colors used for maintenance
South Dakota	amber	n/a	amber for maintenance
Texas	Amber/yellow	red	use different colors for maintenance vs. emergency
Washington	amber, red	blue	use different colors for maintenance vs. emergency

There are existing laws in place in each state that restrict the color and type of light that can be used on emergency, road maintenance, and other vehicles. In general, red and blue warning lights are always allowed for emergency vehicles, and a limited number of red/blue lights can sometimes be used for other service vehicles like highway maintenance vehicles or snow trucks. All states allow amber colored lights on maintenance vehicles.

The Ohio Department of Transportation (ODOT) is the first state to implement green lights on work vehicles. The ODOT use of green lights is limited by statute to snow removal trucks (ODOT 2013), as shown in Figure 1.3.1. The color combination that the ODOT implemented was amber, green, and white. Under the configuration, three ambers are always lit and alternate with three whites or three greens. In a phone interview with the researchers, ODOT personnel indicated that this configuration was determined partly through a survey of trucks set up with different colors at the state fair. ODOT found that a high flash rate was necessary to prevent colors from blending together and sickness from looking at the lights. The deployment found green lights to be more effective in catching the driver’s attention. ODOT predicted that the green lights would help make roads safer because drivers would be able to easily spot work vehicles in snowy weather. ODOT is still in the processing of evaluating the safety impacts of using the green lights but believes that they help to reduce crashes.

Figure 1.3.1 ODOT green light snow-removal truck (ODOT 2013)

Personnel from the Michigan Department of Transportation (MDOT) indicated in a phone interview with the researchers that MDOT is in the process of implementing amber and green lights on its snow removal vehicles. Details regarding the light configuration are still being finalized. It is expected that this implementation will be completed in fall 2018. The Michigan statute passed allows for MDOT to use green lights on both winter maintenance vehicles and regular maintenance vehicles, but MDOT is currently limiting its use to snow removal vehicles.

CHAPTER 2: SIMULATOR TESTS

2.1 Introduction of ZouSim driving simulator

Phase One of the project consisted of the simulator study. The University of Missouri's driving simulator, ZouSim, was used to examine four different TMA lighting configurations in a cost-effective way. The simulator provided safe experiment conditions for the testing of alternatives in a highly controlled environment that limited extraneous causal factors.

ZouSim is built around the half-cab of a sedan with medium-fidelity. ZouSim has a wide range of graphical display capabilities, including virtual reality, augmented reality, and stereoscopic 3D. In this experiment, the triple 120-inch screen was chosen as the most appropriate display for the TMA 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 2.1.1 shows the ZouSim setup for the green light experiment. The primary virtual camera was the forward windshield and side windows views. 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.

(a) **(b)**

Figure 2.1.1 TMA experiment using ZouSim (a) Daytime example: green only TMA (b) Nighttime example: green/amber TMA

2.2 Simulator Setup

The study simulated work zones on a divided, four-lane freeway in Missouri with a speed limit of 60 mph. The entire highway segment was designed without vertical or horizontal curves, in order to eliminate the influence of terrain. The pavement was created based on 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 layout is shown in Figure 2.2.1. In the right lane closed work zone, all work zone vehicles were moving at 10 mph. The work zone configuration followed the requirements of MoDOT Engineering Policy Guide (MoDOT 2018).

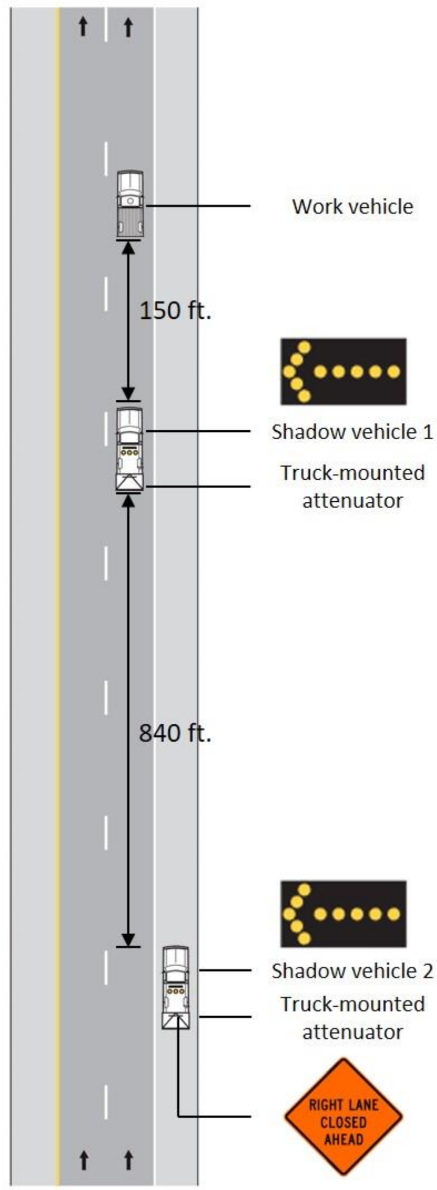


Figure 2.2.1 Mobile work zone layout in simulator tests

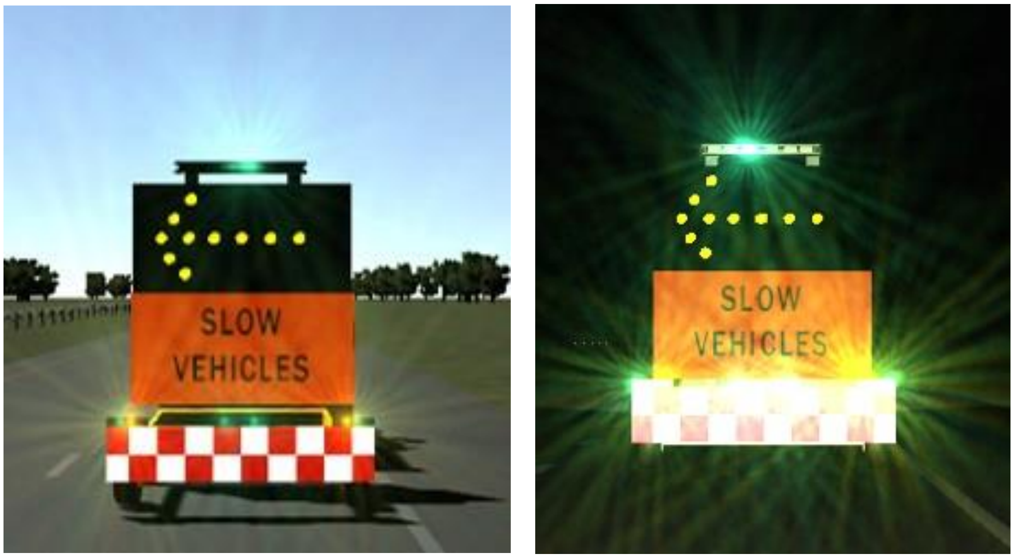
Four TMA light bar configurations were tested in the simulator tests: (1) amber/white (MoDOT typical), (2) green only (MoDOT preferred), (3) green/amber (MoDOT alternative), and (4) green/white (design alternative). There was no other traffic, except the work zone vehicles in the direction of travel, so the participant was free to accelerate/decelerate or change lanes. Therefore, all the measurements derived from drivers were responding to TMAs only. Each configuration was tested for both daytime and nighttime scenarios. The nighttime scenarios used the same settings as the daytime scenarios, except that lights were dimmed by half. An eye tracker was utilized to capture the movement of participants' pupils for nighttime scenarios, as high intensity of lights could cause disability glare issues. Disability glare refers to a situation where the light bar could be so dominant that drivers might be unable to see the flashing arrow and other items near the light bar. A water bottle rolled next to the rear advance TMA, and the eye tracker indicated if participants saw the water bottle, so as to determine disability glare of each configuration. The water bottle was chosen as the least obtrusive and yet measurable option after considering several other options.

The amber and white configuration was the baseline for the experiment. The amber and white TMA was equipped with amber and white light bars on top of arrow board, an arrow board with the arrow flashing, and amber and white light bulbs on the checkerboard, as shown in Figure 2.2.2.

(a) (b)

Figure 2.2.2 amber/white scenarios (a) daytime (b) nighttime

The green only TMA was implemented by MoDOT based on field testing that was performed at Lee's Summit airport. The feedback from the pilot project crew was positive. The crew thought that the green only TMA worked well to attract driver attention, and the visibility was high. TMA operators felt safer with green lights. However, concerns about confusion with traffic signal and arrow board were expressed. The green only TMA was equipped with green light bars on top of arrow board, an arrow board with arrow flashing, and green and amber light bulbs on the checkerboard, as shown in Figure 2.2.3.



(a) **(b)**

Figure 2.2.3 Green only scenarios (a) daytime (b) nighttime

The green and amber was an alternative configuration tested by MoDOT at Lee's Summit airport. The simulated configuration was the same as the one tested by MoDOT, with green/amber light bars on top of the arrow board and green/amber light bulbs on the checkerboard, as shown in Figure 2.2.4.

(a) **(b)**

Figure 2.2.4 Green/amber scenarios (a) daytime (b) nighttime

The research team designed an alternative green/white TMA, with green/white light bars on top of arrow board and amber/green light bulbs on the checkerboard, as shown in Figure 2.2.5.

(a) **(b)**

Figure 2.2.5 Green/white scenarios (a) daytime (b) nighttime

In any simulator study, sequence bias or order effect is possible (Perreault 1975). In order to limit this bias, the test order of scenarios was randomized. Daytime scenarios and nighttime scenarios were randomized separately and combined together randomly. Four configuration scenarios generated 24 orders. Daytime and nighttime scenarios were paired randomly, therefore generating 576 combinations. Each participant was randomly assigned to one of the 576 test orders to minimize sequence bias. Each of the four TMA configurations was tested once in daytime and once in nighttime.

2.3 Simulator trials and MOEs

The campus Institutional Review Board reviewed, evaluated, and approved the study protocols and measurement tools. A standard trial hosting script was used for each trial. The host first introduced the simulator, described the purpose of the experiment, and obtained participant consent for data collection. Then the participant sat in the sedan cab, and the host calibrated the eye tracker to capture participant eye gaze. After calibration, the participant practiced driving the simulator in a free-driving warm-up scenario to become familiar with the simulator. Once the participant felt comfortable driving the simulator, the host initiated the actual work zone scenarios, beginning with the daytime scenarios. Once the daytime scenarios were completed, the nighttime scenarios were initiated. The participant was asked to drive along the highway and stay in the driving lane (right lane) as much as possible since the lane change distance and speed were used as performance measures. Otherwise, a driver might stay in the passing lane for the entire simulator run.

There were three different parts of the simulator tests. The first part was regular simulator trials in which drivers traveled through the work zone under the different scenarios and information regarding speeds and distances was collected. The second part of the simulator testing was the disability glare test in which the eye tracker was utilized to capture participants' eyes and examine the disability glare of each light configuration. This test was conducted as part of the regular simulator trials. The third part of the simulator testing was the visibility test in which the participant would push a button when he/she first recognized the work zone and arrow direction, separately. The visibility test was conducted apart from the regular simulator trials to avoid distracting participants when they were driving.

The simulator trials, including eye tracking, were all recorded. After simulator experiments were completed, the research team reviewed the videos and extracted data. Nine measures of effectiveness (MOEs) were defined for data reduction.

2.3.1 Regular trials

In this part of the simulator testing, six MOEs were captured. These MOEs were measured for both daytime and nighttime scenarios.

- MOE 1: - First blinker distance (ft.). This MOE is the distance to the shoulder TMA when the participant flashed the blinker for the first time. This distance could help to indicate where a driver recognized the work zone and/or recognized the arrow direction. An example of MOE 1 is shown in Figure 2.3.1. The figure shows the green blinker indicator that flashes on the vehicle's heads up display and the distance superimposed on the video. For illustration purposes, Figure 2.3.1 and subsequent figures show a composite view of the front windshield view and right side mirror view. Although the side view appears to be distorted in these figures, the rear view and side mirrors are situated properly from the perspective of sitting inside the vehicle cab.

Figure 2.3.1 MOE 1 example: first blinker distance (ft.)

- MOE 2: First blinker speed (mph). This MOE is the speed when the participant flashed the blinker for the first time. The speed is available on the heads up display as shown in Figure 2.3.2. Speed is a common effectiveness measure that is related to safety.

Figure 2.3.2 MOE 2 example: first blinker speed (mph)

- MOE 3: Merge distance (ft.). This MOE is the distance to the shoulder TMA when the participant started to merge to the passing lane. This distance indicates how far upstream the participant reacted to the work zone and/or arrow board. An example of MOE 3 is shown in Figure 2.3.3.

Figure 2.3.3 MOE 3 example: merge distance (ft.)

- MOE 4: Merge speed (mph). This MOE is the speed of vehicle when it started to merge to the passing lane. An example of MOE 4 on the screen is shown in Figure 2.3.4.

Figure 2.3.4 MOE 4 example: merge speed (mph)

MOE 5: Speed when passing the shoulder TMA (mph). This MOE is the speed of the vehicle when it passed the rear end of the shoulder TMA. A lower speed is desirable for safety. An example of MOE 5 is shown in Figure 2.3.5.

Figure 2.3.5 MOE 5 example: speed when passing shoulder TMA (mph)

- MOE 6: Speed when passing the rear advance TMA (mph). This MOE is the speed of vehicle when it passed the rear end of rear advance TMA. A lower speed is more desired for safety consideration. An example of MOE 6 is shown in Figure 2.3.6.

Figure 2.3.6 MOE 6 example: speed when passing rear advance TMA (mph)

2.3.2 Disability glare test

The light bars above the arrow board could potentially impact arrow visibility due to light intensity and may cause disability glare, especially during nighttime. The simulator study was used to assess possible disability glare and discomfort effects. A water bottle was rolling right next to the rear advanced TMA. The eye tracker was utilized to track a participant's eyes and to determine if the participant saw the water bottle. The eye tracker was shown as a bubble on the monitoring screen of the host, but not shown on the driver's display monitor to avoid distraction. The following MOE was used to assess disability glare:

- MOE 7: Water bottle recognition is a binary measurement, indicating if the participant saw the water bottle or not. This MOE is for nighttime only. Figure 2.3.7 shows an example of the eye tracker indicating that water bottle was recognized.

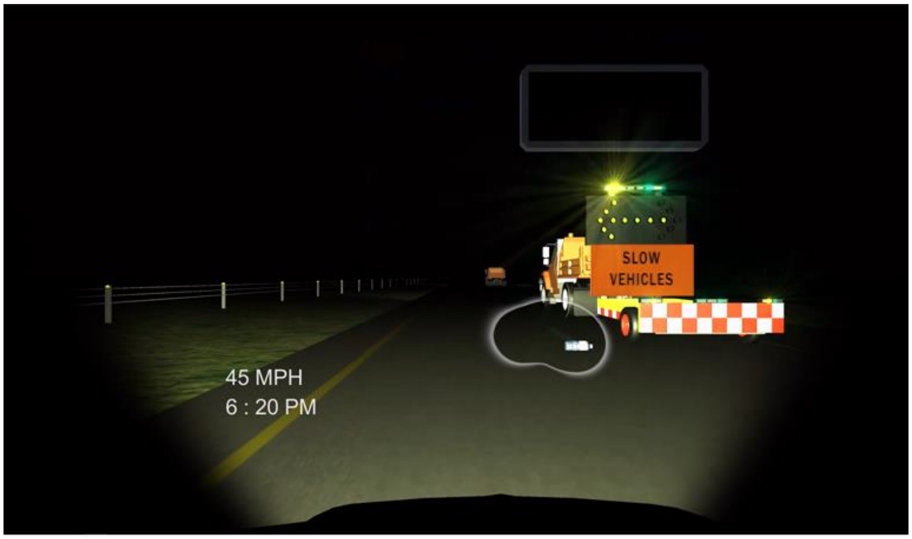


Figure 2.3.7 MOE 7 example: water bottle recognition

2.3.3 Visibility test

In order to measure the visibility of mobile work zones with different light configurations without distracting the participants, a separate visibility test was conducted. Although visibility of the work zone and arrow board could be implied from first blinker and merge distance, a separate test was performed to capture the recognition distance directly. During this test, participants were asked to press two buttons. The first button was pressed when the participants realized that there was a moving work zone ahead, based on the visibility of light bar. The second button was pressed when they could tell what direction the arrow is pointing, to test the visibility of the arrow aboard. The simulator logged the distance measurements automatically when participants pressed the buttons. For the visibility testing, twenty participants were invited to drive through the four light bar configurations twice (daytime/nighttime). Two MOEs were generated from this test as described below.

- MOE 8: Work zone recognition distance (ft.). This MOE is the distance from the rear end of the shoulder TMA when the participant first recognized the work zone. A farther distance indicated that the work zone was more visible and could be safer because of longer reaction times.

- MOE 9: Arrow direction recognition distance (ft.). This MOE is the distance from the rear end of the shoulder TMA when the participant first recognized the arrow direction. This could be an indication of disability glare as well. A farther distance is desirable.

Both MOE 8 and MOE 9 were automatically recorded onto a data log when the buttons were pushed.

2.4 Simulator results

Videos of regular trials and the disability glare test were recorded, and MOEs 1 through 7 were extracted. Video was useful to visually confirm data accuracy and identify potential data issues. The data for MOE 8 and MOE 9 of the visibility test were extracted from automated data files because they were very straight forward and did not require visual confirmation and interpretation.

To compare MOEs among the TMA light bar configurations, the differences between them were calculated. Statistical analysis was performed to calculate significance, confidence level, and effect size. A confidence level higher than 90 percent was regarded as significant in this study. Effect size was presented as Cohen's d value, and difference is defined to be small (effect size < 0.5), medium (effect size between 0.5 and 0.8), and large (effect size > 0.8) (Cohen 1977).

Thirty participants participated in the first part of the simulator tests and completed the trials. However, distance data for one of the participants was lost due to a data issue. MOE 1 and MOE 2 data were not obtained for some participants because they did not flash their blinker before they merged.

The eye tracker was utilized for 18 participants because it became available during the middle of the simulator testing. Due to contact lens issues, some eye tracking calibrations were not successful and eye tracking data was not collected.

The visibility test was conducted separately after the simulator trials because it would be distracting if participants were asked to push a button when they first recognized the work zone and arrow direction while they were driving in a normal manner. The objective for the visibility test was to distinguish the configuration with the earliest recognition of the work zone and arrow board. Twenty participants participated in the visibility test. Some of them were participants from the previous simulator tests, and the others were newly recruited.

2.4.1 Daytime results

MOE 1 measured the distance of a vehicle from the rear end of the shoulder TMA when the participant flashed the blinker for the first time. As shown in Table 2.4.1, participants reacted to amber/white TMA the quickest among all four configurations and flashed the blinker at an average distance of 1039.1 ft. Both the green only and green/white TMA had significantly closer first blinker distances than the amber/white TMA, but Cohen's d showed that the effect sizes were small.

Table 2.4.1 Daytime MOE 1: First blinker distance (ft.)

	MOE 1: First blinker distance (ft.)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	24	1039.1	589.2	Baseline			
Green only	24	813.8	377.7	-225.3	97.6%**	0.46	Small
Green/amber	24	973.1	508.6	-66.0	73.1%	n/a	n/a
Green/white	25	788.4	444.4	-250.7	99.8%*	0.48	Small

* indicates significance at 99%.
** indicates significance at 95%.

MOE 2 captured the speed of a vehicle when the participant flashed the first blinker, and the results are shown in Table 2.4.2. The amber and white had the highest first blinker speed, the results being statistically significant. However, the Cohen's d indicated that the differences were small. The reason why the speed for amber/white TMA was higher could be that the speed was captured when vehicle was farther away from the TMA compared to other light configurations.

Table 2.4.2 Daytime MOE 2: First blinker speed (mph)

	MOE 2: First blinker speed (mph)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	25	57.8	7.6	Baseline			
Green only	25	55.7	7.7	-2.0	91.5%***	0.27	Small
Green/amber	25	54.8	8.6	-3.0	96.7%**	0.36	Small
Green/white	26	54.8	9.1	-3.0	92.3%***	0.35	Small

** indicates significance at 95%.
*** indicates significance at 90%.

Since the rear advance TMA was on the driving lane, it is important to capture the merge distance of vehicles as a surrogate measure of safety. The merge distance was recorded as MOE 3, and the results for this MOE are shown in Table 2.4.3. The results indicate that drivers merged earlier when they encountered the amber/white TMA, followed by green/amber TMA. The merge distance for the green only TMA was significantly closer than the amber/white TMA, and the effect size was medium. It could be implied that the visibility of the green only TMA was lower and drivers reacted later.

Table 2.4.3 Daytime MOE 3: Merge distance (ft.)

	MOE 3: Merge distance (ft.)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	29	971.0	599.5	Baseline			
Green only	29	649.0	336.6	-322.0	99.7%*	0.66	Medium
Green/amber	28	814.5	468.2	-156.5	83.2%	n/a	n/a
Green/white	29	750.1	643.4	-220.9	98.0%**	0.36	Small

* indicates significance at 99%.
** indicates significance at 95%.

Merge speed was recorded as well as MOE 4. Table 2.4.4 shows that the merge speed for the amber/white TMA was higher than the other light configurations. This may be due to the farther merge distance, while drivers had not slowed down yet.

Table 2.4.4 Daytime MOE 4: Merge speed (mph)

	MOE 4: Merge speed (mph)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	30	57.4	6.5	Baseline			
Green only	30	53.7	11.4	-3.7	95.1%**	0.40	Small
Green/amber	30	53.5	10.4	-3.9	96.2%**	0.45	Small
Green/white	30	53.0	8.5	-4.4	98.3%**	0.57	Medium

** indicates significance at 95%.

MOE 5 measured the speed of the vehicle when it passed the shoulder TMA. The results for this MOE are shown in Table 2.4.5. The results show that the green only TMA had the highest passing speed, and the green/white TMA had the lowest passing speed which is desirable. However, the differences among all four configurations were not statistically significant.

Table 2.4.5 Daytime MOE 5: Speed when passing shoulder TMA (mph)

	MOE 5: Speed when passing shoulder TMA (mph)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	30	52.3	9.4	Baseline			
Green only	30	53.2	9.3	0.9	81.5%	n/a	n/a
Green/amber	30	52.1	9.4	-0.2	55.0%	n/a	n/a
Green/white	30	50.5	8.9	-1.8	87.7%	n/a	n/a

MOE 6 is similar to MOE 5, and it measured the vehicle speed when it passed the rear advance TMA. The results for this MOE are shown in Table 2.4.6. The green only TMA had the highest passing speed, and green/amber TMA had the lowest. However, the speeds for all four configurations were close to each other, and they were not statistically significantly different from each other.

Table 2.4.6 Daytime MOE 6: Speed when passing rear advance TMA (mph)

	MOE 6: Speed when passing rear advance TMA (mph)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	30	51.0	8.3	Baseline			
Green only	30	52.1	9.6	1.2	89.1%	n/a	n/a
Green/amber	30	50.6	9.6	-0.4	63.0%	n/a	n/a
Green/white	30	50.8	8.5	-0.2	57.3%	n/a	n/a

The second part of the simulator tests was the disability glare test. The eye tracker was utilized, and results were presented as binary data to indicate whether or not the participant recognized the water bottle. MOE 7, water bottle recognition, was the only measurement in the disability glare test. This MOE was assessed for nighttime only because the disability glare issue was not considered as a critical factor during daytime. Therefore, the daytime results did not contain MOE 7. The nighttime results for this MOE are presented following the daytime results.

Table 2.4.7 shows the results of work zone recognition distance (MOE 8) in the daytime. Since the sample size of the visibility testing was smaller than the regular simulator trials, the statistical tests conducted were different. A Mann-Whitney test was conducted to assess the statistical significance of the data. The Mann-Whitney test is used to assess 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 results show that the amber/white configuration, as the baseline in this study, had the farthest distance with a mean of 1554 ft. and median of 1604 ft. Meanwhile, the visibility of the green only TMA was the lowest (1166 ft.) among all configurations. However, based on the results of the Mann-Whitney test, there was no significant difference between these four configurations.

Table 2.4.7 Daytime MOE 8: Work zone recognition distance (ft.)

	MOE 8: Work zone recognition distance (ft.)					
	Count	**Mean**	**Median**	**Stdev.**	**Diff.**	**Confidence Level**
Amber/white	20	1554.2	1604.0	746.2	Baseline	
Green only	20	1166.2	1154.5	469.6	388.0	90.9%
Green/amber	20	1292.8	1311.5	546.0	261.4	69.0%
Green/white	20	1382.6	1231.0	722.6	171.6	59.1%

Participants were also asked to state when they could recognize the arrow direction, and the results of this test for daytime are shown in Table 2.4.8 as MOE 9. Even though the green only TMA scored the lowest for work zone recognition distance, it had the farthest distance for recognition of the arrow direction with a mean of 663 ft. and median of 567 ft. In contrast, the configuration of amber and white had the nearest distance (569.70 ft.), but all the differences were not statistically significant among four configurations.

Table 2.4.8 Daytime MOE 9: Arrow direction recognition distance (ft.)

	MOE 9: Arrow direction recognition distance (ft.)					
	Count	**Mean**	**Median**	**Stdev.**	**Diff.**	**Confidence Level**
Amber/white	20	569.7	522.5	195.2	Baseline	
Green only	20	663.0	567.0	224.8	93.3	81.9%
Green/amber	20	644.6	547.0	215.8	74.9	73.3%
Green/white	20	578.6	553.0	137.6	9.6	29.5%

2.4.2 Nighttime results

MOE 1 measured the distance of the vehicle from the rear end of the shoulder TMA when the participant flashed the blinker for the first time, and the results were different from daytime. As shown in Table 2.4.9, participants reacted to the amber/white TMA at 1577.6 ft. which was farther than the same measurement for daytime. It was also the earliest reaction among all four configurations, followed by the green/amber TMA. Both the green only and green/white TMA had significantly closer first blinker distances than the amber/white TMA, and the Cohen’s d showed that the effect sizes were large. It can be implied that the amber/white had significantly higher visibility than the green only TMA and green/white TMA during nighttime. Compared to daytime, participants reacted to the TMA earlier at night.

Table 2.4.9 Nighttime MOE 1: First blinker distance (ft.)

	MOE 1: First blinker distance (ft.)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	24	1577.6	748.1	Baseline			
Green only	23	869.1	389.7	-708.5	100.0%*	1.19	Large
Green/amber	23	1483.0	1218.3	-94.6	66.0%	n/a	n/a
Green/white	23	887.3	462.8	-690.3	100.0%*	1.11	Large

* indicates significance at 99%.

MOE 2 captured the speed of the vehicle when the participant flashed the first blinker, and the results are shown in Table 2.4.10. The overall speed at first blinker at nighttime was higher than daytime. This higher speed may have occurred because the vehicle was located farther away from the work zone. However, although the first blinker distance of the amber/white TMA was the farthest, the speed was not the highest. This result may indicate that amber/white caught drivers' attention and alerted them. The green only TMA had a slightly lower first blinker speed, but the difference was not significant.

Table 2.4.10 Nighttime MOE 2: First blinker speed (mph)

	MOE 2: First blinker speed (mph)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	25	58.3	5.9	Baseline			
Green only	24	57.4	5.6	-0.9	82.7%	n/a	n/a
Green/amber	24	59.5	5.5	1.2	77.8%	n/a	n/a
Green/white	24	59.6	4.2	1.3	85.0%	n/a	n/a

The merge distances at nighttime are shown in Table 2.4.11. The results indicate that drivers merged earlier when they encountered the amber/white TMA and green/amber TMA. Both the green only TMA and green/white TMA had significantly closer merge distances, and the effect sizes were large and medium correspondingly. Similar to the first blinker distance, drivers reacted to TMAs earlier during nighttime and merged earlier.

Table 2.4.11 Nighttime MOE 3: Merge distance (ft.)

	MOE 3: Merge distance (ft.)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	29	1309.4	762.3	Baseline			
Green only	29	706.5	398.1	-602.9	100.0%*	0.99	Large
Green/amber	29	1288.7	1134.5	-20.8	56.1%	n/a	n/a
Green/white	29	851.9	603.6	-457.5	99.8%*	0.67	Medium

* indicates significance at 99%.

Merge speed at nighttime was slightly higher than at daytime, a result which may be due to farther merge distance at nighttime. As shown in Table 2.4.12, the green only TMA and amber/white TMA had slower merge speeds than the other two configurations. However, the differences were not significant. With regard to the merge distance and speed, the green/white TMA did not perform as well as the other three configurations, and this was consistent with the results from first blinker distance and speed.

Table 2.4.12 Nighttime MOE 4: Merge speed (mph)

	MOE 4: Merge speed (mph)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	30	57.3	6.6	Baseline			
Green only	30	56.0	6.2	-1.2	82.3%	n/a	n/a
Green/amber	30	57.9	5.7	0.6	66.0%	n/a	n/a
Green/white	30	58.2	4.5	0.9	77.2%	n/a	n/a

MOE 5 was the measurement of speed when the vehicle drove past the shoulder TMA. The results of MOE 5 are shown in Table 2.4.13. It shows that the green/amber TMA may have caught drivers' attention the most, as it had the lowest speed, and the speed was statistically significantly slower than the speed under the baseline configuration. The speed for the amber/white TMA was the highest. This result may be due to the discomfort brought by the brightness of the amber and white light bars.

Table 2.4.13 Nighttime MOE 5: Speed when passing shoulder TMA (mph)

	MOE 5: Speed when passing shoulder TMA (mph)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	30	51.8	9.5	Baseline			
Green only	30	50.9	10.4	-0.9	74.9%	n/a	n/a
Green/amber	30	48.6	10.1	-3.2	98.2%	0.33	Small
Green/white	30	51.1	8.9	-0.7	70.9%	n/a	n/a

** indicates significance at 95%.

The results for the speed of vehicles when they passed the rear advance TMA are shown in Table 2.4.14 as MOE 6. The passing speeds for the rear advance TMA were slower than the passing speeds for the shoulder TMA. This result may have occurred because the rear advance TMA was on the lane and thus closer to vehicles, while the shoulder TMA was on shoulder. The green and amber TMA had the slowest passing speed. However, the differences between the four configurations were not significant.

Table 2.4.14 Nighttime MOE 6: Speed when passing rear advance TMA (mph)

	MOE 6: Speed when passing rear advance TMA (mph)						
	Count	**Mean**	**Stdev.**	**Diff.**	**Confidence level**	**Cohen's d**	**Effect size**
Amber/white	30	48.6	11.2	Baseline			
Green only	30	49.3	10.4	0.8	73.0%	n/a	n/a
Green/amber	30	47.7	9.6	-0.9	72.9%	n/a	n/a
Green/white	30	48.2	9.4	-0.4	61.2%	n/a	n/a

The disability glare test was used to assess if the light bars were too bright and caused glare issues when drivers drove past the TMA. By using a water bottle next to rear advance TMA and utilizing the eye tracker to determine if participants saw the water bottle, the presence of glare could be implied. As shown in Table 2.4.15, the results indicate that the amber/white TMA had the lowest rate of water bottle recognition, while the green/white TMA had the highest rate of water bottle recognition. Thus, the amber/white configuration exhibited more problems with glare than the other configurations.

Table 2.4.15 MOE 7: Water bottle recognition (binary)

	MOE 7: Water bottle recognition		
	Count	**Recognized**	**Percentage**
Amber/white	14	10	71.4%
Green only	12	11	91.7%
Green/amber	13	11	84.6%
Green/white	13	12	92.3%

The visibility test was also performed in nighttime. Table 2.4.16 for MOE 8 shows the results for participants' recognition of the moving work zone. The amber/white TMA had the farthest recognition distance with a mean of 1388.7 ft. and median of 1390 ft. The green only TMA had the closest recognition mean distance (976.5 ft.), and the difference between it and baseline was statistically significant.

Table 2.4.16 Nighttime MOE 8: Work zone recognition distance (ft.)

	MOE 8: Work zone recognition distance (ft.)					
	Count	**Mean**	**Median**	**Stdev.**	**Diff.**	**Confidence Level**
Amber/white	20	1388.7	1390.0	419.0	Baseline	
Green only	20	976.5	935.5	319.9	412.2	99.6% *
Green/amber	20	1162.5	1155.5	473.3	226.2	89.8%
Green/white	20	1296.0	1154.0	667.8	92.7	67.7%

* indicates significance at 99%.

The results for arrow direction recognition at nighttime are shown in Table 2.4.17. The results show that the green only TMA had the farthest arrow direction recognition distance with a mean of 555.1 ft. and median of 552.0 ft., a result which was consistent with the daytime findings. However, there was not a statistically significant difference among the four configurations.

Table 2.4.17 Nighttime MOE 9: Arrow direction recognition distance (ft.)

	MOE 9: Arrow direction recognition distance (ft.)					
	Count	**Mean**	**Median**	**Stdev.**	**Diff.**	**Confidence Level**
Amber/white	20	530.9	500.0	156.4	Baseline	
Green only	20	555.1	552.0	161.5	24.2	78.0%
Green/amber	20	546.9	517.0	110.6	16.0	54.3%
Green/white	20	519.5	479.0	142.5	11.4	2.3%

The results of MOE 8 and MOE 9 imply that the recognition of work zone and recognition of arrow direction are negatively correlated. In other words, a more intense light that leads to the earlier recognition of the mobile work zone also means that there is greater disability glare and a later recognition of the arrow direction.

The overall simulator test results indicate that amber/white TMA had the highest visibility of work zone, but the lowest visibility of arrow board. The green only TMA had the lowest visibility of work zone, but the highest visibility of arrow board. The tradeoff between work zone visibility and arrow board visibility is an important consideration.

CHAPTER 3: POST-SIMULATOR SURVEY

3.1 Post-simulator survey methodology

A post-simulator survey was used to collect driver preferences. The 12-question survey consisted of four parts. Part 1 asked participants to rate the daytime light bar configurations. It asked participants to indicate their preferences and rate each daytime configuration with respect to the visibility of work zone vehicles, awareness of work zones, clear recognition of arrow direction and easiness on the eyes. Part 2 asked participants about their preferences for the nighttime configurations. It contained the same questions as Part 1 and one additional question regarding disability glare. Part 3 asked for participants' opinions about simulator fidelity while Part 4 collected demographic information. A 16-question simulator sickness questionnaire (SSQ), which is widely used in diagnosing the simulator sickness severity of participants (Kennedy et al. 1993) was included at the end of the survey. The complete simulator survey is shown in Appendix A.

An effort was made to balance the proportion in each age group and gender during the recruitment process. However, since the simulator study was conducted in the Columbia metropolitan area, where there are many universities, the majority of participants were between the ages of 16 and 40, and 90% of the participants were from an urban area. Gender was balanced, with 57% male participants and 43% female participants. All participants drove passenger cars as their regular vehicles. Table 3.1.1 shows the demographics of the 30 simulator test participants.

Table 3.1.1 Demographics information for simulator participants

	Age				Gender		Residency	
	16-25	26-40	41-55	56-70	Male	Female	Urban	Rural
Count	12	13	4	1	17	13	27	3
Percentage	40%	43.3%	13.3%	3.3%	56.7%	43.3%	90%	10%

3.2 Post-simulator survey results

The following sections describe the post-simulator survey results. Additional comments from the survey are provided in Appendix B.

3.2.1 Part 1: Daytime evaluation

Part 1 of the survey asked the participants to rank the light bar color options on the TMA for daytime on a scale of 1-5, with 5 representing "like it very much" and 1 representing "dislike it very much". The results from this question are summarized in Table 3.2.1. The green/amber scored the highest with an average score of 3.72 while the green only scored the lowest with an average score of 2.97. The amber/white ranked second and the green/white ranked third with scores of 3.48 and 3.14, respectively. The score of 3 represents a neutral opinion, so all configurations were at or above neutral.

Table 3.2.1 Daytime TMA configurations preference

	Average score	Rank
Amber/white	3.48/5	2
Green only	2.97/5	4
Green/amber	3.72/5	1
Green/white	3.14/5	3

Based on the preference results, a Friedman rank test was carried out to see if there were differences in preference based on TMA configurations. As shown in Table 3.2.2, although the average scores were different in each configuration, the non-parametric test shows that rank differences among TMA configurations were not statistically significant.

Table 3.2.2 Friedman test: Rank vs. TMA configurations blocked by participants

S = 6.03 DF = 3 P = 0.110 (adjusted for ties)			
TMA Configurations	N	Est. Median	Sum of Ranks
Amber/white	29	2.1	69.5
Green only	29	3.1	82.5
Green/amber	29	1.9	61
Green/white	29	2.9	77

After the preference question, the participants were asked to score different attributes of the various TMA configurations during the daytime on a scale of 1-10, with 1 representing the "lowest" and 10 representing the "highest". These attributes included visibility of work zone vehicles, awareness of work zones, clear recognition of arrow direction, and easiness on the eyes.

Table 3.2.3 shows the results of ratings. The amber/white, as the baseline, scored the highest for visibility and awareness of work zones. However, the amber/white TMA scored the lowest in the clear recognition of the arrow direction and easy on the eyes attributes. The green only TMA scored lowest in the visibility and awareness of work zones and scored the highest in the clear recognition of the arrow direction and easy on the eyes attributes. The green/amber and the green/white TMAs scored second and third in all categories respectively. The confidence level for the range of differences was set to be 95 percent in this study based on the Mann-Whitney test. The results show that the amber/white TMA only had a significantly lower score in one category, easy on the eyes, with scoring on average being 5.55, while the green only and green/amber TMAs scored on average 8.62 and 8.07, respectively.

Table 3.2.3 Ratings for daytime TMA configurations

	Visibility of work zone vehicles			
	Mean	**Median**	**Diff.**	**Confidence Level**
Amber/white	8.3	9.0	Baseline	
Green only	7.2	8.0	-1.1	92.8%***
Green/amber	8.0	8.0	-0.3	50.6%
Green/white	7.7	8.0	-0.6	78.2%
	Awareness of work zones			
	Mean	**Median**	**Diff.**	**Confidence Level**
Amber/white	8.9	10.0	Baseline	
Green only	7.8	8.0	-1.1	95.0%**
Green/amber	8.5	9.0	-0.4	67.4%
Green/white	8.1	8.0	-0.8	86.8%
	Clear recognition of arrow direction			
	Mean	**Median**	**Diff.**	**Confidence Level**
Amber/white	7.1	7.0	Baseline	
Green only	8.0	8.0	0.9	85.8%
Green/amber	8.0	8.0	0.9	82.6%
Green/white	7.1	7.0	0.0	5.0%
	Easy on eyes			
	Mean	**Median**	**Diff.**	**Confidence Level**
Amber/white	5.6	6.0	Baseline	
Green only	8.6	9.0	2.6	99.9% *
Green/amber	8.1	8.0	2.5	99.9% *
Green/white	6.1	6.0	0.6	51.6%

* indicates significance at 99% confidence level.
** indicates significance at 95% confidence level.
*** indicates significance at 90% confidence level.

3.2.2 Part 2: Nighttime evaluation

Part 2 of the survey asked the participants to rank the light bar color option on the TMA for nighttime using the same scale of Part 1. The results from this question are summarized in Table 3.2.4. The green/amber scored the highest with an average score of 3.59 while the amber/white scored the lowest with an average score of 2.93. The green/white ranked second and the green only ranked third with scores of 3.24 and 3.21, respectively.

Table 3.2.4 Nighttime TMA configurations preference ranking

	Average Score	Ranking
Amber/white	2.93/5	4
Green only	3.21/5	3
Green/amber	3.59/5	1
Green/white	3.24/5	2

Another Friedman rank test was conducted, and the test showed that the rank versus TMA configurations by participants were not significantly different from all four TMA configurations. The results are shown below in Table 3.2.5.

Table 3.2.5 Friedman test: Rank vs. TMA configurations by participants

S = 5.63 DF = 3 P = 0.131 (adjusted for ties)			
TMA Configurations	**N**	**Est. Median**	**Sum of Ranks**
Amber/white	29	3.3	83.5
Green only	29	2.4	74.0
Green/amber	29	1.9	62.0
Green/white	29	2.6	70.5

The participants were asked whether the lights on the TMA were too bright or not, and 66% of participants agreed that the lights of the amber/white were too bright. Meanwhile, only five participants thought the lights of green only were too bright, which is the lowest among all four configurations. The results are shown below in Table 3.2.6.

Table 3.2.6 Light intensity

Lights too bright?	Agree	Neutral	Disagree
Amber/white	19 (66%)	5 (17%)	5 (17%)
Green only	5 (17%)	3 (10%)	21 (72%)
Green/amber	8 (28%)	11 (38%)	10 (34%)
Green/white	10 (34%)	14 (48%)	5 (17%)

The questions regarding the rating of attributes were then asked using the same format as the daytime part of the survey. The average and median scores for each of the four attributes are shown in Table 3.2.7. The amber/white scored the highest in the visibility and awareness of work zones. However, the amber/white also scored the lowest in the clear recognition of arrow direction and easy on the eyes attributes, which showed the same trends for both the daytime and nighttime parts. The green only configuration scored the highest in the clear recognition of arrow direction and easy on the eyes attributes, third in visibility of work zone vehicles and last in awareness of work zones. The green/amber scored second in all four attributes. Finally, the green/white scored last in visibility of the work zone, and third in awareness of work zones, clear recognition of arrow direction, and easy on the eyes.

The Mann-Whitney test shows that the green only TMA had a significantly higher score on clear recognition of arrow direction than the amber/white, as amber/white scored a mean of 6.47 while the green only TMA scored an average of 7.97. For the easy on eyes attribute, the amber/white was significantly lower than all three other TMAs, scoring an average of 4.83. The green only, green/amber, and green/white scored average values of 8.10, 7.50, and 6.20, respectively.

Table 3.2.7 Ratings for nighttime TMA configurations

	Visibility of work zone vehicles			
	Mean	**Median**	**Diff.**	**Confidence Level**
Amber/white	8.7	10.0	Baseline	
Green only	8.1	9.0	-0.5	76.5%
Green/amber	8.6	9.5	0.0	44.6%
Green/white	8.0	9.0	-0.7	87.7%
	Awareness of work zones			
	Mean	**Median**	**Diff.**	**Confidence Level**
Amber/white	9.1	10.0	Baseline	
Green only	8.2	8.5	-0.9	93.8%***
Green/amber	8.7	9.5	-0.4	82.4%
Green/white	8.4	9.0	-0.7	88.2%
	Clear recognition of arrow direction			
	Mean	**Median**	**Diff.**	**Confidence Level**
Amber/white	6.5	6.5	Baseline	
Green only	8.0	8.5	1.5	98.3%**
Green/amber	7.6	8.0	1.1	93.7%***
Green/white	7.0	8.0	0.5	56.2%
	Easy on eyes			
	Mean	**Median**	**Diff.**	**Confidence Level**
Amber/white	4.8	5.0	Baseline	
Green only	8.1	9.0	3.3	99.9% *
Green/amber	7.5	8.0	2.7	99.9% *
Green/white	6.2	6.0	1.4	97.2% **

* indicates significance at 99% confidence level.
** indicates significance at 95% confidence level.
*** indicates significance at 90% confidence level.

3.2.3 Part 3: Simulator fidelity

In Part 3 of the survey, questions were designed to evaluate the fidelity of the simulator. Among the participants, 83.3% of them agreed that they felt like they were driving on the highway and that they could drive freely. Only 10% of participants disagreed with both the fidelity and feeling of driving freely in the simulator. The results are shown in Table 3.2.8.

Table 3.2.8 Simulator fidelity

	Fidelity of highway			Drive freely		
	Count	Percentage		Count	Percentage	
Strongly Agree	9	30%	83.3%	9	30%	83.3%
Agree	16	53.3%		16	53.3%	
Neutral	2	6.7%	6.7%	2	6.7%	6.7%
Disagree	2	6.7%	10%	3	10%	10%
Strongly Disagree	1	3.3%		0	0%	

3.2.4 Simulator sickness questionnaire (SSQ) results

The post-simulator survey was followed by a 16-question SSQ, to assess motion sickness of participants after the simulator experiment. The results are shown in Table 3.2.9. Most participants felt no or slight discomfort, and only five out of 30 participants had moderate or severe symptoms.

Table 3.2.9 Summary of SSQ Results

	General discomfort		Fatigue		Headache		Eye strain	
	count	pct.	count	pct.	count	pct.	count	pct.
None	24	80%	27	90%	24	80%	16	53.3%
Slight	6	20%	1	3.3%	6	20%	11	36.7%
Moderate	0	0%	2	6.7%	0	0%	3	10%
Severe	0	0%	0	0%	0	0%	0	0%
	Difficulty focusing		**Salivation increasing**		**Sweating**		**Nausea**	
	count	pct.	count	pct.	count	pct.	count	pct.
None	26	86.7%	29	96.7%	28	93.3%	25	83.3%
Slight	4	13.3%	1	3.3%	2	6.7%	4	13.3%
Moderate	0	0%	0	0%	0	0%	0	0%
Severe	0	0%	0	0%	0	0%	1	3.3%
	Difficulty concentrating		**Fullness of the Head**		**Blurred vision**		**Dizziness with eyes open**	
	count	pct.	count	pct.	count	pct.	count	pct.
None	29	96.7%	22	73.3%	28	93.3%	26	86.7%
Slight	1	3.3%	8	26.7%	2	6.7%	3	10%
Moderate	0	0%	0	0%	0	0%	1	3.3%
Severe	0	0%	0	0%	0	0%	0	0%
	Dizziness with eye closed		**Vertigo**		**Stomach awareness**		**Burping**	
	count	pct.	count	pct.	count	pct.	count	pct.
None	28	93.3%	29	96.7%	29	96.7%	30	100%
Slight	2	6.7%	1	3.3%	1	3.3%	0	0%
Moderate	0	0%	0	0%	1	3.3%	0	0%
Severe	0	0%	0	0%	0	0%	0	0%

3.2.5 Summary of post-simulator survey results

The overall post-simulator survey results indicate that amber/white TMA was too bright and not easy on eyes, and the visibility of the green only TMA was too low. On the other hand, the results indicate that the green only TMA allowed clear recognition of the arrow direction and was easy on eyes. Green/amber scored in between amber/white and green only and was preferred in both daytime and nighttime scenarios.

CHAPTER 4: FIELD TEST

Two major tasks for this project were to conduct simulator and field studies to evaluate the performance of different TMA light configurations. After the simulator tests, a field test was performed to collect data on field performance for two of the configurations.

4.1 Field test set up

The field test examined the amber/white TMA and green only TMA deploying the TMAs in the same way as in a regular mobile work zone. The test was conducted on a section of US 50, a four-lane freeway, near Kansas City, Missouri. A TMA started eastbound near the intersection of MO-291 and US 50 at the speed of 10 to 20 mph and turned around at the Buggy Stop at the intersection of US 50 and MO 58, near Centerview, Missouri, as shown in Figure 4.1.1. The data collection took place on two days: December 19th, 2018, and December 20th, 2018. The green only TMA was tested on the first day, and the amber/white TMA was tested on the second day. Both TMAs were tested for four hours during the daytime and four hours during the nighttime. On the first day, the green only TMA was utilized as the rear advance TMA. However, due to an equipment availability issue, there was only one green only TMA available, so the green only TMA was followed by an amber/white shoulder TMA. On the second day, two amber/white TMAs were utilized, one as the rear advanced TMA and the other as the shoulder TMA.

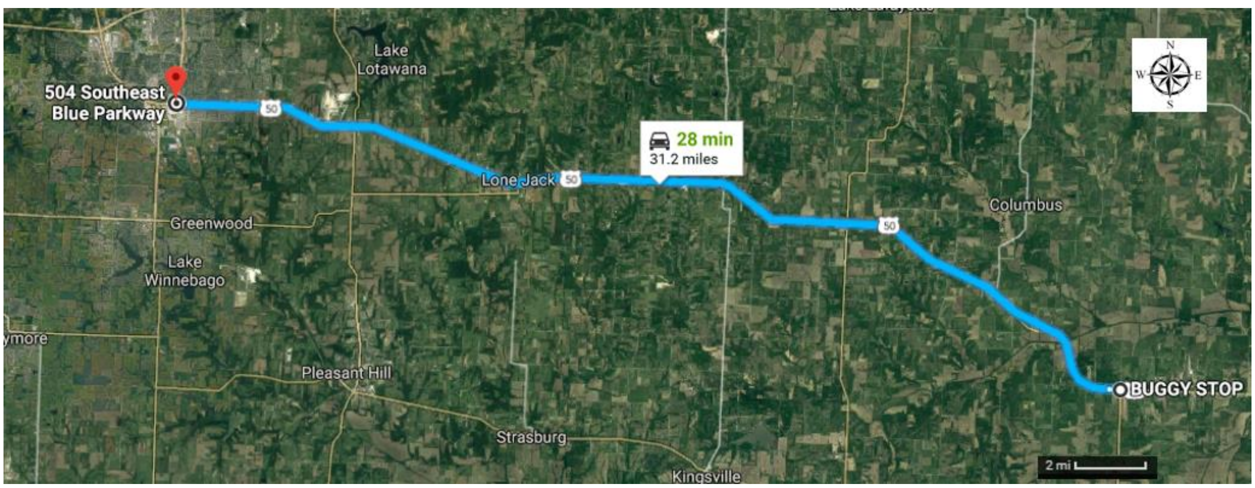


Figure 4.1.1 Route travelled for data collection on US 50 (Google maps 2017)

In order to capture the distance of vehicles from the rear advance TMA, a LiDAR detector was utilized. The LiDAR used was an active infrared detector, and it rated as eye safe. It was mounted on the TMA with a LED display. A camera was mounted on the TMA to record traffic behavior and LED readings for post video image processing. This video perspective was useful since the traffic conditions surrounding the LiDAR readings were captured. The MoDOT custom-mounted LiDAR is shown in Figure 4.1.2, and an example of LiDAR capturing vehicle distance from rear advance TMA is presented in Figure 4.1.3. Although the decimal dot was not shown on the LED monitor, data was recorded with two decimal points. In the example of Figure 4.1.3, the distance of the vehicle was 142.47 feet from the rear end of the rear advance TMA.

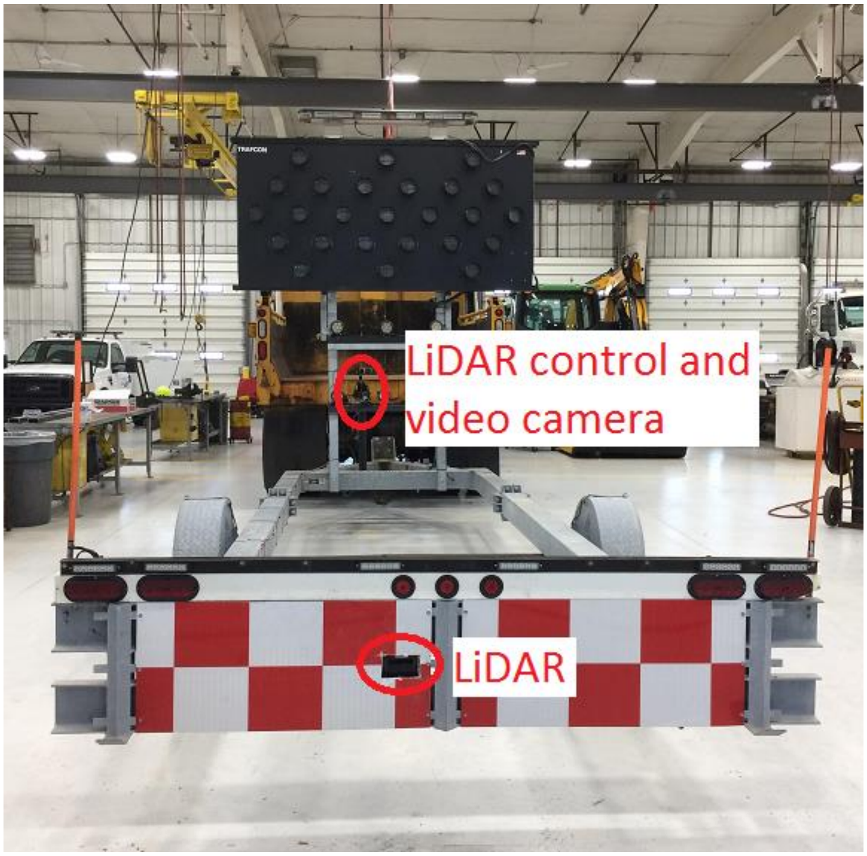


Figure 4.1.2 MoDOT custom-mounted TMA

Figure 4.1.3 Example of LiDAR capturing distance from vehicle to rear advance TMA

4.2 Video image processing methodology

After the field study was completed, videos recorded from the field were reviewed by the team to extract data. Video recording started when the TMAs departed the garage, but the data was not valid until TMAs started to operate as a mobile work zone. Within the valid data collecting time period, 4,966 vehicles passed through the mobile work zone, and 2,589 of them were platoon leaders. There were 2,756 instances in which the LiDAR captured distance measurements to various objects behind it, such as vehicles in the travel lanes, roadside barriers, or the shoulder TMA. The general information from the data collection is shown in Table 4.2.1.

Table 4.2.1 General information

	19th daytime (green only)	19th nighttime (green only)	20th daytime (amber/white)	20th nighttime (amber/white)
Total vehicles counted	1079	787	1918	1182
Total vehicles shown on right lane within field of view	58	4	78	12
Vehicles merged after passing shoulder TMA	2	2	1	3

The speed of vehicles when they passed the rear advance TMA was the only measurement of effectiveness processed in the field study. Vehicle speeds were derived from videos using photogrammetry. This technique allows the derivation of speeds of any vehicles when driving past a TMA, in contrast to speed radars which typically track vehicles only within a limited distance or angle. When a vehicle approached the rear advance TMA and passed a beginning dash line selected by the analyst, the time stamp was recorded as T_1, as shown in Figure 4.2.1. Then the analyst selected an end dash line (say the fifth dash), and when the vehicle passed the end dash line, the time stamp was recorded, as T_2, as shown in Figure 4.2.2. The number of dash lines used varied from two to five, depending on visibility due to geometry and nighttime lighting conditions. The distance travelled was 40 feet multiplied by the number of dashes traveled, and the travel time was T_2 minus T_1. From the travel distance and travel time, the vehicle speed was calculated. This technique was validated by computing the speed several times using different number of dash lines; the results were consistently the same regardless of the number of dashes used.

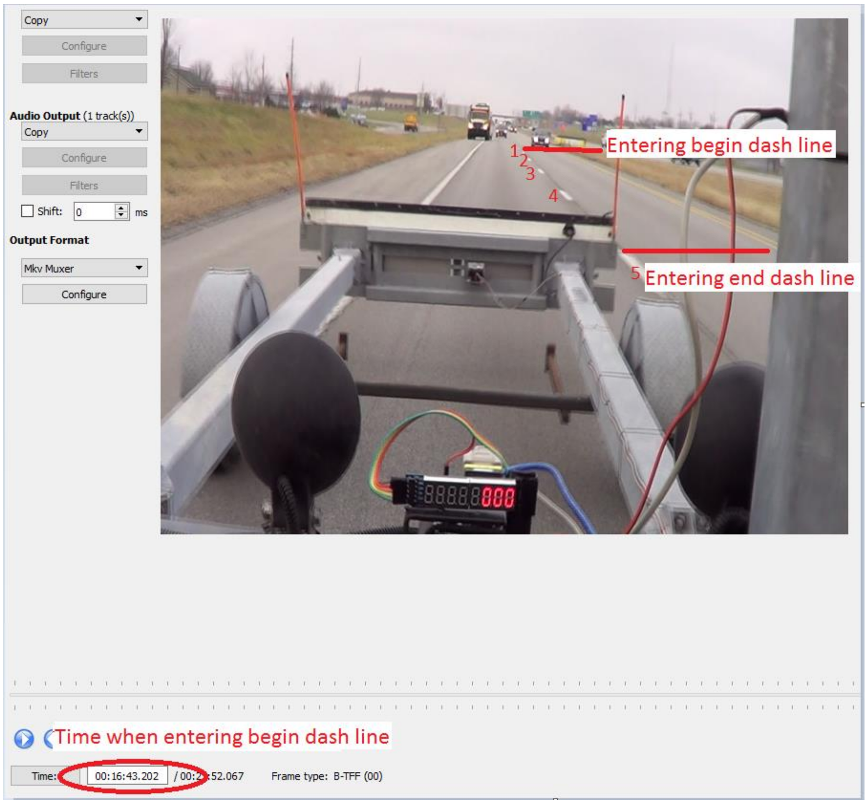


Figure 4.2.1 Time stamp one: vehicle entering begin dash line

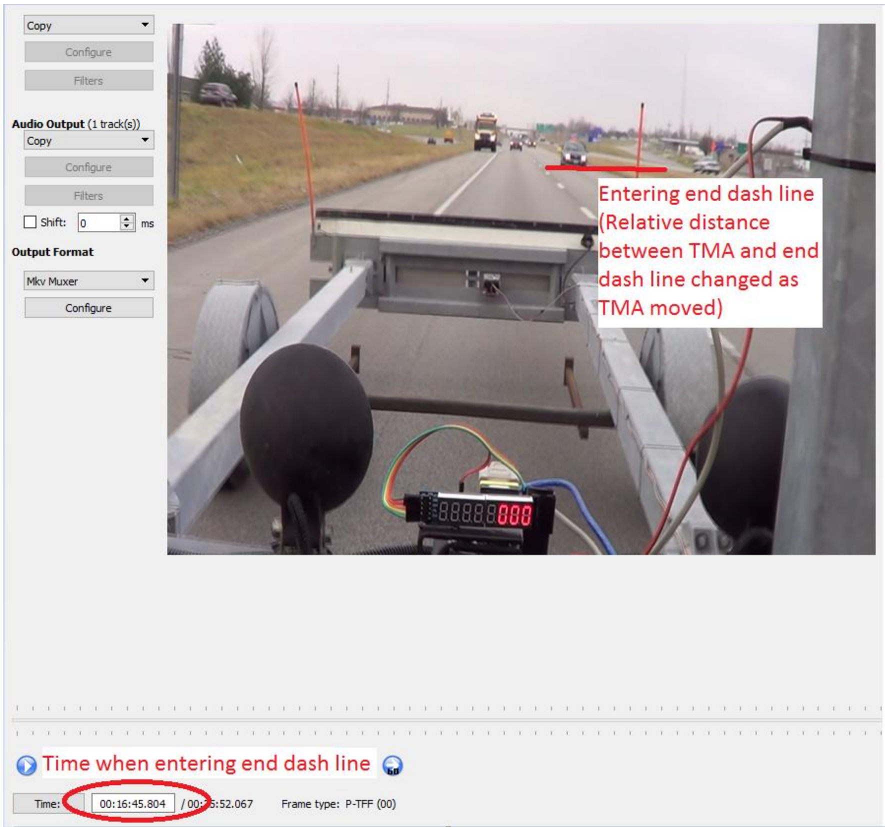


Figure 4.2.2 Time stamp two: vehicle entering end dash line

Besides the impact of different light bar configurations, the speed of vehicles may be affected by many other factors, such as the speed of a platoon leader if in a platoon, the speed of TMA, entering or exiting ramp, curves, or commercial vehicles and buses. To limit the impacts of other factors, data for vehicles entering and exiting the highway was discarded, as they were not reacting to the TMA but to entering/exiting maneuvers. Only the platoon leader speeds were captured to eliminate the influence of vehicle platooning. The speed of the rear advance TMA was sampled every five minutes and combined with vehicle passing speed to see how vehicles reacted to different TMA speeds. A total of 186 TMA speeds were sampled.

4.3 Field results

During the two-day field study, the travel speeds of the TMAs were not consistent due to different drivers and other factors. The speed of the green only TMA was consistent during daytime, but the speed of the amber/white TMA was significantly different from morning and afternoon. As TMA speed could influence vehicle passing speed, a statistical test was run for the speed data, with amber/white as the baseline. As shown in Table 4.3.1, the amber/white TMA travel speed in the afternoon was significantly lower than in the morning, and the speed of leading vehicles in the afternoon was significantly lower than in the morning. This is potential evidence that lower TMA speeds lead to lower vehicle passing speeds.

Table 4.3.1 Daytime speeds for amber/white (mph)

	Daytime speed: amber/white (mph)			
	TMA Speed		Leader speed	
	Morning	Afternoon	Morning	Afternoon
Count	13	35	186	566
Mean	20.3	9.8	64.5	61.9
Stdev.	1.1	2.9	6.0	6.9
Confidence level	100.0%*		100.0%*	
Cohen's d	4.76		0.40	
Effect size	Large		Small	

* indicates significance at 99%.

The results of the statistical analysis indicate that the TMA speeds may impact vehicle passing speeds. Therefore, the field data results are presented along with different TMA speeds. The overall mean daytime speeds are shown in Table 4.3.2. The amber/white TMA speed was significantly lower than the green only TMA speed, and the leading vehicle passing speed for amber/white TMA was slightly higher than for the green only TMA. It could be implied that if TMAs were travelling at the same speed, the leading vehicle passing speed for green only TMA would be much lower. In terms of impacts on vehicle speeds, the daytime performance of green only TMA was more desirable.

Table 4.3.2 Mean daytime speed (mph)

	Mean daytime speed (mph)			
	TMA Speed		Leader speed	
	green only	amber/white	green only	amber/white
Count	45	48	702	752
Mean	19.0	12.6	62.5	62.6
Stdev.	1.6	5.4	6.1	6.7
Confidence level	100.0%*		52.0%	
Cohen's d	1.67		n/a	
Effect size	Large		n/a	

* indicates significance at 99%.

In order to test if drivers behaved similarly under comparable TMA speeds, another statistical test was performed to compare the green only daytime data and amber/white morning data. The average morning amber/white TMA speed was 20.3 mph which was close to the green only TMA speed of 19 mph. The results are shown in Table 4.3.3. Although the speed of leading vehicles for green only TMA was slower, the speed of green only TMA was slightly slower than amber/white as well.

Table 4.3.3 Mean speed: green only daytime vs. amber/white morning (mph)

	Mean speed: green only daytime vs. amber/white morning (mph)			
	TMA Speed (mph)		Leader speed	
	green only daytime	amber/white morning	green only daytime	amber/white morning
Count	45	13	702	186
Mean	19.0	20.3	62.5	64.5
Stdev.	1.6	1.1	6.1	6.0
Confidence level	99.8%*		100.0%*	
Cohen's d	0.90		0.32	
Effect size	Large		Small	

* indicates significance at 99%.

During nighttime, even though the green only TMA travelled at a significantly higher speed than amber/white TMA, the vehicle passing speed for green only TMA was slightly lower, as shown in Table 4.3.4. The results show that green only TMA performed better than amber/white TMA during nighttime.

Table 4.3.4 Mean nighttime speed (mph)

	Mean nighttime speed (mph)			
	TMA speed		Leader speed	
	green only	amber/white	green only	amber/white
Count	45	48	504	631
Mean	22.2	12.6	52.1	52.9
Stdev.	2.7	1.2	8.4	7.9
Confidence level	100.0%*		94.6%***	
Cohen's d	4.60		0.10	
Effect size	Large		Small	

* indicates significance at 99%.
*** indicates significance at 90%.

For the same TMA configuration, driver behavior in daytime and nighttime was different. As shown in Table 4.3.5, even though the green only TMA travelled faster during nighttime, the vehicle passing speed was significantly slower during nighttime.

Table 4.3.5 Green only speed: daytime vs. nighttime (mph)

	Mean speed for green only (mph)			
	TMA Speed		Leader speed	
	Daytime	Nighttime	Daytime	Nighttime
Count	45	45	752	504
Mean	19.0	22.2	62.6	52.1
Stdev.	1.6	2.7	6.7	8.4
Confidence level	100.0%*		100.0%*	
Cohen's d	1.43		1.36	
Effect size	Large		Large	

* indicates significance at 99%.

The mean speeds of amber/white were similar for daytime and nighttime. As shown in Table 4.3.6, under the same TMA speeds, drivers tended to slow down during nighttime, and the passing speed at nighttime was significantly slower than daytime by almost 10 mph.

Table 4.3.6 Amber/white speed: daytime vs. nighttime (mph)

	Mean speed for amber/white (mph)			
	TMA Speed		Leader speed	
	Daytime	Nighttime	Daytime	Nighttime
Count	48	48	752	631
Mean	12.6	12.6	62.6	52.9
Stdev.	5.4	1.2	6.7	7.9
Confidence level	50.4%		100.0%	
Cohen's d	n/a		1.32	
Effect size	n/a		Large	

* indicates significance at 99%.

4.4 Luminance measurement

TMA light bar luminance was measured in order to study the light intensity of different TMA configurations. A luminance meter was utilized for measurement. Each light bar was measured three times to obtain the maximum and minimum light intensity. The mean of three readings is shown in Table 4.4.1. The data shows that the intensity of green light was higher than amber and white lights.

Table 4.4.1 Luminance measurement of TMA light bars (cd/m^2)

	Max	Min
Green (Undimmed)	6800	28
Amber (Undimmed)	7033	1329
White (Undimmed)	6333	551

It was difficult to measure the light intensity due to different flash patterns, because under different flash patterns, the intensities of lights were not consistent. Also, the dim/undim switch control was not available for amber/white TMA. There was a sensor of day light intensity on amber/white TMA, and the light bars were controlled by the day light sensor. When it was dark outside, the amber/white TMA was dimmed automatically. Also, there were some issues related to the calibration of the NIT gun. For future studies, it would be helpful to have greater laboratory control over the light bars.

4.5 Summary and discussion of field study results

The results for vehicle passing speeds showed multiple findings:

- Lower TMA speed led to lower vehicle passing speeds.
- Vehicles slowed down during nighttime.
- The green only TMA performed better than the amber/white TMA, in both daytime and nighttime. This result could be due to various reasons. It could be that green color caught

people's eyes better, or it could be the novelty effect of the green only TMA.

The field study results should be viewed with some considerations in mind. As the green color was deployed for the first time on work vehicles in Missouri, the novelty effect of green light TMAs may have impacted the results. Once drivers become familiar with green light TMAs, the performance of the configuration may be different. The results may vary in a different state, and the novelty effect of green lights should be examined in a study of longer duration. The field test was conducted during winter, and the green color stood out from the background of road. It is unclear if the effect of green light will be the same during spring and summer because of the lack of contrast due to green foliage.

Due to the limited availability of green only TMAs, the shoulder TMA was amber/white instead of green during the green only data collection. Since drivers passed the shoulder TMA first, they may have reacted to the amber/white shoulder TMA instead of the green only rear advance TMA. Because the TMA speeds were not consistent between the baseline and green only TMA, it was challenging to determine the magnitude of the effects caused by TMA speeds and light color configurations.

The field study attempted to record merge distance as one critical measurement from the perspective of collision prevention. However, most of the vehicles did not merge near TMAs, and only 8 out of 4,966 vehicles merged to the passing lane after bypassing the shoulder TMA; most merged upstream of the shoulder TMA.

CHAPTER 5: CONCLUSIONS

The simulator tests and post-simulator survey indicated that the amber/white TMA had the highest work zone visibility but lowest arrow recognition, and the green only TMA had the reverse effect. An inverse relationship between visibility/awareness of work zone and arrow board recognition/easy on eyes was derived from the results. This is consistent with literature, such as the NCHRP study on warning lights on roadway maintenance vehicles (Gibbons 2008). The green/amber TMA light configuration performed roughly between the two aforementioned configurations.

The field test results showed that lower TMA speeds led to lower vehicle passing speeds. In addition, the green light TMA performed better than the amber/white TMA, as the overall passing speed for the green only TMA was significantly lower. It was also found that drivers slowed down significantly during nighttime. The results from simulator study and field tests were complementary to each other, and all four configurations appear to be viable although none is clearly superior.

The study made several original and significant contributions to the body of existing knowledge regarding the use of green lights on work vehicles. This was the first study to quantitatively assess the use of green lights on work vehicles in the United States. In addition, the Missouri testing was the first on TMAs; DOT implementations have currently been limited to snow removal vehicles. The study included both simulator and field testing. The driving simulator allowed for multiple configurations to be tested efficiently in a controlled environment. Implementation of an eye tracker in the disability glare test provided for the tracking of human eye movement to determine if a specific object was recognized. The field study yielded data regarding vehicle speeds in a real-world implementation of green lights on TMAs.

The results of this project could be enhanced in many ways. Deploying a green only shoulder TMA to accompany the green only rear advance TMA would help to ensure that only the green light configuration was seen. Other configurations, such as green/amber could be tested in the field. The TMAs should be driven at the same speed to control for the effects of TMA speed on traffic speed. An additional study of longer duration could be undertaken to assess any possible novelty effects. A field evaluation during spring or summer could help to determine if there are any seasonal effects due to foliage color.

The study represented an effort to try and improve work zone visibility. Enhancing mobile work zone visibility with low cost countermeasures can help provide warning to drivers of the work zone and improve safety for both drivers and the work crew. Mobile work zone safety can be improved by other complementary measures, such as 1) better public education on texting and driving, especially near work zones; 2) exploration of other warning systems such as audio alerts in addition to visual cues; 3) working with connected autonomous vehicle industry to develop new technologies that could automatically recognize mobile work zones in the future.

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APPENDICES

Appendix A: Post-simulator survey

Truck-Mounted Attenuator (TMA) Simulator Survey

Proper communication of work zone information is critical for the safe movement of traffic through work zones. Please tell us your perspective on how to make work zones better.

Daytime TMA	 Figure 1a (green only)	 Figure 1b (green and yellow)	 Figure 1c (yellow and white)	 Figure 1d (green and white)
1.	**Please rate each lightbar color option from [5] Like it very much to [1] Dislike it very much.**			
	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]
2.	**Please rate all lightbar options from a scale of 10 (highest) to 1 (lowest) with respect to following:**			
Visibility of work zone vehicles				
Awareness of work zones				
Clear recognition of arrow direction				
Easy on the eyes				
Comments				

Nighttime TMA	 Figure 2a (green only)	 Figure 2b (green and yellow)	 Figure 2c (yellow and white)	 Figure 2d (green and white)
3.	**Please rate each lightbar color option from [5] Like it very much to [1] Dislike it very much.**			
	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]	[5] [4] [3] [2] [1]
4.	**I think the lights are too bright.**			
	[Disagree] [Neutral] [Agree]	[Disagree] [Neutral] [Agree]	[Disagree] [Neutral] [Agree]	[Disagree] [Neutral] [Agree]
5.	**Please rate all lightbar options from a scale of 10 (highest) to 1 (lowest) with respect to following:**			
Visibility of work zone vehicles				
Awareness of work zones				
Clear recognition of arrow direction				
Easy on the eyes				
Comments				

Please answer questions about your simulator experience.

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

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

7. I felt like I could drive around freely.

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

Please answer the demographic questions below.

8. Age range

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

9. Gender

[ ] Male [ ] Female

10. My Residency

[ ] Urban [ ] Rural

11. My Regular Vehicle Type

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

[ ] Tractor trailer truck [ ] Bus

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

____

____

____

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

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

Simulator Sickness Questionnaire

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

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

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

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

Appendix B: Additional comments from post-simulator survey

Participants commented on both daytime and nighttime configurations. As shown in Table B.1 (daytime) and Table B.2 (nighttime). The major comments concerned brightness, visibility of the work zone, disability glare, and clarity and effectiveness of the work zone.

Table B.1 Daytime comments

	Number of comments					
	Too bright	Too dim	Glare	Distracting	Clear/effective	Blurry/strain on eyes
Amber/white	6	-	2	-	-	-
Green only	-	2	1	-	2	1
Green/amber	1	-	1	-	2	-
Green/white	1	-	1	1	-	1

Table B.2 Nighttime comments

	Number of comments			
	Too bright	Hard to see	Glare	Clear/Effective
Amber/white	4	-	2	1
Green only	1	1	-	3
Green/amber	2	1	-	3
Green/white	2	-	2	2

Other overall comments are listed as:

- Green/amber- best mix of visibility and comfort (4).
- Preferred green/amber, but was more used to amber/white (1).
- Green is easy on the eyes at night, but may confuse drivers (2).
- Looking at the arrow more than the lights- only made a difference at night (1)
- Work zone was easy to see, but difficult to tell merge direction (1).
- Most helpful thing was the light bar pulsing in the direction of the arrow with the yellow color (1).