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Strategies to Reduce Truck Mounted Attenuator Crashes

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16. Abstract:

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ABSTRACT

Virginia has seen an annual increase in TMA crashes since 2015. These have primarily been struck-from-behind crashes during mobile operations. The objective of this project was to identify the most promising methods that could reduce the occurrence and severity of TMA crashes in construction and maintenance work zones, including both stationary and mobile operations. Specifically, this study examined the impact of various retroreflective panel configurations on the speed and lane selection of traffic in the area behind the TMA truck. A literature review was performed identifying aspects of a truck mounted attenuator (TMA) and TMA truck that could be modified to reduce crashes. Of these aspects, marking patterns and colors were selected for field testing. A TMA truck was parked on the right shoulder of a public highway and data was collected regarding the lane selection and speed of traffic that traveled past the truck. Ten treatments were tested: two different patterns, four different color schemes, and two panel configurations. Effectiveness was measured by the left lane occupancy rate and mean traffic speed for each treatment. A higher left lane occupancy and lower average speed were considered desirable. Results showed that a checkered pattern was more effective than chevrons, that green and black was the best performing color scheme, and that the addition of an upper panel increased effectiveness. A yellow and orange color scheme was found to be the worst performer. However, due to limitations of the study – specifically that testing was only conducted in daylight at one location – no recommendations for changes to TMA markings are being made. The results of this study should be used to inform further research which expands on this effort.

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INTRODUCTION

Truck-mounted attenuators (TMAs) are designed to improve mobile work zone safety by shadowing the work truck, enhancing work zone visibility, and capturing drivers' attention so they can merge into a work-free lane early and safely.

Virginia has seen an annual increase in TMA crashes since 2015. These have primarily been struck-from-behind crashes during mobile operations (while moving or during stops of up to 15 minutes). Major contributors to TMA crashes include driver inattention/behavior, road geometrics/sight distance, configuration of the mobile operations, and not following the Virginia Department of Transportation's (VDOT's) *Virginia Work Area Protection Manual* (2003). Recommendations to improve the safety of TMA use in Virginia include improving operator training, reviewing the position of the first TMA during mobile operations, improving guidance near ramps during mobile operations, and working with other stakeholders on media and outreach campaigns (Cottrell, 2015).

PURPOSE AND SCOPE

The objective of this project is to identify the most promising conspicuity methods that could reduce the occurrence and severity of TMA crashes in construction and maintenance work zones, including both stationary and mobile operations. Specifically, this study examined the impact of various retroreflective panel configurations on the speed and lane selection of traffic in the area behind the TMA truck.

METHODS

Overview of Research Approach

The project included the following tasks:

- Review of TMA Crash Countermeasures
  - Literature Review
  - Examination of Best Practices
  - Identification of Most Promising Approaches
- Field Evaluation
- Final Report

Review of TMA Crash Countermeasures

A review of TMA crash countermeasures was conducted which included a literature review, an examination of best practices, and identification of the most promising approaches. The Virginia Tech Transportation Institute (VTTI) research team conducted an extensive literature review and examination of best practices regarding TMAs. During these tasks, the team reviewed both published and unpublished domestic and international material as well as practical applications and field experiences. Major works that were referenced include United States (US) Department of Transportation (DOT) and national standards, state DOT standards, National Cooperative Highway Research Program (NCHRP) reports, and work zone conference proceedings. All documents obtained in the literature search were initially reviewed to determine if they contained more detailed information applicable to the project.

In addition, the research team conducted interviews with VDOT personnel and the industry that allowed us to identify causes and contributing factors of TMA crashes, including type of traffic, road category, time of day and work zone activities. Interviewees also identified potential countermeasures for the different taxonomies of TMA crashes.

Over the years, VDOT has incorporated in the *Virginia Work Area Protection Manual* (2003) significant countermeasures to reduce crashes, including the number of TMAs, staging of TMAs, signing of the work zone regarding the number and staging of TMAs, and work zone configuration. Thus, the coverage on these types of countermeasures in the report is limited.

The results of these tasks are presented later in this report (TMA Crash Countermeasures Review), and these results were used to provide guidance for establishing a field evaluation of TMAs on the roadway to determine the best marking pattern options for TMAs.

Field Evaluation Study Design

A human factors experiment was undertaken to clarify the needs for a TMA signage crash countermeasure. The literature review identified a variety of TMA marking pattern options in terms of color, placement, and auxiliary system which could influence the behavior of drivers around the functioning TMA. The process consisted of placing a TMA in a simulated simplified work zone on the shoulder and monitoring driver behavior around the TMA. Metrics of interest captured during data collection were the percent of vehicles in the left lane, vehicle speed, and speed variation while passing the TMA.

Research Questions

1. What are the best TMA marking color combinations to increase TMA awareness and conspicuity?
2. What are the best TMA marking patterns to increase TMA awareness and conspicuity?
3. Does increasing the area of the TMA marking pattern increase TMA awareness and conspicuity?
4. What are the best combinations of TMA marking color, pattern, and area to increase TMA awareness and conspicuity?

Test Location

Data collection took place at two locations along US 460 in Blacksburg, Virginia between Tom's Creek Road and North Main Street (Figure 1). These locations provide a long, straight, flat area with wide shoulders and long sight distances. Figure 2 and Figure 3 show the street-level view of these locations. This stretch of highway has no intersections or interchanges, and no hills. This means drivers can select their speed without influences beyond the posted speed limit (65 mph), and in this case, the presence of the TMA truck.

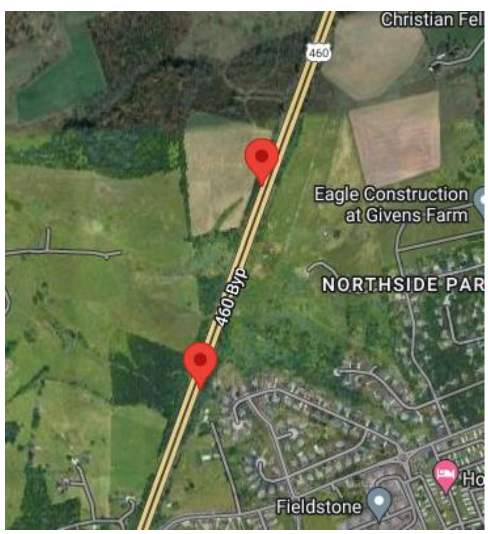

Figure 1. Data collection locations

Figure 2. Test location – Route 460 westbound

Figure 3. Test location – Route 460 eastbound

Test Vehicles and Equipment

The study used a flatbed VDOT truck equipped with a Scorpion attenuator (Figure 4). The rear of the attenuator was modified so that custom reflective panels could be attached. Additionally, an upper panel frame was mounted on the back of truck below the arrow board so an additional panel could be mounted above the attenuator when it was lowered. This upper panel extended the pattern on the rear of the attenuator, giving it a larger visual impact.

Figure 4. TMA truck with Scorpion attenuator and custom-mounted panels

The TMA truck was also equipped with a custom Move-Over Law (MOL) System developed by VTTI. The system consisted of a camera and radar array mounted on the rear of the truck (Figure 5), which captured the speed and lane position of vehicles approaching the truck from the rear, and a data acquisition system to record the data.

Figure 5. Move-Over Law data collection unit mounted on Stinger support beam

TMA Treatments

The 10 treatments identified in the literature were used. These consisted of five different color/pattern variants with and without the upper panel (Table 1, Figure 6). Four flashing lights at each corner of the arrow board were active with all configurations. The arrow board itself was not used to isolate the effect of the panels. For each TMA treatment, the volume of retroreflective material presented to approaching drivers was calculated. Retroreflective material area ranged from 5.6 to 26 sq ft covering either 50 or 100% of the panels, as shown in Table 1.

Table 1. TMA Treatments, Including the Volume of Retroreflective Material

TMA Treatment	Color and Pattern	Upper Panel	Lights	Retro Area (sq ft)	Panel Coverage
1	Fluorescent Yellow and Orange Chevrons 8" Stripes	No	Yes	12.6	100%
2	Fluorescent Yellow and Orange Chevrons 8" Stripes	Yes	Yes	26.0	100%
3	Red and White Checkers 12" Squares (Checkers)	No	Yes	12.6	100%
4	Red and White Checkers 12" Squares (Checkers)	Yes	Yes	26.0	100%
5	Yellow and Black Checkers 12" Squares (Checkers)	No	Yes	6.2	49%
6	Yellow and Black Checkers 12" Squares (Checkers)	Yes	Yes	12.8	49%
7	Lime Green and Black Chevrons 8" Stripes	No	Yes	6.2	49%
8	Lime Green and Black Chevrons 8" Stripes	Yes	Yes	12.6	49%
9	Yellow and Black Chevrons 6" Stripes	No	Yes	5.6	50%
10	Yellow and Black Chevrons 6" Stripes	Yes	Yes	12.3	50%

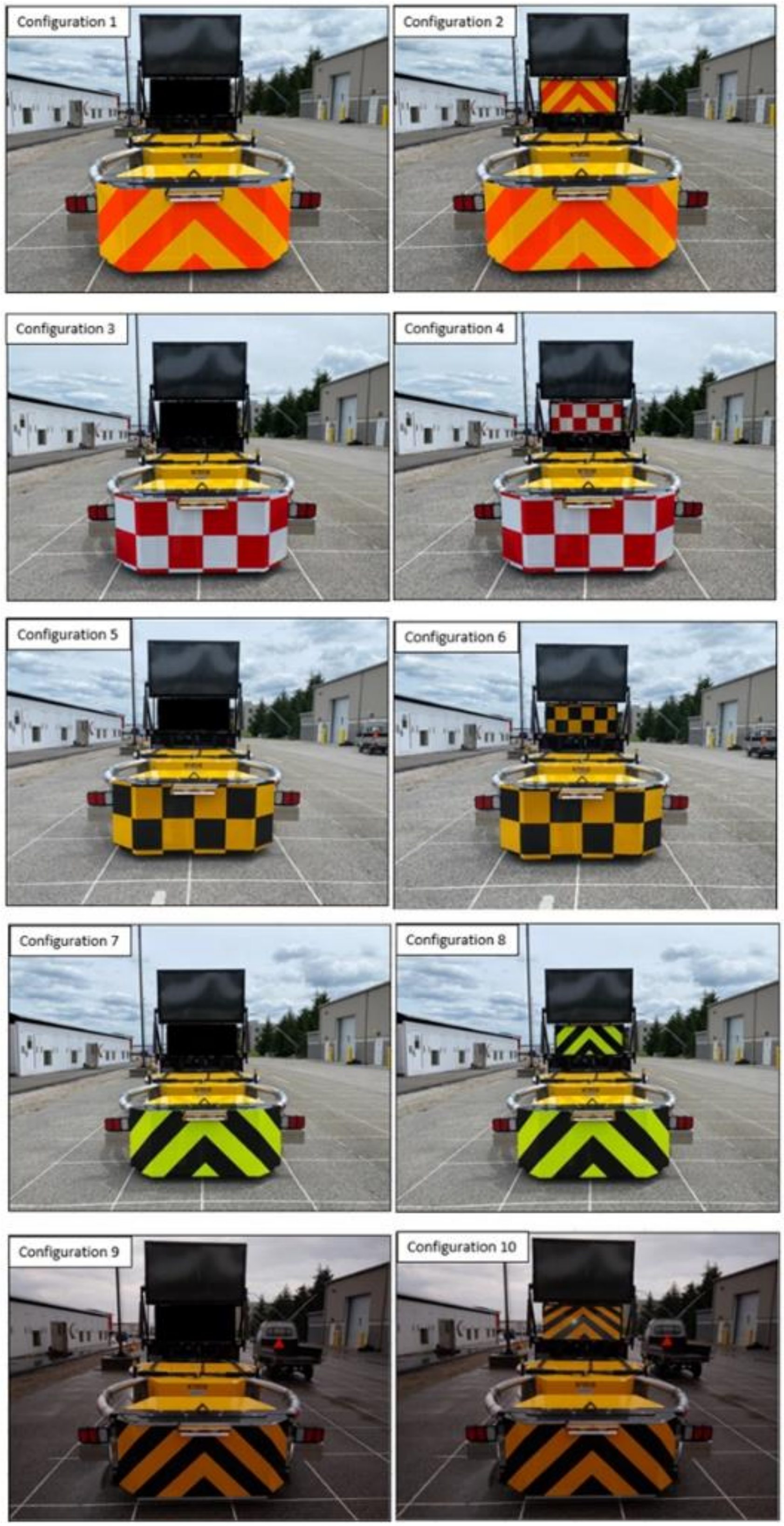

Figure 6. All 10 tested panel configurations

Experimental Procedure

Prior to leaving VTTI, the TMA truck was equipped with the appropriate panels. An experimenter collected traffic cones and put on standard work zone personal protective equipment (high-vis shirt, pants, and hard hat). The experimenter then drove the truck to the test area and engaged the truck's warning lights before pulling over onto the shoulder at the designated area on westbound US 460. The experimenter parked the truck as far onto the shoulder as possible, giving a clearance of approximately 3 to 4 feet from the nearest edge line. The experimenter then lowered the crash cushion and once lowered, exited the vehicle to set up the traffic cones on the shoulder of the road approximately 50 feet ahead of the TMA to mimic a small work area. No work zone signage was used so that changes in drivers' behavior could be isolated to the presence of the truck. The experimenter then engaged the data collection system, re-entered the vehicle, and notified the VDOT Traffic Operation Center of the location of the truck. Data was collected for 2 hours.

Once this session was complete, the experimenter exited the truck and stopped data collection. They then either added or removed the upper panel (depending on the presentation order) to prepare the truck for the next session. The experimenter then picked up the cones, raised the crash cushion, and drove the truck to a turnaround location. Once turned around, the experimenter parked the truck on the shoulder of eastbound US 460 and repeated the previous steps to collect another 2 hours of data. Once complete, they stopped data collection, picked up the cones, raised the crash cushion and returned to VTTI.

Data Collection, Reduction, and Analysis

Data Collection Schedule

Table 2 shows the data collection schedule. Each day, data collection consisted of a morning (10:00 a.m. to 12:00 p.m.) and afternoon (12:15 p.m. to 2:15 p.m.) session. These times were selected based on recent traffic data, which indicated an average volume of approximately 400 vehicles per hour, while also avoiding a.m. and p.m. peak volume times. Each configuration was used twice: once on the westbound lanes and once on the eastbound lanes. Because data collection required placing the TMA along the same stretch of roadway for multiple days, there was a possibility that a driver who frequently traveled along the test route might recognize, after several viewings, that there was no real work being conducted. The treatments were presented in an order such that treatments seen near the beginning of data collection were presented again near the end of data collection so any learning effects would be washed out. Additionally, repeated presentations of individual treatments were spread out by at least 1 month.

Table 2. Data Collection Schedule

Date	TMA Treatment	Location	Start	End
12/12/2022	1	Westbound	10:07 a.m.	12:00 p.m.
12/12/2022	2	Eastbound	12:19 p.m.	2:19 p.m.
12/13/2022	3	Westbound	10:04 a.m.	12:00 p.m.
12/13/2022	4	Eastbound	12:18 p.m.	2:18 p.m.
12/14/2022	5	Westbound	10:06 a.m.	12:00 p.m.
12/14/2022	6	Eastbound	12:16 p.m.	2:00 p.m.
12/19/2022	7	Westbound	10:08 a.m.	12:00 p.m.
12/19/2022	8	Eastbound	12:14 p.m.	2:14 p.m.
12/20/2022	9	Westbound	10:04 a.m.	12:00 p.m.
12/20/2022	10	Eastbound	12:14 p.m.	2:14 a.m.
1/23/2023	10	Westbound	10:07 a.m.	12:07 p.m.
1/23/2023	9	Eastbound	12:17 p.m.	2:17 p.m.
1/24/2023	8	Westbound	9:55 a.m.	11:55 a.m.
1/24/2023	7	Eastbound	12:08 p.m.	2:08 p.m.
1/26/2023	6	Westbound	10:02 a.m.	12:02 p.m.
1/26/2023	5	Eastbound	12:17 p.m.	2:17 p.m.
1/30/2023	4	Westbound	9:55 a.m.	11:55 a.m.
1/30/2023	3	Eastbound	12:08 p.m.	2:08 p.m.
2/7/2023	2	Westbound	10:00 a.m.	12:00 p.m.
2/7/2023	1	Eastbound	12:10 p.m.	2:10 p.m.

Data Reduction

Researchers at VTTI developed a machine vision algorithm to analyze video recorded by the MOL system. This algorithm allowed for the automatic tracking of vehicles as they approached the truck and provided the speed and lane position for each vehicle (Figure 7). Vehicles which were straddling the center lane line were assigned to a lane based on where the center of the vehicle was located. The results of the algorithm were compared to results of manual data reduction for a subset of the video files to ensure that the algorithm’s results were within an acceptable range of accuracy. Algorithm results were within 95% accuracy of manual vehicle counts, with the algorithm results tending to slightly overcount vehicles due to anomalies such as vehicles being counted twice when tracking was momentarily lost.

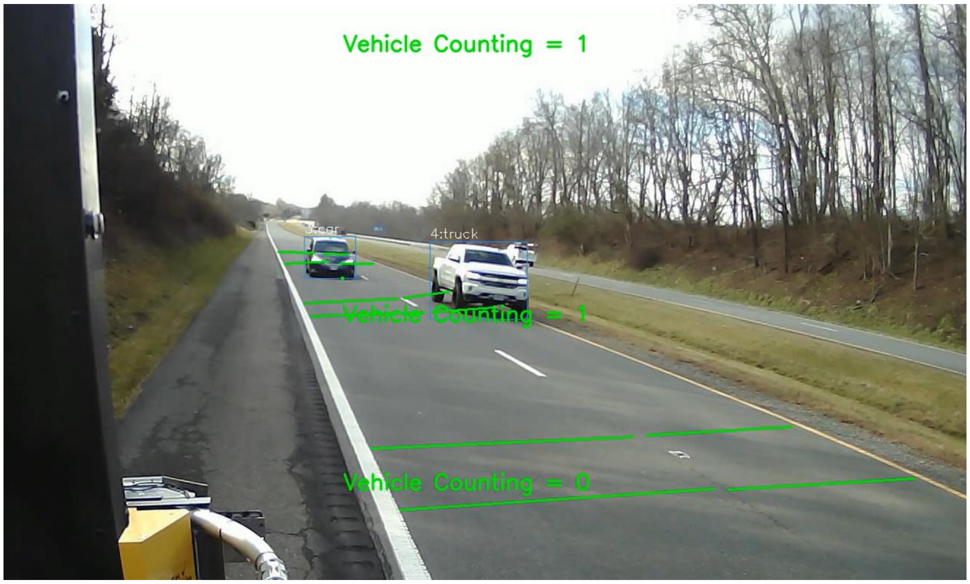

Figure 7. Example of machine vision and the use of gates to track vehicle speed and lane position

Data Analysis

For data analysis, the 10 TMA treatments were categorized into three independent variables so that the impact of each could be examined. Table 3 lists the factor levels and naming convention of each independent variable.

Table 3. Independent Variables

Variable	Levels
Marking Pattern	Chevrons
	Checkers
Color Scheme	Yellow+Orange
	Red+White
	Yellow+Black
	Green+Black
Panel	Yes (With)
	No (Without)

The influence of all independent variables and their interactions were assessed for each driver behavior metric. Three dependent variables were identified, and their descriptions are shown in Table 4. Vehicle speed, speed variation, and lane occupancy were obtained by analyzing the data recorded by the MOL system. As Virginia Law requires vehicles to change lanes away from a stopped vehicle or to slow down, the primary metrics are based on this driver behavior.

Table 4. Dependent Variables

Variable	Description
Left Lane Occupancy Rate	The rate of vehicles in the left lane reported as a portion of total vehicles.
Speed (mph)	The speed of vehicles measured approximately 40 to 80 ft behind the TMA.
Standard Deviation of Speed (mph)	The standard deviation of all vehicle speeds.

For analysis of speed data, the inter-quartile range (IQR) method was used to identify outliers. Table 5 gives the IQR procedure results. Based on these results, and the research team's knowledge of typical traffic speeds for the test site, it was decided to exclude speeds below 30 mph and above 85 mph as outliers that do not represent typical driving behavior. Overall, 1.7% (187) of total unique vehicles were identified as outliers and removed from the analysis dataset.

Table 5. Inter-Quartile Range Results (mph)

Lower Fence	Quartile 1	Quartile 2 (Median)	Quartile 3	Upper Fence
32.74	50.6	55.92	62.5	80.36

When reviewing data, it also became clear that measured speeds for one data collection session (Treatment 10 on the Westbound lanes) were not consistent when compared to all other data. Specifically, the mean speed was measured as 38 mph –11 mph lower than the next lowest – and no vehicles were measured going faster than 62 mph where there are typically hundreds of vehicles going over the speed limit. When investigating why speeds from this session looked so different, data collection notes taken by the TMA truck driver indicated that the weather was overcast with light snow flurries and a damp road. It was unclear if the weather conditions were poor enough to cause the difference in speeds, but to be safe, this data was excluded from the speed analysis. However, data for Treatment 10 was also collected on a different day, and this provided an ample sample size for analysis.

For all statistical tests, a familywise error rate of 5% was considered acceptable. P-values with values less than 0.05 were considered statistically significant for all tests. If multiple tests were performed, a Bonferroni or Tukey adjustment was carried out to keep the familywise error rate at 5%.

Due to the high number of unique vehicles which were captured in the data, analysis of the speed data resulted in statistically significant comparisons between factor levels, even when the speed difference was as small as 1 mph. For the purposes of the speed analysis, the research team instead decided to focus on a practical difference in speeds, which was defined as a difference of 4 mph or greater. At highway speeds, a reduction in speed of 4 mph translates to a stopping distance that is approximately 40 ft shorter.

During data analysis preparation, researchers considered whether vehicle platooning was having a significant influence on the speed of vehicles approaching the TMA. A review of existing research established vehicle headway and platoon size as two factors to account for when assessing the influence of platooning on mean vehicle speeds.

Studies looking to categorize platooned vehicles were found to, at highway speeds, assign vehicles as platooned when a 2- to 4-second headway distance between the vehicles was identified. Additionally, research indicated that vehicle speed was most likely to significantly deviate from free flow speeds when a car was in third or later position in a platoon grouping. Consequently, the research team investigated the difference in speed between platooned and free flow vehicles, as well as the rate of platoons three vehicles or larger.

Any vehicle with less than a 3-second headway between them and the preceding vehicle, within each lane, was marked as being platooned. Using the 3-second headway benchmark, on average, 23% of left lane vehicles were identified as being platooned and 10% of right lane vehicles were identified as such. Platoon size was assessed for all vehicles, with results showing that a significant majority (70%) of platooned vehicles were categorized as being in two car platoons. Overall, the rate of vehicles in a three car or larger platoon was less than 5% of total vehicles that passed the TMA. Speed data was summarized for each platoon category and platoon position, as displayed in Table 6.

Table 6. Mean Vehicle Speed by Platoon Category and Position Within Platoon Group

Platoon Category	Platoon Position	Mean Speed (mph)
Free flow	Lead	57.3
Follow Vehicle 1	Second	56.3
Follow Vehicle 2 +	Third or later	55.8

Data showed that, on average, speeds were reduced by 1.8% for vehicles in second position within a platoon when compared to free flow vehicles. For vehicles third position or later in a platoon, speeds were reduced by 2.6% compared to free flow. Overall, mean vehicle speeds were reduced by 1.5 mph when a vehicle was third or later within a platoon grouping. Due to the limited impact platooning had on the mean speed of vehicles and the low rate of large (3 +) platoon groups, the research team chose to include all vehicles, regardless of platoon position, in the analysis data set, as this provided a more comprehensive approach to the research questions.

RESULTS

TMA Crash Countermeasures Review

The primary objective of a TMA crash countermeasure is to prevent crashes or minimize the consequences of the crash (minimize injury). Preventing and minimizing crashes can be achieved at different stages of the crash. During the pre-crash, all the focus is centered on getting the driver’s attention to assure safe navigation through the work zone. During the crash, efforts must concentrate on countermeasures that reduce the consequences of the crash. During the post-crash, the objective is to improve the chances of survival by providing quick rescue and medical attention. The major focus of this project was to identify pre-crash countermeasures, excluding those related to truck characteristics, training countermeasures, changes in legislation, and enforcement. Countermeasures have been grouped into four major categories:

1. TMA Markings
2. TMA Truck Lighting
3. TMA Sign Countermeasure

4. TMA driver safety (seat belt)

In addition to the specific countermeasures the review also considers advancements made in automated and intelligent or connected TMA systems.

Category: TMA Markings

The TMA markings countermeasure refers to the use of markings on the rear panel of the TMA. Current VDOT standards include alternating 6- to 8-inch-wide orange and black stripes or yellow and black chevron (inverted V) stripes. Stripes are sloped at a 45-degree angle in both directions.

Potential solutions for evaluation included different patterns (chevrons or checkers), different sizes (6-, 8-, or 12-inch stripes), and different colors. As an example, the Verdegro TMA approved for VDOT can be configured in six different colors, as shown in Figure 8, however current VDOT specifications only allow for yellow and black or orange and black color combinations.

Figure 8. Color options for the Verdegro TMA (Verdegro)

The research team conducted a review of TMA colors, widths, and configurations in use at several DOTs. The majority of DOTs used the black and yellow inverted 'V.' A summary of the TMA chevron colors for some DOTs are presented in Table 7.

Table 7. TMA Chevron Color Used by DOTs

State	Black & Yellow	Red & White	Orange & White	Yellow-green & Orange	Orange & Black	Lime Green & Black
Alabama	X					
Alaska	X					
Arizona	X					
California	X					
Connecticut		X				
Delaware	X					
Florida			X			
Hawaii	X					
Indiana	X					
Iowa	X					
Kansas	X		X			
Louisiana	X	X	X			
Massachusetts	X					
Michigan	X					
Minnesota	X					
Nebraska	X					
Ohio	X					
Oklahoma	X					
Oregon	X					
Rhode Island	X					
Texas				X		
Virginia	X				X	
Washington	X					
Washington D.C.	X	X	X			X
West Virginia	X					
Wisconsin	X					
Total	**23**	**3**	**4**	**1**	**1**	**1**

Current VDOT standards require the rear panel of the TMA cushion to have alternating 6- to 8-inch-wide orange and black or yellow and black inverted 'V' chevron stripes. Stripes should be sloped at a 45 degrees angle downward in both directions from the upper center of the rear panel. It is necessary that stripes be fabricated from fluorescent orange or yellow retroreflective sheeting in compliance with Section 247 of the Road and Bridge Specifications (VDOT, 2020). To this end, a number of studies have been conducted to evaluate the effectiveness of various TMA markings for optimum vehicle visibility.

Smiley et al. (2017) conducted tests with nine different color and sheeting combinations during daytime and nighttime winter conditions on snowplows. The tests demonstrated that the best conspicuity panel that facilitated vehicle identification was a checkerboard pattern in fluorescent yellow-green and black.

Bham et al. (2010) evaluated the effectiveness of four TMA markings used by various DOTs in work zones: (1) lime green and black inverted 'V;' (2) red and white checkerboard; (3) yellow and black inverted 'V;' and (4) orange and white vertical striped. Participants were tested in a driving simulator to evaluate their driving behavior in highway work zones and assess their perceptions of the four TMA markings. Additionally, 32 DOTs evaluated their use and policy regarding TMAs by completing an online survey. Twenty-eight states (88%) indicated they used the yellow and black inverted ‘V’ pattern for TMA stripes in work zones. Eleven DOTs also specified the use of the color and pattern to conform to the *Manual on Uniform Traffic Control Devices* (MUTCD) guidelines for work zones, warning colors, and object markers (Federal Highway Administration [FHWA], 2013). Likewise, the participants’ perceptions were evaluated with a driving simulator as they drove through virtual highway work zones. The red and white checkerboard pattern had the highest rating for visibility, captured drivers’ attention the most, best contrasted with the TMA truck, and was generally the most preferred marking. However, the yellow and black inverted ‘V’ pattern was ranked the most effective in alerting drivers to work zones. A summary of the research findings is presented in Table 8.

Table 8. Surrogate Measures of Performance for TMA Markings (Rankings: Lower Number is Better)

TMA Marking Color	Visibility	Alerts Driver to Work Zone	Captures Driver Attention	Color Contrast with TMA Truck	Overall Preferences
Red and White	1	4	1	1	1
Orange and White	3	2	4	3	4
Lime Green and Black	2	3	2	2	2
Yellow and Black	2	1	2	4	3

A similar study by Lan et al. (2019) evaluated the effectiveness of different colors and patterns of retroreflective tapes that could potentially increase the visibility of trucks. While this study refers to trucks, the findings are useful for the TMA study. The five options for pattern markings on the rear of trucks are presented in Figure 9.

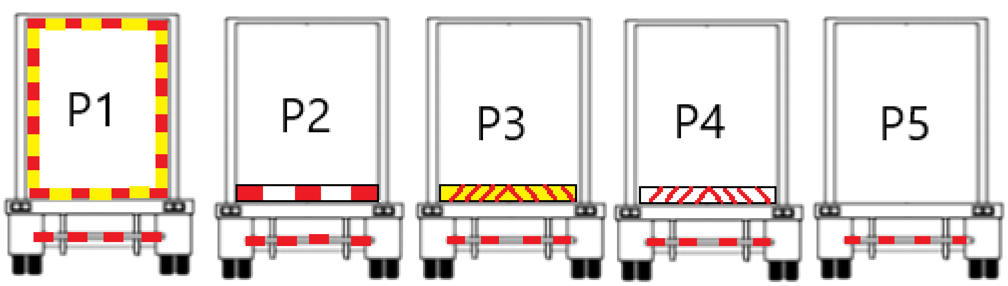

Figure 9. Pattern options and placement on the rear of trucks (Adapted from Lan et al. (2015)

The results revealed that, among all patterns tested, the most visible retroreflective tape pattern was the fully outlined alternating red and yellow retroreflective tape, placed horizontally and vertically on both the right and left, upper and lower rear sections of the truck (P1 in Figure 9). The next most visible were the orange and yellow chevron, the red and white chevron, and then the red and white squares (P3, P4, P2 in Figure 9).

Category: TMA Truck Lighting

Warning Lights

Warning lights are mounted on trucks with TMAs for several reasons pertaining to safety during travel. These include warning motorists of maintenance vehicle activities on a road or near the roadway, notifying drivers to react in advance, defining the shape and size of work vehicles, and conveying the intent of the TMA. The warning light countermeasures refer to the different possible configurations of lighting on the truck top.

Warning lights can be classified by light source, colors, intensity, flashing rates, and position. Warning lights should be bright enough to be seen during daytime and nighttime, but not so bright that they cause glare or distraction (Bullough, 2015). Glare can be caused by a bright light source in a person's field of view, which can significantly reduce the person's ability to see other objects. Trench et al. (2014) distinguished between two types of glare:

- Disability glare is a condition in which the driver may be temporarily blinded and unable to see hazards in the road even when looking directly toward them.
- Discomfort glare is a more general effect that may cause motorists to avert their eyes. During this time, they may fail to see obstacles soon enough to avoid them.

State DOTs have expressed concern regarding:

1. Inconsistency of warning lights configurations for the same type of equipment.
2. Inconsistency of warning lights patterns for the same light level.
3. Need for a brighter daytime effect and possibly a passive nighttime effect.
4. Whether the driving public has become desensitized to amber only lights.

The introduction of new lighting technologies, such as strobes, halide bulbs, and LEDs have spurred the rapid development of a wide range of products aimed at law enforcement, fire, and ambulance fleets. State DOTs and county and municipal Departments of Public Works soon followed the trend of adopting more and brighter warning lights. New developments also gave these agencies the option of using colors other than amber, although individual states restrict the use of forward-facing red (and blue in some states) to authorized emergency vehicles. Table 9 outlines some common warning light colors and known applications. DOTs have devised numerous combinations of amber, white, blue, and green lights, and even rear-facing red only, to increase conspicuity of working vehicles. The lower electrical draw and smaller sizes of newer lighting devices allow for more of them to be installed on vehicle tops, sides, rears, and even fronts (e.g., grill lights and "wig-wag" headlights). Furthermore, electronic circuitry allows for a range of set or variable flash patterns, rates, and light intensity. The following sections provide a brief description of the type, color, intensity, flash patterns, and position of warning lights.

It is also noteworthy that warning light systems may be used in conjunction with other alerts such as auditory or motion based. These systems are currently being researched at VTTI.

Light Type. Trench et al. (2014), on behalf of the Federal Emergency Management Agency, summarized four main types of emergency lights used on emergency vehicles in the U.S.

Rotating Lights are among the oldest types of warning lights in use on emergency vehicles. A flashing sensation is created as the light beacon rotates within its casing and catches the attention of motorists. Rotating lights provide coverage over the full 360 degrees surrounding the vehicle on which they are mounted.

Fixed Flashing Lights provide a beam of light that is projected in a single direction. These lights draw attention by flashing on and off. In most cases, these types of lights are used as supplemental lighting on the middle to lower portions of the vehicle to augment the larger lighting system on top of the vehicle.

Strobe Lights were the first new additions to emergency vehicle lighting capabilities following the era of rotating lights. Strobes are fixed lights that flash in only one direction. During normal daytime maintenance operations, the functions of flashing warning beacons may be provided by rotating lights or strobe lights on a maintenance vehicle (FHWA, 2013).

Light-emitting Diodes (LED)s emit a powerful beam of light yet use a minimal amount of electrical energy and have exceptionally long lifespans. In addition to their brightness and high level of visibility, they create a low level of draw on the vehicle's electrical system compared to strobes or traditional flashing lights.

Light Color. The color of warning lights is one the primary ways that information is transferred to drivers. Although some have called for the international standardization of lighting colors to reduce confusion among drivers, there is currently no uniformity in warning light color. The color of warning lights is regulated by state motor vehicle codes.

Table 9. Warning Light Colors and Uses

Light Color	Applications
Red	Most other non-emergency service vehicles are prohibited from displaying red flashing lights. Motor vehicle codes usually require motorists to yield or come to a complete stop for vehicles displaying red warning lights.
Amber	Typically have the broadest range of acceptable use in most motor vehicle codes. Commonly used on construction and maintenance vehicles, they are typically considered cautionary warning lights, and other motorists are not required to yield or stop for them.
White	Typically used as a contrasting color to other light colors used on an emergency vehicle.
Green	Most commonly used to signal the dedicated position of an Incident Command Post. In some states, green lights are also used on volunteer firefighter or EMS personnel's privately owned vehicles or on private security guard vehicles.
Blue	Have the widest variety of uses in the U.S. In many states, they are used as a contrasting color with red and/or other colors of lights on all types of emergency vehicles. In other states, tow trucks, snowplows, and other public utility vehicles have blue lights.

Table 10 shows the different type of warning lights used by a selected number of state DOTs. Amber light was most closely associated with maintenance vehicles. Red, amber, and white are generally used on emergency vehicles. Blue is sometimes reserved for law enforcement; however, they are seeing increased use on all types of emergency and public utility vehicles due to the visibility benefits and the public recognizing the need to move over for blue lights. A survey by Howell et al. (2015) found that all 16 state DOTs surveyed used amber-colored lights in their warning systems. Green is typically reserved for stop lights, fire service, and incident command posts (Trench et al., 2014). Bullough and Rea (2016) found little difference in response times to steady green and steady yellow lights and demonstrated that the nighttime reaction times of participants to red, yellow, and green lights of the same intensity were equivalent. However, they also found that yellow light at 900 candela (cd) and green light at 450 cd received the same discomfort glare rating. These results suggest that alternative light sources should be used cautiously at night.

Table 10. DOT Warning Light Colors Used in Various States

DOT	Amber	White	Blue	Red
Alabama	X	X		
Alaska	X		X	
Colorado	X		X	
Illinois	X	X	X	X
Indiana	X		X	
Iowa	X			
Kentucky	X			
Maine	X			
Massachusetts	X	X		X
Minnesota	X		X	
Mississippi	X		X	
Missouri	X	X	X	
New Hampshire	X	X		X
Ohio	X	X		
Oklahoma	X	X	X	X
Rhode Island	X	X		
South Dakota	X			
Texas	X		X	
Washington	X	X		X
Virginia	X			
Total	21	9	10	5

Of particular interest for this research are states that have incorporated green lights in their warning light configurations. In a recent survey regarding the use, and interest in the use of green lights on maintenance vehicles, Zockaie et al. (2020) noted that DOTs who answered “No” were further asked the reason they were not using, or interested in using, green light configurations. The most common responses were current legislation or state regulations, satisfactory performance of their current color combinations, using green for other vehicle types, and one state that mentioned that green means “go.”

Texas DOT (TxDOT) categorizes vehicles by their types and defined standards and specifications for warning light requirements for various maintenance, emergency, or service vehicles. Highway maintenance or construction vehicles make use of flashing amber lights but are prohibited from using or being equipped with flashing white lights. Moreover, conditions are specified for the use of simultaneous amber and blue warning lights, such as during snow removal, during continuous or intermittent mobile operations with stoppage time of approximately 15 minutes, while working beside moving traffic or the shoulder edge without supporting channeling devices, and in response to incidents. It was recommended that blue and amber lights be set up to operate independently. The installation of the blue warning light was suggested on the driver's side to enhance visibility (TxDOT, 2017).

One of the most comprehensive studies, by Brown et al. (2018), on behalf of Missouri DOT (MoDOT), investigated the use of green versus traditional amber lights on TMAs to examine whether their use could improve safety in mobile work zones. Amber/white, green only, green/white, and green/amber color configurations were evaluated via a combination of simulator and field study. Additionally, the TMA was enhanced with lights on the hood; however, the purpose of the study was to evaluate light bars on the top. The simulator study results indicated that the amber/white combination had the highest work zone visibility but created the highest level of concern with disability glare. In contrast, the green-only configuration yielded the least disability glare but produced a low overall visibility. A summary of the simulator research findings is provided in Table 11.

Table 11. Performance Results of Various TMA Warning Light Color Configurations

Performance Measurement	Daytime		Nighttime	
	Best	Worst	Best	Worst
First blinker distance	Amber/white	Green/white	Amber/white	Green only
Merge distance	Amber/white	Green only	Amber/white	Green only
Work zone visibility	Amber/white	Green only	Amber/white	Green only
Arrow direction recognition	Green only	Amber/white	Green only	Green/white
Disability glare	N/A	N/A	Green/white	Amber/white

The simulator and field study findings were complementary, but none of the configurations outperformed the others. The most important findings of the field study are as follows:

- Lower TMA speeds led to lower vehicle passing speed.
- The green light TMA overall passing speed was significantly lower than for the yellow light.

Note that the Code of Virginia defines what light colors can be used in given conditions and vehicle types. Not all options of light color are currently available for use. As the code and the additional research is updated, more color configurations may be possible.

Light Intensity. Daytime and nighttime conditions require different light intensity ranges. During the day, higher minimum thresholds are necessary for the lights to stand out against the ambient light of the sky. Conversely, nighttime conditions necessitate lower maximum thresholds to prevent the approaching driver from encountering intrusive glare conditions (Howell et al., 2015). Therefore, there should be a balance between vehicle conspicuity and light intensities to allow motorists to identify a potential hazard in ample time to take early avoidance action. Rea and Bullough (2015) showed that response times for warning beacons increased at intensities exceeding 600 cd during the day and 200 cd at night when viewed on-axis, which validates the work of NCHRP 13-02: Guidelines for Selection and Application of Warning Lights on Roadway-Operations Equipment (National Academies of Sciences, Engineering, and Medicine, 2008). While the American Association of State Highway and Transportation Officials (AASHTO) guidelines take a one-size-fits-all approach to lighting requirements, they also note that the roadway conditions should be considered carefully; for example, a higher intensity light source may be required in urban areas to overcome external light sources along with fixed roadway lighting. To this end, AASHTO provides recommendations for daytime and nighttime lighting intensities by light source, as shown in Table 12.

Table 12. AASHTO Recommendations for Daytime and Nighttime Intensities of Various Light Sources

Light Source	Intensity (Lumens)		
	Daytime	Nighttime	
	Minimum	Minimum	Maximum
Halogen	3,500	900	2,200
LED	4,000	1,650	-
Strobe	3,500	1,200	2,200

Flash Pattern. While selecting the correct flash pattern can help drivers safely navigate through work zones and snow, the effectiveness of the light pattern can be limited by the flash rate. The flash rate of a warning light can help drivers judge the situational urgency level and aid in the detection of oncoming traffic. Because flash rates interact with the flash pattern, both must be considered when choosing the appropriate warning light configuration. Turner et al. (2014) combined flash rates of 1 and 4 Hz with flash patterns of one and three pulses and found statistically significant interactions; all four combinations increased hazard perception compared to no lights. Rea and Bullough (2016) found that the ability to flashlights in a synchronized pattern was the second most useful feature of warning lights. However, in the same study, participants in a human factors experiment rated a sequential pattern easiest to navigate at night. The use of an incorrect flashing pattern can also cause drivers to improperly judge the directions of vehicles in front of them. A side-to-side alternating flash pattern using red lights caused participants to judge approaching lights as stationary and biased participants towards judging movement as away from them (Berkhout, 1979). These aforementioned studies indicate that a significant amount of effort is required to identify the needs of the driver with respect to the flash rate and flash pattern to clearly provide guidelines for the user.

Light Position. Muthumani et al. (2015) observed that lights mounted at a height near a driver's line of sight tend to increase glare, especially at close distances. Therefore, lights should be placed as high as possible on the vehicle to reduce the potential for visual impairment. In addition, specialty vehicles used in mobile operations should have 360-degree coverage with self-contained LED units using mounting specifics dictated by the vehicle's physical characteristics (Gibbons et al., 2008).

The Kentucky Transportation Center (KTC) in cooperation with the Kentucky Transportation Cabinet recommended the use of amber and white colors for KTC work vehicles, an asynchronous flashing pattern with slow flash frequencies, and LED bulbs. KTC also suggested placing warning lights at high elevations on the vehicle against a solid-colored background that contrasts with the sky (Howell et al., 2015).

In a study that considered both color and position of the light source, Michigan DOT investigated the use of strobe green lights on maintenance vehicles. Researchers conducted static and field studies to investigate the degree to which the visibility of Winter Maintenance Trucks (WMT) was affected when green lights were incorporated. They evaluated situations for which green lighting was the most or least effective, evaluated flash patterns (single versus quad or fast versus slow), and provided recommendations for the placement of green auxiliary lights (Fakhrmoosavi et al., 2021).

The study was conducted for normal and adverse weather conditions. A total of 37 warning light configurations were generated using various color combinations (green and amber) and flashing patterns (single and quad) on the back side (LED) and/or top (beacon) of the WMTs. Controlled field studies showed that the treatment option with all amber lights (LC03) had the lowest conspicuity; the highest conspicuity was attributed to all quad flashing lights and green in both LEDs and beacons, (LC 32). However, there were no statistical differences among the configurations for the surrogate measure “Action-Taking Distance” (Fakhrmoosavi et al., 2021).

As expected, the results suggest that there is a tradeoff between sufficient level of conspicuity and satisfactory level of glare. The flashing pattern also affects conspicuity and glare.

- A single flashing amber LED does not provide enough conspicuity.
- A green LED used in a quad flashing pattern generates excessive glare.
- The use of single flashing green lights along with quad flashing amber lights provides adequate conspicuity and a satisfactory level of glare.

To maximize the benefits of warning lights for different conditions, implementation of programmable warning lights that facilitate use of various warning light configurations, intensities and flashing patterns is recommended.

Enhanced Working Lights

In addition to warning lights, the truck or TMA are also equipped with working lights, which include headlights, rear lights, and side lights (Figure 10). Rear working lights increase the awareness and conspicuity of the TMA for following vehicles. In general, rear working lights are typically mounted on the TMA’s hood or at the side or top of the TMA’s hood. The type of lights, the color, the number of lights, and their position can be changed to increase TMA conspicuity and awareness. The rear end working lights can be permanently activated or can be sensor or manually activated when a vehicle approaches the TMA.

Figure 10. Enhanced working lights

The impact of enhanced rear end working lights configuration has not been formally evaluated yet and there are concerns about the crash worthiness of lights added to the TMA; however, the MoDOT study evaluation of warning lights included extra lighting on top of the hood in some of the alternatives.

Category: TMA Sign Countermeasure

This countermeasure refers to modifying the type or number of TMA signs. For the purposes of this report, “TMA sign” will refer to any sign mounted on the TMA or truck that provides the driver with information as to what action to take or the type of work being conducted.

Some of the strategies provided below have not been evaluated specifically on a TMA, but it has generally been assumed that some types of signs will provide similar benefits to those obtained using the sign in other applications (e.g., speed feedback sign).

Extra Sign: Static

For the purposes of this report, “static sign” refers to a sign that maintains the configuration and is not activated by the TMA driver or the approaching vehicle (Figure 11). Examples of this application include the incorporation of a retroreflective sign or a variable message sign with a static message.

Figure 11. A TMA truck with a static sign

Extra Sign: Dynamic

A “dynamic” sign refers to one which can be activated by the TMA operator or through the detection of approaching vehicles. A typical example of this countermeasure is the addition of a speed feedback sign (Figure 12). At the time of this report there has not been a formal evaluation of speed feedback signs on TMAs.

Figure 12. Dynamic message sign activated by operator or approaching vehicle

Several studies have confirmed the effectiveness of speed feedback signs for regular road conditions (Hallmark, et al., 2015; Gibbons et al., 2015). In 2019, the Iowa DOT evaluated speed feedback signs in work zones (Thapa, 2019). The results showed that drivers were 5 times more likely to respond to a dynamic speed feedback sign than a regular static speed limit sign. In general, Iowa DOT asserted that speed feedback trailers were more effective under the following conditions:

(a) if perception of regular enforcement (and threat of citation) exists at site.

(b) the sight distance to the treated condition is less than decision sight distance.

(c) where only one lane exists per direction.

(d) if used with other information indicators of a need to reduce speed.

(e) if the speed feedback trailer is used to support a regulatory speed limit.

Extra Markings

Similar to the inclusion of cushion markings, there is the possibility to include extra markings on other parts of the TMA truck (Figure 13). This extends the area of the markings beyond the crash cushion to create a greater visual impact.

Figure 13. Extra markings placed above the cushion and below the arrow board

Category: Driver Safety Countermeasure (Seat Belts)

Even when the most advanced methods of crash prevention are employed, impacts involving TMAs can still occur. If a crash cannot be avoided, it is important to make sure that the TMA is equipped to protect the operator. Advances in previously existing technology and new research have the potential to modernize the TMA and make it a safer work vehicle. The main areas to be improved are the seat belt system used, the seat construction and orientation, and the cockpit area the driver occupies in the vehicle.

There are four seatbelt systems that are applicable to the TMA. Each system is categorized based on the number of attachments the belts have to the vehicle or seat. The five- and six-points system seat belts are not allowed on public highways, as they do not meet all the requirements of the Federal Motor Vehicle Safety Standards (FMVSS) standard on seatbelt assemblies which requires the buckles to permit easy and rapid removal from the assembly (National Highway Traffic Safety Administration, 2021). The legislation is not totally clear on four-point harness systems and there is no consensus on the benefits compared with the three-point system. Each of the four seatbelt systems are discussed in detail below.

Three-point System

The standard three-point system found in most vehicles has three points of attachment: one to the vehicle at the occupant's shoulder, one at the waist attached to the seat, and the last where the entire system is secured at the buckle. Although "the 3-point seat belt is acknowledged to be the most important safety feature in motor vehicles today" it is still not the best option when restraining an occupant during an impact (Rouhana, et al., 2003). The three-point system provides minimal support to prevent the occupant from being thrown forward in the event of a collision. The principal issue with this belting system is the potential for the operator to submarine under the belt during the accident or be thrown against it, causing thoracic injury, which is otherwise known as the seat belt sign (Forman et al., 2009).

Four-point System

The next option is the four-point seat belt system, of which there are two common orientation options for the chest straps or harness portion. The first is an X-form configuration where two shoulder belts crisscross the occupant's chest in an "X" shape; the belts secure at each shoulder and on each side of the waist with the lap belt. All the belts meet in the middle and either secure here, or at either side of the occupant's waist. The second is the V-form four-point system, where the two shoulder belts come down over the occupant's chest parallel to one another in a "V" shape. The lap belt originates from the seat on each side of the occupant's waist and the shoulder belts to the lap belt on each side of center. The buckle is either in the middle where all the belts meet or on either side of the occupant's waist. A V-form four-point "system showed decreased chest deflection and thoracic injury" because it controlled "the upper torso motion by applying load predominantly to the shoulders and pelvis and avoided loading the chest and abdomen" (Rouhana et al., 2003). The V-form belt out-performed the X-form, as the X-form has a tendency to ride "up on the torso…and interact with the neck" (Rouhana et al., 2003). This interaction can cause more injuries than the belt prevents in the event of a crash, including submarining under the belt, thoracic injury, and organ injury.

Five-point System

A five-point belt system is thus named because its belts have five origination points. The harness portion consists of two belts, each anchored to the seat on each side of the occupant above shoulder level. These two belts meet the lap belt, which originates from the seat on each side of the occupant at the waist, and a fifth belt, in the middle of the occupant's waist. This fifth belt originates from the seat between the occupant's legs and buckles in the middle, where it meets the rest of the harness. It anchors the occupant in their position in the seat, preventing the occupant from sliding down in the seat and preventing significant forward motion of the occupant's torso.

Six-point System

The last type of restraint system is the six-point seat belt. This harness is almost identical to a five-point system, but instead of having one crotch strap, this system has two belts that originate from the seat between the occupant's legs and each wraps around one of the occupant's thighs and anchor directly below the lap belt anchors on each side of the seat. These belting systems are used in Indy car racing. Sled tests performed using six-point restraint systems "have shown that the early restraint of forward pelvic motion provided by the double rear-facing crotch belts promotes early engagement of the shoulder belts, thereby reducing chest loading" (Melvin et al., 2006). This reduced chest loading prevents all serious thoracic injuries seen in crashes where the driver was not wearing a six-point harness.

"The performance of the occupant restraint system is directly related to the occupant's injury" (Du et al., 2019). Based on the research done by Melvin et al. and Rouhana et al., the safest belting system is the six-point system as it is the most successful at preventing excess forward motion. Ultimately, "injury can be minimized with a properly adjusted seat belt" (Du et al., 2019). This can be done further by implementing a progressive force-limiting pre-tensioning seat belt to "remove slack from the belt so that it engages earlier to better prevent injury in the occupant" (Forman et al., 2009).

Additional Restraint Systems

Also, of concern in a rear-end impact are whiplash injuries, or injuries caused by the unrestrained motion of the head and neck. Five-point and six-point seat belt systems allow for the integration of head and neck restraint devices to prevent whiplash. The two most common are the HANS device and the Hutchens device. The HANS device is yoke-like and loads the forward motion from the head into the shoulders, preventing just the neck from snapping back and forward. The Hutchens device is similar, but instead of sitting on the shoulders, this device attaches to a series of straps that wrap around the occupant's shoulders, chest, and waist. Each system requires the occupant to wear a helmet that the restraint system attaches to. The HANS device is more expensive and restrictive than the Hutchens system but may better prevent whiplash and the accompanying basilar skull fractures. Both the HANS and Hutchens systems allow whatever belted restraint system (five-point or six-point) the operator is wearing to secure the head and neck when it secures the torso and prevents chest deflection during an impact.

Aside from head and neck support devices, existing head rests and seatbelts are thought to act in conjunction to help mitigate whiplash. Unfortunately, "the vast majority of occupants failed to raise adjustable head restraints high enough to reduce whiplash," and positioned themselves too far from the headrest (Viano, 2008). Integrating pre-crash sensing technology in TMAs would allow the seatbelt and headrest to function properly (Kusano and Gabler, 2010). Specifically, occupant pre-positioning would diminish the impacts of whiplash by sensing when "rear-end impact is unavoidable" (Jakobsson et al., 2015). This would trigger "an electrical reversible safety-belt pretensioner…to retract and keep the occupants in position" (Jakobsson et al., 2015). This seatbelt apparatus in combination with a seat in which the "design of the backrest and head-restraint together with energy-absorbing functionality of the seat cushion/frame allows occupant to sink into seat in event of impact" would completely eradicate whiplash concerns for TMA operators (Jakobssen et al., 2015).

The head and neck are not the only part of the TMA operator's body that needs to be protected in the event of a rear-end collision. After the head and neck, the chest is the most vulnerable part of the body (Danelson et al., 2011). A lightweight "chest plate appears to offer some protective value" (Danelson et al., 2011). This may not be the most applicable fix to this situation, though, as body armor is usually unwieldy and may get in the way of operating a vehicle. The seat itself could also be altered to help prevent thoracic injuries to its operator. According to a study conducted by Viano (2008), maintaining low seat stiffness and increasing frame stiffness in the seats can better prevent whiplash injuries. This could be achieved by enhancing the seats in a truck with a TMA with memory foam (Wang and Nevo, 2018). Wang and Nevo's study showed that when only stiff seats were used in a crash, lumbar spinal injury would occur, but when polyurethane foam cushions were introduced, injury could be reduced or prevented completely (2018). Further injuries could also be prevented by introducing a more comprehensive package of airbags into the seat and cockpit of the truck with a TMA (Ryan et al., 2008). The system proposed by Ryan et al. (2018) would have at least two extra airbags; one would deploy from the top of the door, providing shoulder-thorax protection and the other would deploy from the middle of the door providing pelvic-thorax protection. A system like this could help the TMA operator avoid injuries associated with rear-end collisions.

Another option is to change the way the seat sits in the cockpit of the truck. In Indy cars, drivers use harnesses and reclined seats "and there have been no significant rib cage, thoracic organ, or shoulder injuries noted since…1999" (Melvin et al., 2006). Parts of this arrangement could be modified for the cockpit of a truck, such as "using a custom polystyrene bead foam insert between the interior walls and the driver from head to knee…and a custom shaped foam seat supporting the pelvis (Melvin et al., 2006). When the seat is configured in an optimal position for the "safety of occupants under acceleration and impact loads…the probability of injuries to the head and neck can be reduced up to 0.17 and 0.23" (Afshari et al., 2018). The optimal position in a truck with a TMA will be fluid, as TMAs are utilized in both stationary and active operations.

Category: Intelligent Transportation Systems

Intrusion alarms can provide audio and visual alerts to drivers and workers. They can be kinematic such as the Sono Blaster which was tested in New Jersey and Kansas (Krupa, 2010; Novosel, 2014) or Intellicone tested at the University of Kansas (Novosel, 2014). They can also be radar-based, such as the AWARE system which has been tested in Missouri and Texas (Cleaver, 2016; Theiss et al., 2018). The previously mentioned studies focus on worker protection and the capability of detecting vehicles. Additionally, Ukkusuri et al. (2016) concluded that the effectiveness of loudspeakers as an advance warning device varies, and an array of multiple loudspeakers in an appropriate pattern was found to be the most suitable for long-distance auditory warnings. Theiss et al. (2018) measured the performance of an alarm system under different conditions for a work zone intrusion detection system. The pre-collision warning involved flashing LEDs and an audible alarm. Using different vehicle trajectories, lane closures, and flagging operations showed that the alarm system was effective. The Missouri DOT tested a directional audio system alarm that can be operated in continuous, manual, and actuated modes (Brown, 2015).

Vehicle-to-vehicle (V2V) communications and vehicle-to-infrastructure (V2I) communications have the capabilities to improve awareness and safe driving in work zones (Morris, 2017). Warning messages of approaching work zones significantly reduce acceleration rate and speed (Qiao, 2016) and devices like the iCone support several systems that post GPS location and work zone status to major navigation data services like Waze and DOTS (Sanni, 2019). Widespread adoption of these technologies has significant potential safety impact; however, it will require vehicles to be equipped with communications capabilities and drivers to have access to internet capable mobile devices.

Members of the VTTI research team have led the development of VCC Mobile, which is a mobile application created for the Virginia Connected Corridors (VCC) to communicate pertinent traffic and incident information, including work zones, though a driver interface. VTTI has also pioneered the development of the VCC Worker app. This application allows a worker to send the GPS location and type of work to the VCC cloud. The app then builds dynamic traveler messages and pushes them to motorists via VCC mobile, enhancing the situational awareness of passing motorists who receive the message. Furthermore, private companies have developed automated TMA vehicles, and VTTI is in the process of developing its own.

TMA Countermeasures Review Summary

In the review of TMA crash countermeasures, possible combinations of treatments for the TMA were considered, including marking color, marking pattern, extra markings, signage, lighting, safety restraints, and intelligent transportation systems. Each showed potential benefits. Except for the safety restraint systems, the countermeasures considered were focused on the prevention of crashes with the TMA, whereas the safety restraints were focused on protecting the operator if a crash were to occur. The crash countermeasures review is summarized in Table 13 and helped to inform the selection of field evaluation variables. Based on the results of the review, marking color, marking pattern, and extra markings were selected for inclusion in a field evaluation.

Table 13. Countermeasure summary table.

Countermeasure	**Variables**	**Selected for Field Study**
TMA Markings	Pattern, Size, Color	Yes
TMA Truck Lighting	Type, Color, Intensity, Flash Pattern, Enhanced Working Lights	No
TMA Signage	Static, Dynamic, Sign Contents	No
Seat Belt	3, 4, 5, 6-Point	No
Intelligent Transportation Systems	Advance Warning Devices, Dynamic Traveler Messages, Vehicle-to-Vehicle, Vehicle-to-Infrastructure	No

Field Evaluation Results

Field Evaluation Results Summary

This section contains a summary of the field evaluation data analysis results. The summary is broken down by each of the TMA treatment independent variables. Only a subset of the results is mentioned in the summary; the full analysis is presented in the subsequent sections.

Extra Upper Panel

When including the extra upper panel of markings, the Green+Black chevrons and Yellow+Black checkered patterns led to the highest rates of left lane occupancy for upstream approaching drivers (83% and 78%, respectively). Overall, adding the extra marking panel led to an increase in left lane occupancy rate for all treatments except the Yellow+Orange chevrons. Speed analysis results showed that when using the Green+Black colored TMA treatment, mean vehicle speeds were 63 mph without the extra upper panel of marking. Adding the extra upper panel to the Green+Black treatment reduced mean speed by 20% from 63 mph without to 50.3 mph with the extra upper panel, representing the largest speed decrease across all TMA treatments. Adding the extra upper panel increased speed variation for all TMA color scheme and marking treatment combinations except for the Red+White checkered treatment, which saw a decrease in speed variation while using the extra upper panel.

Marking Pattern

Independent of color scheme, using a checkered pattern and the extra upper panel reduced vehicle speeds by 12% (7.3 mph) compared to checkered patterns without the extra upper panel, and 9% (5.5 mph) compared to chevrons using the extra upper panel. Overall, the left lane occupancy rate was 74% for checkered patterns and 72% for chevrons, independent of color scheme. The left lane occupancy rate difference between marking patterns was statistically significant; however, both marking patterns produced a high rate of vehicles traveling in the left lane. Across all color schemes and extra upper panel inclusion, equipping the TMA with chevrons was found to increase speed variation by 6.8% compared to when the TMA was equipped with a checkered pattern.

Color

The Green+Black color scheme (77%) was observed to have the highest left lane occupancy rate amongst all colors, independent of extra upper panel usage. The Green+Black treatment, including the extra upper panel, also led to the lowest mean speed behavior (50.2 mph), which was 6.5% (3.44 mph) lower than any other treatment. When using Yellow+Black coloring and the extra upper panel, speeds were reduced 9% (5.75 mph) by outfitting the TMA with a checkered pattern, and the left lane occupancy rate improved by around 3%. Equipping the TMA with Green+Black and Yellow+Black chevrons increased speed variation by 18% (1.25 mph) and 14% (0.95 mph), respectively, as compared to the TMA equipped with Yellow+Orange chevrons.

Left-Lane Occupancy Analysis

Data Summary Table

Lane occupancy data collected by the research team is summarized and presented in Table 14. Results were compiled for each of the 20 data collections. Data is summarized by direction of travel and TMA treatment for the left lane occupancy rate, average speed, and traffic volume.

Table 14. Data Summary Showing Left Lane Occupancy Rate and Average Speed by TMA Treatment

TMA Treatment	Traffic Direction	Pattern	Color Scheme	Upper Panel	Left Lane Occupancy Rate	Avg. Speed (mph)	Traffic Volume (vehicles/hr)
1	Eastbound	Chevron	Yellow+Orange	No	66.2%	56.2	392.0
1	Westbound	Chevron	Yellow+Orange	No	73.0%	54.4	391.3
2	Eastbound	Chevron	Yellow+Orange	Yes	60.0%	61.7	413.5
2	Westbound	Chevron	Yellow+Orange	Yes	75.5%	56.1	381
3	Eastbound	Checkers	Red+White	No	71.6%	60.8	295.5
3	Westbound	Checkers	Red+White	No	72.1%	53.2	404.5
4	Eastbound	Checkers	Red+White	Yes	69.9%	57.7	422.5
4	Westbound	Checkers	Red+White	Yes	78.1%	60.0	392.5
5	Eastbound	Checkers	Yellow+Black	No	73.4%	61.8	369
5	Westbound	Checkers	Yellow+Black	No	73.5%	56.7	274.2
6	Eastbound	Checkers	Yellow+Black	Yes	75.3%	57.1	410.8
6	Westbound	Checkers	Yellow+ Black	Yes	78.1%	55.3	292.5
7	Eastbound	Chevron	Green+Black	No	75.2%	61.7	375.5
7	Westbound	Chevron	Green+Black	No	75.4%	57.3	409.8
8	Eastbound	Chevron	Green+Black	Yes	74.4%	56.1	410
8	Westbound	Chevron	Green+Black	Yes	83.3%	49.3	396
9	Eastbound	Chevron	Yellow+Black	No	71.4%	53.8	372.5
9	Westbound	Chevron	Yellow+Black	No	68.4%	52.4	404.5
10	Eastbound	Chevron	Yellow+Black	Yes	69.1%	61.9	470
10	Westbound	Chevron	Yellow+Black	Yes	75.5%	38.2	373

Overall, Across All TMA Treatments

The influence of placing a TMA on the vehicle lane occupancy behavior of upstream approaching drivers was investigated using a series of contingency table analyses. The impact of the 10 unique TMA treatment combinations, as outlined in Table 1, was investigated by testing the association between TMA treatment and the frequency with which vehicles occupied the left lane as they passed the experimental TMA parked on a highway shoulder. Figure 14 shows the rate at which vehicles occupied the left lane broken down by the treatment marking pattern, color scheme, and whether an additional upper panel of marking was included.

The initial overall analysis considered a sample of 15,013 unique upstream vehicles that approached the TMA while it was equipped with any of the treatments. Researchers performed a chi-square test of independence comparing the left and right lane frequencies of each of the treatments. Results showed that there was a significant association between TMA treatment and lane occupancy frequency ($\chi2 = 84.1435$, df = 9, $p < 0.001$).

Researchers opted to perform a series of post hoc analyses to determine what aspects of the TMA treatments were producing the differences in the left lane occupancy rate found in the initial test. These analyses, which looked at the impact of modifying the color scheme, marking pattern, and the inclusion of an extra upper panel, are summarized in detail in the following sections.

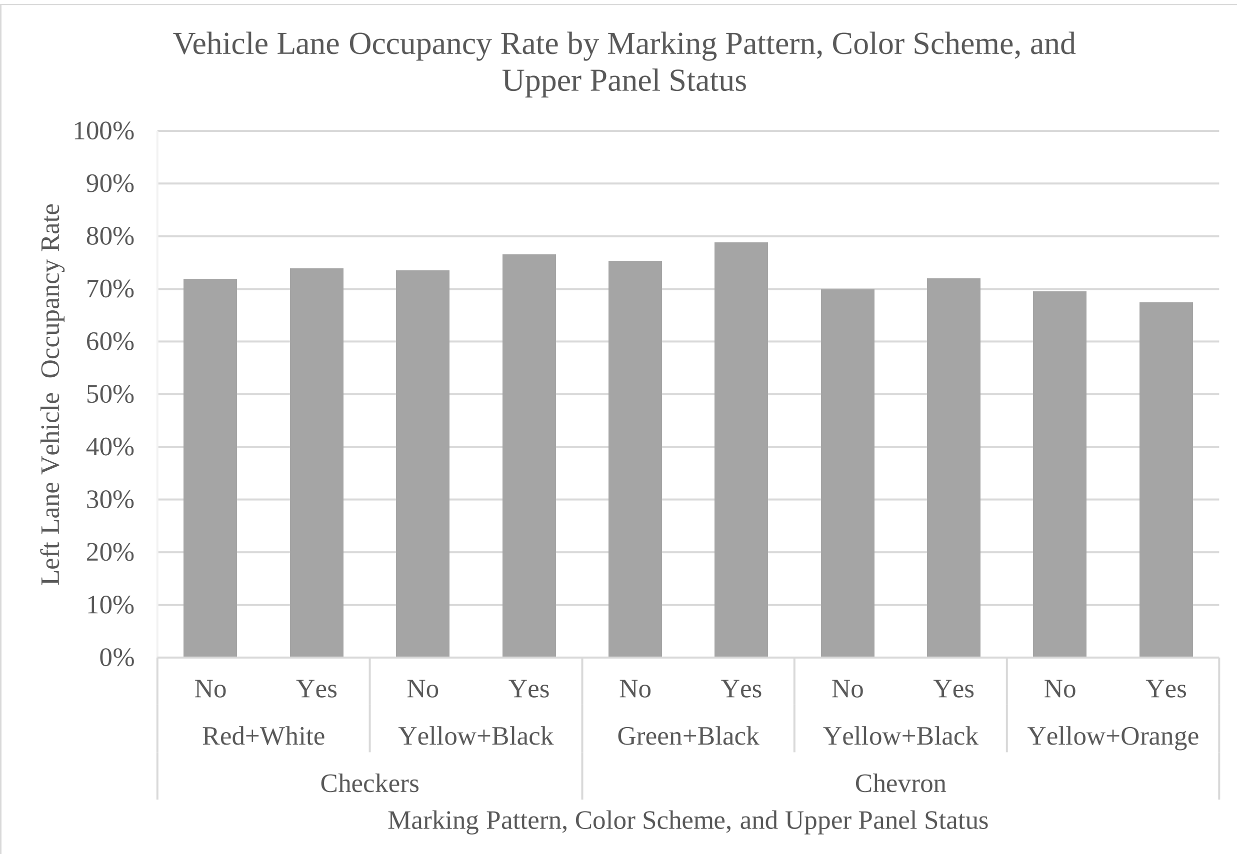

Figure 14. Left lane occupancy rate by TMA marking pattern, color, and extra upper panel inclusion. Data is reported for the percentage of vehicles traveling in the left lane

Extra Upper Panel Inclusion Analysis – Between Treatments

The interaction between TMA marking pattern and color scheme on vehicle lane occupancy behavior was investigated using a contingency table analysis, which tested the association between TMA treatment and the frequency with which vehicles occupied the left lane. This analysis compared the left lane occupancy rate during the five treatments that included the extra upper panel of material.

Data collection resulted in a sample size of 7,816 unique upstream approaching vehicles while the TMA was equipped with an extra upper panel of markings. Table 15 outlines the data set considered in this analysis and presents the frequency distribution for each treatment. An overall chi-square test of independence found a significant association between TMA treatment and lane occupancy frequency ($\chi 2 = 62.0092$, df = 4, $p < 0.001$).

Table 15. Vehicle Lane Occupancy Count for all TMA Marking Treatments That Included the Extra Panel

Color Scheme	Pattern Type	Panel Inclusion	Traffic Volume (vehicles/hr)	Right Lane Rate	Left Lane Rate
Yellow+Orange	Chevron	Yes	397.25	33%	67%
Red+White	Checkers	Yes	407.5	26%	74%
Yellow+Black	Checkers	Yes	351.6	23%	77%
Green+Black	Chevron	Yes	403	21%	79%
Yellow+Black	Chevron	Yes	421.5	28%	72%

Post hoc analysis was performed comparing each of the treatment combinations containing the extra upper panel to each other. This required 10 comparisons as determined by Equation 1 where n = 5 and k = 2. To keep the familywise error rate at 0.05, a correction to the chi-square test of independence p-values was applied using a Bonferroni correction. After the correction, p-values less than 0.05 were used to identify treatment combinations that produced significantly different left lane occupancy rates.

$$c_k^n = \frac{n!}{k!\,(n-k)!} \qquad \text{[Eq.1]}$$

Pairwise comparisons of all possible combinations of color scheme and marking pattern for TMA treatments that included the extra marking panel revealed significantly different left lane occupancy behavior between most of the treatments. The post hoc analysis summary, including corrected P-values for all comparisons, is shown in Table 16.

Table 16. Chi-Square Test for Independence Results for Left Lane Occupancy Rate for All Comparisons Between TMA Marking Treatments That Included the Extra Panel – Bold Corrected P-Values Were Considered Statistically Significant

Color Scheme 1	Pattern Type 1	Color Scheme 2	Pattern Type 2	Raw P-value	Corrected P-value
Yellow+Orange	Chevron	Red+White	Checkered	0.0001	**0.001**
Yellow+Orange	Chevron	Yellow+Black	Checkered	0.0001	**0.001**
Yellow+Orange	Chevron	Green+Black	Chevron	0.0001	**0.001**
Yellow+Orange	Chevron	Yellow+Black	Chevron	0.0047	**0.047**
Red+White	Checkers	Yellow+Black	Checkered	0.094	0.94
Red+White	Checkers	Green+Black	Chevron	0.001	**0.01**
Red+White	Checkers	Yellow+Black	Chevron	0.2138	1
Yellow+Black	Checkers	Green+Black	Chevron	0.1516	1
Yellow+Black	Checkers	Yellow+Black	Chevron	0.0044	**0.044**
Green+Black	Chevron	Yellow+Black	Chevron	0.0001	**0.001**

Results indicated that when the TMA was equipped with the Yellow+Orange colored chevrons, significantly fewer vehicles than expected occupied the left lane compared to all other treatments. The difference ranged from 4.55% to 11.38% as shown in Table 15. Results also showed that when the TMA was equipped with the Red+White colored checkered patterns, significantly fewer vehicles occupied the left lane when compared to the Green+Black chevron treatment (4.91% difference). Additionally, when the TMA was equipped with the Yellow+Black colored chevrons, significantly fewer vehicles occupied the left lane when compared to Green+Black chevrons (6.83% difference) and Yellow+Black checkered pattern (4.61% difference). Overall, the Green+Black chevrons and Yellow+Black checkered treatments experienced the highest rates of left lane occupancy for upstream approaching drivers.

Extra Upper Panel Inclusion Analysis – Within Treatments

The influence of adding an extra upper panel of marking material on vehicle lane occupancy behavior within treatments was investigated using a contingency table analysis. The analysis tested the association between adding the extra upper marking panel and the frequency with which vehicles occupied the left lane. This analysis was done within TMA treatment and compared lane occupancy frequency for each of the five color schemes and pattern combinations without the extra marking panel against the frequency when using it. Comparing within treatment allowed for researchers to isolate the impact of adding the extra marking panel within each of the color scheme and pattern combinations.

Data collection resulted in a sample size of 15,013 unique upstream approaching vehicles for this analysis. Table 17 outlines the data set considered in this analysis and presents the left lane occupancy rate for each treatment. An overall chi-square test of independence was performed for each color scheme and pattern combination. As highlighted in Table 17, only the Green+Black chevrons were found to produce significantly different lane occupancy behavior than expected when the extra upper panel was added.

Table 17. Chi-square Test for Independence Results for Left Lane Occupancy Rate for all Comparisons Between Including and Excluding the Extra Marking Panel – Bold Corrected P-Values Were Considered Statistically Significant

Pattern	Color Scheme	Panel	Statistic	DF	Value	P-Value	Left	Significance
Chevron	Yellow+Orange	No	Chi-Square	1	1.5755	0.2094	69.5%	No
Chevron	Yellow+Orange	Yes	Chi-Square	1	1.5755	0.2094	67.4%	No
Checkers	Red+White	No	Chi-Square	1	1.4789	0.2239	71.9%	No
Checkers	Red+White	Yes	Chi-Square	1	1.4789	0.2239	73.9%	No
Checkers	Yellow+Black	No	Chi-Square	1	3.2573	0.0711	73.5%	No
Checkers	Yellow+Black	Yes	Chi-Square	1	3.2573	0.0711	76.5%	No
Chevron	Green+Black	No	Chi-Square	1	5.2816	**0.0216**	75.3%	Yes
Chevron	Green+Black	Yes	Chi-Square	1	5.2816	**0.0216**	78.8%	Yes
Chevron	Yellow+Black	No	Chi-Square	1	1.666	0.1968	69.9%	No
Chevron	Yellow+Black	Yes	Chi-Square	1	1.666	0.1968	71.9%	No

In our sample of 3,110 unique approaching vehicles while the TMA was equipped with Green+Black chevrons, a chi-square test showed that there was a significant association between inclusion of the extra upper panel and left lane occupancy rate ($\chi 2 = 5.2816$, df = 1, $p < 0.0216$). Results showed that when the TMA was equipped with Green+Black chevrons, the inclusion of the extra panel lead to significantly more vehicles than expected occupying the left lane than without the panel (3.5% difference). While not statistically significant, adding the extra marking panel led to an increase in left lane occupancy rate for all treatments except the Yellow+Orange chevrons.

Marking Pattern Type Analysis

The impact of the TMA marking pattern on vehicle lane occupancy behavior was investigated by testing the association between marking pattern type and the frequency with which vehicles occupied the left lane. This analysis looks at the influence of TMA marking pattern regardless of color scheme or inclusion of the extra upper panel.

Data collection resulted in a sample of 15,010 unique approaching upstream vehicles while the TMA was equipped with either checkered or chevron patterns, as shown in Table 18. To determine if left lane vehicle occupancy rate was consistent between checkered and chevron treatments, a chi-square test of independence was performed. The chi-square test results indicated that there was a significant association between the two TMA pattern treatments and the frequency with which vehicles occupied the left lane ($\chi 2 = 5.4$, df = 1, $p = 0.0197$).

Table 18. Vehicle Lane Occupancy Count for Checkered and Chevron Patterns

Pattern	Lane	Count
Checkers	Right	1450
Checkers	Left	4109
Chevron	Right	2631
Chevron	Left	6820

When the TMA was outfitted with checkered patterns, left lane occupancy behavior increased by 2%. Overall, 74% of vehicles traveled past the TMA in the left lane when checkered patterns were used. In comparison, 72% of vehicles traveled in the left lane past the TMA when chevron patterns were used. While the difference between marking pattern treatments was statistically significant, both patterns produced a high rate of vehicles traveling in the left lane.

Subsequent analysis compared the Yellow+Black checkered treatment to the Yellow+Black chevron treatment. This was the only color scheme in the experiment that was used with both TMA marking patterns. The analyses compared the TMA marking pattern for the Yellow+Black color scheme without the use of the extra upper panel; the comparison when using the extra marking panel was previously presented in Table 17.

Data collection resulted in a sample of 2,786 unique approaching upstream vehicles while the TMA was equipped with the Yellow+Black color scheme without the extra panel of marking material (Table 19). To determine if left lane vehicle occupancy rate was consistent between checkered and chevron patterns for Yellow+Black color treatments a chi-square test of independence was performed. Results indicated that there was a significant difference in left lane occupancy rate between the checkered and chevron patterns ($\chi 2 = 4.37$, df = 1, p = 0.0364).

Table 19. Vehicle Lane Occupancy Count for Yellow and Black Marking Patterns

Color Scheme	Pattern	Panel	Right Lane	Left Lane
Yellow+Black	Checkers	No	334	925
Yellow+Black	Chevron	No	460	1067

When the TMA was outfitted with the Yellow+Black checkered pattern, left lane vehicle occupancy rate increased by 3.5%. Overall, 73.5% of vehicles traveled past the TMA in the left lane when the checkered pattern was used, while the rate was only 70% for the Yellow+Black chevrons. Both marking patterns produced a high rate of left lane vehicle occupancy; however, the increased rate when using checkered patterns could provide significant safety benefit.

Color Scheme Analysis

To investigate the impact of TMA color scheme on vehicle lane occupancy behavior of upstream approaching drivers, a contingency table analysis was performed. The color scheme analysis was done within marking pattern to isolate the impact of color from the marking pattern used. The checkered color schemes used were Red+White as well as Yellow+Black. The chevron color schemes used were Yellow+Black, Green+Black, and Yellow+Orange. Analysis used two data sets that combined the vehicle counts for all treatments using the checkered and chevron color schemes.

Checkered Pattern. The sample size for the checkered marking color scheme analysis included 5,559 unique upstream approaching vehicles, while the TMA was equipped with either the Red+White or Yellow+Black colored patterns, as shown in Table 20. To assess the influence of color on lane occupancy rate, a chi-square test for independence was conducted to determine if the frequency of left lane vehicles was significantly different between the checkered color treatments. Results showed no significant difference in frequency of left lane vehicles between Red+White and Yellow+Black color schemes ($\chi2 = 3.09$, df = 1, p = 0.0785). While there was no significant difference between the treatments, results indicated both color schemes had high left lane occupancy rates. The Yellow+Black checkered markings (75.04%) were found to have a slightly higher left lane occupancy rate than the Red+White checkered markings (72.96%).

Table 20. Vehicle Lane Occupancy Count for Checkered Patterns

Pattern	Color Scheme	Lane	Count
Checkers	Red+White	Left	2191
Checkers	Red+White	Right	812
Checkers	Yellow+Black	Left	1918
Checkers	Yellow+Black	Right	638

Chevrons. The sample size for the chevron color scheme analysis included 9,451 unique approaching vehicles while the TMA was equipped with any of the three chevron patterns, as shown in Table 21. To evaluate the impact of color scheme on left lane occupancy rate, a chi-square test for independence was conducted to determine if the frequency of left lane vehicles was significantly different between the chevron color treatments. The results indicated a significant difference in frequency of left lane vehicles between at least two of the chevron color schemes ($\chi2 = 62.0525$, df = 2, $p < 0.001$). A follow up analysis was conducted to determine how the left lane occupancy rate varied between all combinations of chevron color treatments.

Table 21. Vehicle Lane Occupancy Counts for All Color Schemes of Chevrons Used

Pattern	Color Scheme	Lane	Count
Chevron	Green+Black	Left	2412
Chevron	Green+Black	Right	716
Chevron	Yellow+Black	Left	2280
Chevron	Yellow+Black	Right	933
Chevron	Yellow+Orange	Left	2128
Chevron	Yellow+Orange	Right	982

Post hoc analysis was performed by comparing all possible chevron color treatment combinations to each other. This required three comparisons as determined by Equation 1, which was given in a previous section, where $n = 3$ and $k = 2$. To keep the familywise error rate at 0.05, a correction to the obtained p-values was applied using the Bonferroni method. After the correction, p-values less than 0.05 were used to identify treatment combinations that produced significantly different left lane occupancy rates.

A chi-square test of independence was performed three times on two-by-two tables containing the left and right lane vehicle count frequencies when the TMA was outfitted with chevron patterns. Results showed a significant difference in left lane occupancy rate between both the Green+Black (77%) and Yellow+Black (71%) color schemes and the Yellow+Orange (68%) color scheme.

Table 22 summarizes the results of the pairwise comparisons including their chi-square test results and corrected p-values. Before correcting for multiple tests, a significant difference in left lane occupancy rate between Yellow+Orange and Yellow+Black chevrons was found. However, after correcting for multiple tests, the Yellow+Black to Yellow+Orange chevron comparison was not deemed statistically significant. The Green+Black chevron treatment was still significantly different than the other two.

Table 22. Post Hoc Chi-Square Test Summary for all Three Combinations of Chevron Color Treatment – Bold Corrected P-Values Were Considered Statistically Significant

Pattern	Color Scheme 1	Color Scheme 2	Chi-Square	Raw P-Value	Corrected P-Value
Chevron	Green+Black	Yellow+Black	31.14	<0.001	**0.0003**
Chevron	Green+Black	Yellow+Orange	59.38	<0.001	**0.0003**
Chevron	Yellow+Black	Yellow+Orange	4.82	0.0282	0.0846

Overall, there was no difference found between either of the color schemes when using the checkered patterns. Both color schemes produced similar rates of left lane occupancy. A significant difference in left lane occupancy rate was found between two combinations of chevron colors. The Green+Black treatment (77%) was observed to have the highest left lane occupancy rate, and post-hoc testing confirmed significantly higher rates than both the Yellow+Black treatment (71%) and the Yellow+Orange treatment (68%).

Vehicle Speed Analysis

By Lane

Move-over-laws stipulate that upon approaching a stationary vehicle displaying flashing, blinking, or alternating emergency lights, that drivers shall yield the right of way by merging into the left lane away from the stationary vehicle. If moving over is unreasonable or not safe, then vehicles should proceed with caution and maintain a safe speed (slowing down). TMA treatments that encourage this behavior can provide significant safety benefits and reduce TMA collisions. Lane occupancy data showed a significant deviation in lane occupancy behavior when the TMA was present, across all conditions, compared to normal traffic flow conditions (Table 14 and Table 23). Due to this significant difference in lane occupancy behavior the research team investigated the influence of TMA marking pattern, color scheme, and extra upper panel usage on speed behavior to assess the treatment impacts within each lane.

Table 23. Control data without a TMA present.

Lane	Lane Occupancy	Average Speed (mph)	Speed Variation (mph)
Left	29.6%	69.43	3.73
Right	70.4%	66.28	5.11

Control data, without a TMA present, suggested that typical left lane vehicle speeds in the test area were around 69 mph and typical right lane speeds were around 66 mph (Table 23). However, data collection with the TMA deployed determined that vehicle speeds were significantly slower than the control for the left lane traffic, and somewhat similar to control speeds for right lane traffic.

Some TMA treatments saw right lane speeds only marginally lower than the control, while others saw reductions in speed up to 8 mph. Conversely, for left lane traffic, all TMA treatments were found to reduce average vehicle speeds significantly below the speed limit. Additionally, comparisons between lanes showed that speeds were significantly higher in the right lane than left lane for all treatments (Figure 15). Left lane vehicle speeds ranged, on average, from 52 mph to 61 mph based on TMA treatment. Right lane speeds ranged, on average, from 57 mph to 66 mph depending on TMA treatment. Note that the impact of platooning, particularly in the left lane could influence this result as vehicles that are strictly compliant to the Move Over Law would both move over and slow down which could cause vehicle to back up behind in the left lane.

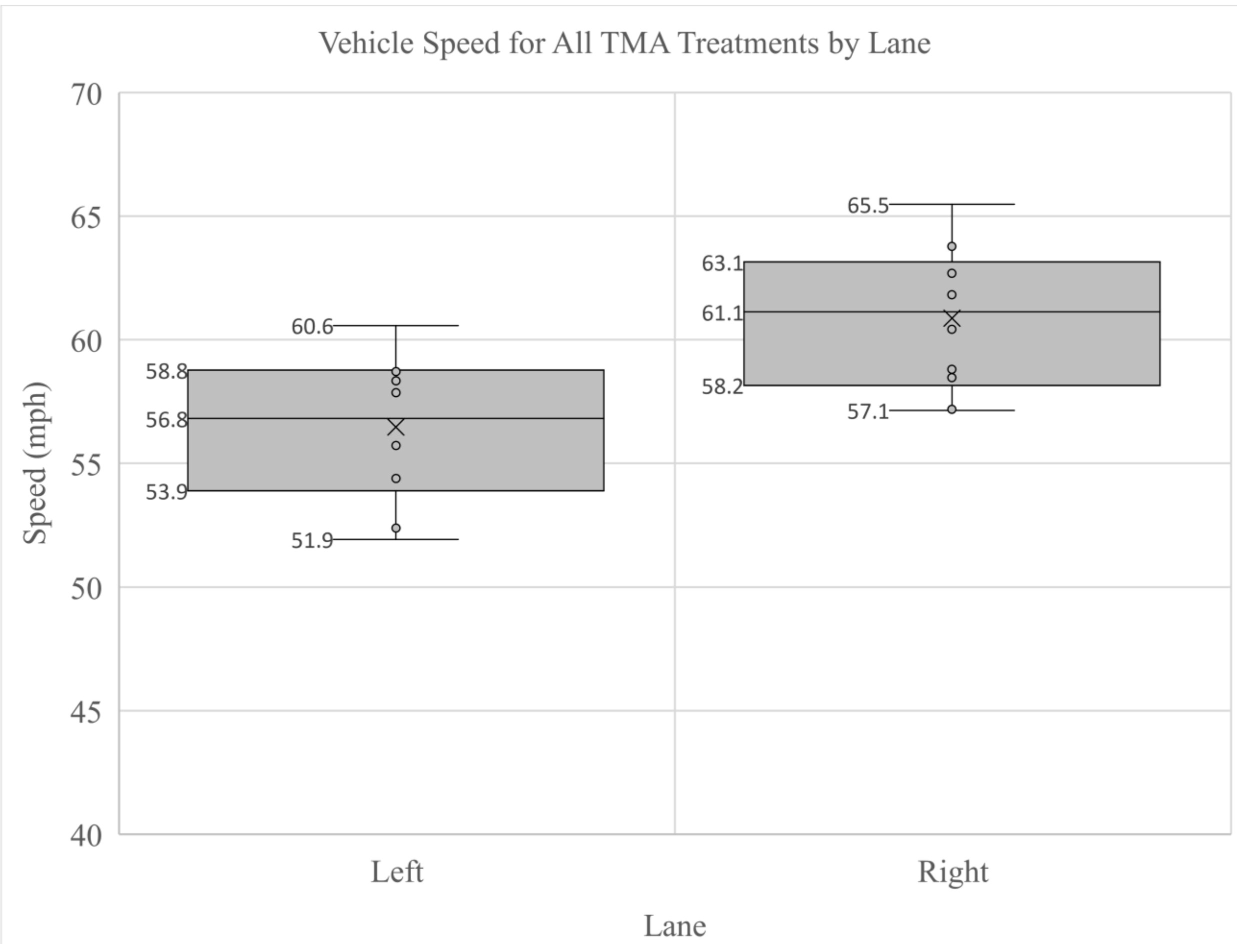

Figure 15. Vehicle speed for all TMA treatments summarized in a box-and-whisker plot for right and left lane traffic. Speeds are reported in mph.

When compared within TMA treatment, results found statistically significant difference in mean vehicle speed between the right and left lane for all TMA presentations. Vehicle speeds were higher in the right lane regardless of color scheme, marking pattern, or usage of an extra upper panel of markings. Even though right lane speeds were higher across the board, the influence of the TMA treatments was similar across lanes, as shown in Figure 16.

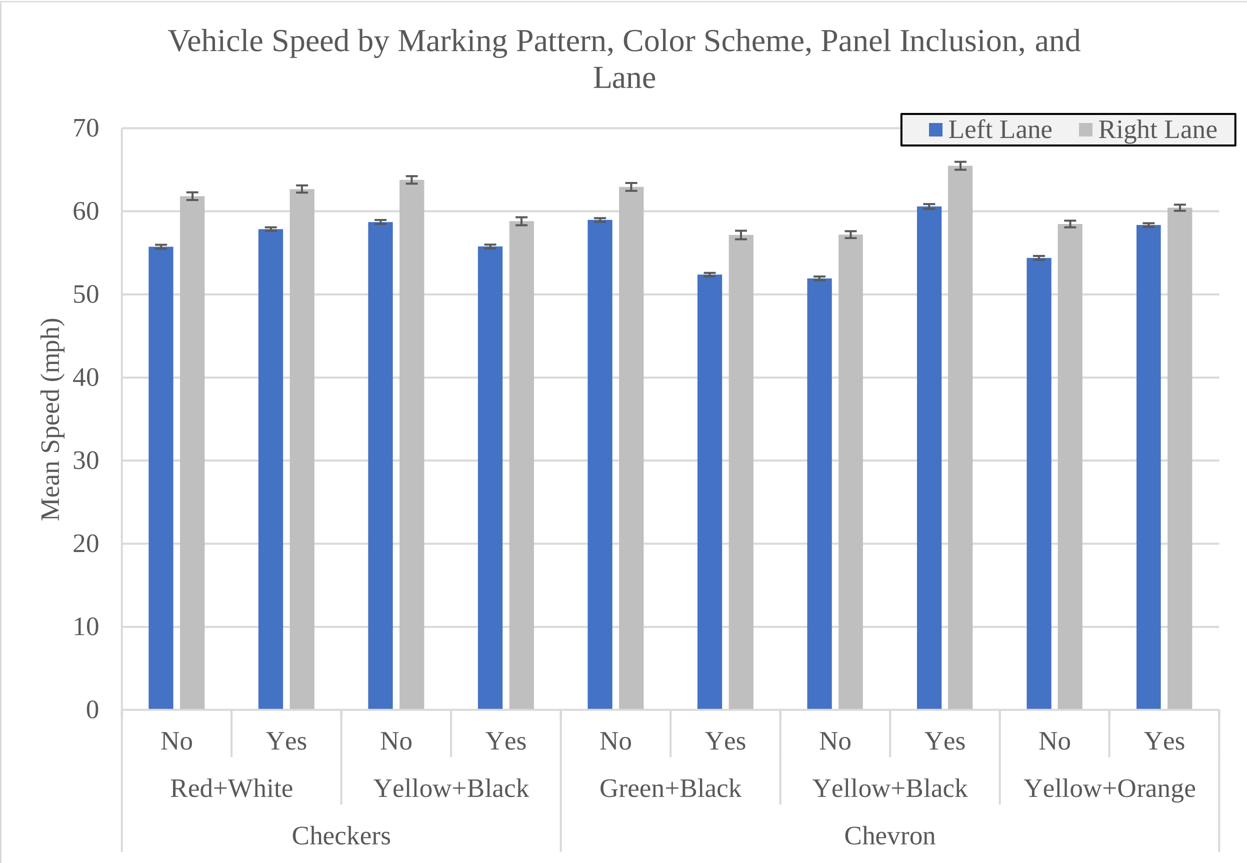

Figure 16. Vehicle speed by marking pattern, color scheme, and extra upper panel inclusion by lane. Speeds are reported in mph.

Due to the similarity of influence TMA treatments had in each lane, the research team sought to assess the linear association between left and right lane vehicles speeds. Analysis found a high level of linear association (R^2= 0.85) between the right and left lane mean vehicle speeds (Figure 17). For a 1 mph increase in right lane speed there would be an expected increase of 0.92 mph in the left lane, across all treatments. Additionally, while the mean vehicles speeds varied between TMA treatments the effect looked to be consistent. If a given treatment was measured as having lower vehicle speeds in the right lane, then left lane speeds for that treatment were also measured lower. The data suggests that TMA treatments were having the same influence on speed behavior between lanes.

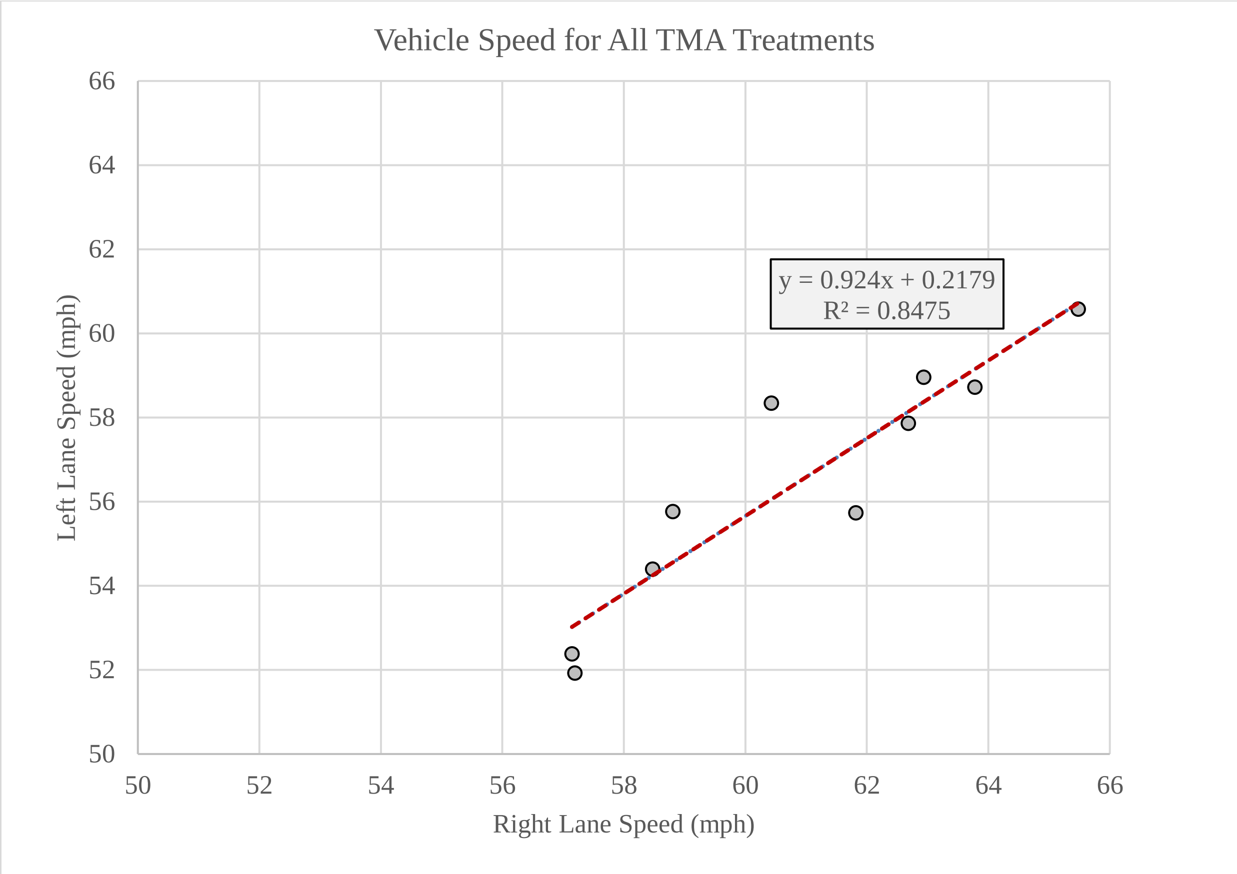

Figure 17. Vehicle speed for all TMA treatments by left and right lane speed. Data is reported in mph.

The research team also sought to identify why the right lane speeds were consistently higher than left lane speeds, when the expected speed behavior was the opposite. Raw speed data was binned into categories and counted to give the frequency of vehicles within each lane traveling within a given speed range. Both lanes looked to have normally distributed speeds (Figure 18). Overall, the mean across all TMA treatments was higher for right lane vehicles (60.77 mph) than left lane vehicles (56.26 mph). Comparisons between lanes within the same speed bin found that left lane vehicles travelled at speeds under 60 mph at a higher rate. In contrast, right lane vehicles travelled over 60 mph at a significantly higher rate, and the difference was most pronounced between 65 and 75 mph. For example, only ~2% of left lane vehicles speeds fell into the 71 mph bin, while ~9% of right lane vehicles fell into the 71 mph bin.

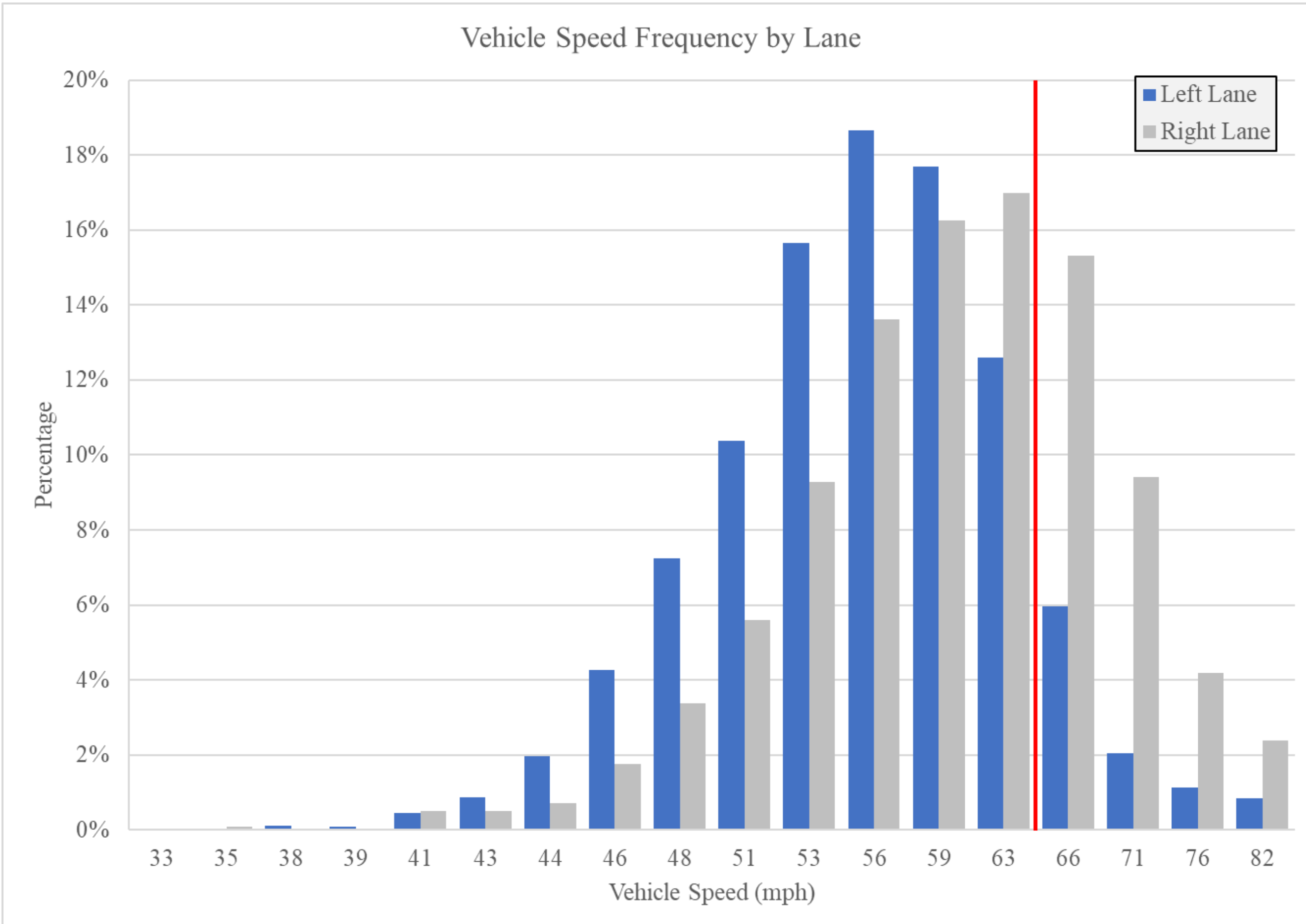

Figure 18. Vehicle speed frequency across all TMA treatments by lane. Frequency is reported by the percentage of vehicles, within each lane, travelling within each speed bin. The red vertical line indicates the speed limit within the testing area.

Researchers saw that more vehicles were travelling over the speed limit (65 mph) in the right lane than the left lane and a follow up analysis was conducted to determine if TMA treatment was having an impact on speeding behavior. Overall, left lane vehicles reduced their speed below the speed limit at a rate of 89% to 91% across all color scheme and marking pattern combinations. TMA color scheme and marking pattern did not appear to be affecting the slow down behavior of left lane vehicles. Researchers were more interested in the slow down behavior of right lane vehicles who did not, or could not, switch lanes. Since the move-over law stipulates that vehicles should proceed with caution and maintain a safe speed (slowing down) when moving over is unsafe or unreasonable, the rate at which right lane vehicles reduced their speed was assessed. Speed reduction data is reported in Figure 19 for all color scheme and marking pattern combinations. The Yellow+Orange chevrons had the best slowdown behavior with 75% of right lane vehicles reducing their speed to under 65 mph. The Green+Black chevrons also saw significantly better slow down behavior (70%) than the remaining color scheme and marking pattern combinations. Changing between checkers and chevrons did not influence the right lane slowdown behavior for the Yellow+Black color scheme, suggesting that neither marking pattern was causing drivers to slow down at a higher rate. Overall, some color scheme and marking pattern combinations resulted in better slowdown behavior for right lane vehicles, however all treatments saw significant amounts of vehicles travelling over the speed limit in the right lane when passing the TMA. Additionally, the color scheme of the marking pattern looked to be driving slowdown behavior more than the marking pattern.

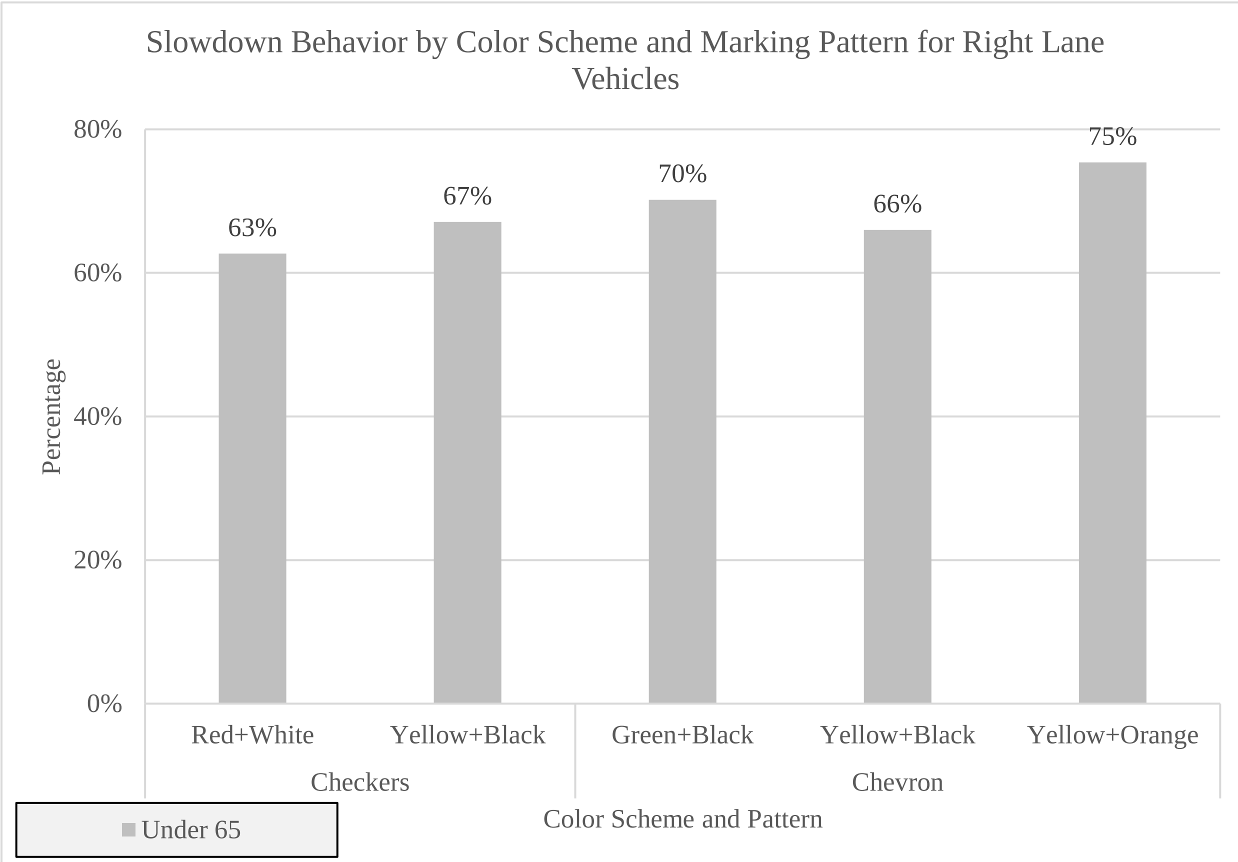

Figure 19. Slowdown behavior by color scheme and marking pattern for right lane vehicles. Data is reported as the percentage of vehicles travelling under and over the speed limit.

Speed variation was found to be inconsistent between lanes of travel, as shown in Figure 20. For the Red+White checkers without the extra upper panel and Green+Black chevrons with the extra upper panel treatments speed variation was similar between lanes. For all other treatments vehicle speed variation was significantly larger in the right lane. Comparisons between lanes found that the checkered patterns, generally, had a smaller difference in speed variation between the right and left lanes. Conversely, the chevron patterns generally had much larger speed variation in the right lane.

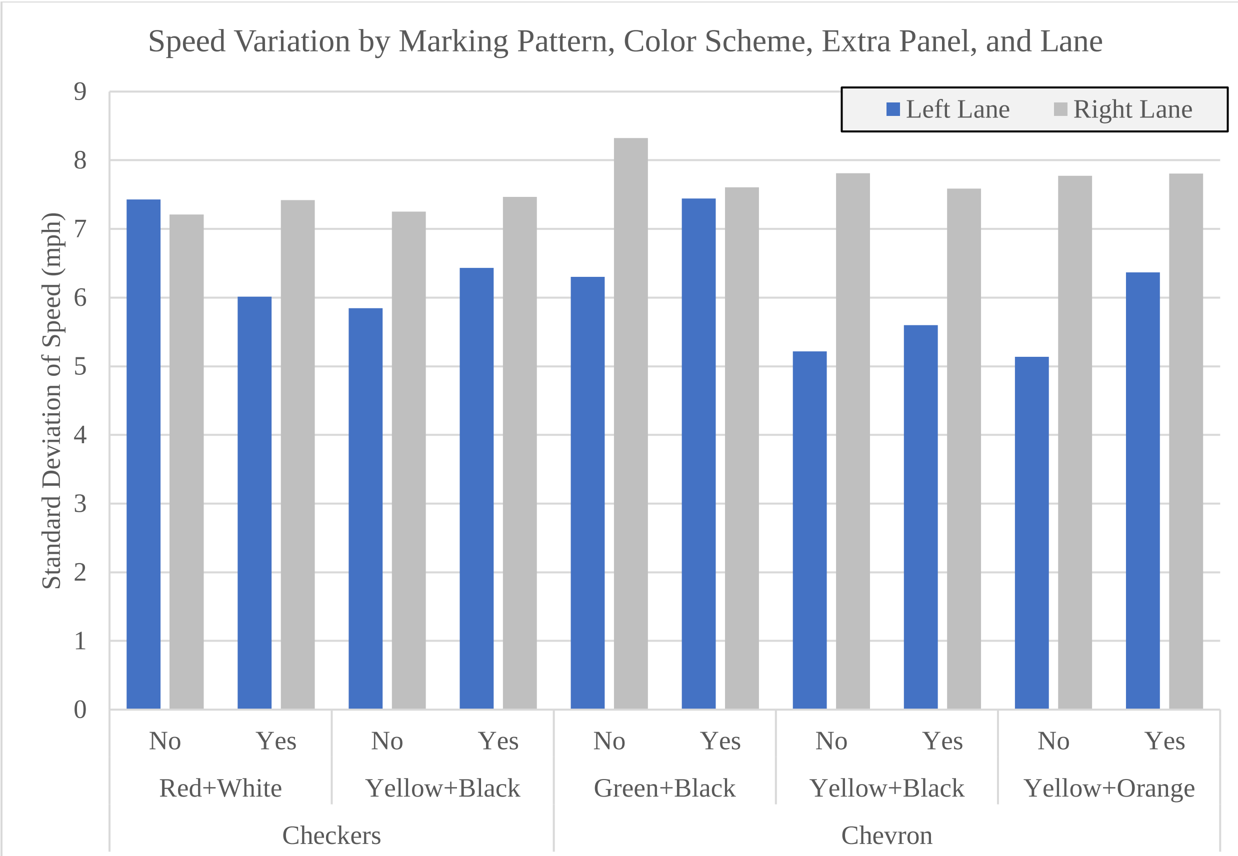

Figure 20. Speed variation by marking pattern, color scheme, extra upper panel inclusions, and lane. Speed variation is reported as the standard deviation of speed.

Considering all speed behavior, the data suggested that within each lane, two groups of vehicle actions were present, those who slowed down and those who did not. The difference in frequency of this behavior was inconsistent between lanes. Left lane vehicles were shown to slow down at a much higher rate and chose to lower their speeds under the speed limit at a higher frequency. In contrast, for right lane behavior, some vehicles slowed down but were not able to, or chose not to move over. While others chose to remain in the right lane and seemingly not slow down at all. With the available data it was not possible to determine whether right lane vehicles were either trapped and unable to merge to the left lane or stayed in the right lane for other unknown reasons. The research team determined that the higher right lane speed variation is likely due to the higher rate of vehicles not slowing down which increased the within lane speed variation.

Overall, the by lane analysis results found that the effect of TMA treatments on vehicle speed was consistent across lanes. Therefore, the research team opted to conduct the rest of the analysis without consideration for each individual lane. This decision was also made due to practical application. A TMA, when deployed, could not reasonably be expected to display one pattern to influence right lane behavior and another for left lane behavior at the same time. The influence of each pattern on the overall behavior is of utmost importance as traffic safety workers will only be able to equip each TMA with a single treatment.

Overall, Across All TMA Treatments

Linear regression modeling was used to determine if placing a TMA with any of the 10 treatment combinations had an impact on the speed of upstream approaching vehicles. The first modeling effort used speed, which was measured within 80 feet of the TMA, as the dependent measure and included the TMA treatment as the only independent variable. The TMA treatment variable combined all TMA treatments into one factor for comparison.

The overall chi-square goodness of fit test results ($\chi 2 = 184.25$, df = 9, $p < 0.001$) indicated that at least one of the TMA treatment combinations led to significantly different mean vehicle speed behavior. In lieu of post-hoc analysis comparing the factor levels of the TMA treatment variable to each other, researchers opted to separate the TMA treatment variable into its component parts. TMA treatment was broken down into marking pattern, color scheme, and extra upper panel variables for subsequent analysis. Due to a lack of numerator degrees of freedom in modeling, researchers were unable to estimate the 2-way interaction between color and pattern, and subsequently the 3-way interaction between color, panel, and pattern. Therefore, the research team conducted three follow up analyses to investigate the impact of marking pattern, color scheme, and inclusion of the extra upper panel on driver speed behavior.

Interaction Between Marking Pattern, Color Scheme, and Extra Upper Panel Usage

Linear regression was used to create a model fitting mean vehicle speed as the dependent variable and TMA marking pattern, color scheme, and extra upper panel inclusion as main effects. To assess the impact of adding the extra upper panel of different colors and marking types, the model also included the interaction between marking pattern and extra upper panel as well as color scheme and extra upper panel.

The overall chi-square goodness of fit test results are summarized in Table 24. Modeling efforts found a significant difference between at least two factor level combinations of extra upper panel and color scheme as well as extra upper panel and marking pattern. Post hoc analyses focused on identifying the significant differences in speed behavior between the factor levels of color scheme, marking pattern, and extra upper panel.

Table 24. Type 3 Tests of Fixed Effects for Color, Pattern, and Panel as Well as the Interaction Between Color/Panel and Pattern/Panel – Bolded P-Values Were Considered Statistically Significant

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Color (C)	3	1.00E + 04	10.44	**< .0001**
Pattern (P)	1	1.00E + 04	5.73	**0.0167**
Panel (Pa)	1	1.00E + 04	67.7	**< .0001**
C*Pa	3	1.00E + 04	488.84	**< .0001**
P*Pa	1	1.00E + 04	731.73	**< .0001**

Pattern and Panel

Post-hoc analysis was performed using a least squares means procedure to investigate which factor level combinations of panel and marking type produced significantly different vehicle speeds. Figure 21 visualizes the least squares means obtained during the procedure. Statistically significant differences were found for all comparisons within and between marking patterns; however, some results were not practically significant.

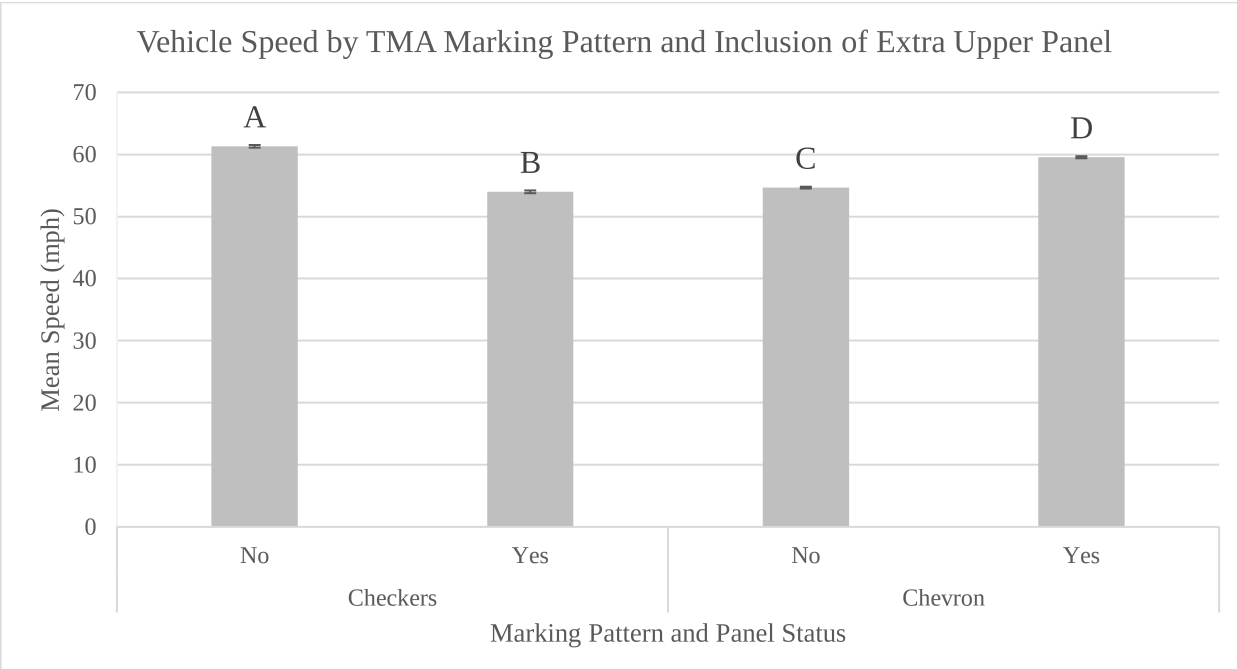

Figure 21. Mean vehicle speed by TMA marking pattern and extra upper panel inclusion status. Data is reported for mean speeds and the error bars represent standard error. Upper case letters indicate post-hoc grouping from pairwise comparisons.

Comparison within checkered patterns revealed that adding the extra panel of material resulted in a reduction in mean vehicle speeds of 12% (7.3 mph), independent of color choice. Conversely, comparison within chevrons revealed that adding the extra panel of material when using a chevron pattern resulted in an increase in mean vehicle speeds of 8% (4.8 mph), independent of the color choice.

Comparison between marking pattern type showed that when the extra upper panel of markings was added, using a checkered pattern resulted in mean vehicle speeds 9% lower (5.5 mph) than when the TMA was outfitted with chevrons, independent of color choice. When the extra upper panel was not included, results showed that average vehicle speeds were 11% lower (6.6 mph) when the TMA was outfitted with chevrons compared to the checkered patterns, independent of color choice.

Overall, the investigation into the interaction between TMA marking pattern and inclusion of the extra upper panel found that a checkered pattern produced significantly lower average speeds when the extra panel was included. Additionally, when the extra panel was not included, significantly lower average vehicle speeds were observed when the TMA was equipped with chevrons. Modeling efforts suggest pairing the extra upper panel with the checkered pattern and using chevrons without the extra upper panel.

Color and Panel

Post-Hoc analysis was performed using a least squares means procedure to investigate which factor level combinations of extra upper panel and color scheme produced significantly different vehicle speeds. Figure 22 visualizes the least squares means obtained during the procedure. Statistically significant differences were found for nearly all comparisons within and between color schemes; however, some results were not practically significant.

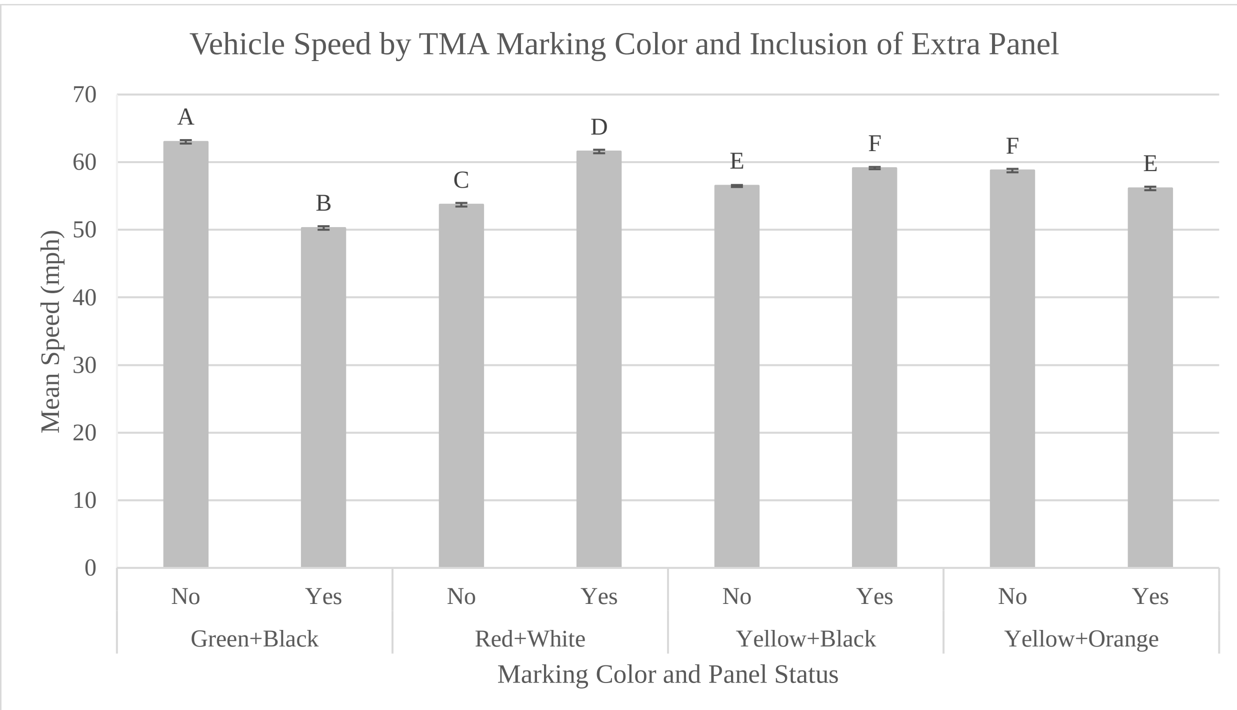

Figure 22. Mean vehicle speed by TMA marking color and extra upper panel inclusion status. Data is reported for mean speeds and the error bars represent standard error. Upper case letters indicate post-hoc grouping from pairwise comparisons.

Pairwise comparisons found a significant reduction in mean vehicle speed upon adding the extra upper panel of marking when using the Green+Black color scheme. Mean vehicle speeds were 63 mph without the extra upper panel of marking. Adding the extra upper panel resulted in mean vehicle speeds of 50.2 mph, representing a reduction in mean speed of 20% (12.7 mph). In contrast, adding the extra upper panel of markings corresponded with an increase in mean vehicle speed when using a Red+White color scheme. Mean vehicle speed increased by 13% (7.8 mph) when a Red+White extra upper panel of material was added to the TMA. While statistically significant, mean speed differences between Yellow+Black treatments (2.65 mph difference) and Yellow+Orange treatments (2.64 mph difference) were not large enough to be considered practically significant.

Overall, the investigation into the interaction between TMA color scheme and inclusion of the extra upper panel revealed that outfitting the TMA with the extra upper panel of markings while using a Green+Black color scheme significantly lowered mean speeds. Additionally, exclusion of the extra upper panel resulted in significantly lower mean vehicle speeds when the TMA was outfitted with a Red+White color scheme. Modeling efforts did not produce a consensus as to whether adding the extra panel of material provided a reduction in average vehicle speed; however, the speed reduction observed for the Green+Black color scheme (20%, 12.7 mph) could provide safety benefit.

Within Yellow and Black Color Scheme Treatments

Four of the TMA treatments tested used a Yellow+Black color scheme, which enabled researchers to isolate the influence of including the extra upper panel and changing the marking pattern for that color scheme. Multiple linear regression was used to fit a model using speed near the TMA as the dependent measure and included TMA marking pattern and extra upper panel inclusion as independent variables. To assess the impact of adding the extra upper panel of each marking type, the model also included the interaction between marking pattern and extra upper panel.

The overall chi-square goodness of fit test results are summarized in Table 25. Modeling outcomes found significant differences between at least two factor level combinations of extra upper panel and marking pattern. Post hoc analysis focused on identifying the significant differences in mean speed behavior between the factor levels of marking pattern and extra upper panel.

Table 25. Type 3 Tests of Fixed Effects for TMA Marking Pattern and Extra Upper Panel Status as well as the Interaction Between Marking Pattern and Extra Upper Panel Status for Yellow+Black Color Scheme Treatments. Bolded P-Values were Considered Statistically Significant

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Pattern (P)	1	3758	6.27	**0.0123**
Panel (Pa)	1	3758	150.3	< **.0001**
P*Pa	1	3758	800.64	< **.0001**

Post hoc analysis was performed using a least squares means procedure to investigate which factor level combinations of extra upper panel and marking pattern produced significantly different mean vehicle speeds. Figure 23 visualizes the least squares means obtained during the procedure. Pairwise comparisons established statistical and practical significant difference between the mean vehicle speeds of three comparisons. When outfitting the TMA with Yellow+Black color chevrons and adding the extra upper panel, mean vehicle speeds increased by 14% (8.7 mph change) compared to speeds without the extra upper panel. The same comparison for the checkered pattern revealed a decrease in mean vehicle speed of 6% (3.5 mph), which was statistically significant; however, the change in mean speed did not meet the established threshold for practical safety significance.

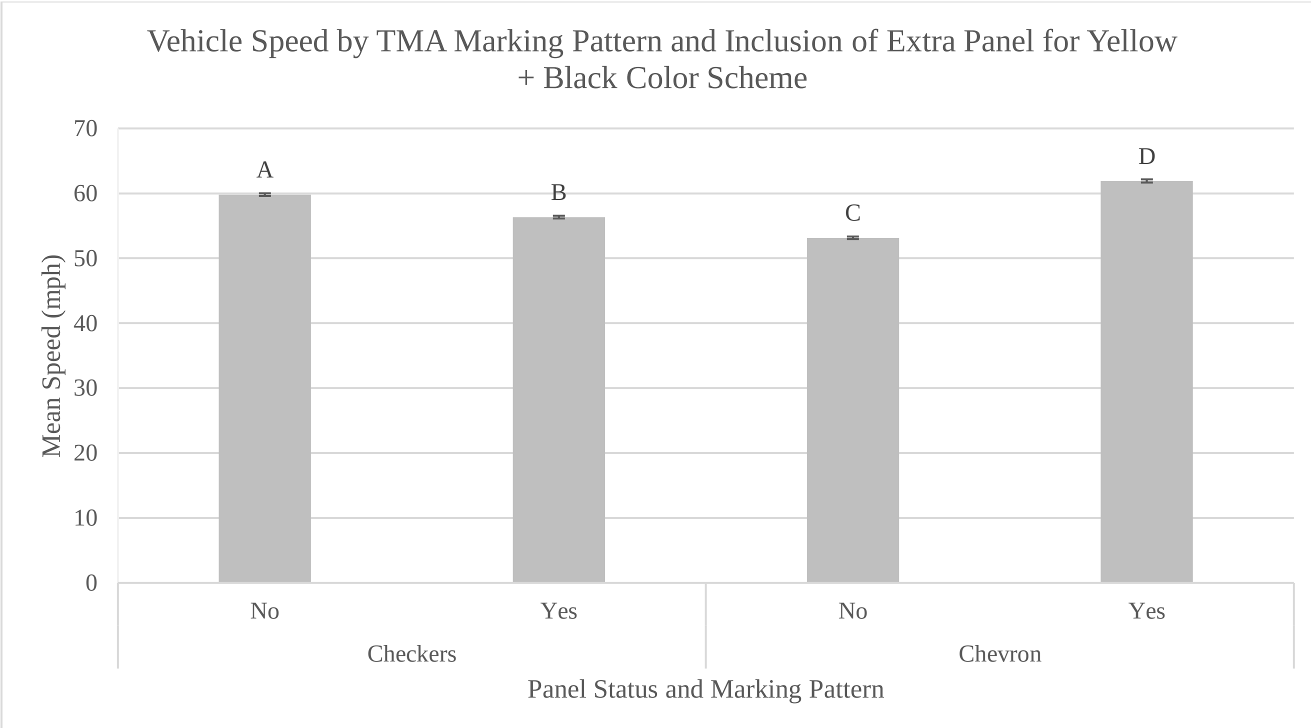

Figure 23. Mean vehicle speed by TMA marking pattern and extra upper panel inclusion status for yellow and black color scheme. Data is reported for mean speeds and the error bars represent standard error. Upper case letters indicate post-hoc grouping from pairwise comparisons.

Between marking type comparisons for the Yellow+Black color scheme found statistical and practical significance between including and excluding the extra upper panel. When using the extra upper panel, mean vehicle speeds for the checkered pattern were 9% (5.5 mph) lower than chevrons. Additionally, when the extra marking panel was excluded, mean vehicle speeds for chevrons were 11% (6.6 mph) lower compared to the checkered patterns.

Overall, when the TMA was equipped with a Yellow+Black color scheme and no extra upper panel, the mean vehicle speed was reduced. When the extra panel was included, mean vehicle speeds were lowest when using checkered patterns. While there was no consensus across extra upper panel usage and marking pattern for the Yellow+Black color scheme, data suggests using the extra panel would provide safety benefit alongside the checkered pattern, and that the extra panel might not be necessary when using chevron patterns.

Color

Linear regression was used to fit a model using mean vehicle speed as the dependent variable and color scheme as the main effect. Data was subset by marking pattern and grouped all checkered and chevron speed data separately. Analysis was conducted individually for each marking type to isolate the influence of color scheme on driver speed behavior, independent of extra marking panel inclusion. The overall chi-square goodness of fit test results are summarized in Table 26. Modeling revealed a significant difference between at least two factor level combinations of chevron color. No significant difference was found between the two checkered color schemes. Post-hoc analysis focused on identifying the significant differences in speed behavior between the factor levels of chevron color.

Table 26. Type 3 Tests of Fixed Effects for Chevron and Checkered Marking Chi-Square Goodness of Fits Tests – Bolded P-values Were Considered Statistically Significant

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Chevron	2	6278	11.56	**<.0001**
Checkered	1	4117	0.07	0.7961

As summarized in Figure 24, no significant difference in speed behavior was observed between the Red+White or Yellow+Black checkered color schemes. These results agree with the lane occupancy behavior in that if a checkered pattern is used, neither of these color schemes seem to have an impact on driver behavior. Extra consideration when choosing a checkered treatment could then be given to elements not accounted for in the analysis such as night/daytime visibility differences, color blind perception, cost, etc.

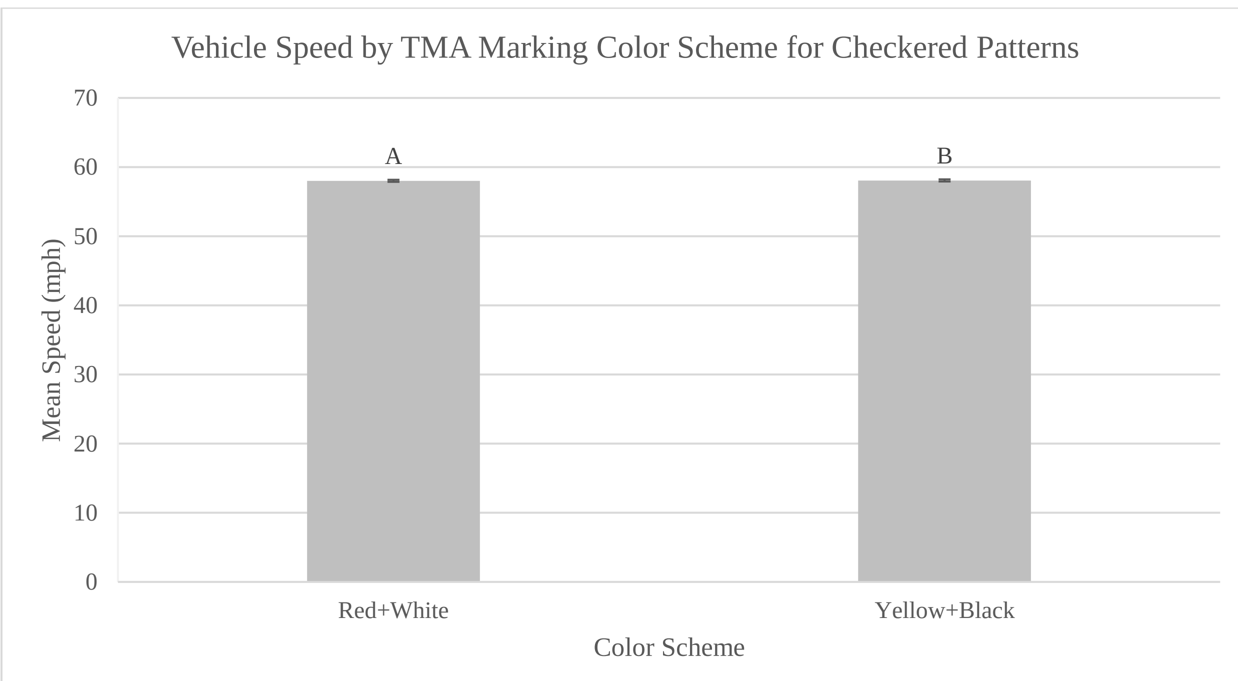

Figure 24. Vehicle Speed by TMA marking color scheme for the checkered pattern treatments. Data is reported for mean speeds and the error bars represent standard error. Upper case letters indicate post-hoc grouping from pairwise comparisons.

Figure 25 gives the mean speed results for the three chevron treatments by their color scheme. A significant difference was found between the mean speed of vehicles passing the TMA when outfitted with the Green+Black (56.2 mph) and the Yellow+Orange (57.3 mph) color schemes. A significant difference was also found between the Yellow+Black (56.5 mph) and the

Yellow+Orange color schemes. While statistical significance was found, there were no practical differences between any of the color treatments when using chevron patterns. When isolating for color, there was only a 1.05 mph difference in mean vehicle speed between the three chevron color treatments.

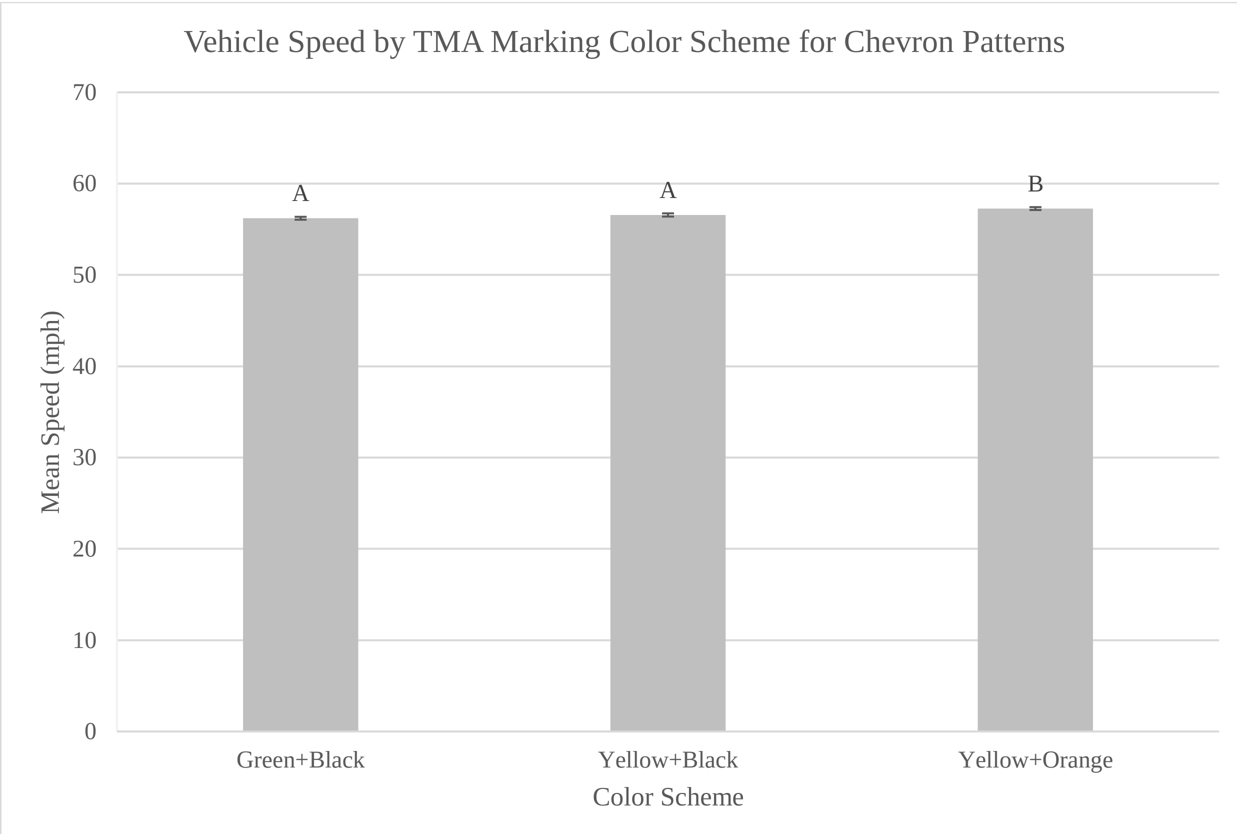

Figure 25. Vehicle Speed by TMA marking color scheme for the chevron pattern treatments. Data is reported for mean speeds and the error bars represent standard error. Upper case letters indicate post-hoc grouping from pairwise comparisons.

Speed Variation Analysis

Overall, Across All TMA Treatments

The interaction between marking pattern, color scheme, and inclusion of an extra upper panel was examined to determine if the TMA treatment factors had an impact on the speed variation of upstream approaching vehicles. Data collection produced a sample size of 10,400 unique vehicles that passed the TMA when it was equipped with any of the 10 TMA treatments. For this analysis, data was compiled for each of the TMA marking patterns, color scheme, and extra panel status combinations, as shown in Figure 26. Summary statistics were calculated for each vehicle grouping to obtain sample standard deviations.

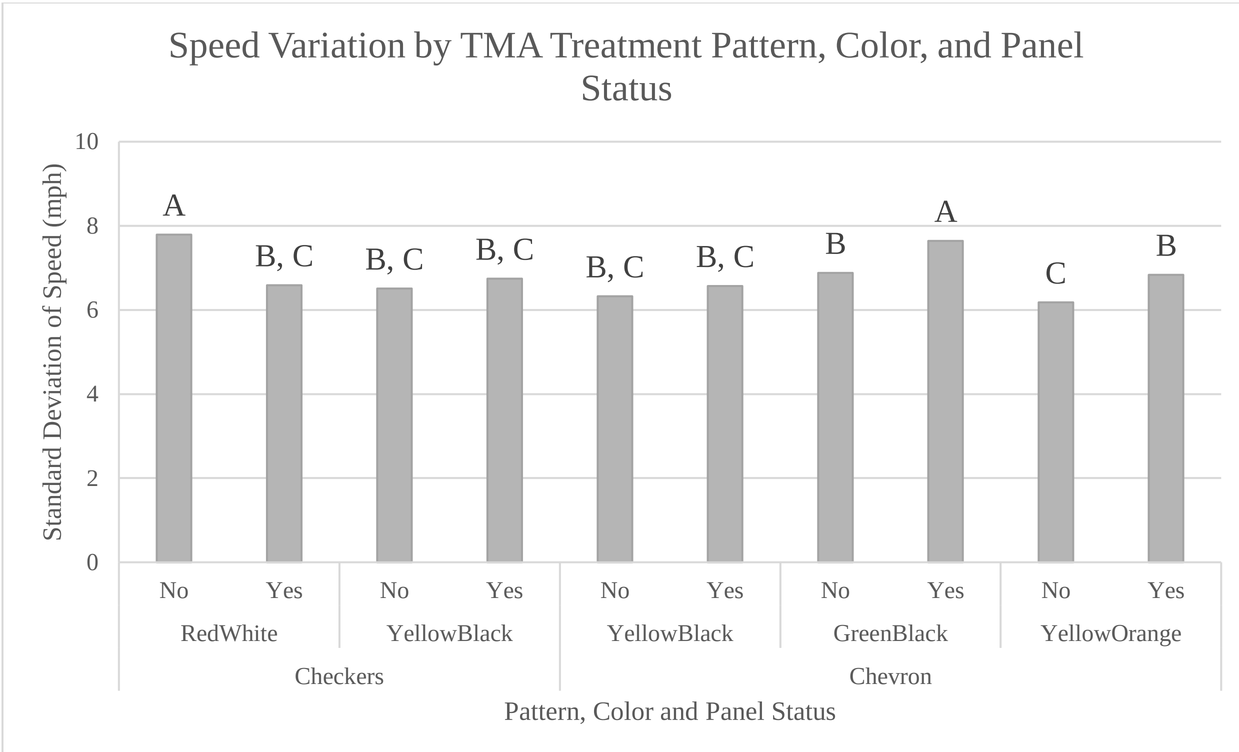

Figure 26. Vehicle speed variation by TMA marking pattern, color, and extra panel inclusion status for all treatments. Data is reported for standard deviation of speed. Uppercase letters indicate post-hoc grouping from pairwise comparisons.

To determine if vehicle speed variation changed with respect to TMA treatment, a series of F-tests for equality of two variances were performed. The null hypothesis for all tests asserted equal speed variation between pairwise treatment combinations, and rejection of the null hypothesis indicated a difference in speed variation. Pairwise tests for all treatment combinations, as determined by Equation 1 ($n = 10$, $k = 2$), were performed to compare the ratio of speed variances between each of the marking pattern, color scheme, and panel status factor levels. Due to the large volume of pairwise comparisons required, the resulting p-values were adjusted using a Bonferroni correction to keep the familywise error rate at 0.05. Significant results, as indicated by capital letter differences in Figure 26 (A, B, C), are described below.

Pairwise comparisons found that two TMA treatments saw significantly larger speed variation than all other treatments. Speed variation was largest when the TMA was equipped with the Red+White checkered treatment that did not use the extra upper panel (SD = 7.79 mph) and the Green+Black chevrons with the extra upper panel (SD = 7.64 mph), as shown in Figure 26. The largest magnitude of speed variation difference across all TMA treatments was between the Yellow+Orange chevrons not using the extra upper panel (SD = 6.17 mph) and the two previously mentioned treatments. Speed variation increased by 26% and 24% when comparing the Yellow+Orange chevrons without the extra upper panel to the Green+Black chevrons with the extra marking upper panel and the Red+White checkers without the extra panel.

The Green+Black chevron treatments experienced the second and third highest speed variation amongst all treatment combinations tested. Additionally, when speed variation was averaged across extra upper panel status, the Green+Black treatments saw the largest speed variation of any color scheme and marking pattern combination. Within color comparisons were made for the Yellow+Black color scheme, and results showed no significant difference in speed variation when changing the marking pattern or when adding the extra upper panel.

Overall, 70% of the TMA treatments experienced statistically similar speed variation. All treatments utilizing Yellow+Orange or Yellow+Black color schemes and one Red+White treatment had speed variation ranging from 6.3 to 6.8 mph. Pairwise comparisons of speed variation found no significant difference between any of these TMA treatments, as shown in Figure 26. Across all color scheme and marking pattern combinations, data indicated that adding the extra upper panel increased the speed variation except for the Red+White checkers treatments.

Extra Upper Panel

Researchers sought to assess the influence of adding an extra panel of markings to the TMA on the speed variation of upstream approaching vehicles. Data collection resulted in sample sizes of 5,151 unique vehicles that passed the TMA without the extra marking panel and 5,249 unique vehicles that passed the TMA when it was outfitted with the extra marking panel. Summary statistics were calculated for each of the vehicle groupings to obtain the sample standard deviation. For this analysis, data was compiled across all color schemes and both patterns for each of the extra upper panel factor levels, as shown in Figure 27.

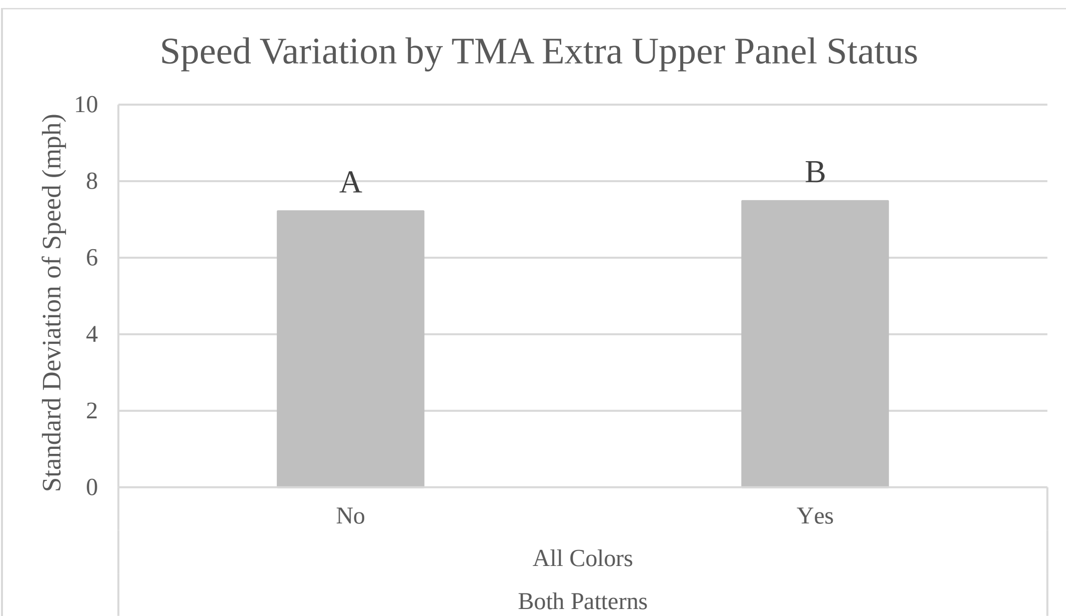

Figure 27. Vehicle speed variation by TMA extra marking panel inclusion across all treatments. Data is reported for standard deviation of speed. Upper case letters indicate post-hoc grouping from pairwise comparisons.

To determine if speed variation was different for vehicles based on inclusion of the extra marking panel, the research team performed an F-test for equality of two variances. The procedure compared the ratio of speed variances between treatments where the null hypothesis tested if the sample groups had equal speed variation. Results found a significant difference in speed variation between the extra marking panel factor levels (F = 0.93, num df = 5150, denom df = 5248, p = 0.008915, 95% CI = (0.88, 0.98)). Including the extra marking panel (SD = 7.48 mph) was found to produce a larger speed variation than not including the extra marking panel (SD = 7.21 mph). Due, in part to the large sample size, difference in speed variation was statistically significant; however, the magnitude of difference was only 3.5% (0.27 mph).

Marking Pattern

Researchers also looked to investigate the influence of TMA marking type on the speed variation of upstream approaching vehicles. Data collection resulted in sample sizes of 4,119 unique vehicles that passed the TMA when it was equipped with checkered marking patterns and 6,281 unique vehicles that passed the TMA when it was outfitted with chevrons. Summary statistics were calculated for each of the vehicle groupings to obtain the sample standard deviation. For this analysis, all data was compiled across color schemes and extra marking panel statuses for each of the TMA marking patterns, as shown in Figure 28.

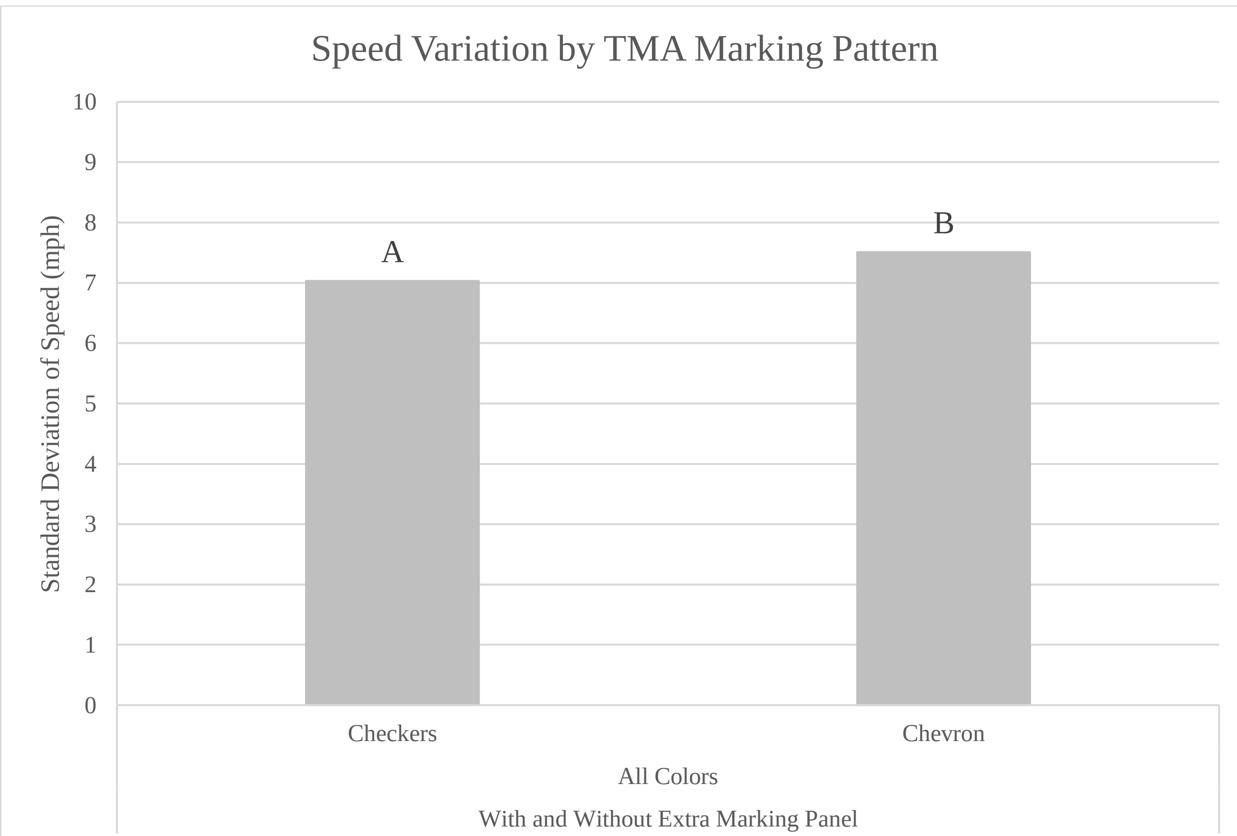

Figure 28. Vehicle speed variation by TMA marking pattern across all treatments. Data is reported for standard deviation of speed. Upper case letters indicate post-hoc grouping from pairwise comparisons.

To establish if speed variation changed for approaching vehicles based on TMA marking pattern, an F-test for equality of two variances was performed. The test compared the ratio of speed variances between treatments where the null hypothesis suggested that checkered and chevron treatments had equal speed variation. Results showed a significant difference in speed variation between chevron and checkered TMA marking treatments (F = 0.88, num df = 4118, denom df = 6280, $p < 0.001$, 95% CI = (0.83, 0.93)). Equipping the TMA with chevrons (SD = 7.51 mph) was found to produce a larger speed variation than when the TMA was equipped with a checkered pattern (SD = 7.03 mph). Speed variation increased by 6.8% (0.48 mph) when the TMA was equipped with chevrons.

Color Scheme

Color was examined within marking pattern to determine the impact that changing TMA color scheme had on the speed variation of upstream approaching vehicles. Data collection produced a sample size of 4,119 unique vehicles that passed the TMA when it was equipped with checkered marking patterns. Of these vehicles, 2,148 vehicles saw the Red+White checkered pattern and 1,971 saw the Yellow+Black checkered pattern. Additionally, there were 6,281 unique vehicles that passed the TMA when it was outfitted with chevrons: 2,239 saw Green+Black, 1,791 saw Yellow+Black, and 2,251 saw Yellow+Orange. Summary statistics were calculated for each vehicle grouping, by color, to obtain sample standard deviations. For this analysis, data was compiled across extra marking panel status for each of the TMA marking patterns and color combinations, as shown in Figure 29.

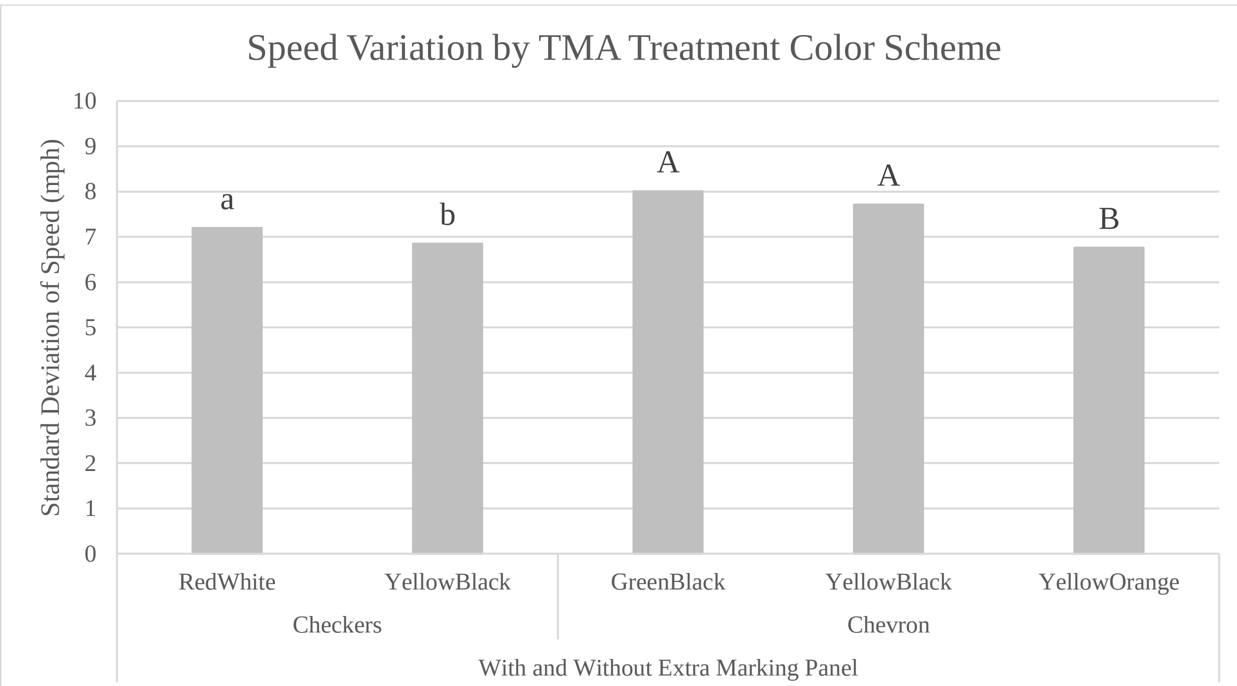

Figure 29. Vehicle speed variation by TMA color scheme across all treatments. Data is reported for standard deviation of speed. Comparisons were made within pattern type with lower- and upper-case letters indicating post-hoc grouping from pairwise comparisons.

To determine if vehicle speed variation changed with respect to TMA color scheme, a series of F-tests for equality of two variances was performed. The null hypothesis suggested that all color schemes within checkered and chevron treatments had equal speed variation. Pairwise tests compared the ratio of speed variances between each of the color schemes within marking pattern type. The chevron comparisons required three comparisons and the resulting p-values were adjusted using a Bonferroni correction to keep the familywise error rate at 0.05, as shown in Table 27.

Testing found a significant difference in speed variation between Red+White and Yellow+Black checkered TMA marking treatments (F = 1.1, num df = 2147, denom df = 1970, p = 0.025, 95% CI = (1.01, 1.2)). For checkered patterns, the Red+White (SD = 7.2 mph) color scheme was found to produce a larger speed variation than Yellow+Black (SD = 6.85 mph). Speed variation was reduced by 5.1% (0.35 mph) when the TMA used a Yellow+Black color scheme.

Table 27. F-tests for Equality of Two Variances Results for all Color Scheme Comparisons for Chevrons – Bold Corrected P-values Were Considered Statistically Significant

Color 1	Color 2	F	Num df	Denom df	P-Value	Corrected P-Value	95% CI Lower	95% CI Upper
Green+Black	Yellow+Orange	1.4	2238	2250	< 0.001	**< 0.001**	1.3	1.52
Yellow+Black	Yellow+Orange	1.3	1790	2250	< 0.001	**< 0.001**	1.2	1.42
Green+Black	Yellow+Black	1.08	2238	1790	0.10	0.2872	.99	1.18

As summarized in Table 27, the within chevron color scheme analysis found a significant difference in speed variation between Green+Black and Yellow+Orange as well as Yellow+Black and Yellow+Orange. There was no significant difference in speed variation between Green+Black and Yellow+Black chevron treatments. Equipping the TMA with Green+Black (SD = 8.00 mph) and Yellow+Black (SD = 7.71 mph) chevrons was found to produce a larger speed variation than when the TMA was equipped with Yellow+Orange (SD = 6.76 mph) chevrons. Overall, the Green+Black treatment was found to have the largest speed variation of any TMA color scheme tested, while the Yellow+Orange color scheme was found to have the smallest.

DISCUSSION

The goal of the field evaluation was to determine what, if any, TMA treatments result in improved safety for the TMA operator and the public. For this study, improved safety is defined as a higher left lane occupancy rate and slower mean speed for vehicles approaching the TMA. If a treatment encourages drivers to move over at a higher rate and to slow down as they approach the truck, then the likelihood of a collision with the truck is reduced. It’s currently unclear if speed variation has an impact on safety in this scenario. Because none of the TMA treatments provide a target speed or explicitly instruct drivers to slow down, any treatment that does encourage some drivers to slow down will inevitably lead to an increase in speed variation because other drivers will not change their behavior. The results of this study showed that the treatments that resulted in the greatest reduction in average speed also resulted in the highest speed variation. It’s the current belief of the research team that a slower average speed is likely a greater benefit to safety and offsets any impact of an increase in speed variation. However, an analysis of long-term data would be needed to verify if this is true.

Based on the results of a survey of DOTs summarized in Table 7, the closest condition to a “standard” TMA configuration would be the Yellow+Black chevrons, as that color and pattern combination is used by 23 of the 26 DOTs surveyed, with orange and white chevrons being the second most common, though only 4 DOTs utilize that color and pattern combination.

When comparing the 10 treatments against each other as discrete conditions, the Green+Black chevrons with the upper panel performed best for left lane occupancy (78%) and speed (50 mph), while the Yellow+Orange chevrons performed significantly worse for left lane occupancy (69%) and had an average speed of approximately 56 mph. For comparison, the "standard" Yellow+Black chevrons without the extra upper panel had a left lane occupancy of 73% and average speed of approximately 55 mph.

For the current study, data was collected for each of the 10 treatments but because the data collection equipment was attached to the truck, no baseline data could be collected without the truck present on the shoulder. While this study did not have a baseline measurement for left lane occupancy or speed when no vehicle was present on the shoulder of the road, another study, conducted on the same portion of westbound U.S. 460, did include these measurements. Williams and Gibbons (2022) measured the left lane occupancy and average speed at three locations along the westbound lanes. When no vehicle was present on the shoulder of the road, left lane occupancy ranged between 23% and 30%, while speed measurements from the radar station nearest to the TMA deployment location showed that the average left lane speed was approximately 69 mph, and the average right lane speed was approximately 66 mph. Although this data was collected at night and may not be directly comparable to lane occupancy and speed during daylight, it does seem to indicate that even the worst performing TMA treatment still had a significant impact.

By-lane speed behavior assessment found that the influence of color scheme, marking pattern, and extra upper marking panel was consistent across lanes, but not between TMA treatments. Right lane traffic was found to be traveling faster, on average, than left lane traffic. The research team determined this was likely due to a significant group of vehicles that were unable to, or chose not to, move over who also did not reduce their speed. Additionally, speed variation was consistent for right lane vehicles across all TMA treatments. In practice, when deploying a TMA, the crew will only be able to outfit the attenuator with one marking pattern and thus subsequent analysis considered the influence of TMA treatment on the speed behavior of both lanes combined.

When examining the effect of the addition of the extra upper marking panel, researchers found that including it provided a benefit for left lane occupancy (although not always statistically significant) across all treatments except for the Yellow+Orange chevrons. With regard to traffic speed, some of the lowest speeds were achieved when the upper panel was present with a checkered pattern. When a chevron pattern was used, the presence of the upper panel tended to result in a smaller decrease in traffic speed. One notable exception was the Green+Black chevrons with the upper panel, which had the lowest mean speed of any treatment.

When examining the difference between marking patterns across all color combinations, the checkers performed slightly better for left lane occupancy. When only considering treatments which used the same color combinations (Yellow+Black), the effect of the checkers was even more pronounced. The checkers pattern provided a safety benefit over chevrons. With regard to traffic speed, the effect of pattern was also dependent on the presence of the upper panel, as previously mentioned, with some of the lowest speeds achieved using a checkered pattern with the upper panel.

When examining the effect of color, the Green+Black chevrons performed significantly better for left lane occupancy and traffic speed compared to the Yellow+Orange and Yellow+Black color schemes. For the checkers, the Yellow+Black and Red+White color schemes performed similarly, though the Yellow+Black performed better for left lane occupancy when the upper panel was included. In general, the Green+Black color scheme provided the greatest left lane occupancy and lowest traffic speeds.

Based on the results of the individual aspects of the marking designs, a Green+Black checker pattern with an extra upper marking panel may provide the greatest benefit. However due to experimental limitations, this condition was not tested. This aligns with the results of Smiley et al. (2017), which similarly recommended a fluorescent yellow-green and black checkerboard pattern.

Limitations

One limitation of this study is that only two patterns were tested. While the checkered pattern showed a statistically significant improvement for safety over chevrons, there may be other patterns which could further increase this safety benefit. Future research could build upon this study and examine other patterns.

Another limitation is that not all color and pattern combinations were tested. In order to maintain a manageable number of treatments, some colors were tested only with specific patterns. For example, there was no Green+Black checker treatment, which this research suggests could be the best combination. Further research could take the results of this study to narrow down the most promising combinations and test them directly.

Another limitation of the study is that testing was only done on one highway. To minimize confounding variables and isolate the effects of the treatments, a section of highway with particular characteristics was selected for this test. This also diminished the external validity of the results because a TMA truck could be used in a very different setting where traffic may behave differently. For example, the traffic volume on US-460 (Table 14) ranged between 250 and 500 vehicles per hour and effects may differ as volume increases or decreases. Additionally, the effects may differ as the mix of vehicle types varies as the study only measured a semi-rural stretch of highway. Future research could take the results of this study and examine the effects in various locations to determine if they are consistent across environments (e.g., urban or visually complex environments).

Another limitation of the study is that testing was only done during daylight hours. Future research could take the results of this study and examine whether the effectiveness of the treatments remains consistent during nighttime operations. It is possible that during nighttime operations, the truck’s warning lights could take over, as they would be much more salient.

The final limitation is that this study considered a brief evaluation of alternative marking designs on a roadway. No long-term effects with a crash evaluation were considered. In this study.

CONCLUSIONS

- *Using Green+Black chevrons with an extra upper marking panel resulted in the best MOL behavior.* This treatment saw the lowest right lane vehicle speeds (57 mph) for vehicles that did not move over, and the highest rate of left lane occupancy (79%) amongst all treatment combinations.

- *For the Yellow+Black color scheme, marking pattern did not significantly influence the rate that drivers slowed their speed, however using a checkered pattern significantly increased left lane occupancy rate (increased by 5%).*

- *The effect of increasing the area of the marking pattern (adding the extra upper panel) had inconsistent results among different color and pattern combinations; sometimes improving performance, and sometimes hurting performance.* This may be a result of testing during daylight when the retroreflective sheeting has less of a visual impact.

- *The Green+Black color combination was the most effective color scheme at promoting left lane occupancy rate (4% - 9% increase). Green+Black (70%) and Yellow+Orange (75%) resulted in the best slowdown behavior (below the speed limit) for right lane vehicles. The color schemes tested resulted in similar levels of safety performance for speed and speed variation.*

RECOMMENDATIONS

As the results of the experiment showed mixed results, additional research is needed before a recommendation to change the TMA pattern is made. However, the following recommendations for future research are provided.

1. *Further research should be conducted to examine additional patterns and color schemes, particularly the Black and Green Checkered pattern.* Due to limitations of the study, this pattern was not used in the investigation and the statistical results are based on a partial factorial not a full factorial experiment. As such there are limitations in the data.

2. *Further investigate the effectiveness of TMA treatments in nighttime operations and more visually complex environments.* Given the limitations in the study, especially testing during the daytime only and only at one location.

IMPLEMENTATION AND BENEFITS

The researchers and the technical review panel (listed in the Acknowledgments) for the project collaborated to craft a plan to implement the study recommendations and to determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

The plans for implementation of these project results are to recommend additional research. An NCHRP or similar level effort, is suggested that will consider the limitations and future research suggestions in this document including daytime versus nighttime effects, multiple types of roadways, dynamic signage, a full factorial evaluation of the signage and marking configurations and finally a long term assessment. VTRC staff with assistance from VTTI and TOD staff will develop and submit a research needs statement to NCHRP for additional research.

Benefits

Implementation of the future research recommended in this report is expected to reduce the opportunity for TMA crashes by using TMA markings that encourage drivers to move over and slow down when approaching a TMA. This could result in enhanced safety for TMA operators and motorists who encounter TMA operations, as well as save money by reducing crashes.

ACKNOWLEDGMENTS

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