EFFECTIVENESS OF GREEN STROBES ON WINTER MAINTENANCE VEHICLES AND EQUIPMENT

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16. Abstract

Snow removal and deicing activities are performed by roadway agencies to enhance winter mobility and safety. Due to slower travel speeds during these operations, low visibility and reduced pavement friction, safety and collision avoidance remain persistent concerns. To improve the visibility of winter maintenance vehicles, the Michigan Department of Transportation (MDOT) has added green lights to the warning system of winter maintenance trucks (WMTs) since 2016. This study investigates the degree to which the visibility can be affected by including these green lights. First, the current state of practice by all state transportation agencies is explored through a comprehensive survey that shows most agencies consider using alternate colors in addition to amber. To evaluate impacts of adding green lights to the warning system of WMTs in terms of visibility, 37 warning light configurations are 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. These configurations are evaluated to identify the most effective ones based on feedback provided by several expert and public panels. Three sets of experiments (static, dynamic and weather) are designed and implemented to evaluate the visibility effectiveness in different contexts (day versus night conditions, clear versus snowy weather and static versus dynamic scenarios). Each of these experiments contains multiple tests that aim to identify different measures to assess the light configuration efficiency. Panels of experts and from the public are employed to conduct the experiments, and the test results are evaluated using statistical analyses. Conspicuity during the day and glare at night are the two main criteria with statistically significant results that are used to compare various configurations. The results show that adding green lights with a single flash pattern to amber warning lights improves the conspicuity significantly, while keeping the glare at an acceptable level relative to configurations using only amber warning lights.

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winter maintenance, warning light, green strobe, safety, visibility, snowplow, flashing pattern, conspicuity, glare

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EFFECTIVENESS OF GREEN STROBES ON WINTER MAINTENANCE VEHICLES AND EQUIPMENT

FINAL REPORT

May 2020

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EXECUTIVE SUMMARY

Winter maintenance operations, particularly snow removal and deicing, are key activities of state transportation agencies to improve roadway safety and mobility during winter weather conditions. However, due to slower travel speeds during these operations, low visibility and reduced pavement friction, there is an increased risk of collisions between motorists and winter maintenance trucks (WMTs). Thus, improving the visibility and conspicuity of winter maintenance vehicles and equipment is a critical research topic. Of particular interest are the colors and configurations of auxiliary warning lights that are installed on these vehicles. Michigan Public Act 161 of 2016, which went into effect September 7, 2016, allows for the use of green lights as an alternative to traditional amber lights. Subsequently, the Michigan Department of Transportation (MDOT) added green warning lights to all of its WMTs over a three-year period.

This study involved a comprehensive investigation of the efficacy of various warning light system configurations used on WMTs with an emphasis on the use of green lights. First, the current state of practice was assessed across the United States through a comprehensive survey of state transportation departments. In this survey, agencies were asked to provide details of current warning light configurations in terms of the colors, flash/synchronization patterns and types of light that are utilized for both winter and general maintenance operations. In addition, the level of interest and degree to which green warning lights are currently used were explored among these states. Finally, the survey provides documentation of other innovative solutions that agencies have implemented to improve visibility during maintenance operations. The results showed that every state DOT uses amber warning lights on WMTs. However, most states incorporate alternate complementary colors, including blue, red, white and green. About 50% of responding agencies are interested in or already use green warning lights. For those agencies where green lights are not in use or under consideration, a primary reason was state legislation that prohibited their use. The survey results provided support for investigating the impacts of using green warning lights on WMTs. This study provided important insights that can serve as support for policy discussions in Michigan and other states.

The study utilized a series of closed course studies to evaluate the visibility of 37 different warning light configurations that comprised various color combinations (green and amber) and flashing patterns (single and quad). The warning light system includes two LED style lights that

were installed on the perimeter of the rear side of the truck, as well as two beacons that were mounted on top of the cab. The light color (green only, amber only, or green and amber) was varied at each of these locations (rear LED and top beacon), resulting in nine different combinations of color and light placement. Within each of these groups, four flashing patterns were considered, totaling 36 different warning light configurations. The first flash pattern used single flashing for both rear and top warning lights. The second and third flash patterns used single flashing on the rear or top warning lights and quad flashing for the other placement. The last flash pattern used quad flashing at both placements (rear and top). In addition, the current MDOT warning light configuration was included, resulting in the final set of 37 warning light configurations that were evaluated in this study.

These configurations were evaluated to identify the most effective configurations based on feedback provided by several panels of human subjects. Three sets of experiments were designed in consideration of potential differences in performance under day versus night lighting conditions, clear versus snowy weather and static versus dynamic scenarios.

In the static experiment, the full set of 37 configurations was assessed by both expert and public panels while the research subjects and WMTs were both stationary at distances of 450 feet and 150 feet. Subsequently, a subset of the 37 warning light configurations was selected based on the results of the static experiments for further consideration in a dynamic experiment by the same panels. Both the static and dynamic experiments were conducted under clear weather conditions. In addition, the performance under adverse weather conditions was examined by repeating a portion of the static experiments under snowy conditions. This evaluation engaged the expert panelists under both daytime and nighttime conditions.

Under each of these experiments, multiple tests were conducted to evaluate different measures of effectiveness as to how the light configurations impact visibility. These tests included the following: a conspicuity assessment to discern the degree to which each configuration was able to attract the attention of the human subjects; the level of glare introduced by each configuration; the maximum peripheral detection angle for each configuration; the minimum distance from the WMT at which the subject would choose to take action (e.g., brake or change lanes); and the specific action that would be taken in each scenario. Human subjects were employed to conduct these experiments, and the test results were evaluated using analysis of variance (ANOVA) to discern where there were statistically significant differences in performance across the various configurations.

In general, adding green lights is shown to improve the visibility of the WMTs across the various scenarios that were evaluated. Results suggest that the use of green lights in the warning light configuration is a trade-off between a sufficient level of conspicuity and a satisfactory level of glare. The flashing pattern is another important factor affecting both conspicuity and glare levels. A green LED used in a quad flashing pattern generates excessive glare, while a single flashing amber LED does not provide sufficient conspicuity. According to the test results, the use of single flashing green lights along with quad flashing amber lights provides adequate conspicuity and a satisfactory level of glare, which is what MDOT uses in the currently implemented configuration. However, to provide maximum flexibility across a variety of conditions, implementation of programmable warning lights that facilitate use of various warning light configurations, intensities and flash patterns is recommended. Such a system would allow for the use of quad flashing green lights in combination with amber lights to maximize conspicuity during daytime conditions, while changing to single flashing green lights to reduce glare at night. The programmable warning lights may be also used in a similar fashion to decrease glare in other situations, including at signalized intersections when drivers are queued in close proximity behind a WMT.

CHAPTER 1 – INTRODUCTION

1-1- Statement of the Problem

The roadway maintenance task is a significant challenge for transportation agencies in states with severe winter seasons, such as Michigan. Poor visibility and the accumulation of snow and ice on the roadway surface degrade traffic operations and increase the risk of traffic crashes. Winter maintenance activities, particularly snow removal and deicing, are critical to maintaining acceptable levels of mobility and mitigating crash risks. However, winter maintenance budgets are limited and, as such, it is crucial for state, county and local road agencies to make informed investments that optimize the use of available resources.

One of the most critical elements of winter maintenance planning is how agencies implement snowplowing and deicing operations. These operations generally require winter maintenance trucks (WMTs) to travel at a lower range of speeds (i.e., from 30 to 40 mph) to maximize their efficiency. These speeds are significantly lower than the operating speeds of many highways, resulting in large speed differentials between the WMTs and other vehicles. Considering the adverse weather conditions (e.g., low visibility and reduced pavement friction) under which these maintenance operations take place, this speed differential can become a significant hazard. In this regard, to address the safety issues associated with WMT operations, Senate Bill 477 passed the Michigan Senate, and was signed into law by the Michigan governor (Lawler, November 2018). The new law mandates all vehicles to drive 10 mph lower than the posted speed limit when passing a stopped vehicle with flashing lights on. Vehicles must also move over to another lane unless it is not possible due to the lane availability or gap availability in the other lane.

To address these concerns, transportation agencies have implemented various signing and lighting technologies to raise awareness among drivers as they approach WMTs so that these drivers can adapt their behavior accordingly (e.g., by reducing speeds). For example, the Michigan State University (MSU) research team recently completed an evaluation of a collision avoidance and mitigation System (CAMS) that was designed to provide an active warning to drivers approaching WMTs from behind at high speed differentials (Zockaie et al., 2018; Verma et al., 2019). Given the costs of such systems, an appealing alternative is the consideration of different lighting technologies (e.g., beacons, strobes or LED strobes), flash patterns (e.g., single or quad), and configurations of warning lights on the equipment.

Of particular interest is the color of the lights. Michigan Public Act 161 of 2016 went into effect September 7, 2016, allowing for the use of green lights as an alternative to the traditional color of amber on public vehicles engaged in the removal and control of either snow or ice. However, there are concerns regarding green warning lights confusing drivers, given that the main application of green lights is in traffic signals. This concern is addressed by using flashing (rather than steady) green lights in the WMT warning light system. In the transportation domain, flashing green lights have already been used in applications such as emergency operations in Incident Command Posts (ICPs) and pedestrian crossings.

More recently, Michigan Public Act 342 of 2018 broadened the list of eligible vehicles with green lights to include those involved in highway repair or maintenance. In addition to green, states have also considered colors such as blue and white either instead of or in combination with amber to improve the visibility of WMTs during maintenance operations. Although a few studies have evaluated the use of white and blue lights on WMTs, no rigorous study exists to evaluate and assess the potential impacts of using green warning lights for these purposes.

The present gap in the literature provides a compelling motivation for the current research, which examines the effectiveness of using green lights on WMTs versus other combinations of colors, in addition to assessing complementary parameters such as flash patterns and rates. Since winter maintenance operations are performed at various times of day and under a range of weather conditions (e.g., clear, overcast, rain and snow), it is important to consider such factors in examining the effectiveness of WMTs with different colors and configurations since specific colors and other parameters might be optimal for some but not all of these scenarios.

To determine the optimal design for parameters of WMT lighting systems, a rigorous human factor study is required that evaluates the degree to which drivers are able to perceive, understand and react to the information being conveyed by these systems. This evaluation should mimic real-world conditions as closely as possible. Thus, in this project a research plan is developed that utilizes the American Center for Mobility (ACM) facility to provide a simulation environment that meets this critical objective. In addition to providing a realistic testbed, the ACM allows for a carefully controlled comparison of driver optical response under various lighting conditions. To further mirror actual driving conditions, the field experiments consider scenarios where both the WMT and the following vehicle are moving at realistic speeds (and speed differentials).

Because this type of experiment requires the following vehicles to adapt their speeds (i.e., accelerate and decelerate), at least two additional concerns arise. First, there are potential liability issues with the use of actual drivers. Therefore, the use of professional drivers through ACM mitigates this concern. Second, as both the ACM and Michigan Department of Transportation (MDOT) WMT drivers are trained professionals, the tests are conducted such that the drivers maintain consistent speed and acceleration profiles, providing critical consistency within and across test subjects who ride as passengers in these vehicles. These conditions also provide distinct advantages to other potential environments, such as driving simulators, which are plagued by difficulties in recreating reduced visibility conditions (e.g., night versus day and adverse weather). Ultimately, this report provides a robust and rigorous means to determine the effectiveness of green strobes on WMTs.

1-2- Study Objectives

Given the lack of a comprehensive study on green warning lights in the existing research literature, the primary goal of this study is to determine the effectiveness of green auxiliary lighting on WMTs in Michigan. To this end, the following research objectives are defined for this study:

- Evaluate the impacts, positive or negative, of the use of green auxiliary lighting on roadway WMTs.
- Evaluate the situations (e.g., daytime versus nighttime) and weather conditions (e.g., clear, overcast, rain, fog and snow) for which green lighting is the most or least effective.
- Determine whether green alone is effective or whether the use of two colors (i.e., green with amber) is preferred.
- Evaluate flash patterns to determine which pattern(s) is(are) the most effective (single versus quad or fast versus slow).
- Provide recommendations for the use and placement of green auxiliary lights, including the conditions for use, type of equipment and location of the lights on the equipment.

1-3- Research Plan

To accomplish the aforementioned objectives, the research team prepared a detailed research plan to outline the process for evaluating green auxiliary warning lights on WMTs. To accomplish the project objectives, the proposed research plan was conducted according to the following tasks:

- Task 1: Literature review.
- Task 2: Review of current practice (DOTs survey).
- Task 3: Crash data evaluation.
- Task 4: Experiment design and formation of human subject panels.
- Task 5: Simulated warning light evaluation (static experiment).
- Task 6: Warning light evaluation on controlled test roadway (dynamic experiment).
- Task 7: Recommendations for use and placement of green strobes.
- Task 8: Development and delivery of draft and final reports.

1-4- Report Structure

The remainder of this report is structured as follows: Chapter 2 provides a literature review of the basic concepts of the study. Chapter 3 reviews the current practices utilized by transportation agencies via a conducted survey. Chapter 4 provides the details of an experimental design to evaluate the effectiveness of different warning light configurations in the visibility improvement. Chapter 5 presents the results and statistical findings of the conducted experiments. Chapter 6 provides a review of crash data analyses regarding green auxiliary lighting application in Michigan. To conclude, Chapter 7 includes a summary of findings and the recommendations for consideration by MDOT.

CHAPTER 2 – LITERATURE REVIEW

2-1- Human Vision

Approximately 90% of driving information is acquired visually (Sivak, 1996). Therefore, the visual medium has been suggested as the most appropriate form of delivery of pertinent information to drivers (Saedi and Khademi, 2019; Khademi and Saedi, 2019). The characteristics of the human visual system in terms of sensitivity to the basic image features play an essential preliminary role in the perception and cognition of complex environments such as the driving condition (Blakemore and Campbell, 1969). Visual abilities required for acquisition and perception of dynamic information are correlated with traffic crashes (Henderson and Burg, 1975). Therefore, it is important to understand the human visual system and its response to warning lights. Considerations should include the impacts of different factors such as size, contrast, color, flash pattern and intensity. For example, brightness and visibility were shown to vary across different colors (Gibbons, 2008). As compared to blue and red, white and amber were found to show the highest effective intensity.

There is substantial evidence to suggest that different colors and flash patterns have a significant impact on drivers' attention and response to WMTs. On the other hand, there is no univocal evidence suggesting a priori that one particular color or flash pattern would be better suited than others, which underscores the importance of research studies that investigate this question. Available evidence is summarized below.

Some patterns of visual stimulation tend to draw people's attention and gaze more than others. Arguably, the most reliable way of drawing attention and gaze is to use abruptly changing and moving patterns, known as transients (Yantis and Jonides, 1996; Carrasco, 2011). When it comes to the temporal sequence of flash patterns on service vehicles, it is likely that dynamic flash patterns will have a greater ability of drawing drivers' attention and influencing their behavior than static patterns will have. When it comes to the color of warning lights, even though there are indications that specific colors may have a stronger impact on behavior than others, the evidence indicates that this type of difference is context-dependent. Indeed, the impacts on drivers' behavior highly depend on the situation in which the colors are encountered (Elliot and Maier, 2012). This finding is consistent with a more general observation that people tend to direct their attention to the elements in their environment that are relevant to the task at hand (Most et al., 2001; Melloni et al., 2012). This is in part the direct result of an intentional strategy, but it is also an indirect and involuntary result of task history (Wolfe et al., 2003; Lamy and Kristjánsson, 2013). If certain features (such as the color red) have been relevant to one's behavior in the recent past, then his or her attention is automatically drawn to new elements that have those features (e.g., red objects). In the context of the present study, this consideration raises the possibility that red or amber warning lights might have an increased ability to draw drivers' attention given the behavioral importance of red lights (e.g., traffic lights and brake lights) to people whose context consists of navigating traffic.

The impact of visual information on drivers' behavior depends on multiple factors, which makes it difficult to determine a priori which flash patterns or colors will be the most effective. A significant factor is that attention is involuntarily drawn to the elements of surroundings with uncommon features in the present environment, known as oddball elements (Wolfe et al., 2003; Melloni, et al. 2012). This would suggest a potential benefit of green warning lights since a green light in a sea of red lights amplifies its impact on drivers' behavior. In sum, it is plausible that more dynamic flash patterns have more significant impacts on drivers' behavior, and several different and partly contradictory arguments can be made with regard to color. Thus, empirical research directly addressing this issue is required.

2-2- Warning Lights

Historically, efforts to enhance the visibility of highway maintenance trucks, vehicles and equipment have focused on the provision of various types of warning lights. Various factors (e.g., type of light, configurations and weather conditions) have been investigated to determine how warning lights may be used to make slow-moving vehicles more easily detectable by other road users. Unfortunately, there are no national regulations for warning light configurations, light sources and colors. American Association of State Highway and Transportation Officials (AASHTO) guidance recommends amber and white as the primary warning light colors for WMTs. AASHTO also recommends the use of LEDs, asynchronous flash patterns and installation of lights at high elevations with solid-colored contrast. The Manual on Uniform Traffic Control

Devices (MUTCD) similarly provides recommendations, also suggesting amber and white for highway work.

Prior research suggests that using different color combinations may affect the traffic behavior in response to warning lights (Hanscom and Pain, 1990; Raimondo, 1994; Ullman, 2000; Ullman et al., 1998). In a study by Ullman (2000), the combination of blue and amber was found to be more effective in conveying a sense of hazard to motorists. This combination reduces vehicle speeds when compared to using only amber lights. A similar study by Kamyab et al. (2002) reviewed the state of practice as it relates to enhancing the visibility of WMTs. This study showed almost all responding states use reflective materials to increase the visibility of WMTs. All of these states indicated they use more warning lights on WMTs as compared to other types of maintenance vehicles. Reflective tapes, warning flags, strobe lights and auxiliary headlamps were among the common materials used to enhance the visibility of WMTs and other maintenance equipment. Stidger (2003) reviewed general guidelines for snow removal and ice control vehicles, and suggested that retroreflective magnetic tapes and steady-burning light bars can improve vehicle visibility under adverse weather and nighttime conditions.

Color has been identified as one of the primary factors that influence drivers' response to warning lights. A study conducted for Indiana DOT (McCullouch and Stevens, 2008) investigated the effectiveness of warning lights with different colors and shapes mounted on WMTs under different weather conditions (Figure 2-1). The brightness and visibility of various colors (amber, blue, red and white); lighting technologies (strobes, LEDs and beacons); and shapes (round and rectangular) were compared under cloudy and snowy conditions. Results suggested that amber, rectangular-shaped LEDs were brighter and more effective followed by blue. A recent survey by Howell et al. (2015) in Kentucky found that all respondents used amber LEDs as the main warning light. The application of amber with other color combinations varied depending on the vehicle type and purpose.

Figure 2-1 Examples of warning lights layout (Source: McCullouch and Stevens, 2008)

Flash pattern is another important factor to consider in the design of warning light systems. In a study by Taylor et al. (1967), flasher conspicuity and the type of flashing devices were proposed as factors that may influence the number of crashes. A similar study evaluated the effectiveness of a flashing warning light system for work zone applications (Finley et al., 2001). Results showed significant operational and safety benefits when a flashing device was implemented in a short-term maintenance project.

In addition to color and flash pattern, the light source (such as halogen, strobe, LED and beacon) is also influential in drivers' response to warning lights. Muthumani et al. (2015) summarized best practices in the use of warning lights and found the warning light height, light source, light color and flashing pattern and the use of retroreflective tapes were influential factors affecting road users' behavior when they encounter WMTs. A combination of flashing and steady-burn lights was strongly recommended, and retroreflective tape was found to be effective in providing additional warnings, although the cleanliness of such tape is an issue during winter operations. The study also suggested different intensity settings by time of day to avoid glare discomfort at night.

Gibbons (2008) conducted a comprehensive study on warning light systems. More than 135 different flash patterns and 35 devices were considered to compare the effectiveness of different light sources. Among three light sources (halogen, LED and strobe) and four colors (amber, blue, red and white), halogen-white showed the highest effective intensity. Static screening and field performance experiments were also conducted in this study. Figure 2-2a shows the warning lights layout in the static screening experiment. Results showed that the combination of amber and white provides the highest conspicuity. A higher effective intensity provided greater conspicuity; however, it tended to cause glare discomfort at night. An asynchronous flashing light at a lower frequency was identified as the best flash pattern. LED seemed to provide the best results among all other light sources, and a dark-color contrast was also recommended.

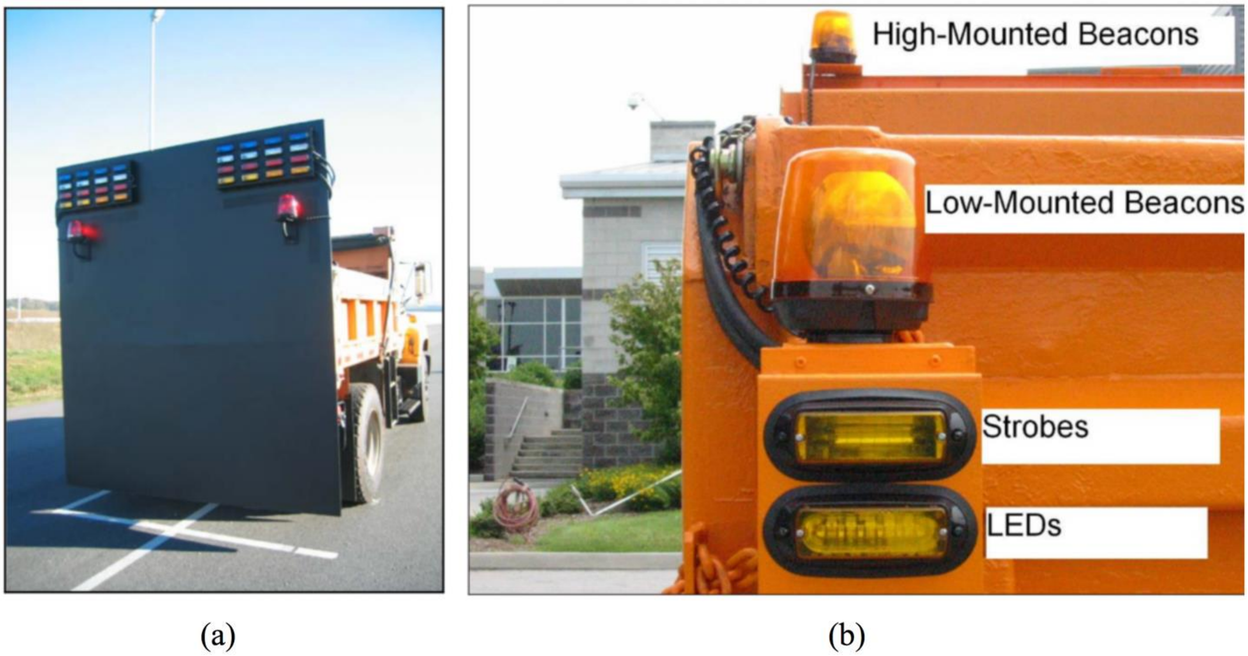


Figure 2-2 Warning lights layout: (a) static screening experiment and (b) field performance experiment (Source: Gibbons, 2008)

Figure 2-2b shows the warning light arrangement from the field performance tests. The experiments showed the configuration of the warning light system affects numerous variables, including lane-change distance, vehicle identification distance, pedestrian detection distance, level of urgency felt by the subject, discomfort glare at night, confidence level of the subject to see the warning light and rated conspicuity. A dark background was found effective for the warning light system, especially during the daytime. Using a double flash pattern was highly recommended to improve the vehicle visibility. Results recommended balancing the effective intensity of the warning lights between the level that provides minimum conspicuity and the level prior to which glare discomfort becomes an issue. Retroreflective tape was also suggested to be used as a supplement to warning light systems. Finally, the research concluded that nighttime and daytime conditions may require alternative warning light systems.

MDOT and other Michigan road agencies have recently started adding green lights to WMTs given minimal implementation costs and better human eye sensitivity to the green/yellow spectrum (Figure 2-3). MDOT has also added lights to the ends of its plows to increase visibility. However, the extant literature has not evaluated the impacts of the green strobes. The lack of evaluation provides motivation for a comprehensive study evaluating the effectiveness of these green strobes, in addition to identifying the best warning light configurations. Furthermore, the recent large-scale installation of green strobes will allow for a detailed crash data analysis to understand the short-term impacts of this program.

(a) (b)

Figure 2-3 Winter maintenance vehicle warning lights: (a) MDOT vehicle warning lights (Source: Weingarten, 2016) and (b) new proposed green warning lights (Source: Walker, 2014)

CHAPTER 3 – REVIEW OF THE STATE OF PRACTICE

3-1- Purpose

In an attempt to investigate the current practice of auxiliary warning lights on maintenance trucks, a nationwide survey was developed and distributed among different states. Each state has its own policy regarding the auxiliary warning lights, and there is not any uniquely defined criterion to unify the policies. Therefore, each state DOT may use a different warning light configuration from other state DOTs. The four main objectives of the current survey were to:

- Compile the current status of the lighting configurations used by different state DOTs for maintenance trucks, particularly as it pertains to WMTs.
- Gather information about the effectiveness of different configurations and the adopted approaches.
- Gather any studies conducted by other states regarding the effectiveness of different auxiliary warning light configurations.
- Identify the most promising and feasible configurations for WMTs in Michigan by investigating the effectiveness of different colors and flashing patterns.

3-2- Survey Design

The MSU research team developed a survey to investigate the state of practice for auxiliary warning lights on maintenance trucks, specifically WMTs. The survey was designed electronically through MSU Qualtrics system. MDOT distributed the survey on behalf of the research team to all 50 state DOTs in October 2019. The survey consisted of 19 questions seeking the following information about WMTs:

- Type and color of auxiliary warning lights.
- Flashing pattern and synchronization type.
- The interest of agencies in installing green lights on maintenance trucks.
- Technologies or equipment to enhance the visibility of winter maintenance operations.
- Previous research on evaluations of auxiliary warning lights.
- Suggestions about snow-covering issue.
- Policies or standards regarding the use of green strobes.

- Initiatives to inform road users of any changes in installed warning lights.

The respondents were asked to provide detailed contact information to allow for follow-up. In November and December, reminders were sent to the state DOTs that did not provide a complete response to the survey. Some states provided multiple responses. Therefore, these states were contacted to clarify the final response in case of some inconsistencies. The original survey template is provided in Appendix A.

3-3- Summary of Results

Transportation agencies responding to the survey included states from the West Coast to the East Coast, affording a vast range of weather and terrain conditions. All states provided complete responses for general maintenance trucks, while 49 states responded to questions regarding WMTs. Hawaii was the only state that did not respond to the questions for WMTs.

The summary of the responses for types, colors and flash patterns of auxiliary warning lights on WMTs and other maintenance trucks is presented in Figure 3-1 and Figure 3-2, respectively. As shown in Figure 3-1a, 88% of state DOTs are using directional or flat light-head warning lights on WMTs under their jurisdictions, while 80% are using a rotational warning light. Approximately 67% of state DOTs are using both warning light types. Two states noted using other light types in addition to the two options provided in the survey: arrow boards and light bars. Figure 3-1b shows the distribution of colors used for the warning light of WMTs among different states. According to this figure, all surveyed states currently use amber as one of their used lights. After amber, the color white has the highest use among different state DOTs. Currently Michigan, Connecticut, Maine, North Carolina and Ohio use green lights on their WMTs.

Figure 3-1c illustrates the distribution of flash patterns used on WMTs by different states. According to this figure, double flash pattern is the most common pattern among all states, while the single flash is the second most common pattern. Although quad flash is not as common as other flash patterns, the National Cooperative Highway Research Program (NCHRP) suggests testing it. According to Figure 3-1c, 17 states use flash patterns other than those provided in this figure and the survey. These flash patterns and the number of states using them are presented in Table 3-1. In terms of synchronization type, as shown in Figure 3-1d, the distribution is almost even among different states. Six states use both synchronous and nonsynchronous patterns, depending on the type of work, location and crew preferences.

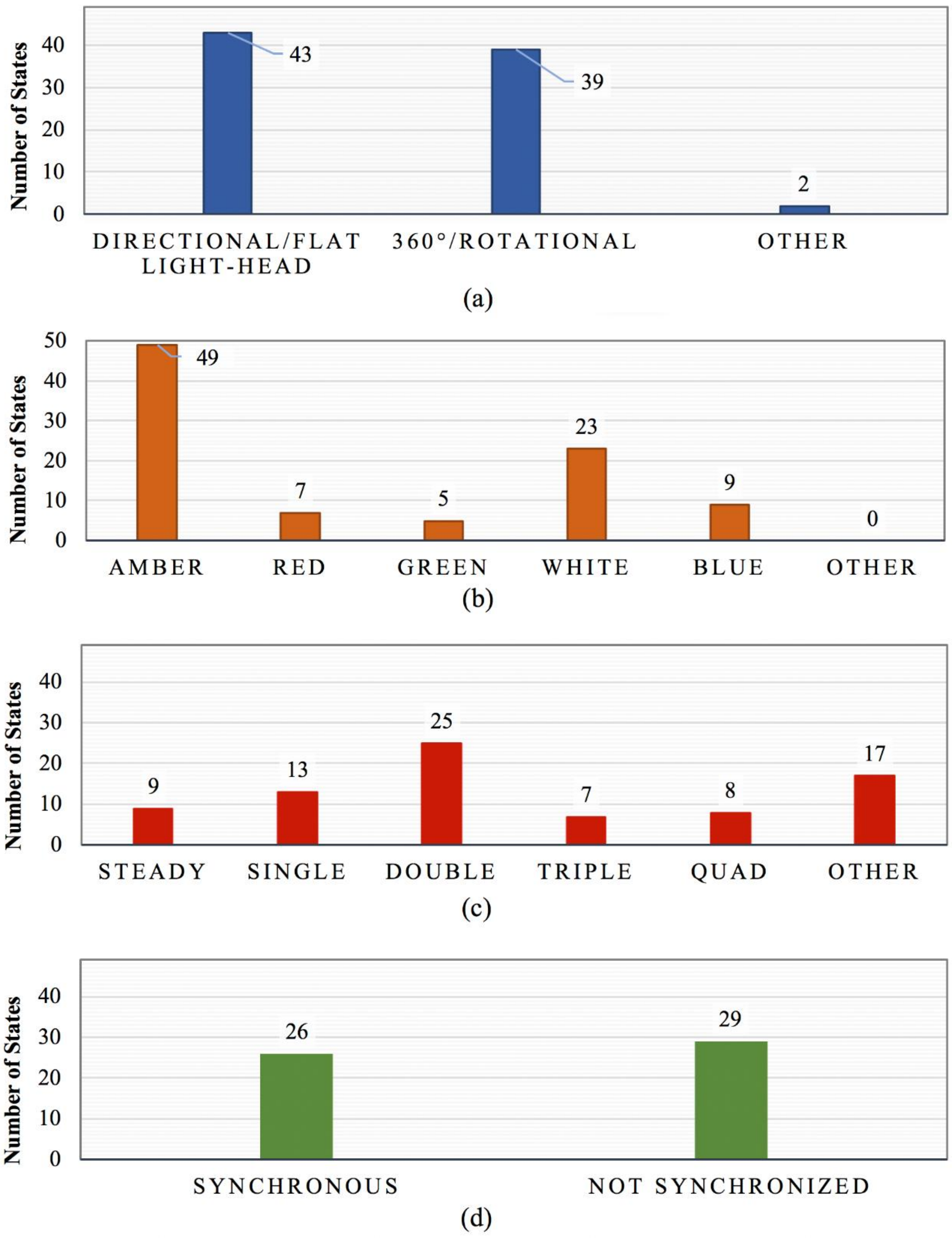


Figure 3-1 Types, colors and flash patterns of auxiliary warning lights on WMTs: (a) types of auxiliary warning lights, (b) colors of auxiliary warning lights, (c) flash patterns and (d) synchronization types

Table 3-1 Flash patterns other than the listed patterns in the survey

Flash Pattern	**Number of States**
Random pattern or automatic rotation of all patterns	9
No standard pattern	3
Wig-wag	2
Pinwheel	1
4-corner flash: Bouncing ball and side-to-side X configuration	1
ActionFlash150	1

Types of auxiliary warning lights on maintenance trucks other than WMTs used by different state DOTs are shown in Figure 3-2a. According to this figure, 86% of the state DOTs use directional or flat light-head warning lights on their maintenance trucks, while 74% use rotational warning lights. Expectedly, in terms of warning light colors, all states use at least an amber warning light, as shown in Figure 3-2b. According to this figure and similar to the pattern for WMTs, white is the second most used color. Oklahoma and Connecticut use green warning lights on maintenance trucks other than WMTs. Figure 3-2c illustrates the use of different flash patterns among different state DOTs. Similar to WMTs, double flash pattern is the most common pattern among state DOTs. As shown in Figure 3-2d, 46% of state DOTs are using only a synchronous flash pattern on their maintenance trucks, 40% are using only a “not synchronized” pattern, and 14% are using both patterns, depending on the type of work and crew preferences.

The respondents were also asked whether they might consider installing green lights on any maintenance vehicle if their agency does not currently use them. The interest in and use of green lights on maintenance trucks working under the jurisdictions of different state DOTs is illustrated in Figure 3-3. As shown in this figure, 12% of states (six out of 50) are currently using green lights on their maintenance vehicles, and 32% of surveyed states are interested in using green lights given that the results of this project or other similar ongoing studies show its effectiveness. However, more than half of the states are not interested in using green auxiliary warning lights on their maintenance vehicles. Most of these states mentioned legislation as an obstacle to the change. A summary of the reasons provided by different states that are not interested in green lights is provided in Table 3-2.

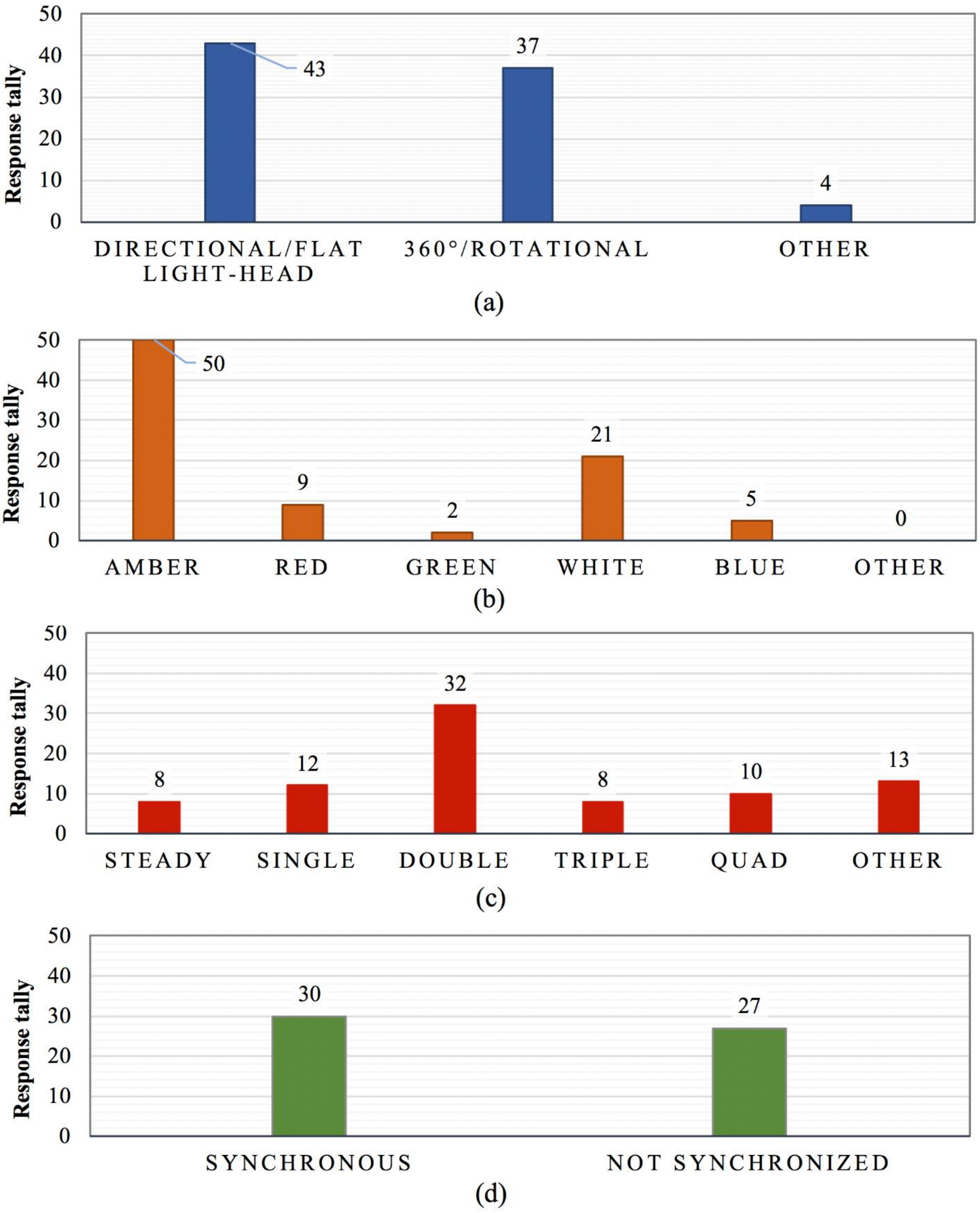


Figure 3-2 Types, colors and flash patterns of auxiliary warning lights on general maintenance trucks: (a) types of auxiliary warning lights, (b) colors of auxiliary warning lights, (c) flash patterns and (d) synchronization types

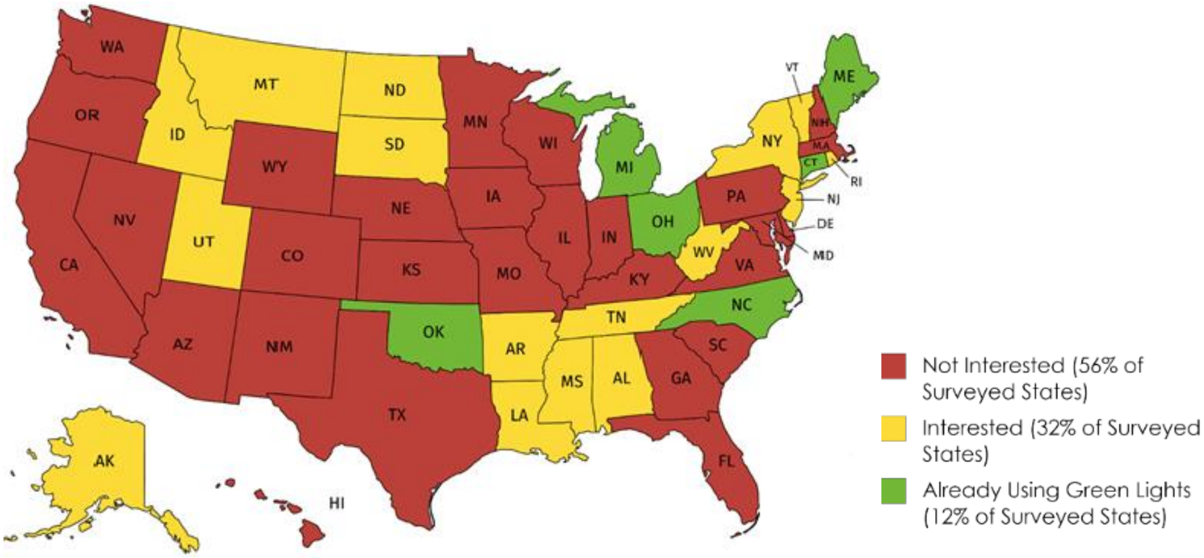


Figure 3-3 Use of/interest in green lights on maintenance trucks

Table 3-2 Comments from states that are not interested in green lights on their WMTs

Reason	**Number of States**
Current legislation or state regulations	13
Satisfactory performance of their current color combinations	6
Using green for other vehicle types such as police, fire and emergency vehicles	5
An informal study on green lights showing their ineffectiveness	1
Green means “go”	1
Perceptions of different colors by the general public	1
Financial concerns regarding the investment cost	1

State DOTs were also asked if they suggest any other technologies and/or innovative equipment to enhance visibility of winter maintenance operations and to avoid the snow accumulation on warning lights. The suggested technologies or equipment are categorized into three main groups as listed below:

1. Technologies on the back or side of trucks:
    - Adding retroreflective auxiliaries such as tapes, glow sticks, and chevron markings or paintings to back or plow of the truck.
    - Using flashing arrow boards on the back of the truck.

    - Incorporating a dynamic warning light controller (e.g., Whelen) for specific applications, such as different configurations for day- and nighttimes or dimming the lights at intersections to reduce glare for drivers when stopped in close proximity behind the WMT at signalized intersections.
    - Using camera systems to improve visibility for the truck driver over the rear zone and blind spots in addition to using midship turn lights.
2. Technologies for the wings:
    - Using innovative approaches, such as LED stick light markers, for outside edge of the plow.
    - Incorporating spotlights for wing plows to make the edge of the road visible for the truck driver.
    - Incorporating wing plow lasers to provide the truck driver a better perspective of where the end of the truck wing plow is located during the maintenance operations.
3. Technologies to avoid snow accumulation on the back of trucks:
    - Adding airfoils to the warning lights.
    - Using heated lenses for warning lights.
    - Placing the warning lights on highest possible locations.
    - Using long rubber flaps on plows to reduce snow fog for front plows, wings and tow plows.

The respondents also suggested some initiatives to inform users of the recently adopted green strobes or any other technologies associated with the visibility of maintenance vehicles. Press releases, public service announcements, social media, websites, media interviews and dynamic message sign boards are among the suggested and used initiatives by different states. Overall, the outcomes of this survey can be used in the current study and other similar studies by other agencies as the current state of practice for warning light configurations on maintenance trucks, determining the impediments to the use of new technologies or light configurations and considering the suggestions of other states for future implementations.

CHAPTER 4 – EXPERIMENTAL DESIGN

To evaluate the effectiveness of different configurations of warning lights on visibility of WMTs, two sets of experiments were designed: static and dynamic. In the static experiment, a greater number of warning light configurations were tested among a sufficient number of participants. The participants evaluated the capability of warning lights to improve the visibility of WMTs utilizing multiple measures of effectiveness, as discussed later. A selected subset of the evaluated light configurations in the static experiment was considered for further assessments in a dynamic experiment. Both static and dynamic experiments were conducted on clear days and nights (with no or minimal snow events). Furthermore, a portion of the static experiment tests were repeated under adverse weather conditions to explore impacts of the weather conditions on the visibility of warning lights. The latter is referred to as the weather experiment in this study.

The main objective of these stepwise experiments was to evaluate the visibility effectiveness of a greater number of light configurations in different contexts (day versus night, clear versus snowy and static versus dynamic). Each of the described experiments contained multiple tests that aimed to identify different measures to assess the light configuration efficiency in terms of the visibility improvement. Details of the experiments are presented in the following sections. The various warning light configurations used in different experiments are also listed in this section.

4-1- Human Subjects

Human subjects were employed to conduct the experiments evaluating various warning light configurations. The research subjects formed two panels of experts and public participants. The expert panel included the MSU research team (mainly graduate students) and MDOT staff, while the public panel members were recruited from nonexpert individuals. The subjects of the public panel participated in the static and dynamic experiments only in clear weather conditions, while the subjects of the expert panel participated in the weather experiments in addition to the static and dynamic experiments to facilitate an impartial comparison between different contexts of experiments. The static experiments included 24 research subjects as participants, and the dynamic experiments included 25 research subjects, with 16 participants in common with the static experiments. The participant population in both static and dynamic experiments included both genders and covered a wide range of ages (from 22 to 65 years old). The weather experiments were conducted only by the expert panel with 14 participants (including 13 participants in common with the static experiments). The public panel research subjects were not employed for these experiments due to uncertainties associated with the weather conditions. To the extent possible, the same participants were employed to conduct the experiments to avoid impartial biases in comparison of different experiments due to the small number of available research subjects. However, since multiple experiments were performed at different events, it was not possible to employ exactly the same research subjects for all experiments.

4-2- Static Experiment

In the static experiment, participants and the experiment vehicle (a WMT with warning lights) were in stationary conditions. Following the instructions of NCHRP Report 624 (Gibbons, 2008), the clearance distance between the participants and the experiment vehicle was set to 450 feet. This value was decreased to 150 feet for a particular test (glare rating). Figure 4-1 illustrates a schematic configuration of the static test beside the visualization of the actual experiment environment.

(a) (b)

Figure 4-1 Static experiment configuration: (a) schematic and (b) field test environment

4-2-1- Conspicuity Test

To measure the effectiveness of the warning lighting configurations in terms of appearances, participants were asked to rate the level of attention-getting of these configurations. Participants were exposed to each light configuration for about 15 seconds at a distance of 450 feet to the experiment vehicle. Then they were asked to declare their perception about the attention-getting capability of each light configuration using an n-point rating scale (Table 4-1). This test was conducted in both daytime and nighttime. The test environment is illustrated in Figure 4-2. Various configurations were ordered randomly with the same order for all participants to prevent any bias in the data collection process. Furthermore, the first three configurations were exactly repeated as the last three configurations to consider a warmup period for participants (to ignore the first three configurations). Note that participants were not aware of these repetitive configurations.

Table 4-1 Conspicuity test n-point rating scale

Description	Score
Not at all attention-getting	1
Minor level of attention-getting	2
Moderate level of attention-getting	3
Quite attention-getting	4
Extremely attention-getting	5

Figure 4-2 Conspicuity test configuration (participants are in stationary vehicles during the test)

4-2-2- Appropriate Driving Action Test

The objective of this test was to identify what driving action (if any) subjects preferred to take when they encountered a truck with warning lights. This test was concurrently accomplished with the conspicuity test. Participants were exposed to each light configuration for 15 seconds at a distance of 450 feet to the experiment vehicle (matching the conspicuity test). Then they were asked to choose what driving action (if any) they preferred to take for each light configuration from Table 4-2. This test was conducted in both daytime and nighttime. The test environment is the same as Figure 4-2, and the same procedure was applied to ensure preventing any bias in terms of the order of various warning light configurations (random but the same order for all participants and repeating the first three configurations at the end).

Table 4-2 Alternatives in appropriate driving action test (static experiment)

Description	Item
No action	1
Take foot off accelerator	2
Apply brake	3
Lane change	4

4-2-3- Maximum Peripheral Detection Angle Test

This test was designed to measure the maximum horizontal angle at which the warning light could be detected. This was conducted only in the daytime, when the light contrast is minimum (the worst condition). Participants were exposed to each light configuration for 15 seconds at a distance of 450 feet to the experiment vehicle. Then they were asked to declare the maximum angle in which they could detect the light for each light configuration. As shown in Figure 4-3, the participants tried seven angles in 15-degree increments to identify the maximum peripheral detection angle.

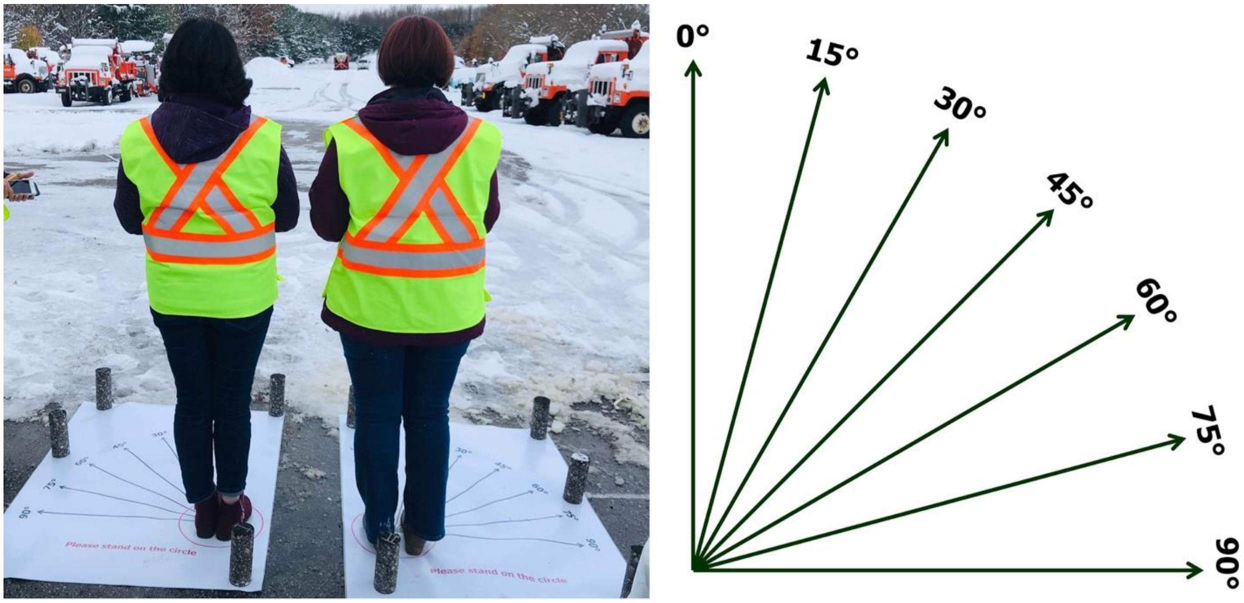


Figure 4-3 Maximum peripheral detection angle test configuration

4-2-4- Glare Rating Test

In this test, the discomfort level posed by the warning lights to drivers of the vehicles that follow the WMT (in this test, experienced by the research subjects who were exposed to these lights) is measured. This test was conducted only at nighttime, when the light contrast is maximum (the worst condition in terms of glare). Participants were exposed to each light configuration for 15 seconds at a distance of 150 feet to the experiment vehicle. Then they were asked to declare the level of discomfort they experienced using an n-point rating scale (Table 4-3) for each light configuration. The same procedure was applied to ensure preventing any bias in terms of the order of various warning light configurations (random but the same order for all participants and repeating the first three configurations at the end). Figure 4-4 illustrates the test environment.

Table 4-3 Glare rating test n-point rating scale

Description	Score
Not noticeable	1
Just noticeable	2
Satisfactory	3

Disturbing	4
Unbearable	5

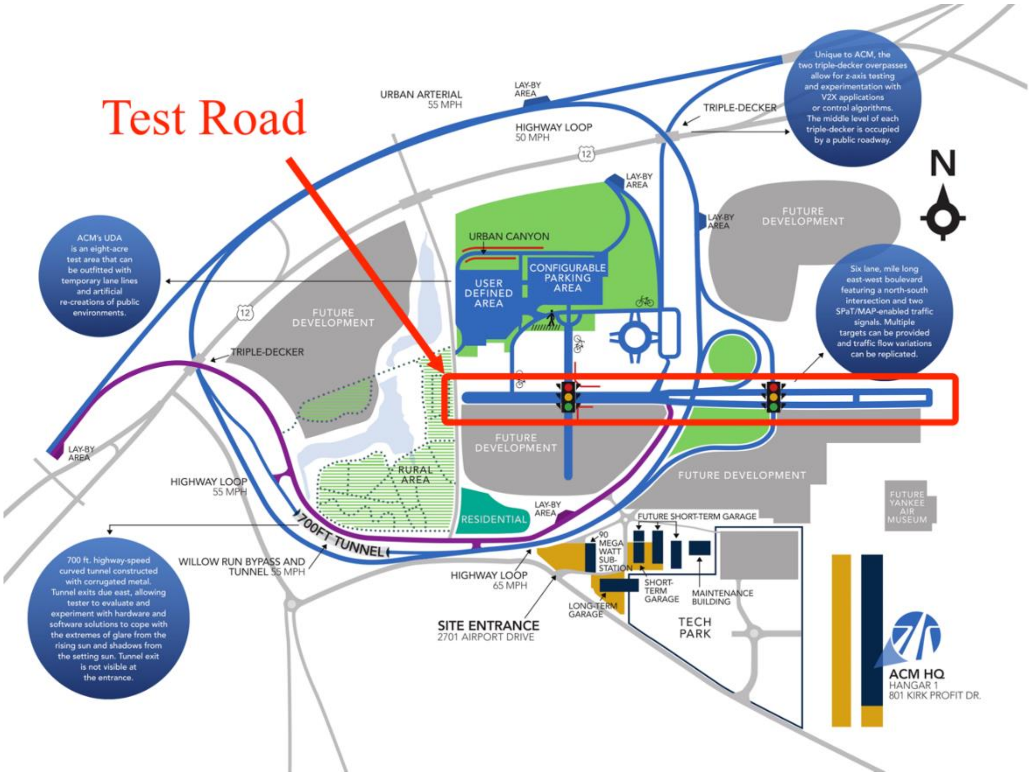
Figure 4-4 Glare rating test configuration

4-3- Dynamic Experiment

The dynamic experiment was an in-field simulation of real-world conditions, where a passenger car encounters a WMT equipped with warning lights. The main objective of this test was to evaluate the efficiency of a set of light configurations (which is a subset of the considered light configurations in the static experiments) in terms of visibility. In this experiment, human subjects were moved as passengers in a participant vehicle that follows the experiment truck displaying a particular warning light configuration at each run. Twenty-five subjects participated (80% of them also participated in the static experiment to make the two experiments as comparable as possible). Figure 4-5 provides a schematic configuration of the dynamic test beside a picture of the experiment environment. A layout of the AMC, where the experiment was conducted, is shown in Figure 4-6.

(a) (b)

Figure 4-5 Dynamic experiment configuration: (a) schematic and (b) field test environment



Unique to ACM, the two triple-decker overpasses allow for z-axis testing and experimentation with V2X applications or control algorithms. The middle level of each triple-decker is occupied by a public roadway.

ACM's UDA is an eight-acre test area that can be outfitted with temporary lane lines and artificial re-creations of public environments.

Six lane, mile long east-west boulevard featuring a north-south intersection and two SPaT/MAP-enabled traffic signals. Multiple targets can be provided and traffic flow variations can be replicated.

700 ft. highway-speed curved tunnel constructed with corrugated metal. Tunnel exits due east, allowing tester to evaluate and experiment with hardware and software solutions to cope with the extremes of glare from the rising sun and shadows from the setting sun. Tunnel exit is not visible at the entrance.

Figure 4-6 Dynamic experiment test road at ACM

Each run of the dynamic experiment included the process in which the participant vehicle and experiment truck began to move from an initial clearance distance up to the point that the participant vehicle passed the truck due to its higher speed. At the beginning of each run, the participant vehicle was positioned at the starting point of an experiment road (see Figure 4-7). The experiment vehicle was stopped at a distance of 0.4 mile from the participant vehicle. The experiment vehicle started moving at 25 mph. At the same time, the participant vehicle accelerated to 55 mph and passed the experiment vehicle at a distance of 0.73 mile from the starting point. In these experiments the participants completed four different tests: action-taking distance (minimum gap), conspicuity, appropriate driving action and glare rating. All of these tests were conducted at once on each run of the dynamic experiment for each warning light configuration. The action-taking distance test was accomplished before the participant car passed the experiment vehicle; the other three tests were completed when the participant car passed the WMT. Details of the tests are discussed in the following sections. Figure 4-7 illustrates the schematic configuration of the dynamic experiment.

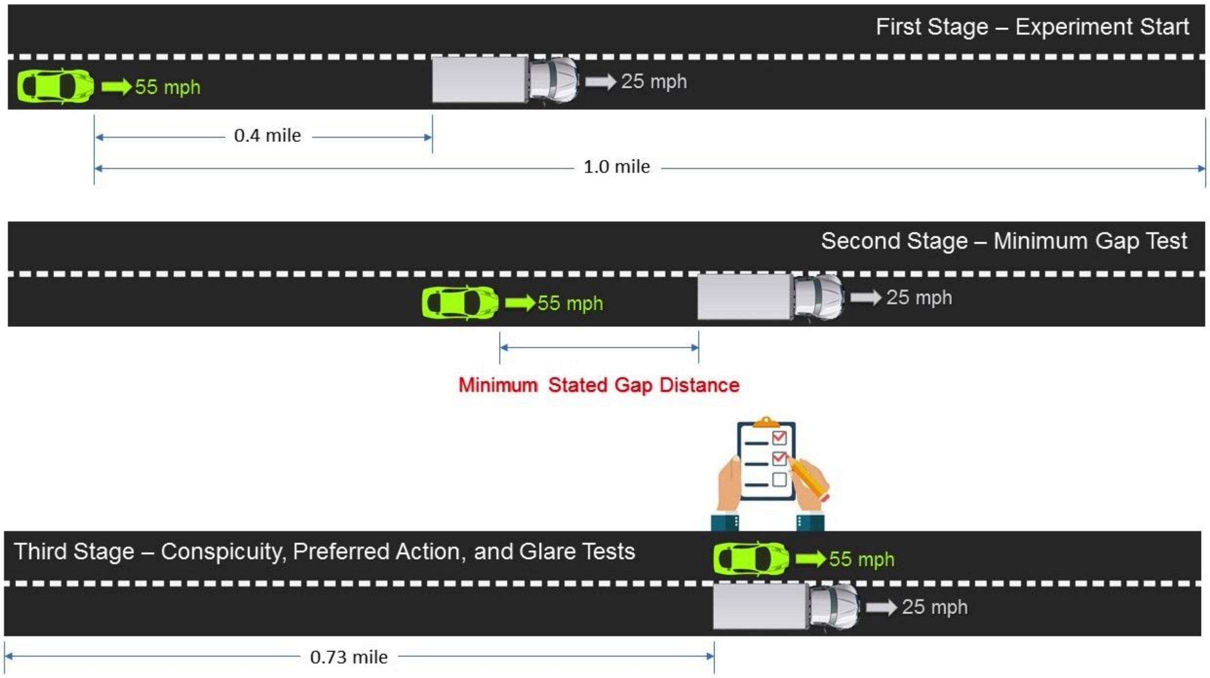


Figure 4-7 Different stages of the dynamic experiment

4-3-1- Action-Taking Distance (Minimum Gap) Test

This test aimed to identify the danger zone (unsafe distance) felt by participants behind a WMT. Participants sat in the front passenger seat of a vehicle parked approximately one-half mile behind a WMT. The participant vehicle (which was driven by an experienced driver) closed the gap between the two vehicles with a relative speed of 30 mph. Participants were instructed to say “Action” as soon as they felt that the gap between the two vehicles (the participant vehicle and the WMT) was unsafe. A member of the research team sitting on the back seat recorded the relative distance between the two vehicles at this moment. Participants were aware that the word “Action” represented one of three driving maneuvers: braking, taking the foot off the accelerator or lane changing. They might prefer one of these actions at the time they felt that the gap was not safe and a driving action (maneuver) must be accomplished. Figure 4-8a illustrates the test environment. The participants and experiment vehicles were equipped with racer tools that provided the information of relative kinematics of the two vehicles such as the longitudinal distance. Racelogic Vbox was used as the racer tool (Figure 4-8b). The accuracy of this tool for collecting the velocity information is 0.1 kilometer per hour and at a distance of less than 50 centimeters per kilometer.

Figure 4-8 Action-taking distance (minimum gap) test: (a) test environment and (b) racer tool

4-3-2- Conspicuity Test

At the end of each run of the dynamic experiment (when the participant car had fully passed the WMT), participants were asked to describe their perception of the attention-getting capability of the ongoing light configuration using an n-point rating scale (Table 4-1). Figure 4-9 shows the test environment.

Figure 4-9 Conspicuity, appropriate driving action and glare rating tests in the dynamic experiment

4-3-3- Appropriate Driving Action Test

At the end of each round of the dynamic experiment (when the participant car had fully passed the WMT), participants were asked to choose the driving action they had on their mind once they said “Action” in the action-taking distance test for each light configuration. They were provided with three options, as shown in Table 4-4. Figure 4-9 shows the test environment.

Table 4-4 Alternatives in appropriate driving action test (dynamic experiment)

Description	Item
Take foot off accelerator	1
Apply brake	2
Lane change	3

4-3-4- Glare Rating Test

At the end of each round of the dynamic experiment (when the participant car had fully passed the WMT), participants were asked to describe the level of discomfort they experienced using an n-point rating scale (Table 4-3) for the ongoing light configuration. Figure 4-9 shows the test environment.

4-4- Weather Experiment

In the weather experiment, efficiency of different warning light configurations in terms of visibility was evaluated on a snowy day, which represented an actual environment that WMTs operate on the roads. For safety concerns, the experiment was only conducted under static experiment settings. The two tests of conspicuity (daytime) and glare rating (nighttime) of the static experiments were performed in the weather experiment. The configuration of the tests was exactly the same as the static experiments for the clear weather conditions. The daytime test conducted from 5 p.m. to 5:30 p.m., when the snow rate was 0.17 inch per hour and the visibility was 1 mile (relative to 10 miles for clear weather conditions). The sunset time was 6:30 p.m., therefore the nighttime test was conducted from 7 p.m. to 7:30 p.m., when the snow rate was 0.15 inch per hour and the visibility was 2 miles. This means that the daytime and nighttime tests had almost the same weather and visibility conditions.

To facilitate an impartial comparison between the different context of experiments (i.e., clear day versus snowy day), the participants of the weather experiment were selected among those who were involved in the static experiment. Overall, 14 subjects participated in the weather experiment (13 of them participated in the static experiment under clear weather conditions as well). Due to uncertainties in arranging an experiment under adverse weather conditions, it was not possible to use the public panel for this experiment (only expert panel participants were the research subjects). Figure 4-10 illustrates the weather experiment environment.

Figure 4-10 Weather experiment environment

4-5- Warning Light Configurations

Different sets of warning light configurations, based on the two elements of color and flashing pattern, were considered in this study to identify the most effective configurations in improving the WMT visibility. MDOT's current configuration for warning lights installed on the WMTs includes two LEDs and two beacons. LEDs are installed on the edges of the rear side of the truck, while beacons are mounted on top of the cab (see Figure 4-11). In the current configuration, the LEDs flash in green and the beacons switch between green and amber. The green warning light (in both LEDs and beacons) flashes in single, while the amber color flashes in quad. Using different color and flashing pattern combinations for LEDs and beacons, 36 configurations were considered. Table 4-5 shows these configurations along with the current setup implemented by MDOT.

In all of these configurations, the two LED lights always synchronously flash on and off the same color. The two beacon lights also always synchronously flash on and off the same color. However, the LEDs flash asynchronously relative to the beacons for each color. In addition, in configurations that use the same color for both LEDs and beacons, if the other color is also used on LEDs or/and beacons, then the green and amber lights flash synchronously between LEDs and beacons. However, in configurations that LEDs and beacons do not use the same color, then the green and amber lights flash asynchronously between LEDs and beacons. Table 4-5 provides these specifications for each configuration. Figure 4-12 illustrates different color combinations of warning lights (nine configurations) considered in this study. For each of these color combinations, four different flashing patterns (in terms of single and quad flashing) were considered, resulting in 36 overall configurations. Note that the color and flashing pattern combinations used by MDOT are similar to warning light configuration 23. The only difference is that in the current MDOT-implemented configuration on WMTs, the LEDs flash independently relative to the beacons.

Note that the two LEDs have the same configuration in terms of the color and flash pattern. Similar colors and patterns are also considered for the two beacons. The color display between the LEDs and beacons are asynchronous. For instance, if the green color is included in both LEDs and beacons, when the green color goes off on the LEDs, this color goes on (or switches to amber) on the beacons. The flashing pattern of the same color of warning lights (included in both LEDs and beacons) are assumed to be synchronized. For instance, in a case that the amber color is included in both LEDs and beacons, the flashing pattern of this color is either single or quad in both LEDs and beacons. These assumptions are established based on the MDOT guidelines on the existing warning light configurations and NCHRP Report 624 recommendations (Gibbons, 2008).

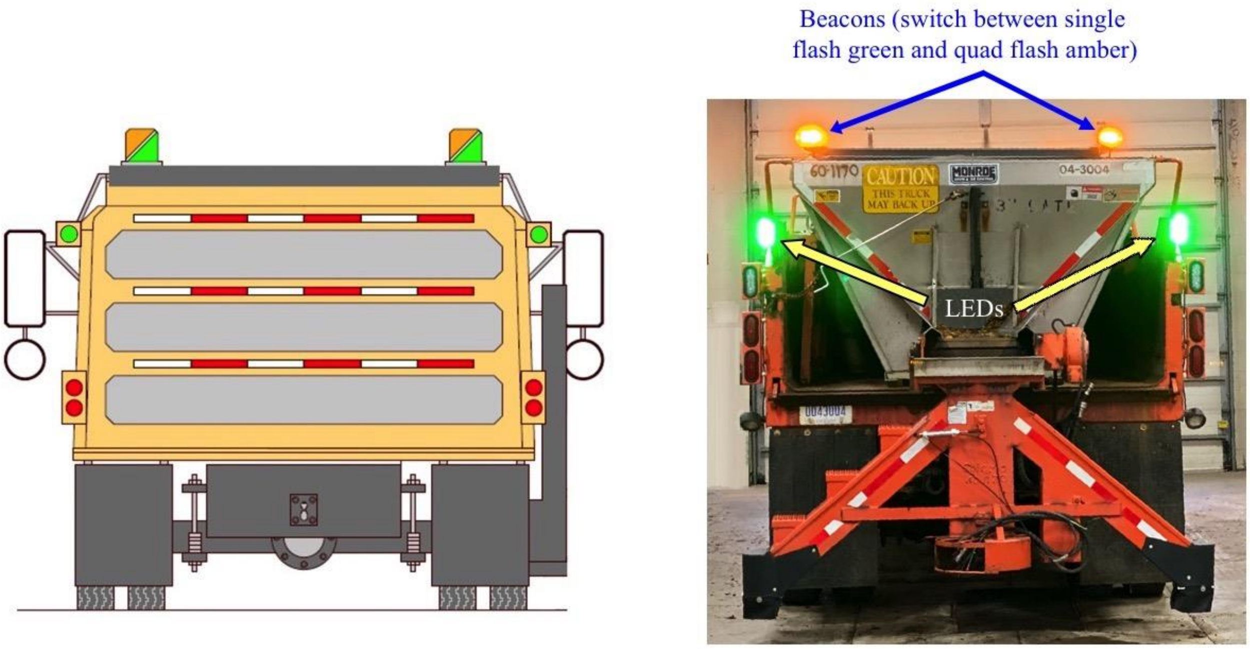
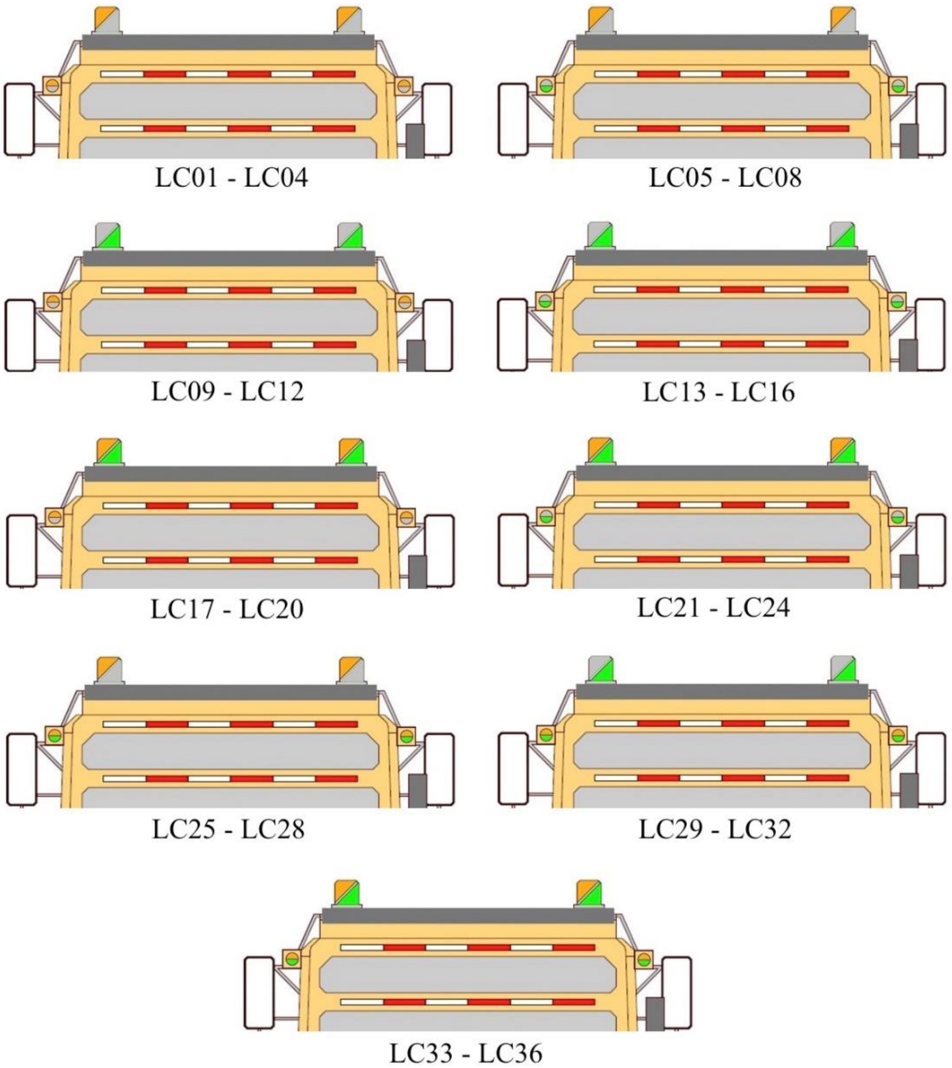


Figure 4-11 MDOT current configuration for warning lights

All light configurations (including 36 designed light configurations plus the MDOT current setup) were evaluated in the static and weather experiments. Due to the complexity of the dynamic experiments, only six candidate configurations, which were selected based on the results of the static experiments, were chosen to be evaluated. As discussed before, different tests were designed to assess the efficiency of each light configuration in terms of the WMT visibility. Results of these tests for all the experiments (static, dynamic and weather) are discussed in the next chapter.

Table 4-5 Warning light configurations (S: single flash, Q: quad flash, Sync: flash at the same time, Async: never flash at the same time, Rand: flash randomly relative to each other)

ID	**Beacons (Color and Flash Type)**	**LEDs (Color and Flash Type)**	**Beacon Lights Relative to Each Other**		**LED Lights Relative to Each Other**		**Beacons Relative to LEDs**	
			Same Color	**Amber and Green**	**Same Color**	**Amber and Green**	**Same Color**	**Amber and Green**
LC01	Amber(S)	Amber(S)	Sync	N/A	Sync	N/A	Async	N/A
LC02	Amber(S)	Amber(Q)	Sync	N/A	Sync	N/A	Async	N/A
LC03	Amber(Q)	Amber(S)	Sync	N/A	Sync	N/A	Async	N/A
LC04	Amber(Q)	Amber(Q)	Sync	N/A	Sync	N/A	Async	N/A
LC05	Amber(S)	Green(S)	Sync	N/A	Sync	N/A	N/A	Async
LC06	Amber(S)	Green(Q)	Sync	N/A	Sync	N/A	N/A	Async
LC07	Amber(Q)	Green(S)	Sync	N/A	Sync	N/A	N/A	Async
LC08	Amber(Q)	Green(Q)	Sync	N/A	Sync	N/A	N/A	Async
LC09	Green(S)	Amber(S)	Sync	N/A	Sync	N/A	N/A	Async
LC10	Green(S)	Amber(Q)	Sync	N/A	Sync	N/A	N/A	Async
LC11	Green(Q)	Amber(S)	Sync	N/A	Sync	N/A	N/A	Async
LC12	Green(Q)	Amber(Q)	Sync	N/A	Sync	N/A	N/A	Async
LC13	Green(S)	Green(S)	Sync	N/A	Sync	N/A	Async	N/A
LC14	Green(S)	Green(Q)	Sync	N/A	Sync	N/A	Async	N/A
LC15	Green(Q)	Green(S)	Sync	N/A	Sync	N/A	Async	N/A
LC16	Green(Q)	Green(Q)	Sync	N/A	Sync	N/A	Async	N/A
LC17	Amber(S)+green(S)	Amber(S)	Sync	Async	Sync	N/A	Async	Synch
LC18	Amber(S)+green(Q)	Amber(S)	Sync	Async	Sync	N/A	Async	Synch
LC19	Amber(Q)+green(S)	Amber(Q)	Sync	Async	Sync	N/A	Async	Synch
LC20	Amber(Q)+green(Q)	Amber(Q)	Sync	Async	Sync	N/A	Async	Synch
LC21	Amber(S)+green(S)	Green(S)	Sync	Async	Sync	N/A	Async	Synch
LC22	Amber(S)+green(Q)	Green(Q)	Sync	Async	Sync	N/A	Async	Synch
LC23a	Amber(Q)+green(S)	Green(S)	Sync	Async	Sync	N/A	Async	Synch
LC23b	Amber(Q)+green(S)	Green(S)	Sync	Async	Sync	N/A	Rand	Rand
LC24	Amber(Q)+green(Q)	Green(Q)	Sync	Async	Sync	N/A	Async	Synch
LC25	Amber(S)	Amber(S)+green(S)	Sync	N/A	Sync	Async	Async	Synch
LC26	Amber(S)	Amber(S)+green(Q)	Sync	N/A	Sync	Async	Async	Synch
LC27	Amber(Q)	Amber(Q)+green(S)	Sync	N/A	Sync	Async	Async	Synch
LC28	Amber(Q)	Amber(Q)+green(Q)	Sync	N/A	Sync	Async	Async	Synch
LC29	Green(S)	Amber(S)+green(S)	Sync	N/A	Sync	Async	Async	Synch
LC30	Green(S)	Amber(Q)+green(S)	Sync	N/A	Sync	Async	Async	Synch
LC31	Green(Q)	Amber(S)+green(Q)	Sync	N/A	Sync	Async	Async	Synch
LC32	Green(Q)	Amber(Q)+green(Q)	Sync	N/A	Sync	Async	Async	Synch
LC33	Amber(S)+green(S)	Amber(S)+green(S)	Sync	Async	Sync	Async	Async	Synch
LC34	Amber(S)+green(Q)	Amber(S)+green(Q)	Sync	Async	Sync	Async	Async	Synch
LC35	Amber(Q)+green(S)	Amber(Q)+green(S)	Sync	Async	Sync	Async	Async	Synch
LC36	Amber(Q)+green(Q)	Amber(Q)+green(Q)	Sync	Async	Sync	Async	Async	Synch



LC01 - LC04

LC05 - LC08

LC09 - LC12

LC13 - LC16

LC17 - LC20

LC21 - LC24

LC25 - LC28

LC29 - LC32

LC33 - LC36

Figure 4-12 Warning light configurations tested in the current study

CHAPTER 5 – EXPERIMENT RESULTS AND ANALYSES

Two panels of human subjects were formed to conduct the static and dynamic experiments under clear and snowy conditions. This chapter presents the test results and the main findings in identifying the most appropriate configurations for warning lights to be installed on WMTs to improve their visibility. As discussed in the previous chapter, each experiment consists of multiple tests providing several measures of effectiveness with reported average values (over all participants). To identify the level of effectiveness of various warning light configurations, the analysis of variance (ANOVA) and Tukey tests were utilized for each measure. These two statistical tests determine if there were any statistically significant differences between the efficiencies of various warning light configurations in terms of the visibility improvement. In this study, the significance level was considered as 95% for these statistical tests. This means that when the significance value of the ANOVA or Tukey tests is equal or less than 0.05, the null hypothesis (there is no significant difference between the groups) is violated, and a statistically significant difference is observed. The test results and interpretations are presented for all the experiments as follows in this section.

5-1- Static Experiment Results

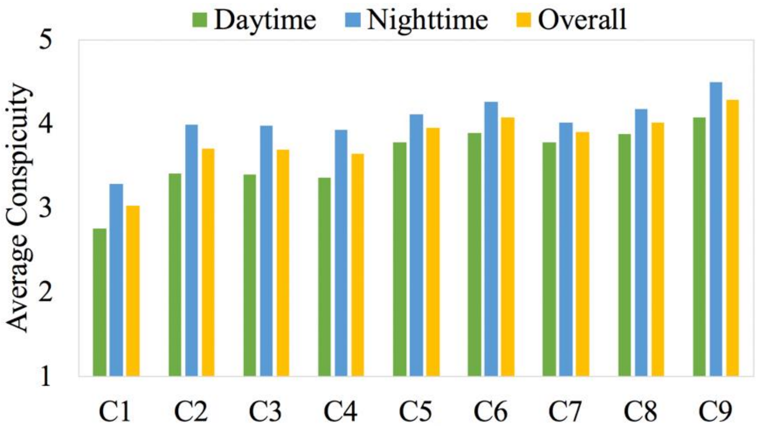
The static experiments under clear weather conditions were conducted at the MDOT garage, located in Paw Paw, Michigan. In these experiments, 24 subjects participated in both daytime and nighttime tests. All the participants examined all 37 light configurations presented in the previous chapter, except for the maximum peripheral detection angle test, where they were only exposed to six light configurations. For this specific test, two participants were tested at the same time in each round of the test. The number of participants in this test was limited to two due to the required space at exactly a right angle behind the truck. For the rest of the tests, the participants were subject to the tests in two rounds, and in each round of the tests two vans were employed to contain 12 participants at the same time. A random order (but fixed over various rounds in daytime and nighttime tests) was used for the warning light configurations in all of the tests. The first three configurations were repeated at the end of each test for all participants, keeping only the repeated test results and ignoring the initial ones. This was done to keep out the unfamiliarity bias impact. It is worth mentioning that there was no statistically significant difference between the average values reported by the research subjects for the first and last (repeated) three configurations. This shows that the order of display of the light configurations does not generate any bias. The results for each test are provided below.

5-1-1- Conspicuity Test Results

The average conspicuity values for the daytime and nighttime tests are illustrated in Figure 5-1 for the nine color categories (see Figure 4-12). The case with all-amber lights has the lowest conspicuity, while the case with amber and green lights in both LEDs and beacons shows the highest attention-getting capability. Intuitively, the conspicuity was higher during the nighttime for all cases in comparison to the daytime. The significance value for the ANOVA test is equal to zero for the nine groups of different color categories for both daytime and nighttime in the conspicuity test (which shows the statistically significant difference between these configurations). Note that all the color groups contained four different subsets of flashing patterns.

Table 5-1 shows the Tukey test results (significance values) for the nine color combinations. The test results indicate which pair of color combinations had a statistically significant difference in terms of the attention-getting rate with 5% confidence level. In this table, the daytime conspicuity test results are shown in the upper corner, while the nighttime test results are shown in the lower corner. The cases with a significance value of less than 0.05 are highlighted in yellow and show that these cases have statistical differences. The results indicate that color groups 1 and 9 have a statistical difference with all, or most, of the other color groups.

The average values of the conspicuity evaluations for the four flash patterns used in this experiment are illustrated in Figure 5-2. The results are provided by considering only the cases with one warning light on LEDs or beacons (C1 to C4). The combined cases (two colors in LEDs and/or beacons) are not included in these analyses as those are not consistent in terms of flashing patterns among all groups of colors (C5 to C9). Figure 5-2 indicates that the flashing pattern of all quad (for both LEDs and beacons) have the highest impact on the attention-getting capability of the lights in comparison to the other flashing patterns. On the other hand, the all-single flashing pattern has the lowest impact. The significance value of the ANOVA test is equal to zero for the flashing pattern groups for both daytime and nighttime in the conspicuity test (confirming a statistically significant difference between the four flashing patterns). The Tukey test results are provided in Table 5-2. A significant difference was not observed between FP2 and FP3, while FP1 and FP4 have a statistically significant difference from each other and from FP2 and FP3.



Color ID	Beacon Color	LED Color
C1	Amber	Amber
C2	Amber	Green
C3	Green	Amber
C4	Green	Green
C5	Amber + Green	Amber
C6	Amber + Green	Green
C7	Amber	Amber + Green
C8	Green	Amber + Green
C9	Amber + Green	Amber + Green

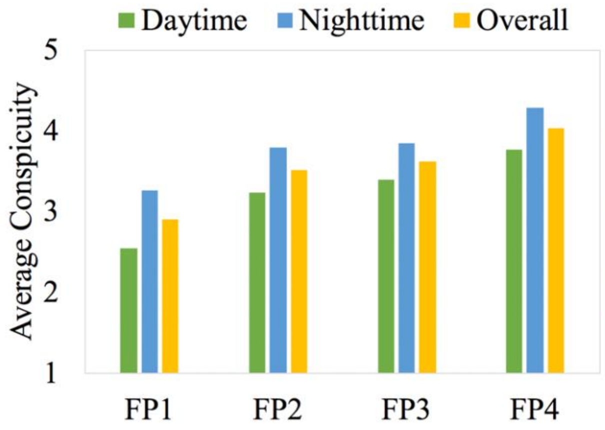
Figure 5-1 Static experiment under clear weather conditions: Conspicuity test results for nine color groups in daytime and nighttime contrasts

Table 5-1 Static experiment under clear weather conditions: Tukey test significance values for the conspicuity of nine color groups for daytime and nighttime contrasts (yellow highlight indicates a p-value less than 0.05)

Daytime* / Nighttime**	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	–	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000
C2	0.000	–	1.000	1.000	0.207	0.015	0.207	0.039	0.000
C3	0.000	1.000	–	1.000	0.177	0.012	0.177	0.031	0.000
C4	0.000	1.000	1.000	–	0.105	0.005	0.105	0.015	0.000
C5	0.000	0.988	0.979	0.869	–	0.997	1.000	0.999	0.502
C6	0.000	0.393	0.339	0.136	0.959	–	0.997	1.000	0.906
C7	0.000	1.000	1.000	0.999	0.996	0.509	–	0.999	0.502
C8	0.000	0.902	0.869	0.629	1.000	0.998	0.951	–	0.890
C9	0.000	0.003	0.002	0.000	0.081	0.606	0.006	0.218	–

** The upper corner of the array shows the daytime results.*

*** The lower corner of the array shows the nighttime results.*



Flash Pattern ID	Beacon	LED
FP1	Single	Single
FP2	Single	Quad
FP3	Quad	Single
FP4	Quad	Quad

Figure 5-2 Static experiment under clear weather conditions: Conspicuity test results for four flash pattern groups in daytime and nighttime contrasts

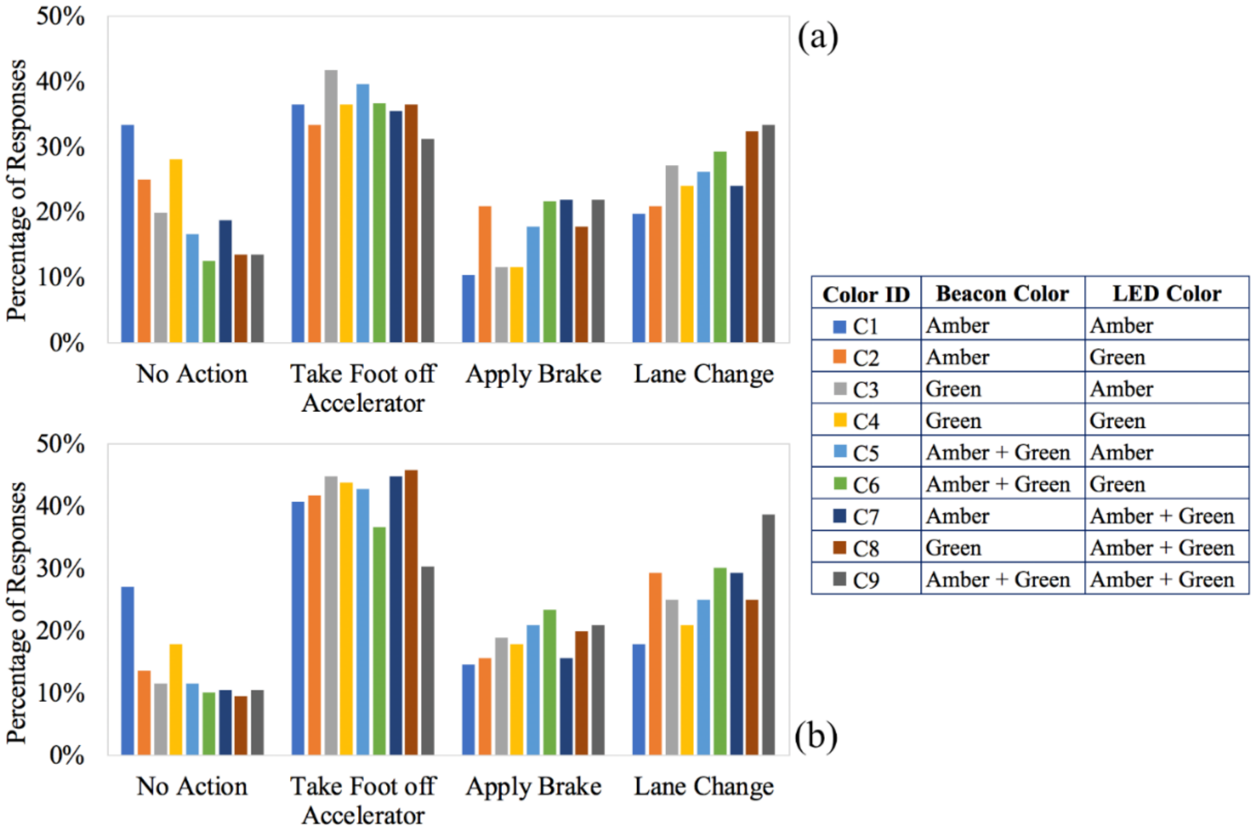
Table 5-2 Static experiment under clear weather conditions: Tukey test significance values for the conspicuity of four flash pattern groups for daytime and nighttime contrasts (yellow highlight indicates a p-value less than 0.05)

Daytime* Nighttime**	FP1	FP2	FP3	FP4
FP1	–	0.000	0.000	0.000
FP2	0.000	–	0.679	0.001
FP3	0.000	0.963	–	0.031
FP4	0.000	0.001	0.006	–

** The upper corner of the array shows the daytime results.*
*** The lower corner of the array shows the nighttime results.*

5-1-2- Appropriate Driving Action Test Results

Results of the appropriate driving action test for the nine color and four flash pattern groups are illustrated in Figure 5-3 and Figure 5-4, respectively. For the static experiment, the action of taking the foot off the accelerator was the most selected action by the participants for almost all the light configurations (colors and flash patterns). However, not a specific pattern could be observed over the various configurations. The ANOVA test results for both color and flash pattern groups (for both daytime and nighttime) indicate that there was no statistical difference between the color and flashing pattern combinations (the significant values of the ANOVA tests are much higher than 0.05). Thus, the observed differences were not statistically significant. However, in color groups, C1 (which indicates all amber) had a high percentage of no action decisions relative to other color groups. Similarly, in flash pattern groups, FP1 (which indicates all-single flashes) had a high percentage of no action decisions relative to other flash pattern groups. This means that by adding the green color or switching the single flashes to quad flashes, the road users are more likely to react and respond to the warning lights at a 450-foot distance.



Color ID	Beacon Color	LED Color
🟦 C1	Amber	Amber
🟧 C2	Amber	Green
⬜ C3	Green	Amber
🟨 C4	Green	Green
🟦 C5	Amber + Green	Amber
🟩 C6	Amber + Green	Green
🟦 C7	Amber	Amber + Green
🟫 C8	Green	Amber + Green
⬛ C9	Amber + Green	Amber + Green

Figure 5-3 Static experiment under clear weather conditions: Appropriate driving action test results for nine color groups: (a) daytime and (b) nighttime

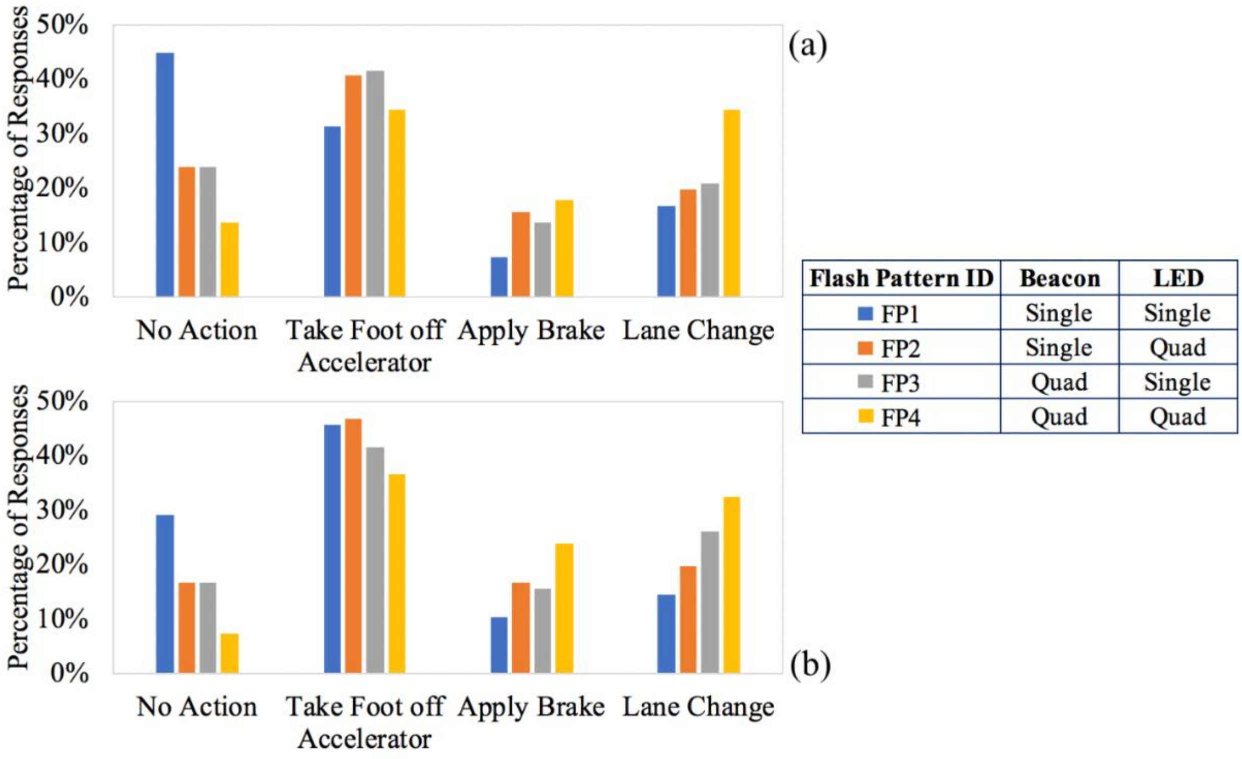
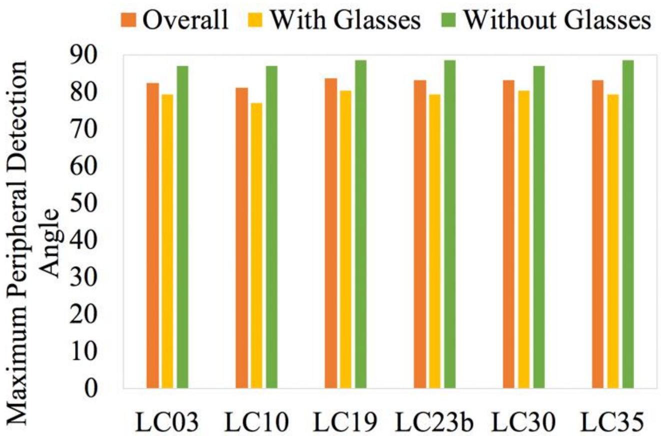


Figure 5-4 Static experiment under clear weather conditions: Appropriate driving action test results for four flash pattern groups: (a) daytime and (b) nighttime

5-1-3- Maximum Peripheral Detection Angle Test Results

Due to the time-consuming nature of the maximum peripheral detection angle test, it was conducted only for six light configurations (see Figure 5-5). These light configurations were selected to cover a spectrum of various color combinations and flashing patterns. This test, similar to the conspicuity test, was conducted only during the daytime, considering the lowest contrast as the critical scenario. Results for the subjects with and without eyeglasses are distinguished in this figure and interestingly higher values were observed for the subjects without eyeglasses. The ANOVA test result suggests that there was no statistically significant difference between the examined light configurations in terms of the maximum peripheral detection angle (the significance value is much higher than 0.05 threshold). Therefore, this measure also failed to distinguish the capabilities of different light configurations in terms of visibility.



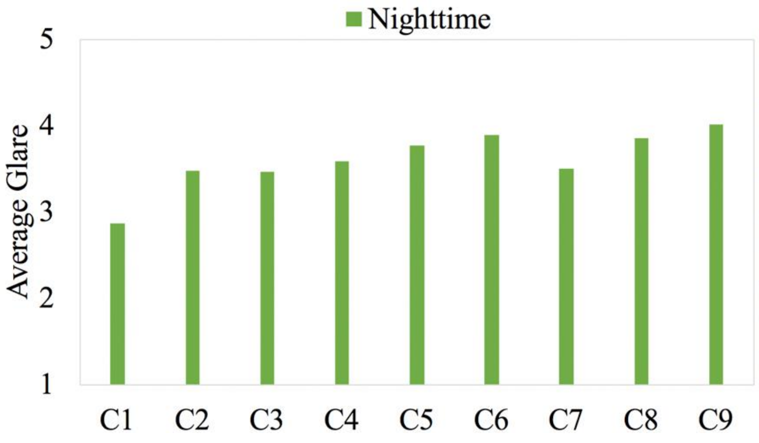
Light Configuration	**Beacon Color (Flash Pattern)**	**LED Color (Flash Pattern)**
LC03	Amber (Quad)	Amber (Single)
LC10	Green (Single)	Amber (Quad)
LC19	Amber (Quad) + Green (Single)	Amber (Quad)
LC23b	Amber (Quad) + Green (Single)	Green (Single)
LC30	Green (Single)	Amber (Quad) + Green (Single)
LC35	Amber (Quad) + Green (Single)	Amber (Quad) + Green (Single)

Figure 5-5 Static experiment under clear weather conditions: Maximum peripheral detection angle test results for six light configurations

5-1-4- Glare Rating Test Results

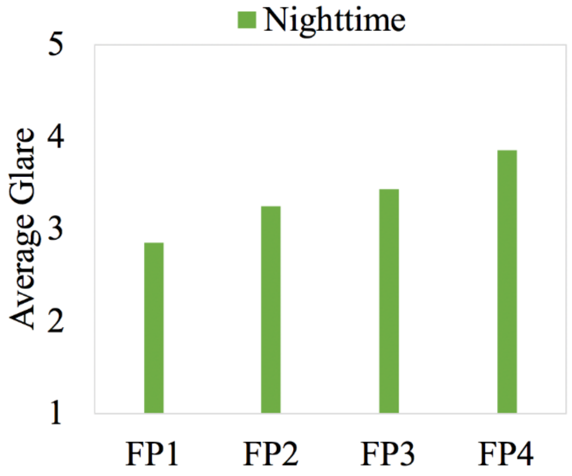
The results of the glare rating test, which was conducted only during nighttime due to the maximum contrast as the critical scenario, for the nine color and four flash pattern groups are illustrated in Figure 5-6 and Figure 5-7, respectively. The color group C9 (in which both green and amber colors are included in both LEDs and beacons) has the highest glare rate, while it has the highest conspicuity level as well. On the other hand, the all-amber case (C1) has the lowest glare, while it also has the lowest conspicuity level. According to the results provided in Figure 5-2 and Figure 5-6, considering green light in the warning light configuration increases the attention-getting capability of the warning light, while it also elevates the glare level.

Based on the average values presented in Figure 5-7 for the glare rates, FP4 (all quad) has the highest glare as well as the highest conspicuity and FP1 (all single) has the lowest glare as well as the lowest conspicuity level. The significance values of the ANOVA test results for both of the color and flash pattern groups are equal to zero. The Tukey test results for nine color and four flash pattern groups are presented in Table 5-3 and Table 5-4, respectively. The significance values show that the C1 and C9 were statistically different with all or most of the other color groups. Also, Table 5-4 indicates that FP1 and FP4 were statistically different from the other flash patterns in terms of the glare effect.



Color ID	Beacon Color	LED Color
C1	Amber	Amber
C2	Amber	Green
C3	Green	Amber
C4	Green	Green
C5	Amber + Green	Amber
C6	Amber + Green	Green
C7	Amber	Amber + Green
C8	Green	Amber + Green
C9	Amber + Green	Amber + Green

Figure 5-6 Static experiment under clear weather conditions: Glare rating test results for nine color groups in nighttime contrast



Flash Pattern ID	Beacon	LED
FP1	Single	Single
FP2	Single	Quad
FP3	Quad	Single
FP4	Quad	Quad

Figure 5-7 Static experiment under clear weather conditions: Glare rating test results for four flash pattern groups in nighttime contrast

Table 5-3 Static experiment under clear weather conditions: Tukey test significance values for the glare of nine color groups in nighttime contrast (yellow highlight indicates a p-value less than 0.05)

Nighttime	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	–	–	–	–	–	–	–	–	–
C2	0.000	–	–	–	–	–	–	–	–
C3	0.000	1.000	–	–	–	–	–	–	–
C4	0.000	0.991	0.970	–	–	–	–	–	–
C5	0.000	0.175	0.111	0.751	–	–	–	–	–
C6	0.000	0.003	0.001	0.082	0.966	–	–	–	–
C7	0.000	1.000	1.000	0.998	0.261	0.006	–	–	–
C8	0.000	0.021	0.011	0.261	0.998	1.000	0.038	–	–
C9	0.000	0.000	0.000	0.004	0.431	0.970	0.000	0.894	–

Table 5-4 Static experiment under clear weather conditions: Tukey test significance values for the glare of four flash pattern groups in nighttime contrast (yellow highlight indicates a p-value less than 0.05)

	FP1	FP2	FP3	FP4
FP1	–	–	–	–
FP2	0.001	–	–	–
FP3	0.000	0.324	–	–
FP4	0.000	0.000	0.000	–

5-1-5- Interpretation of Static Experiment Results

Based on the findings of the conducted tests in the static experiments, the two measures of conspicuity at daytime contrast and glare at nighttime contrast were the most influential factors in identifying the most effective warning light configuration in terms of visibility. Results suggest that there is a direct correlation between the conspicuity and glare levels. Therefore, selecting a proper light configuration is a trade-off between these two factors. Figure 5-8 illustrates the relationship between these two measures for all 37 light configurations. Each plotted point in this graph is an average value over all participants for one particular warning light configuration. Table 4-5 presents the details associated with each warning light configuration.

In Figure 5-8, the most desirable area is the lower right corner, where the conspicuity is the highest and the glare is the lowest. Overall, Figure 5-8 suggests that adding green light increases the conspicuity. The all-amber cases have the lowest conspicuity and glare. If the glare rate is limited to the maximum value of 4 and the conspicuity to the minimum value of 4, three light configurations – LC19, LC27 and LC35 – would be the best candidates (see Figure 5-9). These three light configurations, besides the modified current MDOT warning light configuration (LC23a), MDOT's previously implemented configuration (LC03) and a representative configuration of higher values of glare and conspicuity (LC32), were selected for further assessments in the realistic driving environment experiment (dynamic experiment). See Figure 5-9 for the details of these configurations.

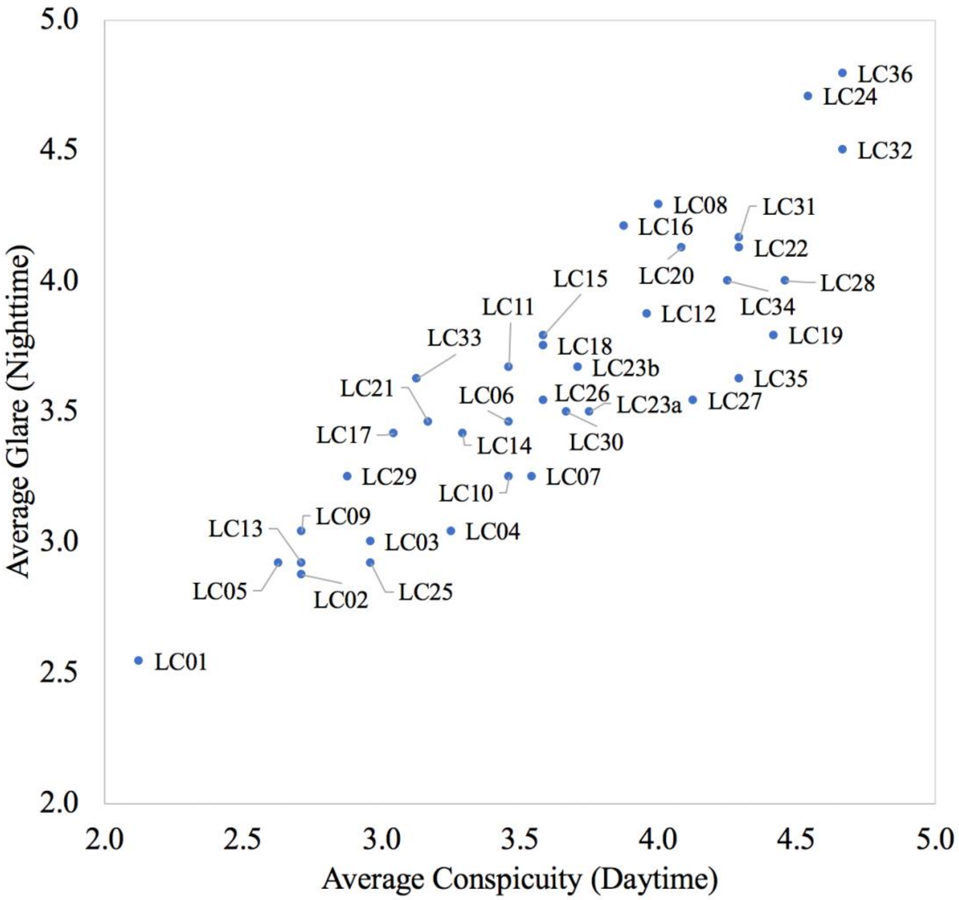
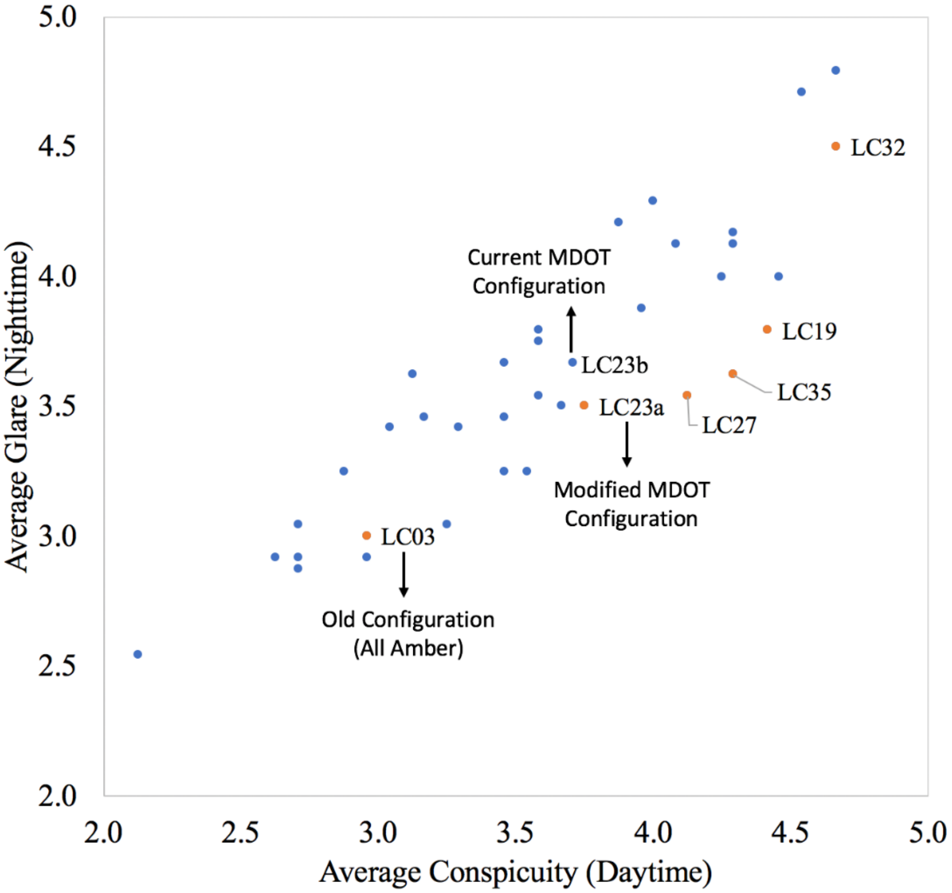


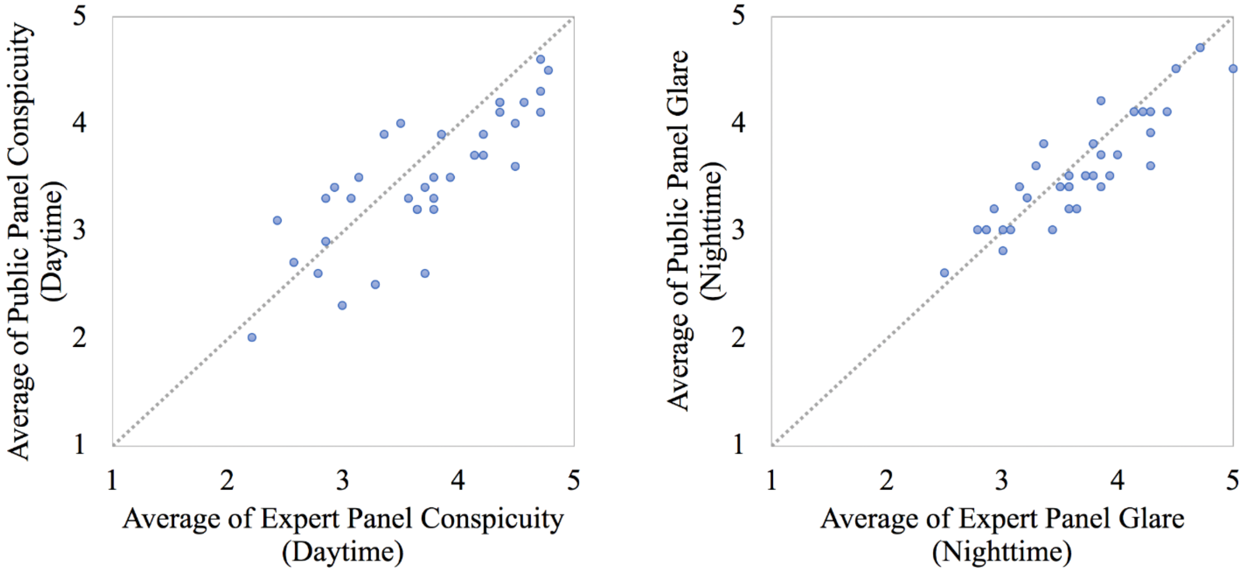
Figure 5-8 Static experiment under clear weather conditions: Relationship between conspicuity (daytime) and glare (nighttime)



Light Configuration	Beacon Color (Flash Pattern)	LED Color (Flash Pattern)
LC03	Amber (Quad)	Amber (Single)
LC19	Amber (Quad) + Green (Single)	Amber (Quad)
LC23a	Amber (Quad) + Green (Single)	Green (Single)
LC27	Amber (Quad)	Amber (Quad) + Green (Single)
LC32	Green (Quad)	Amber (Quad) + Green (Quad)
LC35	Amber (Quad) + Green (Single)	Amber (Quad) + Green (Single)

Figure 5-9 Candidate light configurations for further assessments in the dynamic experiment (orange dots are selected configurations for the dynamic experiment and the blue dots are configurations used only in the static experiment)

Further analysis also compares results of the two subject panels (expert versus public). Only the expert panel research subjects participated in the weather experiments. Therefore, comparing the stated responses between the expert and public panels was needed to better interpret the weather experiment results. Figure 5-10 illustrates the conspicuity (daytime) and glare (nighttime) results for the two panels. Each plotted point is an average value of the measures over all the participants and stands for a certain light configuration. This means that each graph contains 37 data points. The ANOVA test results for both measures (conspicuity and glare) indicate that the difference between the public and expert panels is not statistically significant (the significance value is much higher than 0.05).



(a) (b)

Figure 5-10 Conspicuity and glare results for the expert versus public panels

5-2- Dynamic Experiment Results

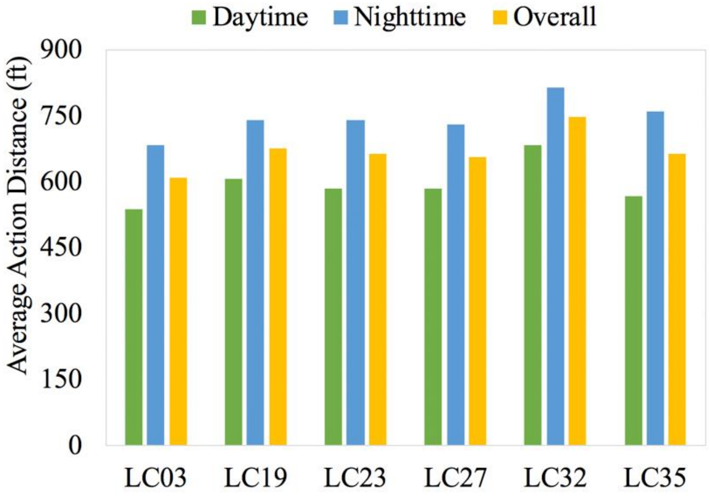
The dynamic experiments were conducted at ACM only for clear weather conditions. In these experiments, 25 subjects participated in both daytime and nighttime tests, 16 of whom were also involved in the static experiments. All participants examined the six light configurations selected based on the static experiment results. For this experiment, each participant performed the tests individually. A random order of the light configurations was shown to each participant. This random order means that different participants were not exposed to the same order of light configurations, unlike the static experiment. This was the case to avoid the order bias since the number of configurations to be tested was limited. To keep out the unfamiliarity bias impact due to the new experiment environment, the first configuration (which was randomly selected out of the six configurations for each participant) was repeated at the end of the test for all participants and its results were eliminated from the analysis. Tests results are provided below.

5-2-1- Action-Taking Distance (Minimum Gap) Test Results

Figure 5-11 illustrates the average action-taking distance (over all participants) for six light configurations in both daytime and nighttime cases. The significance value of the ANOVA test shows that there was no statistical difference between any of these six light configurations when the action-taking distance was considered as a measure of effectiveness (the significance value is much higher than 0.05). Therefore, this test fails to distinguish a statistically significant pattern in performance of different light configurations in terms of action distance. Figure 5-12 indicates that the action-taking distance during the nighttime was higher than the action-taking distance during the daytime, as expected. In this figure, each plotted point is the average action-taking distance value of all light configurations stated by a participant. The higher number of plotted points in the upper corner shows that the action-taking distance was higher during the nighttime.

5-2-2- Conspicuity Test Results

The average conspicuity values calculated over all participants for the daytime and nighttime tests are illustrated in Figure 5-13 for the nine color categories (see Figure 4-12). The case with all-amber lights (LC03) has the lowest conspicuity, while the case with all-quad flashing lights and green color in both LEDs and beacons (LC32) shows the highest attention-getting capability. The significance value for the ANOVA test is equal to zero for the six light configurations during the daytime and nighttime cases. Table 5-5 shows the Tukey test results for the six light configurations. The tests results indicate that the LC03 and LC32 light configurations have statistical difference with all or most of the other configurations in both daytime and nighttime tests. Intuitively, the conspicuity was higher during the nighttime for all cases in comparison to the daytime. This fact is shown in both Figure 5-13 and Figure 5-14. In Figure 5-14, each plotted point is the average conspicuity value of all light configurations stated by a participant. The higher number of plotted points in the upper corner shows that the conspicuity was higher during the nighttime.



Light Configuration	Beacon Color (Flash Pattern)	LED Color (Flash Pattern)
LC03	Amber (Quad)	Amber (Single)
LC19	Amber (Quad) + Green (Single)	Amber (Quad)
LC23a	Amber (Quad) + Green (Single)	Green (Single)
LC27	Amber (Quad)	Amber (Quad) + Green (Single)
LC32	Green (Quad)	Amber (Quad) + Green (Quad)
LC35	Amber (Quad) + Green (Single)	Amber (Quad) + Green (Single)

Figure 5-11 Dynamic experiment under clear weather conditions: Action-taking distance test results for six light configurations in daytime and nighttime contrasts

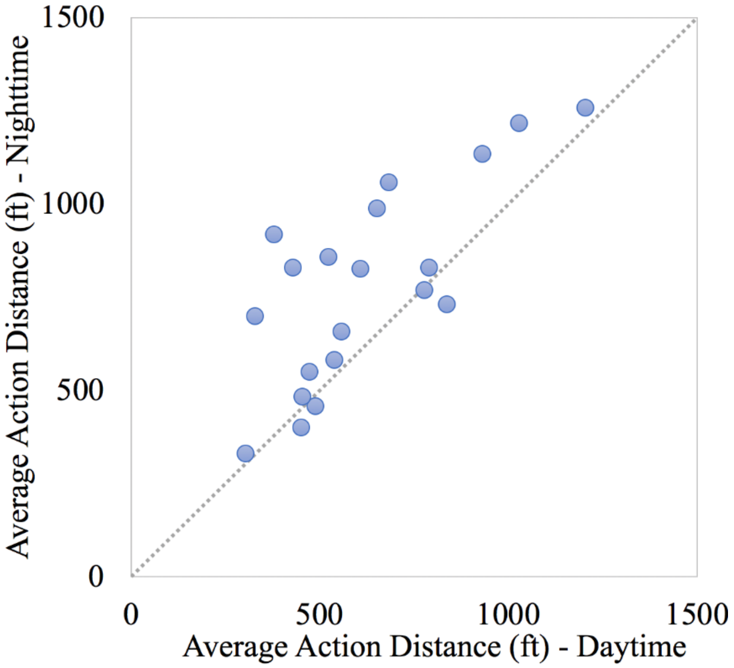
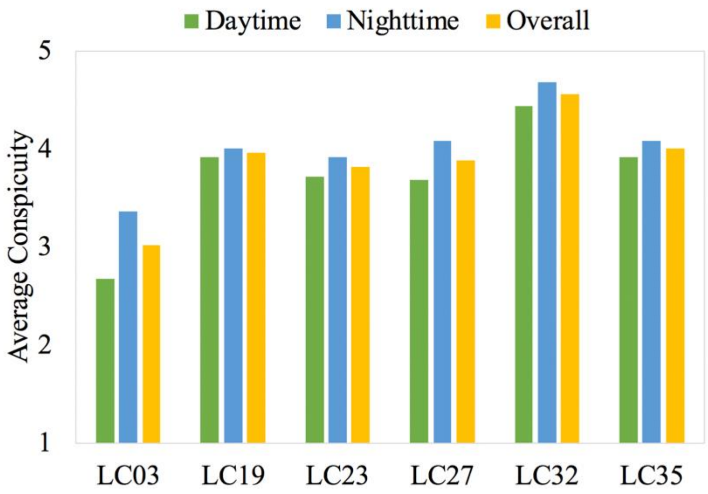


Figure 5-12 Dynamic experiment under clear weather conditions: Comparison of average action-taking distance (for all participants) values in daytime and nighttime contrasts



Light Configuration	Beacon Color (Flash Pattern)	LED Color (Flash Pattern)
LC03	Amber (Quad)	Amber (Single)
LC19	Amber (Quad) + Green (Single)	Amber (Quad)
LC23a	Amber (Quad) + Green (Single)	Green (Single)
LC27	Amber (Quad)	Amber (Quad) + Green (Single)
LC32	Green (Quad)	Amber (Quad) + Green (Quad)
LC35	Amber (Quad) + Green (Single)	Amber (Quad) + Green (Single)

Figure 5-13 Dynamic experiment under clear weather conditions: Conspicuity test results for six light configurations in daytime and nighttime contrasts

Table 5-5 Dynamic experiment under clear weather conditions: Tukey test significance values for the conspicuity of six light configurations in daytime and nighttime contrasts (yellow highlight indicates a p-value less than 0.05)

Daytime* / Nighttime**	LC03	LC19	LC23a	LC27	LC32	LC35
LC03	–	0.000	0.000	0.000	0.000	0.000
LC19	0.012	–	0.939	0.876	0.160	1.000
LC23a	0.042	0.998	–	1.000	0.013	0.939
LC27	0.003	0.998	0.959	–	0.007	0.876
LC32	0.000	0.006	0.001	0.023	–	0.160
LC35	0.003	0.998	0.959	1.000	0.023	–

** The upper corner of the array shows the daytime results.*
*** The lower corner of the array shows the nighttime results.*

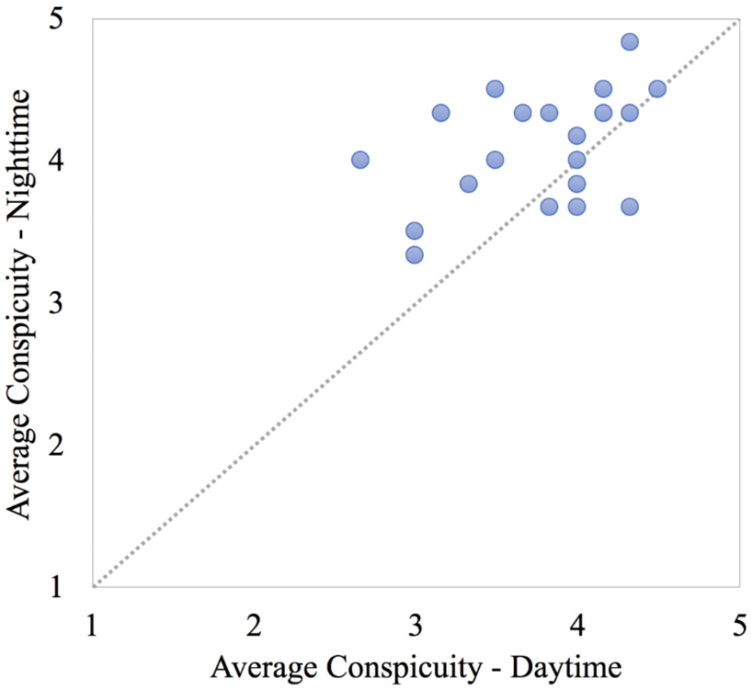
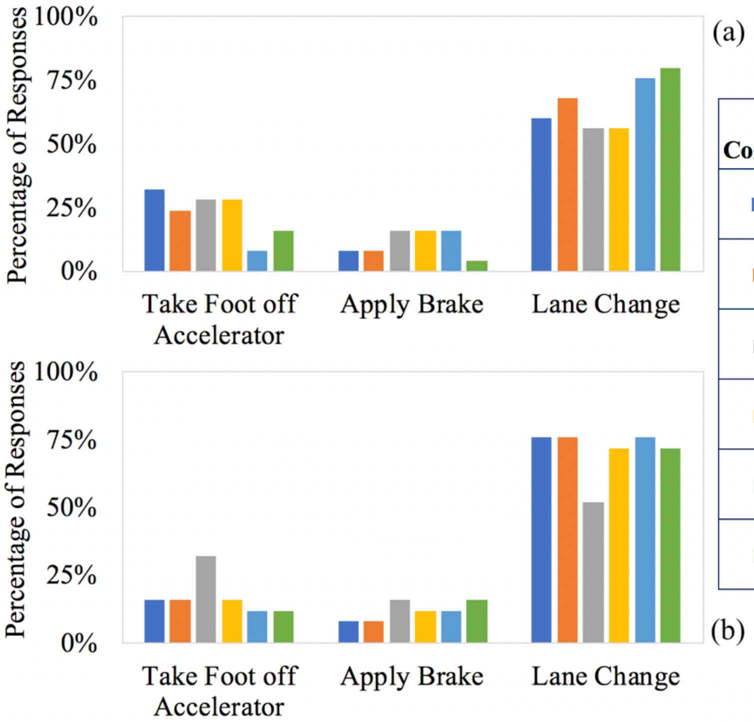


Figure 5-14 Dynamic experiment under clear weather conditions: Comparison of average conspicuity (for all participants) values in daytime and nighttime contrasts

5-2-3- Appropriate Driving Action Test Results

Results of the appropriate driving action test for six defined light configurations are illustrated in Figure 5-15. For the dynamic experiment, the lane change action was selected the most by the participants for all the light configurations in both daytime and nighttime cases. However, no specific pattern could be observed overall for different light configurations. The ANOVA test results for the light configurations (for both daytime and nighttime cases) indicate that there was no statistically significant difference between various light configurations in dictating the appropriate driving action (the significant value of the ANOVA test is much higher than 0.05). Therefore, this measure failed to assess the differences in the capability of various light configurations in terms of visibility.

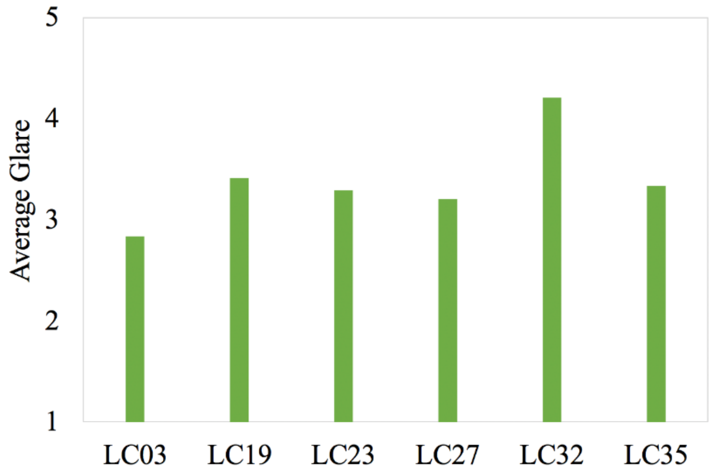


Light Configuration	**Beacon Color (Flash Pattern)**	**LED Color (Flash Pattern)**
🟦 LC03	Amber (Quad)	Amber (Single)
🟧 LC19	Amber (Quad) + Green (Single)	Amber (Quad)
⬜ LC23a	Amber (Quad) + Green (Single)	Green (Single)
🟨 LC27	Amber (Quad)	Amber (Quad) + Green (Single)
🟦 LC32	Green (Quad)	Amber (Quad) + Green (Quad)
🟩 LC35	Amber (Quad) + Green (Single)	Amber (Quad) + Green (Single)

Figure 5-15 Dynamic experiment under clear weather conditions: Appropriate driving action test results for six light configurations: (a) daytime and (b) nighttime

5-2-4- Glare Rating Test Results

The results of the glare rating test, which was conducted only in nighttime as the critical contrast, are illustrated in Figure 5-16 for the six light configurations. The light configuration LC32 has the highest glare rate, while it also has the highest conspicuity level. On the other hand, the light configuration LC03 has the lowest glare and the lowest conspicuity level. According to the results provided in Figure 5-13 and Figure 5-16, considering green light in the warning light configuration increases the attention-getting capability of the light while it also elevates the glare. The significance value of the ANOVA test for the six light configurations is equal to zero, indicating a statistically significant difference between the light configurations. The Tukey test results are presented in Table 5-6. The significance values show that light configuration LC32 was statistically different from all other configurations.



Light Configuration	Beacon Color (Flash Pattern)	LED Color (Flash Pattern)
LC03	Amber (Quad)	Amber (Single)
LC19	Amber (Quad) + Green (Single)	Amber (Quad)
LC23a	Amber (Quad) + Green (Single)	Green (Single)
LC27	Amber (Quad)	Amber (Quad) + Green (Single)
LC32	Green (Quad)	Amber (Quad) + Green (Quad)
LC35	Amber (Quad) + Green (Single)	Amber (Quad) + Green (Single)

Figure 5-16 Dynamic experiment under clear weather conditions: Glare test results for six light configurations in nighttime contrast

Table 5-6 Dynamic experiment under clear weather conditions: Tukey test significance values for the glare of six light configurations in nighttime contrast (yellow highlight indicates a p-value less than 0.05)

	LC03	LC19	LC23a	LC27	LC32	LC35
LC03	–	–	–	–	–	–
LC19	0.012	–	–	–	–	–
LC23a	0.091	0.979	–	–	–	–
LC27	0.258	0.833	0.997	–	–	–
LC32	0.000	0.000	0.000	0.000	–	–
LC35	0.049	0.997	1.000	0.979	0.000	–

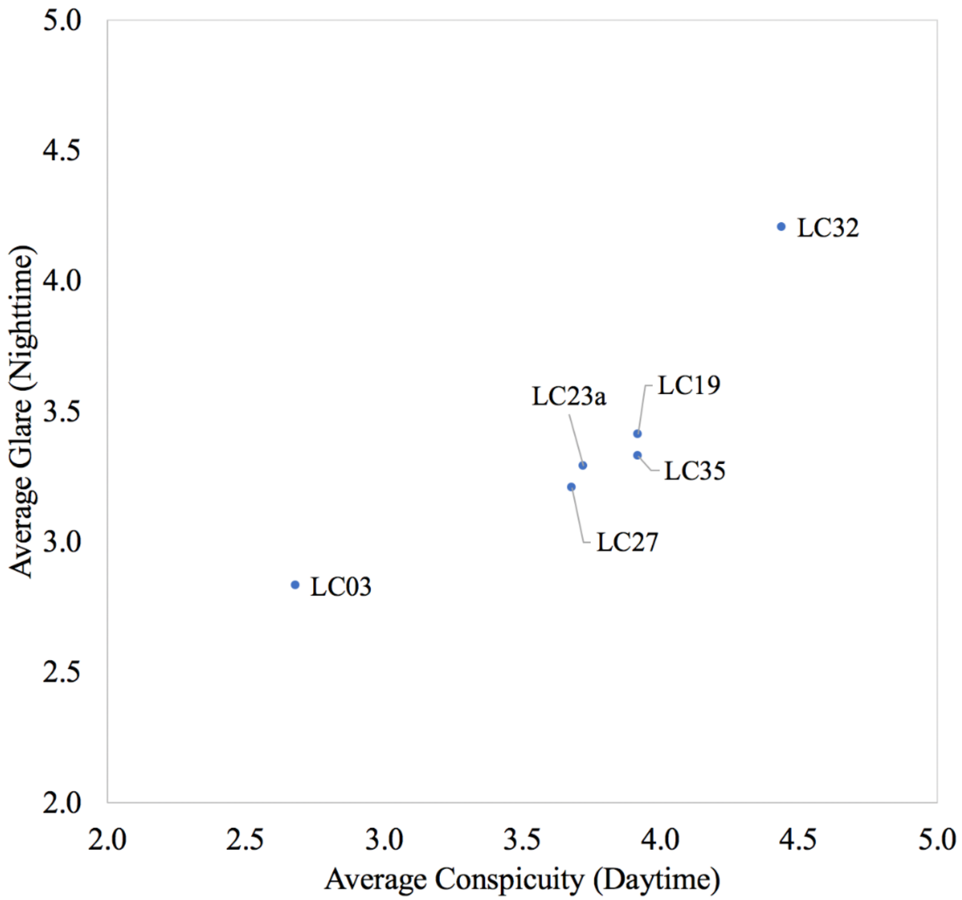
** The upper corner of the array shows the daytime results.*

*** The lower corner of the array shows the nighttime results.*

5-2-5- Interpretation of Dynamic Experiment Results

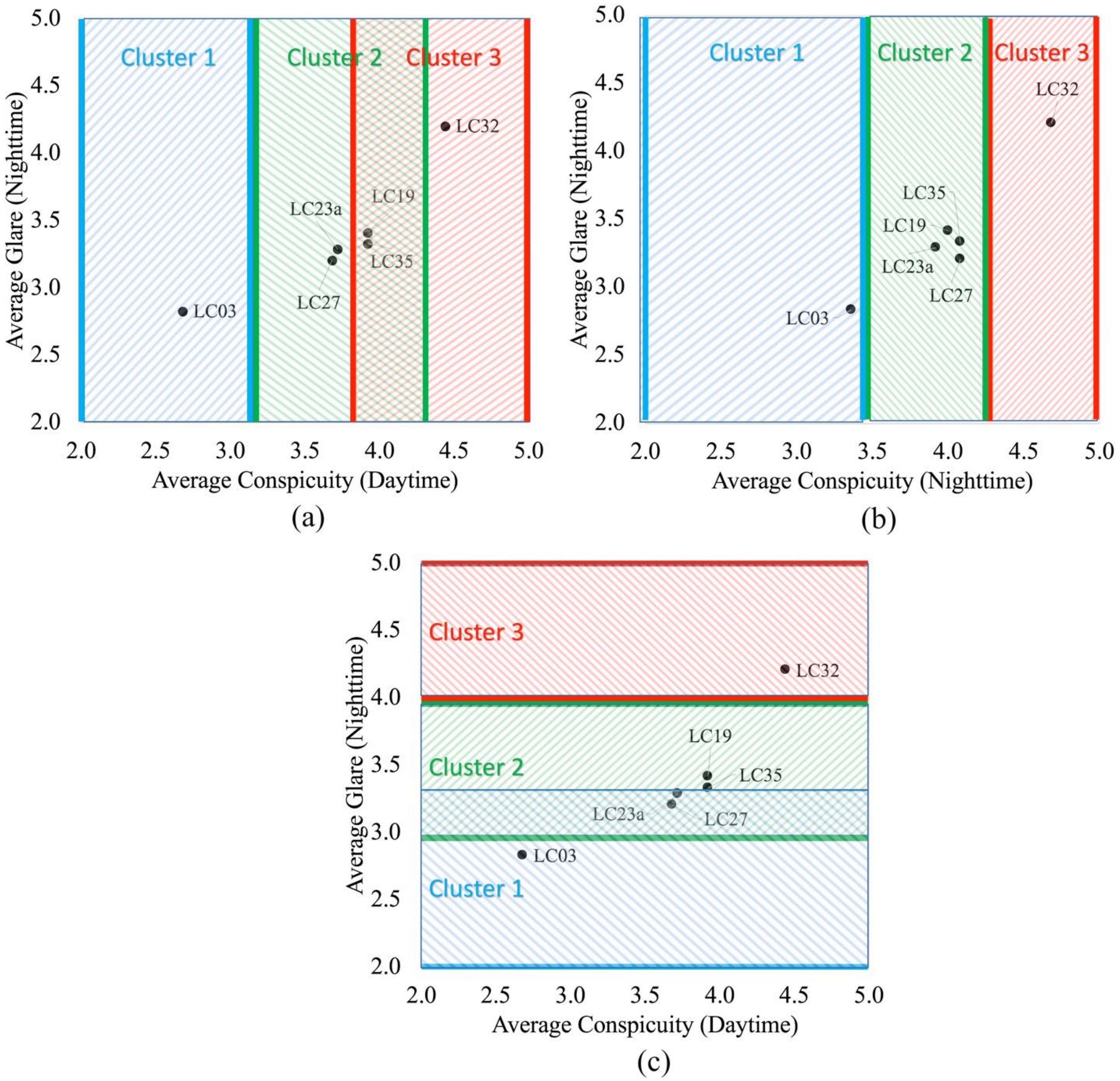
Similar to the static experiments, and based on the findings of all tests in the dynamic experiment, the two measures of conspicuity at daytime and glare at nighttime were the top influential factors in identifying the most effective light configurations. Results suggested that there is a direct correlation between the conspicuity and glare levels. Thus, a trade-off between these two factors is inevitable to identify the most appropriate warning light configuration. Figure 5-17 illustrates the relationship between these two measures for all six light configurations. Each plotted point in this graph is an average value over all participants. Along with the same line of the static experiment findings, the results of the dynamic experiment suggested that adding green light increased the conspicuity significantly, while the all-amber case had the lowest conspicuity and glare.

According to the results of Tukey test (Tables 5-5 and 5-6) for the conspicuity (at daytime and nighttime) and glare (at nighttime), the light configurations were classified in three different clusters: low conspicuity or glare, moderate conspicuity or glare, and high conspicuity or glare. These clusters are shown in Figure 5-18. If a statistically significant difference is not observed between a light configuration of a cluster and the light configurations of the other two clusters, it is included in both clusters. Figure 5-18 shows that the light configuration LC32 provides a disturbing glare and is not a proper configuration. On the other hand, LC03 does not provide a sufficient conspicuity. Four light configurations of LC19, LC23a (modified MDOT current configuration), LC27 and LC35, were the most capable configurations in terms of improving the visibility, while producing a bearable glare discomfort to travelers.



Light Configuration	Beacon Color (Flash Pattern)	LED Color (Flash Pattern)
LC03	Amber (Quad)	Amber (Single)
LC19	Amber (Quad) + Green (Single)	Amber (Quad)
LC23a	Amber (Quad) + Green (Single)	Green (Single)
LC27	Amber (Quad)	Amber (Quad) + Green (Single)
LC32	Green (Quad)	Amber (Quad) + Green (Quad)
LC35	Amber (Quad) + Green (Single)	Amber (Quad) + Green (Single)

Figure 5-17 Dynamic experiment under clear weather conditions – comparing average conspicuity (daytime) and average glare (nighttime) for six light configurations



(a)

(b)

(c)

Figure 5-18 Dynamic experiment under clear weather conditions. Warning light configuration clusters based on Tukey test for conspicuity and glare measures: (a) daytime conspicuity clusters, (b) nighttime conspicuity clusters, and (c) nighttime glare clusters

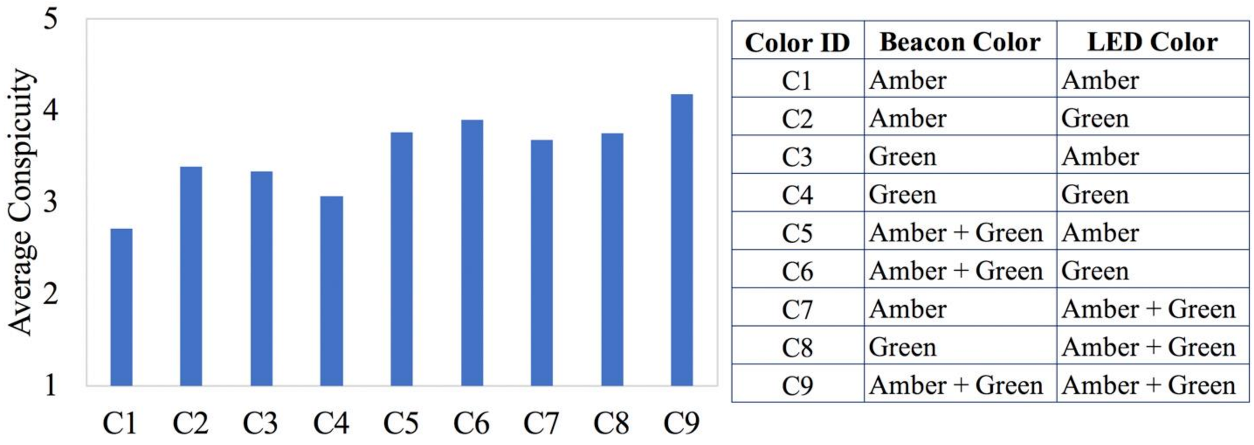
5-3- Weather Experiment Results

The static experiments were repeated under snowy conditions to determine the sensitivity of the presented analyses in the previous sections to the weather conditions. These weather experiments were conducted at a MDOT office in Lansing. In these experiments, 14 subjects participated in both daytime and nighttime tests. Thirteen of these participants were also involved in the static experiment under clear weather conditions. Note that there were no participants from the public panel in the weather experiments due to the arrangement uncertainties associated with the required weather conditions. As it was shown at the end of Section 5-1, Static Experiment Results, no statistically significant difference was observed between the two subject panels (expert and public). Therefore, conducting the weather experiment only employing the expert panel did not introduce any bias in the analyses and kept the results comparable to the static experiments. All participants examined the same 37 warning light configurations. The same random order of the warning lights, which was used in the static experiment under clear weather conditions, was also applied to these tests. Similarly, all other considerations to avoid any bias in the sample were followed in these tests. The test results are provided below.

5-3-1- Conspicuity Test Results

In the weather experiments, due to the weather conditions and limited available time, the conspicuity test was conducted only for the daytime contrast. Furthermore, conspicuity is more critical during the daytime contrast similar to the glare that is critical only at nighttime contrast. The average stated conspicuity values are illustrated in Figure 5-19 for the nine color categories (see Figure 4-12). The case with all-amber lights has the lowest conspicuity, while the case with amber and green lights in both LEDs and beacons shows the highest attention-getting capability. This result is consistent with the static test results, which was conducted on a clear (not snowy) day. The significance value for the ANOVA test is equal to zero for nine groups with different color categories. Note that all color groups contain four different subsets of flashing patterns. Table 5-7 shows the Tukey test results for various color combinations. The tests results indicate that color groups C1 and C9 have a statistically significant difference with all or most of the other color groups. This result is consistent with the static test results, which was conducted on a clear (not snowy) day.

The average conspicuity values for the four groups of flash patterns are illustrated in Figure 5-20. Of note, these results are provided by considering the cases with only one light in LEDs and beacons (C1 to C4). The combined cases (two colors in LEDS and/or beacons) are not included as those were not consistent in terms of flashing patterns among all color groups (C5 to C9). Figure 5-20 indicates that the all-quad flashing pattern (for both LEDs and beacons) has the highest impact on the attention capability of the lights in comparison to the other flashing patterns. On the other hand, the all-single flashing pattern has the lowest impact. The significance value of the ANOVA test is equal to zero for all flashing pattern groups. The Tukey test results are provided in Table 5-8. It verifies the results suggested by Figure 5-20. Note a statistically significant difference was not observed for FP2 and FP3.

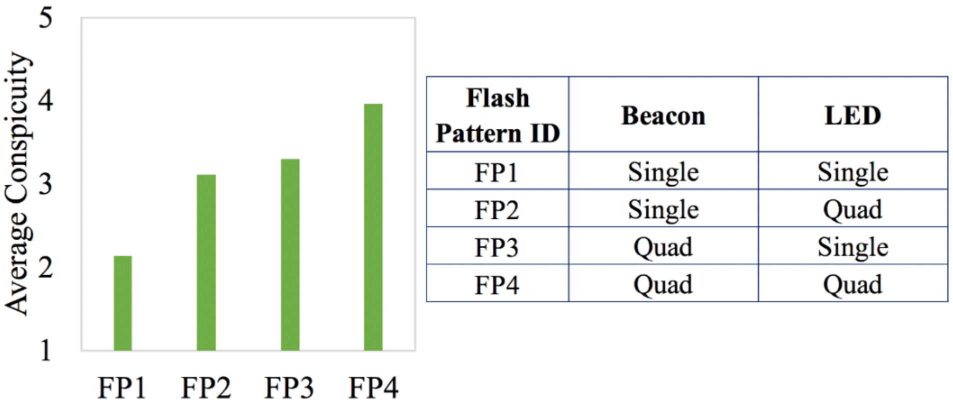


Color ID	Beacon Color	LED Color
C1	Amber	Amber
C2	Amber	Green
C3	Green	Amber
C4	Green	Green
C5	Amber + Green	Amber
C6	Amber + Green	Green
C7	Amber	Amber + Green
C8	Green	Amber + Green
C9	Amber + Green	Amber + Green

Figure 5-19 Static experiment under snowy conditions: Conspicuity test results for nine color groups in the daytime contrast

Table 5-7 Static experiment under snowy conditions: Tukey test significance values for the conspicuity of nine color groups in the daytime contrast (yellow cells show the significance values of less than 0.05)

Daytime	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	–	0.006	0.018	0.565	0.000	0.000	0.000	0.000	0.000
C2	–	–	1.000	0.700	0.496	0.080	0.817	0.565	0.001
C3	–	–	–	0.866	0.306	0.032	0.634	0.365	0.000
C4	–	–	–	–	0.004	0.000	0.024	0.006	0.000
C5	–	–	–	–	–	0.998	1.000	1.000	0.365
C6	–	–	–	–	–	–	0.935	0.994	0.794
C7	–	–	–	–	–	–	–	1.000	0.131
C8	–	–	–	–	–	–	–	–	0.306
C9	–	–	–	–	–	–	–	–	–



Flash Pattern ID	Beacon	LED
FP1	Single	Single
FP2	Single	Quad
FP3	Quad	Single
FP4	Quad	Quad

Figure 5-20 Static experiment under snowy conditions: Conspicuity test results for four flash pattern groups in the daytime contrast

Table 5-8 Static experiment under snowy conditions: Tukey test significance values for the conspicuity of four flash pattern groups in the daytime contrast (yellow highlight indicates a p-value less than 0.05)

	FP1	FP2	FP3	FP4
FP1	–	0.000	0.000	0.000
FP2	–	–	0.517	0.000
FP3	–	–	–	0.000
FP4	–	–	–	–

Figure 5-21 shows the conspicuity average values (at daytime) over all 37 light configurations for static experiments under clear weather conditions versus the same results in the snowy day conditions (weather experiment). The plotted points stand only for the 13 subjects who participated in both clear and snowy day experiments. The relatively higher number of plotted points on the lower corner suggests that snow somehow reduced the conspicuity of the warning lights. Considering the conspicuity values reported by the 13 common participants for all 37 light configurations (13 participants multiplied by 37 light configurations equal 481 data points), the significance value of the ANOVA test (evaluating the statistical difference between the clear and snowy events) is equal to 0.04. The average of the 481 data points for the clear and snowy day was 3.69 and 3.55, respectively. This difference was statistically meaningful as suggested by the ANOVA test result.

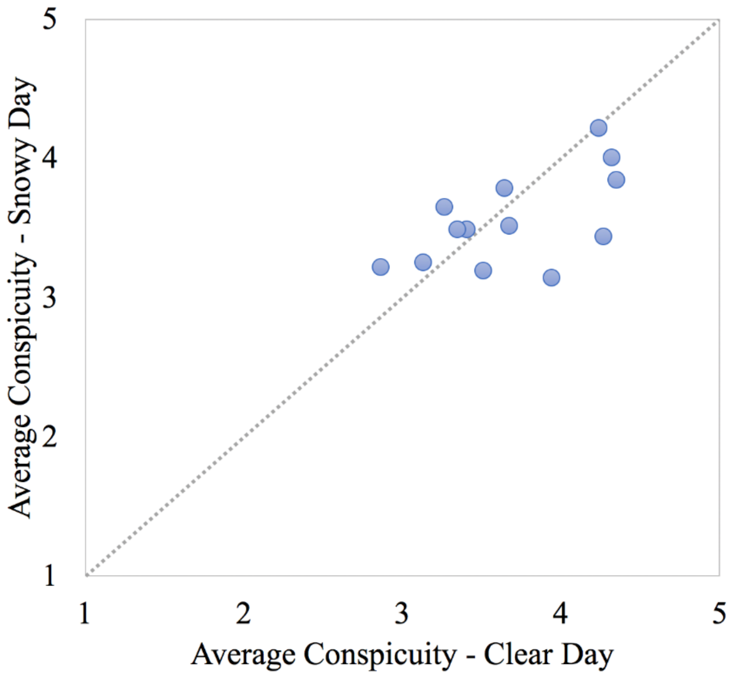


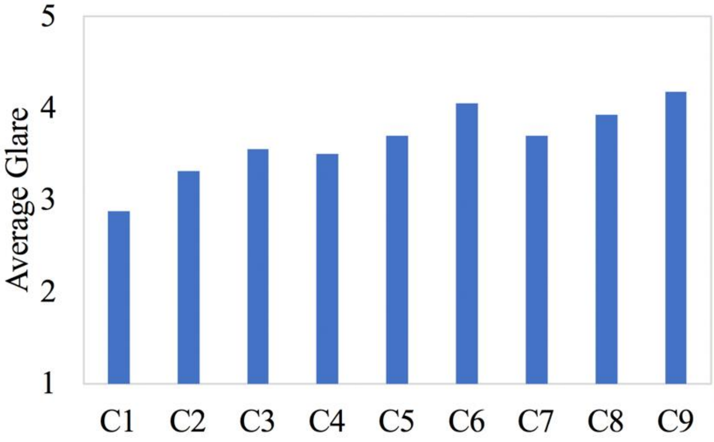
Figure 5-21 Static experiment under snowy conditions: Comparison of the daytime contrast conspicuity average values over various warning light configurations for each participant in clear and snowy weather conditions

5-3-2- Glare Rating Test Results

The results of the glare rating test (which was conducted only with the nighttime contrast) for the nine color and four flash pattern groups are illustrated in Figure 5-22 and Figure 5-23, respectively. Color group C9 (in which both green and amber colors are included in both LEDs and beacons) has the highest glare rate, while it has the highest conspicuity level as well. On the other hand, the all-amber case (C1) has the lowest glare and the lowest conspicuity level. These results align with the results of the static experiments under clear weather conditions.

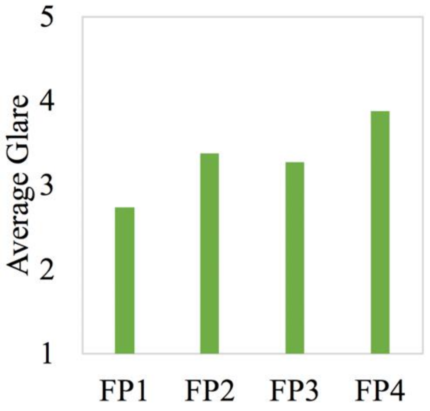
Based on the average values presented in Figure 5-23 for the glare rates, FP4 (all quad) has the highest glare, while it has the highest conspicuity level, and FP1 (all single) has the lowest glare and the lowest conspicuity level. The significance values of the ANOVA test results for all color and flash pattern groups are equal to zero. The Tukey test results for nine color and four flash pattern groups are presented in Table 5-9 and Table 5-10, respectively. The significance values show that color groups C1 and C9 are statistically different from all or most of the other color groups. Also, Table 5-10 indicates that FP1 and FP2 were statistically different from other flash patterns in terms of the glare discomfort.

Figure 5-24 shows the glare average values (at daytime) over all 37 light configurations for clear (static experiment) versus snowy day (weather experiment). The plotted points stand for the 13 subjects who participated in both clear and snowy day experiments. A significant difference was not observed between the two events (clear and snowy) in terms of the glare discomfort level. This can be due to a relatively short distance that the glare test was conducted (150 feet), where the presence of snow did not reduce the glare discomfort. This was unlike the conspicuity, which was affected by the presence of snow at a 450-foot distance. The average values for 481 glare data points (13 participants multiplied by 37 light configurations) for the clear and snowy day are 3.70 and 3.66, respectively. This difference is not statistically significant as suggested by the ANOVA test result (the significance value is 0.532, which is much higher than 0.05).



Color ID	Beacon Color	LED Color
C1	Amber	Amber
C2	Amber	Green
C3	Green	Amber
C4	Green	Green
C5	Amber + Green	Amber
C6	Amber + Green	Green
C7	Amber	Amber + Green
C8	Green	Amber + Green
C9	Amber + Green	Amber + Green

Figure 5-22 Static experiment under snowy conditions: Conspicuity test results for nine color groups in the nighttime contrast



Flash Pattern ID	**Beacon**	**LED**
FP1	Single	Single
FP2	Single	Quad
FP3	Quad	Single
FP4	Quad	Quad

Figure 5-23 Static experiment under snowy conditions: Glare rating test results for four flash pattern groups in the nighttime contrast

Table 5-9 Static experiment under snowy conditions: Tukey test significance values for the glare of nine color groups in the nighttime contrast (yellow highlight indicates a p-value less than 0.05)

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	–	–	–	–	–	–	–	–	–
C2	0.089	–	–	–	–	–	–	–	–
C3	0.000	0.849	–	–	–	–	–	–	–
C4	0.002	0.964	1.000	–	–	–	–	–	–
C5	0.000	0.263	0.991	0.937	–	–	–	–	–
C6	0.000	0.000	0.017	0.005	0.245	–	–	–	–
C7	0.000	0.263	0.991	0.937	1.000	0.245	–	–	–
C8	0.000	0.003	0.263	0.120	0.849	0.994	0.849	–	–
C9	0.000	0.000	0.002	0.000	0.046	0.996	0.046	0.788	–

Table 5-10 Static experiment under snowy conditions: Tukey test significance values for the glare of four flash pattern groups in the nighttime contrast (yellow highlight indicates a p-value less than 0.05)

	FP1	FP2	FP3	FP4
FP1	–	–	–	–
FP2	0.000	–	–	–
FP3	0.001	0.856	–	–
FP4	0.000	0.001	0.000	–

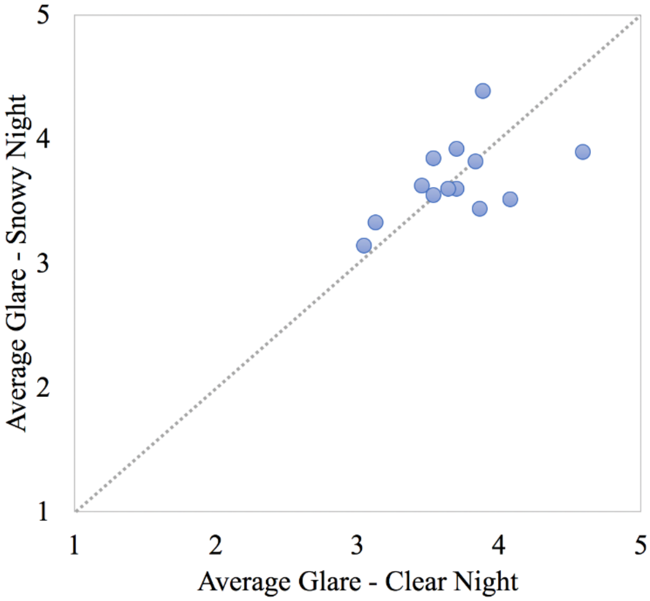


Figure 5-24 Static experiment under snowy conditions: Comparison of glare average values over various warning light configurations for each participant in clear and snowy weather conditions

5-3-3- Interpretation of Weather Experiment Results

As discussed in the two previous experiments, a trade-off analysis between the two factors of conspicuity (at daytime) and glare (at nighttime) provides for selection of an appropriate warning light configuration. Figure 5-25 illustrates the average conspicuity (daytime) versus average glare (nighttime) for all 37 light configurations in the weather experiment. A similar pattern as in the static (clear day) experiments is also observed in this figure. Each plotted point in this graph is an average value over all participants for each warning light configuration (see Table 4-5 for light configuration details). Similar to the results of static and dynamic experiments under clear weather conditions, Figure 5-25 suggests adding green light increases the conspicuity, while the all-amber cases have the lowest conspicuity and glare.

Figure 5-26 highlights the weather experiment results for the six light configurations that were tested in the dynamic experiments. The results of the weather experiments are consistent with the results of the static and dynamic experiments under clear weather conditions for these six configurations. This means that four light configurations – LC19, LC23a, LC27 and LC35 – were the most capable light configurations in improving visibility while resulting in a bearable glare discomfort to travelers.

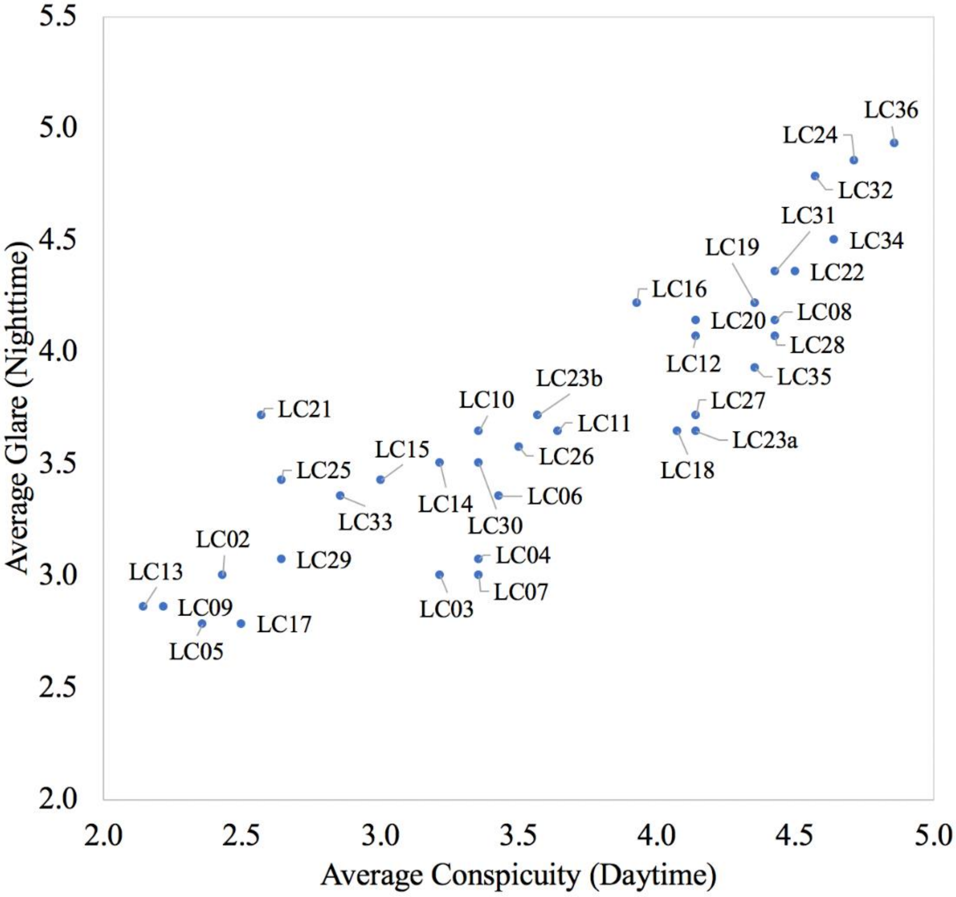
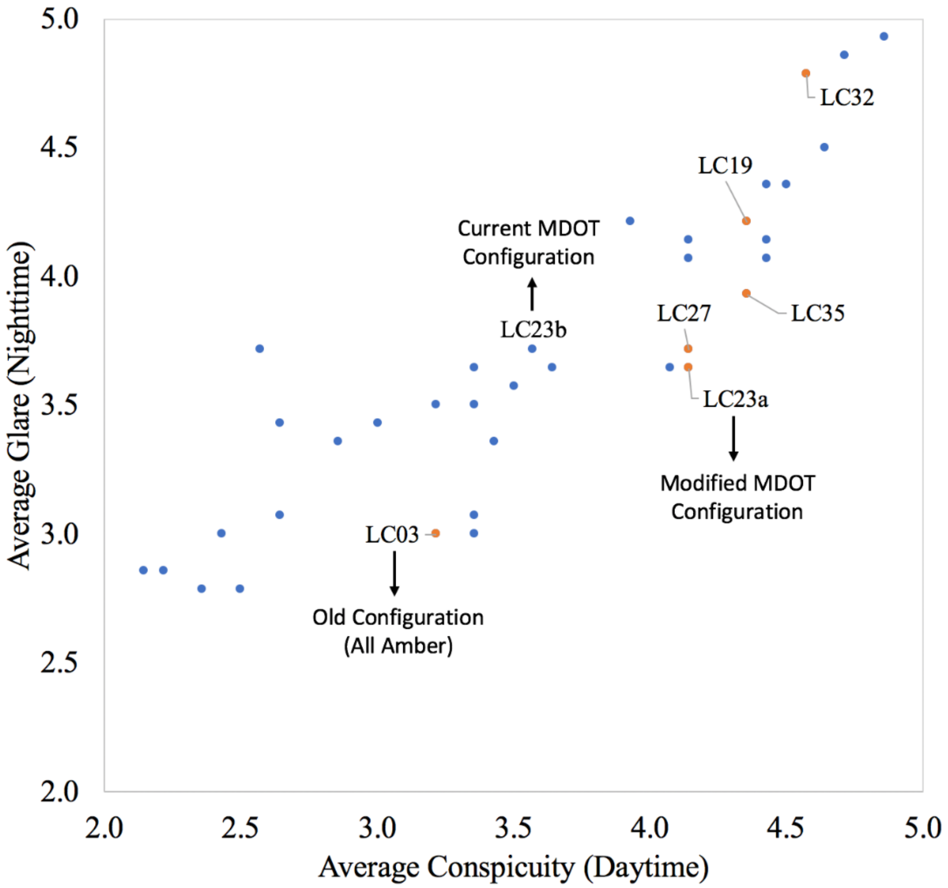


Figure 5-25 Static experiment under snowy conditions: Relationship between conspicuity (daytime) and glare (nighttime) averaged over all participants for each warning light configuration



Light Configuration	Beacon Color (Flash Pattern)	LED Color (Flash Pattern)
LC03	Amber (Quad)	Amber (Single)
LC19	Amber (Quad) + Green (Single)	Amber (Quad)
LC23a	Amber (Quad) + Green (Single)	Green (Single)
LC27	Amber (Quad)	Amber (Quad) + Green (Single)
LC32	Green (Quad)	Amber (Quad) + Green (Quad)
LC35	Amber (Quad) + Green (Single)	Amber (Quad) + Green (Single)

Figure 5-26 Static experiment under snowy conditions: Relationship between conspicuity (daytime) and glare (nighttime) averaged over all participants for six highlighted warning light configurations (used in the dynamic experiment)

CHAPTER 6 – CRASH DATA ANALYSIS

Ultimately, improvements in the visibility and conspicuity of WMTs are expected to result in lower risk of WMT-involved collisions and fewer instances of unsafe behavior by motorists in the immediate vicinity of WMTs during maintenance operations. To this end, an analysis of available crash data was conducted to assess whether any clear trends emerged with respect to crashes involving MDOT WMTs since the initiation of the green light installations.

Data from crashes involving MDOT WMTs were provided over the period from 2015 to 2019. As mentioned previously, the green lights were added to the MDOT-owned WMTs gradually over the period from 2016 to 2018. Thus, this five-year period includes data from the periods before and after green light implementation. However, data were not available to discern how quickly various MDOT regions introduced the new lighting configuration. Nonetheless, these data provide a high-level summary of WMT crash involvement.

The number of total WMT-involved crashes for each year is illustrated in Figure 6-1. On an annual basis, there were between 39 and 64 such crashes during this five-year period. The introduction of green lights may impact a subset of these crashes, specifically those crashes where visibility of the WMT may be impacted by adverse weather. The full data set includes 290 crashes. To identify the crashes that were potentially related to visibility issues, summary data for each crash was carefully reviewed to determine whether an improved warning light system may have helped to prevent the crash from occurring. For example, collisions where a driver rear-ended or sideswiped a WMT were included among the subset of crashes where enhanced visibility may have helped to prevent the collision from occurring. The numbers of potential visibility-related crashes per year are also illustrated in Figure 6-1. Consistent with the overall trend, no clear pattern emerges between the periods before and after implementation of the green lights on WMTs.

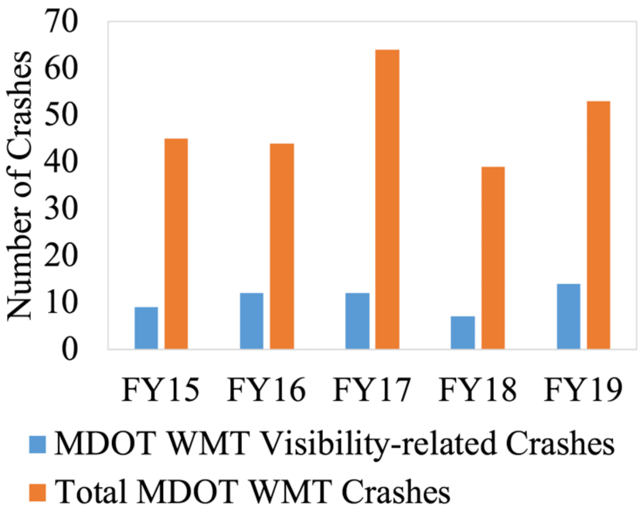


Figure 6-1 Number of total and visibility-related crashes for fiscal years 2015–2019

In addition to examining the aggregate crash statistics from Figure 6-1, the research team also examined potential correlation between the number of WMT-involved crashes and various weather-related variables. To this end, a winter severity index (WSI) was utilized as a representative measure of the prevailing weather conditions during each year of the analysis period. This WSI, provided by MDOT, integrates multiple reported weather variables into a single performance measure. The weather variables incorporated in the WSI are number of snow events, number of freezing rain events, total amount of snowfall (inches), total duration of storm (hours) and duration of blowing snow (hours). In theory, WSI facilitates more effective comparisons in adverse weather-related crashes across a geographical area over time. Figure 6-2 illustrates this index for fiscal years 2015–2019. In general, the crash trends tend to track with changes in the WSI. For example, the higher numbers of crashes observed in 2017 and 2019 coincide with higher values of WSI in general. However, even when controlling for these differences, there is no pattern that emerges with respect to differences in visibility-related crashes.

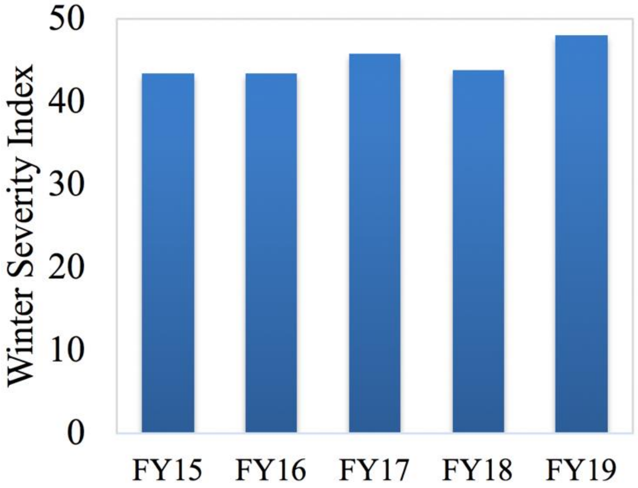


Figure 6-2 Winter severity index (WSI) for fiscal years 2015–2019

Overall, the limited number of crashes involving WMTs, as well as the random and rare nature of such collisions, made it infeasible to discern any potential cause-and-effect relationship from these data. In theory, evaluation of potential impacts on safety would require a larger sample of crash data, though this was also likely to be impractical as the entire MDOT WMT fleet has transitioned to green lights as standard equipment.

Several additional concerns arise that complicate the ability to discern relationships between the green light installation and WMT-involved crashes. While the WSI provides a single measure to quantify the impacts of adverse winter weather, these data are currently captured only at a statewide level. Calculation of a WSI-like metric at a more localized level may provide additional insights. In addition to quantifying weather-related variables, it would also be valuable to assess how the rate of WMT-involved crashes varies with respect to the number of miles and/or hours of use for these vehicles.

As an alternative to crash data, this issue could also be investigated by evaluating various surrogate safety measures. For example, the MSU research team has previously conducted field studies of driver behavior in response to a CAMS (Zockaie et al., 2018). A similar study could be conducted to discern whether drivers adapt their behavior when approaching WMTs with different warning light configurations.

CHAPTER 7 – SUMMARY AND RECOMMENDATIONS

In this study, the impacts of adding green lights to enhance the visibility of WMTs were explored. First, the current state of the practice was reviewed through an online survey of state transportation agencies. Then, an experiment was designed to evaluate different warning light configurations in consideration of light color (green or/and amber), flashing pattern (single or/and quad) and light placement (rear side and on top of the WMT). These configurations were assessed based on feedback provided by research subjects through experiments conducted under three contexts: static, dynamic and adverse weather. The selected research subjects comprised a group of subject matter experts (MSU graduate students and MDOT staff), as well as members of the general public. Finally, a review of available crash data was performed to evaluate whether any short-term trends emerge subsequent to the implementation of green warning lights by MDOT.

The nationwide online survey was developed, distributed and responded to by all 50 state DOTs to investigate current practices related to the use of auxiliary warning lights on maintenance vehicles. This survey had four primary objectives: compiling the current status of warning light configurations used for maintenance operations, gathering available information regarding the effectiveness of different configurations, collating any unpublished studies regarding the effectiveness of different auxiliary warning light configurations, and identifying promising and innovative approaches used by agencies to improve visibility of maintenance vehicles.

In the static experiments, where both the participants and WMTs were stationary, all 37 warning light configurations were evaluated by each research participant. The stationary nature of these experiments provided efficiencies as feedback could be solicited from all participants simultaneously. This is in contrast to the dynamic tests in which each configuration could only be evaluated one at a time by each panelist.

Consequently, the dynamic experiments evaluated a subset of the 37 warning light configurations that were selected based upon performance in the static tests. The dynamic experiments were conducted under simulated driving conditions in a controlled environment at the ACM test bed. The participant vehicle followed the WMT, which called for conducting the tests individually for each participant.

Both the static and dynamic experiments were conducted during clear weather under both daytime and nighttime conditions. As the performance of the warning light configurations under adverse weather conditions is of particular interest, the static experiments were repeated under snowy daytime and nighttime conditions. This experiment was conducted among only a subset of the research participants due to logistical issues associated with the uncertainty in forecasting adverse weather events.

The main objective of these stepwise experiments was to evaluate the effectiveness of as great a number of light configurations as possible under different contexts (day versus night, clear versus snowy and static versus dynamic) in consideration of resource constraints. Each experiment comprised multiple tests, each of which measured a different aspect of the performance of the warning light configuration. These tests evaluated the conspicuity of each configuration; the level of glare introduced by each configuration; the maximum peripheral detection angle for each configuration; the minimum distance from the WMT at which the subject would choose to take action (e.g., brake or change lanes); and the specific action that would be taken in each scenario.

This chapter summarizes the research findings from the review of the current practice, field experiments and crash analysis. Furthermore, recommendations are provided to improve the visibility of WMTs.

7-1- Summary of Findings

Survey of State DOTs

1. 88% of state DOTs use flat light-head LED warning lights on WMTs, 80% use rotating beacon warning lights, and 67% use both types of warning lights. All state DOTs currently use amber in their warning light configurations. Besides amber, white is the most commonly used color, followed by blue, red and green. Currently, Michigan, Connecticut, Maine, North Carolina and Ohio are the only states that use green lights on their WMTs. The double flash pattern is the most common pattern among all states, followed by the single flash. The quad flash pattern is not as common as other flash patterns, which may be reflective of its relatively recent deployment. Similar trends are observed for general maintenance vehicles in terms of the distribution of the warning light types, colors, and flash patterns among the surveyed agencies.
2. 12% of state DOTs currently use green auxiliary warning lights, and an additional 32% are interested in using green lights. The remaining states indicated they are not interested in using

green auxiliary warning lights on their maintenance vehicles, with the most frequently cited reason being prohibition based on state legislation.

3. Retroreflective auxiliaries, flashing arrow boards, dynamic warning light controllers and camera systems covering blind spots were suggested technologies by state DOTs to be incorporated on the back or sides of trucks. LED stick light markers, spotlights and laser markers were suggested technologies by state DOTs to be incorporated on the wing or plow of the trucks. Using airfoils and heated lenses for warning lights, placing the lights at the highest possible locations and using long rubber flaps on plows were suggested approaches by state DOTs to avoid snow accumulation on the back of trucks.

Static Experiments

4. The test results showed a positive correlation between conspicuity and glare tests. This suggests an inherent trade-off as the warning light configurations that were most conspicuous also tended to produce the most severe glare.
5. Statistically significant differences were observed between various color groups and flash patterns in terms of the conspicuity and glare tests. The color group consisting of amber for both beacons and LEDs and the flash pattern consisting of single flashing lights for both beacons and LEDs demonstrated the lowest conspicuity and glare measures, while the color group consisting of amber and green for both beacons and LEDs and the flash pattern consisting of quad flashing lights for both beacons and LEDs demonstrated the highest conspicuity and glare measures. The rest of the color and flash pattern groups demonstrated comparable performance in terms of conspicuity and glare.
6. No significant differences were observed with respect to the maximum peripheral detection angle across the warning light configurations.
7. The most critical measures of visibility under daytime and nighttime conditions were conspicuity and glare, respectively. Glare is less of a concern under daylight, and conspicuity is less of a concern at night.
8. Incorporating green lights increases the conspicuity and ability of the lighting systems to attract the attention of approaching motorists while elevating the glare level, especially when they are used with a quad flashing pattern.
9. As per the static evaluation, the four warning light configurations that were most effective in terms of providing a balance of high levels of conspicuity and low levels of glare were LC19,

LC23a, LC27 and LC35. These four light configurations were selected for further evaluation as a part of the dynamic experiments. In addition, LC03 and LC32 were also included in the dynamic experiments. These represent the most basic warning light configuration (amber quad beacon and single amber LED) and the highest conspicuity (and highest glare) configuration, respectively. Table 7-1 provides details for each of these configuration IDs.

Table 7-1 Selected light configurations for further assessments in the dynamic experiment

Configuration ID	Beacons	LEDs
LC03	Amber (Quad)	Amber (Single)
LC19	Amber (Quad) + Green (Single)	Amber (Quad)
LC23a	Amber (Quad) + Green (Single)	Green (Single)
LC27	Amber (Quad)	Amber (Quad) + Green (Single)
LC32	Green (Quad)	Amber (Quad) + Green (Quad)
LC35	Amber (Quad) + Green (Single)	Amber (Quad) + Green (Single)

Dynamic Experiments

10. No statistically significant difference could be observed over the various configurations in the proper driving action and the action-taking distance tests.
11. Statistically significant differences were observed among the various configurations in terms of both the conspicuity and glare measures. Furthermore, there is a positive correlation between the level of glare discomfort at nighttime and the level of conspicuity under daytime conditions. These findings are similar to those from the static experiments.
12. The all-amber configuration (LC03) produced the lowest daytime conspicuity and nighttime glare discomfort. The configuration that included all quad flashing green lights for both the LEDs and beacons (LC32) showed the greatest conspicuity and highest degree of glare discomfort. These two configurations exhibited statistically significant differences as compared to the other four configurations in terms of both measures. The four remaining configurations were not significantly different from one another.
13. Consistent with the static experiment, the dynamic experiment results suggested that adding green lights increases conspicuity. The level of glare discomfort is kept at an acceptable level when used with a single flashing pattern.

Weather Experiments

14. The general trends observed in the static experiments conducted under adverse weather were consistent with the static experiments under clear weather conditions.
15. The conspicuity levels reported by the research subjects under adverse weather were lower in comparison to what was reported for clear weather during the daytime. This reduction was statistically significant.
16. However, no significant difference was observed between the two weather conditions in terms of the glare discomfort level. This might be a function of the shorter distance between the research subjects and the experiment truck in the glare standard test (150 feet versus 450 feet).

Crash Data Analysis

17. No significant impacts of green lights were shown with respect to the number of visibility-related crashes. This finding was due in part to the low number of WMT-involved crashes that occur on an annual basis, as well as other data limitations. In lieu of crash data, an alternative means of evaluating safety impacts could include evaluations of surrogate safety measures.

7-2- Recommendations

Overall, the results of this study suggest that the addition of green warning lights to WMTs improves visibility. It is anticipated these improvements will result in safer interactions between the traveling public and WMTs, particularly during winter maintenance operations. To this end, the following recommendations are presented based upon the results of this study.

1. The single flash pattern for amber warning lights does not provide sufficient conspicuity during the daytime. As such, the single flash amber lights should not be used as part of the warning light configuration during daytime operations.
2. White is the most commonly used color after amber among state DOTs. However, due to glare concerns during nighttime operations, it is not recommended for use. Blue and red, the other commonly used colors by state DOTs, are prohibited in Michigan by legislation. Thus, the continued use of green auxiliary warning lights is recommended.
3. Based upon the human factors experiments, the use of a combination of quad flashing amber lights and single flashing green lights on the rear side and/or top of the maintenance trucks is recommended as the most effective warning light configuration. This color/flash pattern combination is consistent with current MDOT practice.

4. The current MDOT configuration incorporates quad flashing amber lights and single flashing green lights for the top beacons and single flashing green lights for the rear LEDs. The beacons and LEDs flash independently of each other. Slight improvements in terms of conspicuity and glare were observed once the amber beacons and green LED lights were synchronized. Although the improvements were not statistically significant, synchronizing green LED lights with beacon amber lights can be recommended.
5. Incorporating a quad flash pattern for the green auxiliary lights during nighttime is not recommended. This specific combination produces a high level of glare that introduces potential discomfort among motorists.
6. Incorporating programmable warning light configurations is recommended. These systems allow for the use of different configurations based on prevailing conditions to reduce glare. For example, alternate patterns could be used under daytime versus nighttime or when the WMT is stopped at signalized intersections with vehicles queued behind in close proximity. In these situations, the WMT warning lights can be dimmed to decrease glare discomfort.
7. The use of higher intensity warning lights (e.g., quad flashing green lights) is recommended during daytime maintenance operations under severe weather conditions. Given concerns related to glare under nighttime conditions, this would require a programmable configuration as noted in the preceding point. However, there is an extra cost associated with application of programmable warning light configurations that needs to be considered.
8. As this study showed, green warning lights enhance the visibility of WMTs. Thus, it is reasonable to expect similar visibility enhancements when using green warning lights on other maintenance vehicles and equipment.
9. Lastly, to help inform subsequent decision-making related to winter maintenance, it is recommended that additional information is collected, where practical, to assist in monitoring the safety and effectiveness of winter maintenance operations. This would include collecting basic information such as the number of hours or number of miles that each vehicle accrues while conducting maintenance operations. Further disaggregation of this data, such as by specific tasks (e.g., plowing and deicing) or under certain weather conditions (e.g., defined by temperature, visibility and snowfall rate), would provide additional value. These measures would facilitate comparisons of maintenance operations over time and across MDOT regions and would be useful for both internal and external evaluations.

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APPENDIX A – DOT WINTER MAINTENANCE OPERATIONS SURVEY

Start of Block: Credentials

Pre-Survey

This survey may take 10-15 minutes. Please share your credentials for survey validation and follow-ups.

○ **Agency name ____**

○ **Your name ____**

○ **Role in agency ____**

○ **Contact Information ____**

End of Block: Credentials

Start of Block: Introduction

BRIEF Michigan Department of Transportation (MDOT) has recently implemented a new lighting configuration for its snowplows (winter maintenance trucks) consists of Amber and Green auxiliary warning lights with different flashing patterns. Michigan State University has been recently awarded a project funded by MDOT **to evaluate effectiveness of this lighting configuration regarding visibility of snowplows.** To this end, various lighting configurations will be tested to identify the optimal combination of colors and flashing patterns. In this regard, as part of our project, **we would like to investigate the state of practice in other agencies**. Thus, we would appreciate it if you can provide some information regarding the auxiliary warning light configurations that are used by your agency. Please proceed to begin.

End of Block: Introduction

Start of Block: Note on type of Q

NOTE

You will be asked on two (2) **types of operations**:
1) Winter Maintenance Truck (Snowplow)/Equipment
2) Other Maintenance Vehicles/Equipment

End of Block: Note on type of Q

Start of Block: Q1-WM

1.0 What **type** and **color** of **auxiliary warning lights** are installed on the trucks/equipment you operate for following maintenance services? Check all that apply. Please **skip question 1.1** if your agency **does not perform winter maintenance operations.**

1.1 **Winter Maintenance Truck (Snowplow)/Equipment**

1.1a Type

☐ **Directional / Flat Light-head**

☐ **360° / Rotational**

☐ **Other ____**

1.1b Color

☐ **Amber**

☐ **Red**

☐ **Green**

☐ **White**

☐ **Blue**

☐ **Other** ____

End of Block: Q1-WM

Start of Block: Q1-Other

1.0 What **type** and **color** of **auxiliary warning lights** are installed on the trucks/equipment you operate for following maintenance services? (Check all that apply)

1.2 **Other Maintenance Vehicles/Equipment**

1.2a Type

☐ **Directional / Flat Light-head**

☐ **360° / Rotational**

☐ **Other** ____

1.2b Color

☐ **Amber**

☐ **Red**

☐ **Green**

☐ **White**

☐ **Blue**

☐ **Other** ____

End of Block: Q1-Other

Start of Block: Q2-WM

2.0 Please specify any specific **pattern of flashing / synchronization** that you use on your maintenance trucks.

You may refer to this link for flash pattern examples:

Flash Pattern Samples

Check all that apply. Please **skip question 2.1** if your agency **does not perform winter maintenance operations.**

2.1 **Winter Maintenance Truck (Snowplow)/Equipment**

2.1a Flash Pattern:

- ☐ **Steady**
- ☐ **Single**
- ☐ **Double**
- ☐ **Triple**
- ☐ **Quad**
- ☐ **Other (please specify)** ____

2.1b Synchronization Pattern:

- ☐ **Synchronized**
- ☐ **Asynchronous**
- ☐ **Comments, if any:** ____

End of Block: Q2-WM

Start of Block: Q2-Other

2.0 Please specify any specific **pattern flashing / synchronization** that you use on trucks.

You may refer to this link for flash pattern examples:
Flash Pattern Samples

2.2 **Other Maintenance Vehicles/Equipment**

2.2a Flash Pattern:

☐ **Steady**

☐ **Single**

☐ **Double**

☐ **Triple**

☐ **Quad**

☐ **Other (please specify) ____**

2.2b Synchronization Pattern:

☐ **Synchronized**

☐ **Asynchronous**

☐ **Comments, if any: ____**

End of Block: Q2-Other

Start of Block: Q3-1

Q3 If your agency does not use green lights on maintenance trucks, would you consider installing green lights on any type of maintenance vehicle?

☐ **We do use green lights on maintenance trucks**

☐ **Yes. Please specify reason ____**

☐ **No. Please specify reason ____**

Q4 How long has your agency used any color(s) other than amber, for auxiliary warning lights on maintenance trucks?

____

Q5 Approximately what percentage of your maintenance vehicle fleet uses auxiliary warning lights with any color(s) other than amber?

____

End of Block: Q3-1

Start of Block: Q3-2

Q6 Do you use or suggest any other technologies and/or innovative equipment to enhance visibility of winter maintenance operations?

____

Q7 Have you ever conducted research on evaluations of auxiliary warning lights? If so, please provide some basic information about the study(s) here:

____

Q8 Any additional suggestions or comments regarding use of green auxiliary lighting on maintenance vehicles?

____

End of Block: Q3-2

Start of Block: Q3-3

Q9 If you have ever implemented auxiliary warning lights on snowplows, how do you deal with snow-covering issue, since LED lights do not generate heat? Leave blank if not applicable.

____

Q10 Are there any specific policies or standards regarding the use of green strobes at your agency?

____

Q11 If your agency has recently adopted green strobes or any other technologies associated with the visibility of maintenance vehicles, what initiatives have you used to inform road users regarding these changes?

____

End of Block: Q3-3