Evaluation of ESS H.E.L.P. Hazard Lighting System

Prepared by the Virginia Tech Transportation Institute

for Emergency Safety Solutions

Travis Terry, Ph.D.
Brian Williams
Bradley Myers
Andrew Kassing
Rajaram Bhagavathula, Ph.D.
Ronald B. Gibbons, Ph.D.

Submitted: April 15, 2021

0 TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1 INTRODUCTION

Emergency Safety Solutions (ESS) have developed an enhanced hazard lighting system referred to as the Hazard Enhanced Lighting Package (H.E.L.P.), to improve visibility of potentially hazardous vehicles and better draw the attention of approaching drivers. The use of a hazard lighting system is most often relegated to when a driver is in serious need of assistance or wishes to alert other motorists that their vehicle has now become a potential hazard due to inoperability or inability to achieve a safe speed. It is imperative that activated hazard lighting systems are highly visible both day and night and can divert an approaching driver’s attention away from any secondary tasks. Compliance regulations surrounding hazard lighting systems were developed in the 1960’s when lighting technology was limited. Modern lighting technology, specifically LEDs and wireless technology, allow for alterations to current hazard lighting packages such as increased flash frequency, increased luminance, and the inclusion of additional rear lamps that are standard on most vehicles. This experiment evaluated six alternative hazard lighting configurations for their ability to redirect driver attention to the forward roadway as well as their preference, level of annoyance, and conveyance of urgency.

1.1 Background

Hazard warning lights, sometimes referred to as “hazard flashers” or simply as “hazard lights,” are a pair of intermittent flashing indicator lights that activate in unison to caution other drivers. The prescribed usage for hazard warning lights includes alerting following motorists that the vehicle must be approached with caution due to an inability to gain speed, such as when traveling a steep incline, or to alert downstream motorists of a sudden stop in traffic. Motorists may also use warning lights to signify the vehicle is an obstruction, either when parked on a shoulder or inside a travel lane, and that they should approach with caution (American Automotive Association, 2020).

According to Federal Motor Vehicle Safety Standards (FMVSS), the purpose of the lights is to enhance the conspicuity of motor vehicles on public roads during both day and night as well as during periods of reduced visibility (National Highway Traffic Safety Administration, 2007). Warning light usage varies by US state. Ten states have regulations against driving with active hazard lights and forty states, as well as Washington D.C., allow hazard light usage while driving but with stipulations. Example stipulations include that an emergency or hazardous situation must predicate the use, the vehicle is part of a funeral procession, or when otherwise traveling slower than 30 mph (American Automotive Association, 2020). Figure 1 illustrates the breakdown of hazard light use by state.

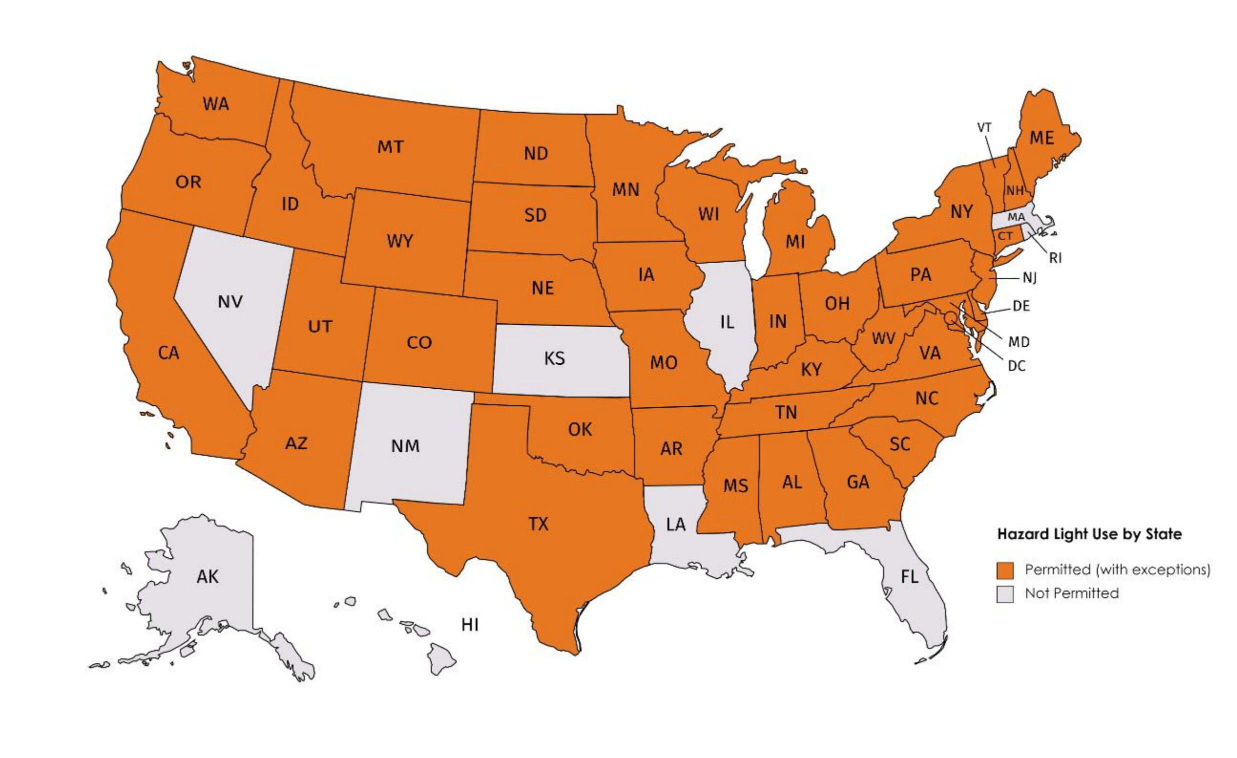


Figure 1: Breakdown of Hazard Light Use by State (American Automotive Association, 2020).

The flashing indicators that make up a hazard lighting system on a vehicle are generally located on the rear, with one on each side. FMVSS regulations apply to hazard warning signals on all passenger vehicles as well as large trucks and buses, and they must meet photometric requirements including light level, light distribution, and light color. The signals can be amber or red in color and the minimum luminous intensity measured in any direction must be 0.3 cd for the duration of the flash pattern (NHTSA, 2007).

Different countries use hazard warning lights in different ways. For example, in the U.K. hazard lights are used to indicate that a driver is slowing down while in the U.S., this is not the case. Drivers in New Zealand are advised to only use hazard lights when the vehicle is disabled on the roadway (Driver Training, 2020). In the U.S., initiating hazard warning lights causes all the turn signal lamps to flash in unison (NHTSA, 2007). Similarly, in Europe a hazard warning signal is the simultaneous operation of all of a vehicle's direction-indicator lamps to show that the vehicle temporarily constitutes a special danger to other road-users (United Nations Economic Commission for Europe, 2019); however, European regulations allow for varied color and placement of direction-indicator lamps and are not FMVSS compliant.

FMVSS Code of Federal Regulations, Standard No.108 requires hazard lights to be equipped on all passenger vehicles (NHTSA, 2007). The technology used in current hazard light systems was designed over 70 years ago and was limited by the mechanical control systems and light bulbs of the time. It is noteworthy that at this time, FMVSS 108 requires a mechanical flasher and does not allow for software control of this feature. Modern lighting systems utilize LEDs and electronic controls and as a result, hazard lighting output on production vehicles today consist of a 1.0 Hz to 2.0 Hz rate of flash operating on a duty cycle ("percentage on time") ranging between 30% and 75% as illustrated in Figure 2 (National Highway Traffic Safety Administration, 2007). Laboratory experiments have shown LED flashers, both in the stop lamps and center high-mounted stop lamp (CHMSL), were more effective than incandescent lamps at preventing rear-impact collisions (Greenwell, 2013).

Created in 1967, the FMVSS rule was developed during a period when the technology of the time limited the speed incandescent bulbs could flash on and off. Research into warning lights from this time is limited; however, advancements in lighting technology since then, such as the advent of LEDs, have eliminated those flash rate limitations (Phelan, 2020).

Flash rate requirements dictate that the performance of the flashers must fall within the unshaded portion of Figure 2 while open flashers must fall anywhere inside the chart area, including the shaded region (National Highway Traffic Safety Administration, 2007). The concept of open and closed flashers involves system hardware, typically pre-modern. As stated in FMVSS, flash having normally closed contacts must open (or turn off) within one second for a device designed to operate two signal lamps or within 1.25 second for a device designed to operate more than two lamps. A flasher with normally open contacts must complete the first cycle (close and open) within 1.5 seconds. These hardware specifications are currently applied to modern lighting systems, such as LEDs, that do not require hardware mechanisms to create a flashing sequence.

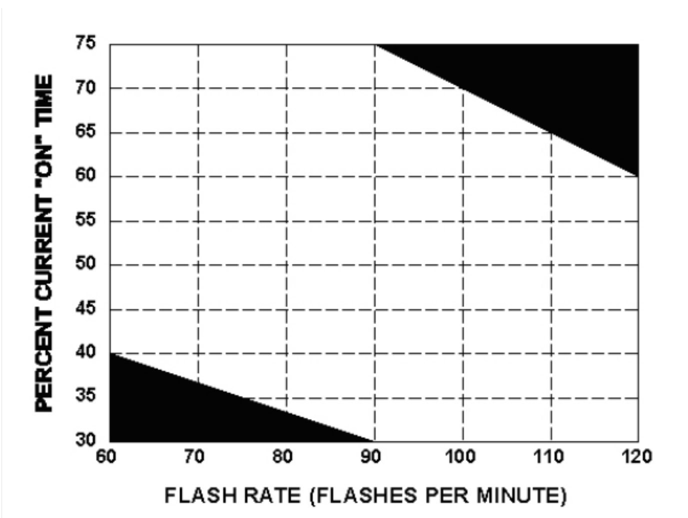


Figure 2: Flasher Performance Chart (National Highway Traffic Safety Administration, 2007).

1.2 Problem

NHTSA's Fatality Analysis Reporting System (FARS) and the Crash Reporting Sampling System (CRSS), as reported by Accident Analysis and Prevention, indicates that between the years 2016 and 2018, 211 fatalities resulted from a disabled vehicle being struck after an initial event. Low conspicuity emergency events, as these scenarios were tabbed, involved 68,298 people and led to ten thousand injuries in those three years (Spicer, Bahouth, Vahabaghaie, & Drayer, 2021).

To address this problem, ESS has developed its HELP safety solution to better protect occupants of disabled vehicles as well as any road user who opts to assist them. The solution provides an advanced warning to oncoming drivers of potential threats on or near the roadway. This software-based solution does not modify the lighting output of the vehicle and is a control system that does not require any hardware modifications. However, the prototype software used for this research could be programmed to effect lighting frequency as well as include other lights on the vehicle into the hazard pattern such as reverse lights or a CHMSL. If rolled out as a product, the ability to reprogram the lighting will be removed.

ESS has identified seven hazard light configurations for scientific evaluation of visibility and attention-getting capabilities, including six alternative configurations and the experimental vehicle's default hazard setting. The goal was to identify a configuration to enhance the visibility of a vehicle in an emergency situation to approaching drivers with the intent to also combat driver distraction. ESS's HELP systems allow for the hazard lights to initiate automatically or manually in conjunction with other emergency equipment inside the vehicle. HELP is automatically deployed after a collision is detected by the vehicle or can be deployed manually by pressing the vehicle's hazard activation button twice (located in the center roof panel accessible to both front occupants) and is intended for use when high visibility is needed such as in an emergency, extreme weather event, or natural disaster. Circumstances where a vehicle is disabled or stopped on or near a travel way is considered an emergency.

FMVSS and SAE recommendations specify that hazard lighting configurations must flash between 1 and 2 Hz and therefore none of the six alternative configurations evaluated in this research are considered FMVSS compliant on Hz range alone. Three of the configurations evaluated in the study are not compliant with FMVSS for additional reasons such as the use of a vehicle's CHMSL or reverse lamps. Deployable flashing devices, such as a beacon that flashes in concert with the vehicle's hazard system, are not recognized by FMVSS and are therefore considered outside of compliance. The alternative hazard light configurations are identified as follows:

(1) 4 Hz flashing
(2) 5 Hz flashing
(3) 6 Hz flashing
(4) 5 Hz flashing with CHMSL flashing
(5) 5 Hz flashing with reverse light flashing
(6) 5 Hz flashing with deployable beacon flashing

To simplify the notation within the report, Hz range compliance is disregarded. Therefore, the 4Hz, 5Hz, and 6Hz configurations are labeled 4Hz Compliant, 5Hz Compliant, and 6Hz Compliant because they do not use additional lighting modules ruled out by FMVSS as configurations (4), (5), and (6) listed above.

2 FLASHING LIGHT ASSESSMENT REVIEW

Previous studies have evaluated the impact of flashing lights across an array of characteristics including color, glare, frequency, and the overall ability of a flashing configuration to grab attention. Research has centered on flashing brake lights, flashing police lights, work-zone caution lights, and rear signal lights. Each of these efforts have employed a different evaluation method for determining the best configuration in terms of better visibility, better attention-getting capabilities, and higher preference for road users.

2.1 Attention-Getting Rear Light Experiments

An evaluation of enhanced brake lights using surrogate safety metrics was performed by VTTI in 2010 (Llaneras, Neurauter, & Perez). This study intended to reduce the frequency and severity of rear end crashes by testing alternative rear-brake lighting. To do this, a computer-based simulation model was developed for estimating the effectiveness of several novel signals that increased the conspicuity of the vehicle and led to improved reaction times by drivers.

The researchers aimed to determine the attention-getting or eye-drawing capabilities of the lighting systems when they were either steady or flashing. For both the steady burn condition and the flashing condition, the lamp luminance presented was 420 cd for one half of the participants and 840 cd for the second half. This was evaluated through two separate tests, one static and one dynamic. During the static test, participant drivers of an instrumented vehicle were distracted with a center stack navigation task, such as tuning to a radio station. The mockup vehicle with the alternative brake light systems was located 100 feet directly in front of the participant. Eye glances toward the mockup vehicle were recorded using video cameras installed inside the participant’s vehicle. The same protocol was used for the dynamic test, however the distance from the mockup vehicle was extended and varied (150ft and 200ft). This study used a single fixed brake lamp configuration of simultaneous flashing at 5Hz under high luminance.

Participants were distracted at three different points during the static task: once while receiving instruction but looking at the center stack display, once when navigating menu items in the center stack display, and once while entering text into the center stack display. These events were chosen based on their high degree of visual, cognitive, and manual loading and were deemed suitably safe for a static task.

Nine brake light configurations were tested:

1. Traffic Clearing Lamp (Incandescent) combined with out-board lamps at increased steady brightness.
2. Simultaneous Flashing of All Lamps with Increased Brightness.
3. Simultaneous Flashing of All Lamps with No Increase in Brightness.
4. Increased Lamp Intensity.
5. Enlarged Brake Lamp Area and Increased Brightness.
6. Outboard Alternating Flashing, CHMSL Steady (Alternating Pair, Outboard), optimized in frequency.

7. Outboard Simultaneously Flashing, CHMSL Alternately Flashing, optimized in frequency.
8. Two CHMSL Lamps Alternately Flashing, Out-board Steady (Alternating Pair, CHMSL), optimized in frequency.
9. Baseline (Conventional, Steady Burn).

The methods for this research were successful in finding relevant results to the development and implementation of effective brake signals. Increased brake signal luminance did not increase detection or response time, however flashing configurations (5Hz) did when increased to the FMVSS allowable level of 420 cd.

A second study was directed at reducing the incidence and severity of rear-end crashes by developing and evaluating rear signaling applications designed to redirect drivers' visual attention. This experiment was set up to determine whether drivers, on encountering the new lighting, would react differently than when encountering a typical baseline braking signal (National Highway Traffic Safety Administration, 2009; Wierwille, Llaneras, & Neurauter, 2009).

This was a naturalistic study where various candidate rear lighting systems (detailed below) were outfitted on a research vehicle that drove on public roadways. The research vehicle "coupled with" other vehicles in a traffic stream to create the following scenario. The vehicle's rear lighting system was activated when a pre-defined condition occurred, such as, if the driver of the following vehicle looked away. The research vehicle did not actually slow its speed, only the vehicle's brake lamps were activated. Researchers evaluated when drivers braked when they looked up or refocused their attention forward in response to the lighting configuration.

Three conditions were tested:

1. Baseline Braking Signal, constant on, at normal brake light level.
2. Optimized Simultaneous Flashing of All Lamps with normal brake lamp level (no increase in brightness).
3. Optimized Simultaneous Flashing of All Lamps with Increased Brightness.

The results showed that 3% more drivers applied their brakes in response to flashing brake lamps with increased brightness versus flashing only. Both flashing lamps and flashing with increased brightness outperformed the baseline brake lamps in the study, by 11 and 14 percent, respectively. Thirty-nine percent more drivers refocused their attention (eye-drawing) to flashing brake lamps versus the baseline. The study concluded that flashing brake lamps with increased brightness had stronger attention-grabbing capabilities than standard, non-flashing brake lamps.

In 2003, research by Wierwille, Lee, and DeHart (2003) found that increased brightness of rear lamps showed a benefit for alerting drivers to a stopped or slower moving vehicle. In addition to increased brightness, the results indicated that alternating flashes accompanied with increased brightness through dispersive lenses were the best available configuration. In 2003 LEDs were not widely implemented and the study focused on the use of halogen lights that were more commonly used at the time (Wierwille et al., 2003).

2.2 Flashing Brake and Hazard System Effectiveness

Three experiments were conducted by Li, Wang, Li, Cheng, and Green (2014) to examine the effectiveness of two forward crash warning systems: a flashing brake system and a flashing hazard system. The experiments were conducted using an advanced driving simulator. Results showed the flashing brake system and flashing hazard system reduced drivers' brake response times by 0.14~0.62 s and 0.03~0.95 s, respectively. There were no significant differences observed in brake response times between flashing brake lights and flashing hazard lights; however, flashing hazards showed benefit when the time gap was a half-second longer.

Results also showed that flashing amber lamps reduced drivers' brake response times significantly by 0.11 s (10%) on average compared with red lamps. Additionally, the size and number of lighted elements affects break response times. Compared to a flashing braking system, a hazard lighting system has more flashing lights in view which possibly contributes to better braking performance. Although, increased size of lighting elements had better attention getting capabilities it did not significantly affect brake response times. In short, the results of Li et al. (2014) indicate that additional flashing lighting elements correlate with better response times from drivers.

2.3 Impact of Alternative Emergency Lighting on Police Vehicles

Hazard lighting systems are not far removed from the flashing emergency lighting systems utilized by first responder vehicles such as that of police. A multi-phase study published in 2020, found that increasing the amount of lighting on a police vehicle in addition to the standard light bar resulted in a higher rate of compliance with move over laws (Terry, Fitchett, & Gibbons).

In that study, additional emergency lighting modules were added to the interior of an unmarked police vehicle. Unmarked vehicles are challenging to see during the day especially as the emergency lighting systems are limited to being placed inside the front and rear windshields of the vehicles. Because of this limitation, an unmarked vehicle in Virginia typically has one internal lightbar on the driver's side front visor and two rear facing modules mounted to the rear windshield. Research found that 20% more traffic merged during the day and began merging sooner when lighting in the rear windshield was doubled. This research found that light color impacted driver behavior in response to the move over law (combinations of red and blue for police) and increasing the size of the lighted area by adding lighting modules to other areas of the vehicle enhanced visibility from further away and improved move over compliance, both day and night.

The results of this study showed that increasing the volume of light on an emergency lighting system generated more favorable driving behaviors such as moving over sooner and slowing down more when passing a traffic stop. This may indicate that a hazard lighting system with increased volume will cause drivers to proceed more cautiously.

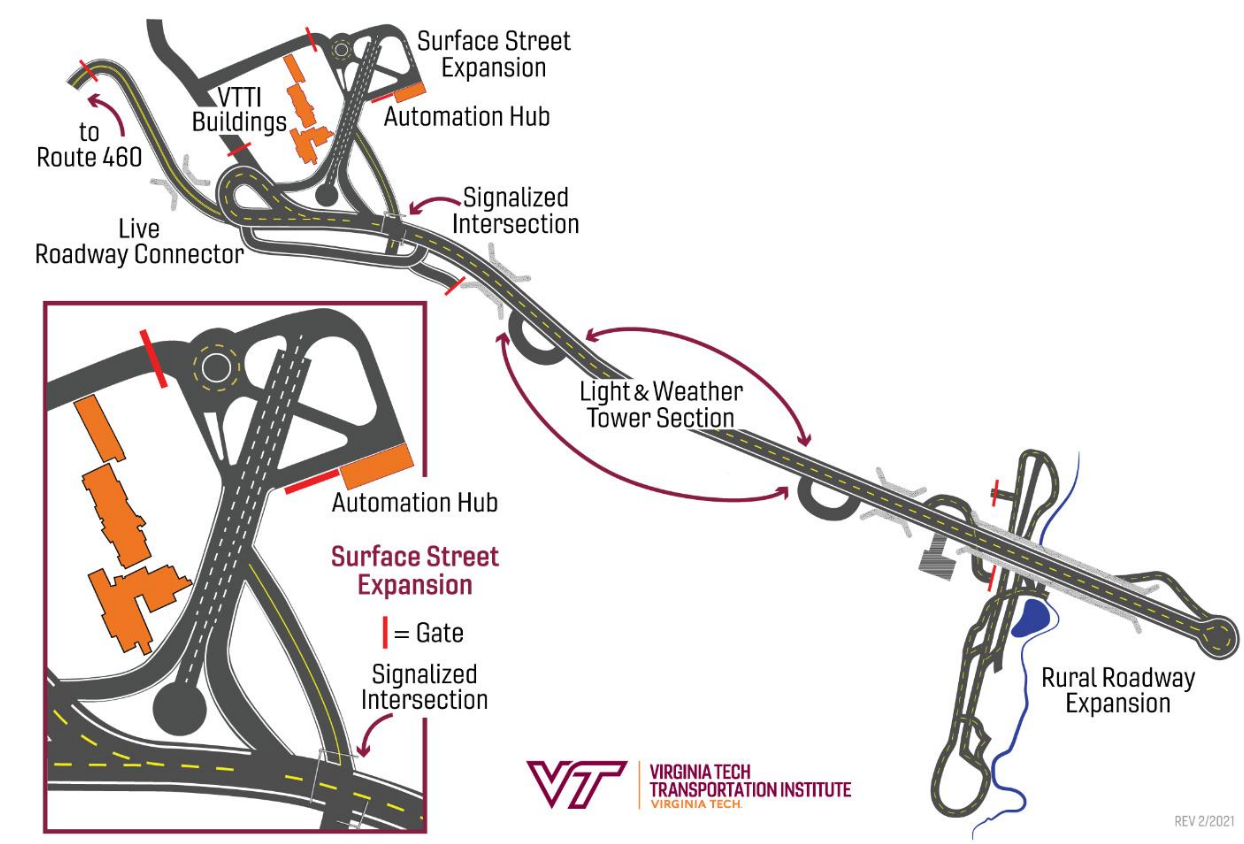
3 EXPERIMENTAL DESIGN

This study consisted of multiple human factors experiments and was conducted on the Virginia Smart Road Highway. The experiments were designed to answer if the alternative lighting configurations provided a benefit over the default hazard lighting systems in terms of refocusing driver attention forward. Additionally, researchers wanted to know how drivers perceived the lighting systems, their safety and overall preference, as well as if the enhanced systems were distinguishable from an emergency lightbar.

ESS provided VTTI with a Tesla model 3 modified to include their HELP system. The HELP system consisted of a single board microcomputer located in the front trunk compartment of the experimental vehicle. The system was programmable via smart phone over Wi-Fi to allow for customization of hazard lighting patterns.

3.1 Facilities

The Virginia Smart Road Highway is a restricted access test track stretching 2.2 miles. The course for this study used a portion of the track to create a loop approximately 3 miles long. The test track simulates a highway complete with pavement markings, shoulders, and guardrails and can be driven on at highway speeds. The participants were tasked with maintaining a speed of 35 mph. Tests were conducted during day and night conditions.



3.2 Vehicles

3.2.1 Participant Vehicle

The vehicles driven by participants were two identical 2017 Ford Explorers (Figure 3). Each vehicle was equipped with a data acquisition system (Figure 4) that captured four camera views inside and outside the vehicle, GPS data, and vehicle network data. In-vehicle experimenters monitored the Data Acquisition System (DAS) from the rear compartment (Figure 5).

Figure 3: Modified 2017 Ford Explorers

Figure 4: Vehicle Instrumentation

Figure 5: View of in-house Hawkeye software used for analyzing multiple variables recorded by the vehicle's DAS

3.2.2 Experimental Vehicle

The modified hazard lighting system was installed by ESS into a Tesla Model 3 (Figure 6 and Figure 7). The decals on the side of the vehicle shown in Figure 7 were non-retroreflective and were not visible or distracting at night.

The hazard system was triggered using the standard hazard light button in the vehicle. The patterns were preloaded by ESS and could be selected by experimenters via a mobile phone connected wirelessly.

Figure 6: Experimental vehicle with beacon deployed, viewed from rear

Figure 7: Experimental vehicle profile

3.3 Participants

Seventy-two participants were recruited to participate in the experiment. Of those, two were unable to complete the entire study due to either equipment failure or adverse weather. Two additional participants were recruited to make up for the lost data, bringing the total number of participants to seventy-four. Participants were recruited using the VTTI participant database and through word-of-mouth. The participants ranged in age from 18 to 65 years old, and an equal number of male and female participants completed the study. Further breakdowns of number of participants and average ages by day and night are detailed in Table 1 and Table 2.

Table 1: Average age (years) by day, night, male, and female

Participant Gender	Average Age by Time of Day		Average Age
	Day	Night	
Male	36.1 *(+/- 16.5)*	34.4 *(+/- 11.0)*	34.6 *(+/- 13.2*)
Female	34.1*(+/- 14.1)*	36.2 *(+/- 12.7)*	35.7 *(+/- 13.7)*
Total	35.1 *(+/- 15.1)*	35.2 *(+/- 11.7)*	35.2 *(+/- 13.4)*

Table 2: Number of participants by day, night, male, and female

Participant Gender	Number of Participants by Time of Day		Total Participants
	Day	Night	
Male	17	20	37
Female	19	18	37
Total	36	38	74

Participants were required to possess a valid driver's license, a US citizenship (or green card), and drive at least twice per week. Visual health related screening factors included that participants must have normal or corrected to normal vision, have the ability to drive without sunglasses or darkened lenses, not be sensitive to bright lights, and have no history of eye surgery. Because the experiment had a deceptive element, participants were required to not have experienced any previous surprise or deception study at VTTI. A complete list of health, vehicular incident, and criminal history related screening criteria can be found in Appendix A: Participant Screening Criteria.

3.4 Variables and Controls

This experiment consisted of two parts: a dynamic task and a static task. In the dynamic task, participants drove past the experimental vehicle and their naïve reactions to the hazard lights were examined. As they drove, participants were intentionally distracted by a task where they attended to the center stack radio display. In the static task, participants observed the hazard lights from a stationary position and provided subjective feedback about each configuration. Each task, explained in detail in Section 4 of this report, used different independent and dependent variables.

3.4.1 Dynamic Task

Several variables were manipulated during the dynamic task. These included the hazard light configuration, the activation distance, and the time of day. These independent variables are described below.

3.4.1.1 Independent Variables

Hazard Light Configuration (7 levels: Listed below): Seven different hazard light configurations were used during the dynamic task. These included the six test configurations, and the default hazard lights which acted as the baseline. They were as follows:

- 4Hz Compliant
- 5Hz Compliant
- 6Hz Compliant
- 5Hz+Beacon (5Hz Compliant plus external flashing beacon)
- 5Hz+CHMSL (5Hz Compliant plus flashing CHMSL light)
- 5Hz+Reverse (5Hz Compliant plus flashing reverse lights)
- Default Hazards (Stock hazard lights on the experimental vehicle)

Note that the term “Compliant” here is used to indicate that no additional light sources were included in the configuration, and ignores the fact that 4, 5, and 6 Hz flash frequencies are not truly compliant. Figure 8 through Figure 11 illustrate the locations of the various light sources on the experimental vehicle.

Figure 8. Photo of the 4, 5, and 6Hz "Compliant" hazard light configuration.

Figure 9. Photo of the "5Hz+CHMSL" hazard light configuration.

Figure 10. Photo of the "5Hz+Reverse" hazard light configuration.

Figure 11. Photo of the "5Hz+Beacon" hazard light configuration.

Hazard light configuration was a between-subjects variable, meaning that an individual participant only saw a subset of the factor levels. All participants observed the Default Hazard configuration and one of the test configurations.

Distance (2 levels: 200ft, 600ft): The distance variable refers to the distance between the participant vehicle and the experimental vehicle when the hazard lights were activated. Two distances were used to examine if the viewing angle or proximity of the experimental vehicle would have an impact on the hazard lights' ability to draw the attention of the participant. The 200ft factor level was chosen as a worst-case scenario, in which a distracted driver could potentially still have time to stop if alerted by the hazard lights (i.e., the distance to the vehicle does not exceed safe stopping distance). The 600ft factor level was used to examine the effects of the hazard lights from a greater distance.

Because the hazard lights needed to be activated manually and had to also be timed to coincide with the start of the participant's distraction task, there was a range of variability involved in both the signal sent by the in-vehicle experimenter to the experimental vehicle operator, and the experimental vehicle operator's manual activation of the hazard lights. This resulted a range of activation distances. For this reason, results of the experiment will be discussed in terms of time rather than distance.

Distance was a within-subjects variable, meaning that all participants saw the hazard lights activated at both distances for every hazard light they observed.

Time of Day (2 levels: Day, Night): Because ambient light conditions can have a large impact on the visual search patterns and the perception of hazard lights, and hazard lights need to be effective in all conditions, the study was conducted both during the day and at night. Daytime sessions were conducted between the hours of 9:00 AM and 4:30 PM, and twilight (sunrise and sunset) conditions were avoided. Nighttime sessions were conducted between the hours of 5:30 PM and 11:00 PM during January and February when sunset was approximately 5:00 PM.

Time of day was a between-subjects variable, meaning that an individual participant performed the study during the day or at night, but not both.

Attention Level (2 levels: Less, More): Participants were divided into two groups based on their relative attention behaviors. To achieve the attention classification, during data processing, the number of times a participant looked up from the center stack radio display during the distraction task was recorded during tasks that did not involve passing the experimental vehicle. Without the presence of the experimental vehicle on the shoulder, a truer representation of attentive behavior could be ascertained. The median was chosen as the measure of central tendency because it is robust with respect to outliers. The overall median number of lookups was found to be 3. Each participant was then classified by comparing the average number of times they looked up from the center stack radio display during the distraction task involving the experimental vehicle against the overall median. Participants whose average number of look ups from the center stack radio display was less than 3 were classified as less attentive and those who averaged more than 3 look ups were classified as more attentive.

3.4.1.2 Control Variables

Speed: The speed of travel was controlled across all participants. Because participants were engaging in distracting tasks while driving past another vehicle, for safety, the speed limit for the study was set at 35 MPH. Participants were instructed to maintain a speed as close to 35 MPH as possible, and the in-vehicle experimenter would remind them to check their speed if they began to drive too slow or too fast.

Experimental Vehicle Location: The location of the experimental vehicle was kept the same across all participants. This ensured that the area around and behind the vehicle appeared identical for all participants.

Weather and Road Conditions: The study was only conducted in clear weather conditions with dry pavement and no snow accumulation adjacent to the roadway. Poor weather, wet pavement, and white snow adjacent to the experimental vehicle were avoided as these may have impacted the visibility and/or perception of the hazard light configurations.

3.4.1.3 Dependent Variables

Distraction Time: To assess the ability of the hazard lights to draw the attention of the distracted driver, the amount of time that it took for the participant to look up at the hazard lights after they were activated was measured. The amount of time that the driver continued to be distracted after the hazard lights were activated was called the distraction time.

Number of Glances: The number of upward glances that participants made during all distraction tasks, even during trials not involving the experimental vehicle, was tracked.

3.4.2 Static Tasks

For the static tasks, only the hazard light configuration and time of day were manipulated. All static tasks were conducted at both day and night similar to the dynamic task described above. The ratings and comparison subtasks both used the same seven hazard light configurations as the dynamic task as well. However, hazard light configuration was a between-subjects variable for the comparison task. A third static subtask tabbed the confusion subtask, assessed the hazard lighting system's likelihood of being confused with a light bar on an emergency vehicle. This was the only task to use different light configurations. This independent variable is described below.

3.4.2.1 Independent Variables

Hazard Light Configuration (7 levels: Listed below): Seven different hazard light configurations were used during the rating and comparison subtasks. These included the six test configurations, and the default hazard lights which acted as the baseline. They were as follows:

- 4Hz Compliant
- 5Hz Compliant
- 6Hz Compliant
- 5Hz+Beacon (5Hz Compliant plus external flashing beacon)
- 5Hz+CHMSL (5Hz Compliant plus flashing CHMSL light)
- 5Hz+Reverse (5Hz Compliant plus flashing reverse lights)
- Default Hazards (Stock hazard lights on the experimental vehicle)

Hazard light configuration was a within-subjects variable for the rating subtask, but a between-subjects variable for the comparison subtask. For the comparison subtask, the configurations were divided into two groups called the frequency cohort and the volume cohort. The frequency cohort included the default hazards and the 4, 5, and 6 Hz Compliant configurations. These were compared against each other to determine how participants perceived hazard lights strictly based on differences in frequency. The volume cohort included the 5Hz Compliant, 5Hz+Beacon, 5Hz+CHMSL, and the 5Hz+Reverse configurations. These configurations all used the same frequency and were compared against each other to determine how participants perceived hazard lights strictly based on differences in the number and types of light sources that were included in the configuration.

Warning Light Configuration (3 levels: Hazard Light, Emergency Light, Hazard and Emergency Light Combination): The confusion subtask utilized three light configurations. They were as follows:

- Hazard Light (5Hz Compliant)
- Emergency Light (An all-red lightbar mounted atop the vehicle)

- Hazard and Emergency Light Combination (5Hz Compliant and all-red lightbar in conjunction).

Warning light configuration was a within-subjects variable, meaning that all participants who took part in the confusion task observed all three configurations.

3.4.2.2 Control Variables

Distance: The distance at which participants observed the experimental vehicle during the static tasks was constant across all participants. For the ratings and comparison subtasks, this distance was 200ft. For the confusion subtask, this distance was approximately 3,200ft.

The experimental vehicle location, weather, and road conditions were similarly controlled for the static tasks as they were for the dynamic task.

3.4.2.3 Dependent Variables

Discomfort Rating: A subjective rating of the amount of discomfort participants experienced due to the glare of the hazard lights. Discomfort was rated using a 5-point Likert-type scale in which a rating of 1 meant there was “no discomfort” and a rating of 5 meant there was “high discomfort”.

Annoyance Rating: A subjective rating of the level of annoyance participants experienced due to the hazard lights. Annoyance was rated using a 5-point Likert-type scale in which a rating of 1 meant there was “no annoyance” and a rating of 5 meant there was “high annoyance”.

Urgency Rating: A subjective rating of the sense of urgency conveyed by the hazard lights. Urgency was rated using a 5-point Likert-type scale in which a rating of 1 meant there was “no urgency” and a rating of 5 meant there was “high urgency”.

Preference: An indication of which hazard light configuration a participant preferred when given two options.

Safety: An indication of which hazard light configuration a participant considered safer when given two options.

Confusion Factor: The rate at which participants were able to correctly identify a warning light configuration during the confusion subtask.

3.4.3 Summary

Table 3 shows a summary of the independent and dependent variables for each task and subtask. Cells highlighted in yellow indicate between-subjects variables in which an individual participant observed a subset of the factor levels.

Table 3. Summary of independent and dependent variables by task.

Variables	Dynamic Task	Static Tasks		
		Rating Task	Comparison Task	Confusion Task
Lighting Configuration	Default Hazards 4Hz Compliant 5Hz Compliant 6Hz Compliant 5Hz+Beacon 5Hz+CHMSL 5Hz+Reverse	Default Hazards 4Hz Compliant 5Hz Compliant 6Hz Compliant 5Hz+Beacon 5Hz+CHMSL 5Hz+Reverse	Default Hazards 4Hz Compliant 5Hz Compliant 6Hz Compliant 5Hz+Beacon 5Hz+CHMSL 5Hz+Reverse	5Hz Compliant Red Lightbar Combination
Distance	200ft 600ft	200ft	200ft	3,200ft
Time of Day	Day Night	Day Night	Day Night	Day Night
Dependent Variables	Distraction Time Number of Glances	Discomfort Rating Annoyance Rating Urgency Rating	Preference Safety	Confusion Factor

4 PROCEDURE

4.1 Screening, Setup

Participants were initially screened over the phone using the criteria found in Appendix A. Those that were eligible to participate were scheduled for an experimental session. Upon arrival, participants were consented and completed a vision screening. Participants were required to have a minimum acuity of 20/40 vision using both eyes, the minimum legal requirement for driving in Virginia.

4.2 Dynamic Task

In order to capture participants' naïve reaction to the experimental hazard lights, deception was used for the dynamic task. Participants were initially told that they would be taking part in a distracted driving study. Participants were told that their task for the study would involve operating the radio using the center stack control dial while driving. The participant vehicle's center stack control system is shown in Figure 12. The radio stations are indicated in the center of the display screen and participants were instructed to tune the station using the tuning knob in the middle-right of the photo.

Figure 12: 2017 Ford Explorer center stack controls and radio display

Participants were not informed of the experimental vehicle (Tesla Model 3) or the hazard lighting system before the dynamic portion of the experiment. Participants were briefed prior to the dynamic task that other VTTI vehicles would be on the road for maintenance and various activities, but that they would remain stationary on the side of the road. Figure 13 shows the positioning and orientation of the participant vehicle (in the travel lane) and the experimental vehicle (Tesla Model 3 with alternative hazard lighting system) positioned on the right shoulder and one car width from the travel lane.

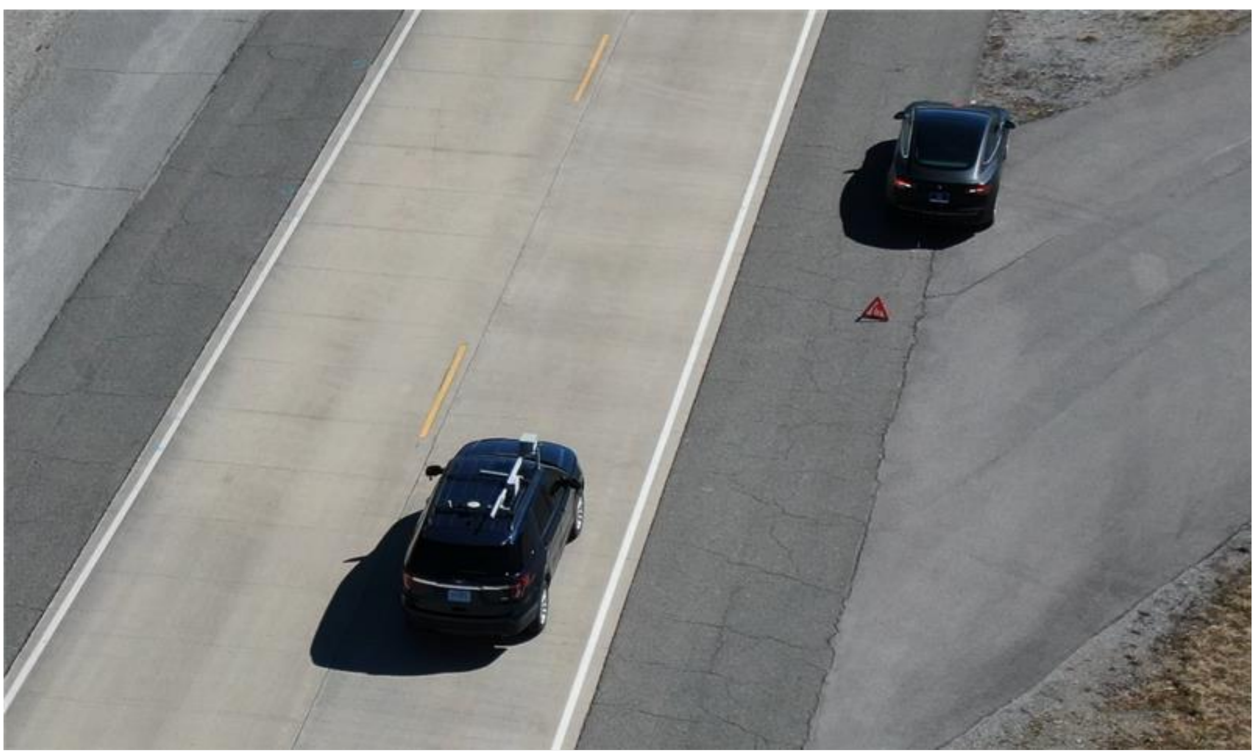


Figure 13: Participant vehicle approaching experimental vehicle stopped on shoulder ahead with beacon deployed

In addition to the experimental vehicle, a pickup truck was also parked on the shoulder of the road approximately one-half mile upstream of the experimental vehicle. The pickup truck's hazard lights were activated for the entirety of the study, and an experimenter near the truck pretended to perform maintenance along the side of the Smart Road to further embed the deception that these vehicles were involved in maintenance activities, and not part of the study.

Participants were presented with distraction tasks as they approached the experimental vehicle. They were instructed to change the vehicle's radio station just before the experimental vehicle activated its hazard lights. There was no volume for the radio during the tasks. Participants were informed of the specific station before each lap began. The events were triggered when the participant vehicle was either 200 or 600 ft away from the experimental vehicle.

Participants completed a total of five laps around the test course. A lap consisted of driving "down" the road in the lane nearest the experimental vehicle, and then driving back "up" the road in the far lane. The first lap was considered a "practice" lap to acclimate participants to the vehicle, and the route they would be driving on the test track. The participant was also given a practice distraction task to ensure that they understood how to complete a task. During this lap, the experimental vehicle only had its park lights activated and the practice distraction task was performed on the way back up the road, away from the experimental vehicle. For each remaining lap, the participant was tasked with performing a distraction task in both the "down" and "up" directions, and the hazard lights on the experimental vehicle were activated just as each task began whenever the participant vehicle was in the nearest lane (i.e., the "down" direction). This was to ensure that the participant was looking down at the radio when the hazard lights were activated so that the time it took for the participant to look up at the hazard lights (i.e., how well the hazard lights grabbed their attention) could be measured. For the second and third laps, the default hazard light pattern was used. For the fourth and fifth laps, one of the experimental hazard light configurations was used. An example of conditions a participant may experience in the study are shown in Table 4. The "distance" listed for each lap was how far away, in feet, the participant vehicle was from the experimental vehicle when the hazard lights were triggered. The "condition" was the type of lighting presented. The "preset" was the starting radio frequency and "task" was the station that participants were instructed to change to.

Table 4: Sample Lap Order with Lighting Presentations and Distraction Tasks

Lap	Direction	Distance (ft.)	Condition	Preset	Task
1	Down		Parking Lights		
	Up		Parking Lights	94.9	102.1
2	Down	200	Default Hazards	102.1	96.7
	Up		Parking Lights	96.7	89.1
3	Down	600	Default Hazards	89.1	96.3
	Up		Parking Lights	96.3	105.3
4	Down	200	4Hz Compliant	105.3	99.1
	Up		Parking Lights	99.1	102.3
5	Down	600	4Hz Compliant	102.3	94.9
	Up		Parking Lights		

The same hazard light configuration was shown at different distances during laps 4 and 5, meaning each participant only saw one of the six experimental hazard light configurations. Because there were six hazard light configurations and two distances, twelve presentation orders were created to balance the presentation of the experimental configurations across all participants. Twelve participants were assigned to each of the twelve orders. Because two sessions had to be ended early, two additional participants were recruited for a total of 74 participants.

4.3 Static Tasks

The static portion consisted of three subtasks: a ratings task, a comparison task, and a confusion task. These evaluations took place immediately following the dynamic portion of the study after participants were debriefed about the use of deception and provided consent to continue. Every participant who completed the dynamic task agreed to continue the study and completed the static task. To begin the static tasks, the participant was instructed to park the participant vehicle in the driving lane 200 feet behind the experimental vehicle. Each of the static tasks were performed from this position and are described in detail below.

4.3.1 Ratings Subtask

Participants were presented with one of the seven hazard light configurations (i.e., the six experimental configurations as well as the default hazard light pattern). While observing the hazard light, the in-vehicle experimenter asked the participant to rate their levels of visual discomfort due to glare, the annoyance they experienced, and the level of urgency conveyed by the hazard light using a 5-point Likert-type scale. A sample of the survey questions administered to participants is shown in Figure 14.

1) On a scale from 1 to 5 where 1 is "no discomfort" and 5 is "high discomfort", how would you rate the amount of discomfort you are experiencing due to the glare from the hazard lights?

1	2	3	4	5
No discomfort				High Discomfort

2) On a scale from 1 to 5 where 1 is "no annoyance" and 5 is "high annoyance", how would you rate the level of annoyance you are currently experiencing due to the hazard lights?

1	2	3	4	5
No annoyance				High Annoyance

3) On a scale from 1 to 5 where 1 is "no urgency" and 5 is "high urgency", how would you rate the urgency being conveyed by the hazard lights?

1	2	3	4	5
No urgency				High Urgency

Figure 14: Sample of Survey Administered during Ratings Subtask

In addition, they were asked for their impressions about the hazard light, and how they would react if they happened upon a vehicle with the lighting pattern they were experiencing. For example, would they merge behind the vehicle, slow down, or merge away from the vehicle. This was repeated until the participant had observed all seven configurations. The presentation of the lights was balanced across twelve orders. The full survey administered to participants during the ratings subtask is located in Appendix B: Static Survey Sample Sheet.

4.3.2 Comparison Subtask

With the participant and experimental vehicles parked in the same position, participants were then tasked with comparing the configurations to each other. To assess participants' opinions of the various flash frequencies, the frequency cohort used only the "compliant" configuration in which the two taillights flashed. This ensured that the only difference among the lights was the frequency. Each of the configurations within the frequency cohort were compared against the others. To assess participants' opinions of additional light sources being used within the hazard light configuration, the volume cohort used the same frequency (5Hz) across each configuration, and only the light sources changed (i.e., the addition of the CHMSL, reverse lights, or an external beacon). For both cohorts, different presentation orders were used to balance the order in which participants saw each configuration (i.e., some participants saw a particular configuration first, while others saw it second). Six pairs were presented to participants for approximately 5 seconds each. After each pair were presented, participants were asked three questions and their answers were audio recorded and later transcribed for analysis. The questions included:

1. Which configuration did you prefer?

2. What differences did you observe between these two configurations?
3. Which configuration would make you feel safer if it were used on your own vehicle?

4.3.3 Confusion Subtask

Forty-seven of the 74 participants took part in an extra experiment to evaluate if any potential confusion existed between the ESS HELP system and an all-red emergency light bar. The experimental vehicle was placed 3,174 ft (or approximately 0.6 miles) away, straight ahead and in the same lane as the participant vehicle. Due to the topography of the area, the experimental vehicle was placed downhill but on a consistent slope with the participant vehicle. A Whelen Liberty II light bar, a market available light bar commonly used by police agencies, was placed on top of the vehicle to simulate emergency lighting. The light bar was modified to include all red flashing LEDs to increase the likelihood of confusion between the hazard lighting system and the light bar. The light bar placed on the roof of the experimental vehicle is shown in Figure 15. Participants were asked to determine which of 3 lighting conditions were active.

1) Hazard lights
2) Emergency light bar
3) Hazard lights and emergency light bar simultaneously active

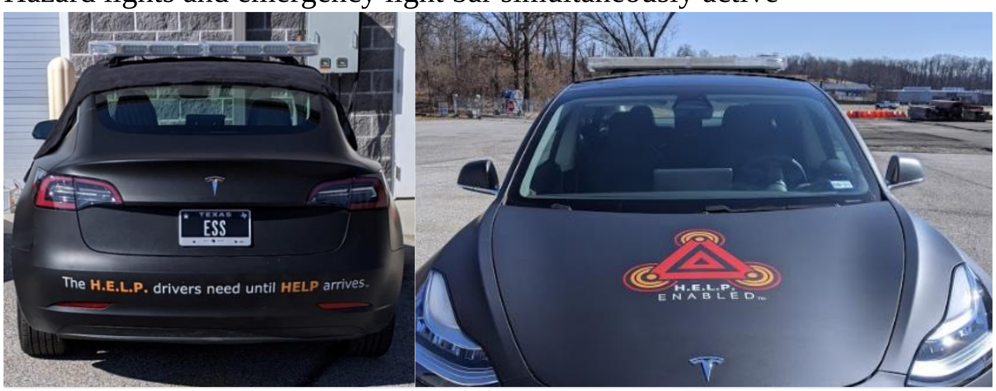


Figure 15: Emergency Light Bar on Roof of Experimental Vehicle

5 DATA ANALYSIS

Each of the tasks were analyzed differently. Each approach is described below.

5.1 Dynamic Task

To determine how well each hazard light configuration was able to grab the attention of the participants, the amount of time it took for distracted participants to redirect their attention forward and at the hazard lights once they were activated was analyzed. This variable is referred to as "distraction time". A researcher reviewed the video recorded inside the participant vehicle and marked the time, to the nearest millisecond, when the hazard lights were first activated, and the time when the participant glanced up from the center stack radio display.

The effect of experimental conditions such as distance, time of day, attention level, and hazard light configuration were investigated for their relationship to both response measures. The level of significance was established at $p < 0.05$ for all statistical tests. Three separate Linear Mixed Modeling (LMM) analyses were conducted to assess the conspicuity of the hazard light conditions. Overall, the data from 69 participants was used for the dynamic analyses. The full data set included 36 daytime and 33 nighttime sessions. A total of 5 participants data were excluded due to inclement weather impacting lighting conditions and participant dismissal due to an inability to perform the tasks. Participants who looked at the experimental vehicle as the hazard lights turned on did not produce a response measure related to the condition presented and those data points were removed.

5.2 Static Tasks

The following section details the data analysis and statistical modeling methods, data reduction methods, and number of complete data points.

5.2.1 Rating Task

For the rating subtask, participant ratings were compared across all hazard light configurations for both day and night sessions. The level of significance was established at $p < 0.05$ for all statistical tests. Performance was assessed using a Linear Mixed Modeling (LMM) procedure evaluating average rating for each configuration. Data from 73 participants was used for the ratings task analyses. Thirty-six participants completed their session during the day and 37 participants ran at night. One experimental session was not included in the analysis due to equipment failure.

5.2.2 Comparison Task

The number of times that participants selected one of the hazard light configurations as their “preferred” or “safer” configuration was counted and descriptive statistics were used to describe how each configuration performed compared to the others. In total the data from 72 participants was used for the comparison analysis. Thirty-five participants completed the task during the day and 37 participants at night. Two daytime sessions were unable to be recorded due to inclement weather.

5.2.3 Transcription of Verbal Feedback

In addition to providing ratings and selecting a preferred configuration, participants were also asked more open-ended questions and sometimes provided general feedback that could not be easily quantified. To analyze this data, participants’ verbal responses were transcribed using a “Near Verbatim” approach, and a content analysis was performed. Near Verbatim primarily cleans up false starts and sentence fillers such as “umms”, “ahs”, “like, you knows”, etc. An example is shown below:

> Verbatim (Don’t do this):
>
> P1: Well, I ah usually… I mostly just try not to drive after ten pm, you know? But, like, sometimes… Well, sometimes you don’t really have a choice. Ummm… When that happens, I… I guess I just try to find something to keep me awake.
>
> Near Verbatim (Do this):

> P1: Well, I mostly just try not to drive after 10pm. But, sometimes you don't really have a choice. When that happens, I guess I just try to find something to keep me awake.

A data reductionist reviewed the audio and video recorded inside the vehicle and transcribed the participant's responses into a spreadsheet which included other data such as whether the participant viewed the hazard lights during the day or at night and the hazard light configuration they were observing, among others. Responses were transcribed for each of the following questions:

- Rating Task
  - Do you have any other impressions of the current hazard light pattern?
  - How do you think you would react if you happened upon a vehicle with this hazard light pattern while you were driving?
- Comparison Task
  - Which configuration did you prefer?
  - What differences did you observe between these two configurations?
  - Which configuration would make you feel safer if it were used on your own vehicle?

Occasionally, participants also provided unprompted feedback about the hazard light patterns. These were also transcribed as "Miscellaneous" comments. While some participants were eager to provide detailed answers, others would provide simple answers without further explanation. In some cases, participants did not provide any response.

5.2.3.1 Content Analysis

After participant's verbal responses and feedback were transcribed, researchers began a content analysis to identify common themes and key phrases used in response to the various hazard lighting configurations. Researchers reviewed the transcripts to become familiar with key themes and subthemes. The initial themes and subthemes closely followed the prompts provided by experimenters. Themes and subthemes were then arranged in a logical order with individual spreadsheets, with the spreadsheet tabs serving as an index.

Responses were coded by theme and subtheme and grouped according to emerging patterns or categories. The indexed comments were arranged into task-specific Microsoft Excel® workbooks, and individual spreadsheets (or thematic charts). These spreadsheets/thematic charts were then further sorted by subtheme (i.e., question or follow-up question) and secondary subthemes. Finally, categories of similar ideas were created based on the subthemes. Once sorted, the secondary subthemes and categorical responses were aggregated and are reported using descriptive statistics.

5.2.4 Confusion Task

Responses to the confusion task were tracked as correct or incorrect, and descriptive statistics were used to show how often participants were able to correctly identify the light source as a hazard light, an emergency light, or both an emergency light and hazard light together. The rate that participants correctly identified the light type was evaluated using a Mixed Effects Logistic

Regression procedure. The level of significance was established at $p < 0.05$ for all statistical tests. The correct identification rate was assessed for all light types, both day and night. Data from 47 participants were used in the confusion analyses. In total 21 daytime and 26 nighttime participants completed the confusion task. This task has a smaller sample size due to time constraints during experimental sessions. Once a large enough sample size was gathered the confusion task was skipped in favor of shortening the time each participant spent at VTTI.

6 RESULTS

The following section provides results from each of the experiments and provides detail and explanation to those figures.

6.1 Dynamic Task

Data analyses did not yield statistically significant results for the dynamic task and therefore the confidence necessary for declaring that any of the configurations yielded more favorable results than the default hazard configuration is removed. However, notable trends in the data did emerge and are detailed below. An increased number of repetitions would reduce the variance of each data point and could indicate significant differences. These results are described as practical differences in terms of time and distance as applied to real-world driving scenarios.

6.1.1 Distraction Time

A Linear Mixed Model (LMM) was fit to the data to investigate the interaction between hazard light configuration, time of day, and distraction time. Subject to subject variability was accounted for by including the participant's assigned number as a random effect in the model. The results of the LMM are shown in Table 5. There was no statistical significance found for the three-way interaction between main effects of the hazard light condition, time, and distance. Significance was found for the two-way interaction between the time of day and hazard light configuration when testing for the overall effect of the interaction on distraction time. Follow up analyses focused on the relationship between the hazard light configuration and the time of day. Pos-Hoc analyses were conducted using a differences of least square means procedure.

Table 5: Test of Fixed Effects for full factorial three-way model using condition, time, and distance as main effects and participant as a random effect.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Condition	6	190	1.47	0.1914
Distance	1	143	0.01	0.9248
Condition*Distance	6	143	0.70	0.6533
Time	1	98.2	0.07	0.7936
Condition*Time	6	190	2.36	0.0322

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Time*Distance	1	143	0.09	0.7667
Condition*Time*Distance	6	143	0.74	0.6206

Figure 16 illustrates the relationship between each hazard light configuration and the distraction time of participants (measured in seconds) across both day and night combined. There were no significant differences found between the hazard configurations and the time of day when using Tukey's Honest Significant Difference (HSD) test to compare specific group means. Tukey's HSD accounts for multiple comparisons to reduce instances of Type 1 errors (false positives) and suggests that, at the current sample size, there are no significant differences between treatment combination means. Further analysis looked into the presence of practical differences between the hazard light conditions.

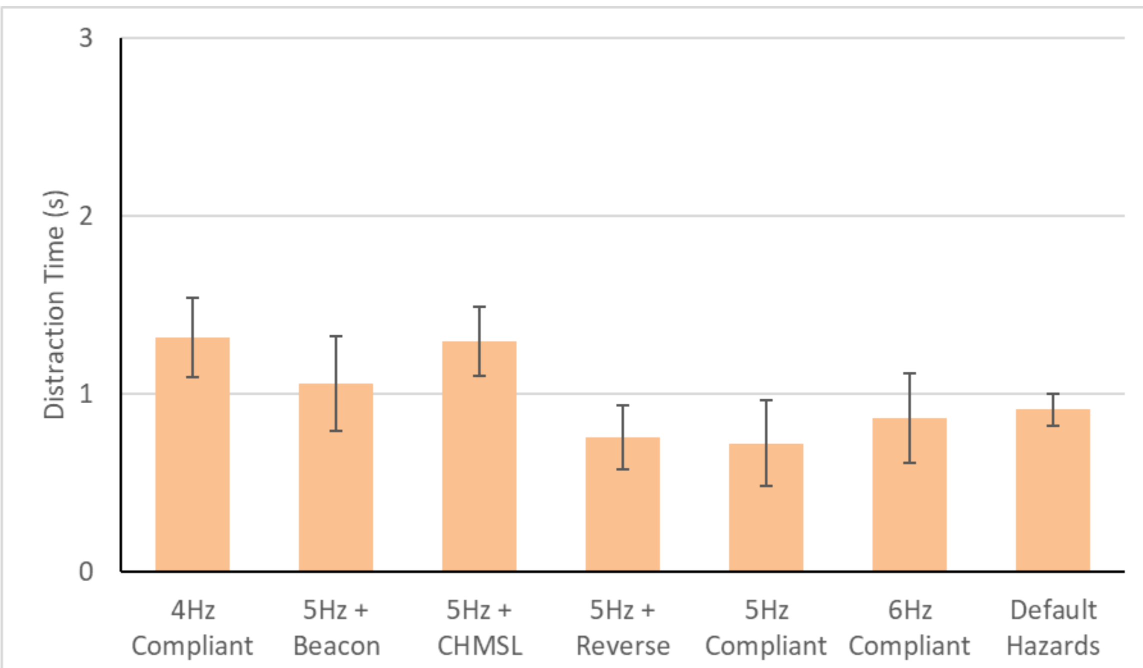


Figure 16: Duration drivers were distracted in seconds approaching each configuration. Values denote least square means and error bars denote standard errors.

A practical difference was observed when comparing the different configurations to the default hazard configuration. Distraction time was found to be the shortest for the 5Hz Compliant and 5Hz+Reverse hazard light configurations. Figure 17 shows that, when compared to the default hazard light configuration, participants spent 20.7% less time distracted when the experimental vehicle activated the 5Hz Compliant condition. This difference was not found to be statistically significant and amounts to a reduction in distraction time of 0.1884 seconds or 17.9 feet when traveling at 65 mph. When compared to the default hazard lights participants who saw the 5Hz+Reverse configuration spent 17.2% (0.16 seconds) less time distracted.

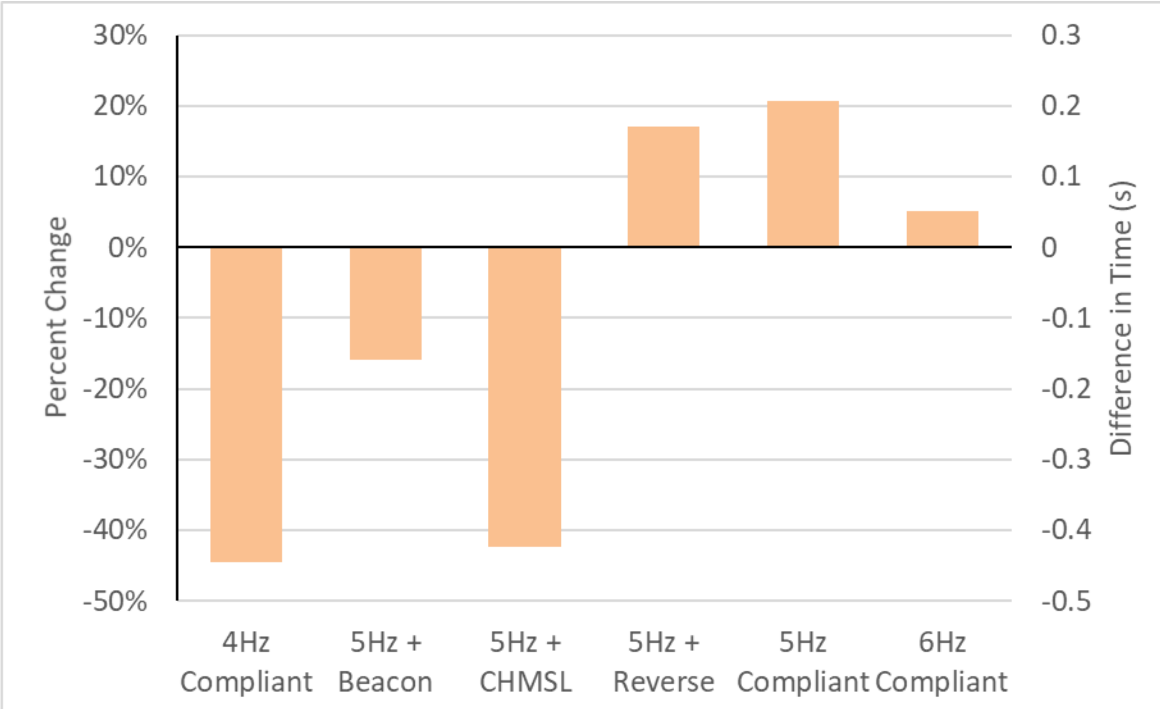


Figure 17: Degree of change from default hazard configuration (positive values show benefit)

Table 6 shows a comparison of the estimated distance that a distracted driver would travel before being alerted by the hazard lights for various travel speeds. Configurations which resulted in distraction distances shorter than the default hazards are highlighted in green.

Table 6: Estimated distance traveled before each hazard light configuration would draw the attention of a distracted driver by travel speed (mph)

Hazard Light Configuration	Mean Distraction Time (s)	Distracted Distance (ft)					
		25mph	35mph	45mph	55mph	65mph	75mph
Default Hazards	0.91	33	47	60	74	87	100
4Hz Compliant	1.31	48	68	87	106	126	145
5Hz Compliant	0.72	27	37	48	58	69	80
6Hz Compliant	0.86	32	44	57	70	82	95
5Hz+Beacon	1.05	39	54	70	85	101	116
5Hz+CHMSL	1.29	48	67	86	105	124	143
5Hz+Reverse	0.75	28	39	50	61	72	83

The interaction between the time of day and hazard light configuration was investigated using a difference of least square means procedure. Figure 18 displays the distraction times for all hazard light configurations for day and night. An overall trend of lower distraction times was observed for the nighttime conditions when compared to daytime across all hazard light types. This trend was reversed for the 4Hz compliant configuration but with further replication the distraction time is expected to mirror the other conditions. No statistically significant differences were found between the time of day and hazard light configuration combinations.

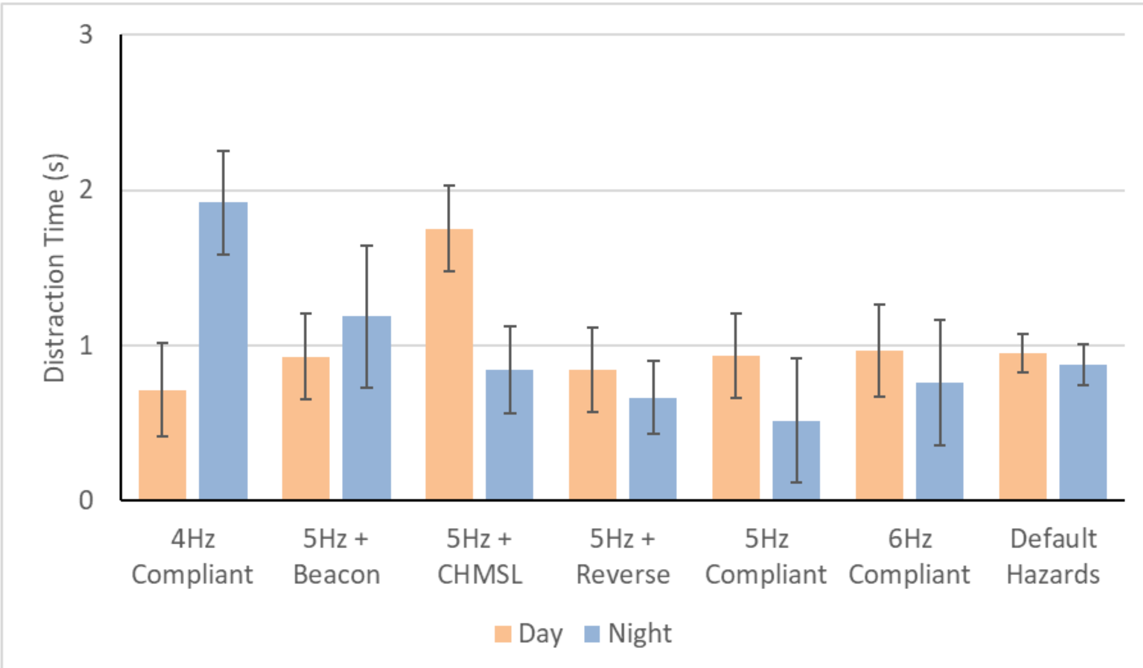


Figure 18: Duration of distraction in seconds for each configuration split by day and night (shorter bars are favorable). Values denote least square means and error bars denote standard errors.

Practical differences were observed between combinations of hazard light type and time of day. These differences are illustrated by comparing each factor combination to the default hazard condition as shown in Figure 19. Participants showed a decrease in distraction time of 41.0% for the 5Hz Compliant configuration when compared to the default hazard light condition at night. A 41.0% reduction in distraction time represents a 36.72 ft decrease in distance traveled while distracted when traveling at highway speeds (70 mph). A practical difference was also observed between the 5Hz+Reverse condition when compared to the default hazard configuration at night. participants were distracted for 23.9% less time when the 5Hz+Reverse lights were activated. When traveling at highway speeds a 23.9% reduction in distraction time would result in a reduction in distracted travel of 21.40 ft. Table shows the estimated distance a distracted driver would travel before being alerted by each hazard light at night. Distances which are shorter than those of the default hazards are highlighted in green. At 75mph, the estimated distraction distance for the 5Hz Compliant was 57ft, compared to 96ft for the default hazards.

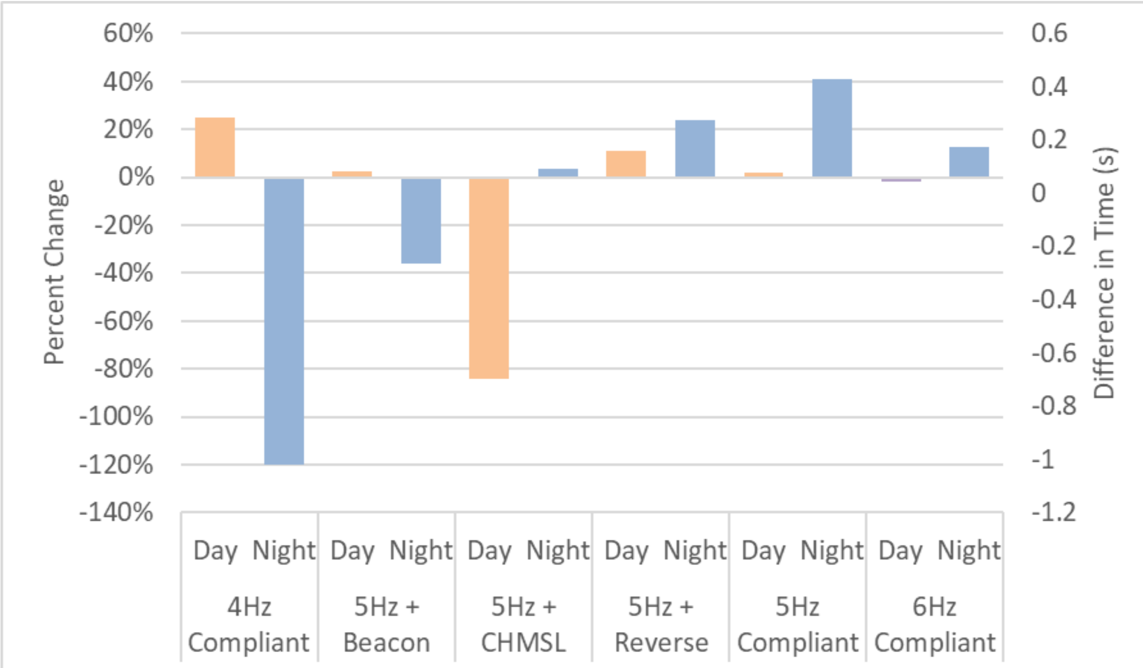


Figure 19: Degree of change from default hazard configuration across day and night (positive values show benefit)

Table 7. Estimated distance traveled before each hazard light configuration would draw the attention of a distracted driver at night by travel speed (mph)

Hazard Light Configuration	Mean Distraction Time (s)	Distracted Distance (ft)					
		25mph	35mph	45mph	55mph	65mph	75mph
Night							
Default Hazards	0.8728	32	45	58	70	83	96
4Hz Compliant	1.9192	70	99	127	155	183	211
5Hz Compliant	0.5151	19	26	34	42	49	57
6Hz Compliant	0.7618	28	39	50	61	73	84
5Hz + Beacon	1.1859	43	61	78	96	113	130
5Hz + CHMSL	0.8423	31	43	56	68	80	93
5Hz + Reverse	0.6644	24	34	44	54	63	73

6.1.2 Divided by Attention Level

To examine the interaction between hazard light configuration and attention level a LMM was fit to the data. Subject-to-subject variability was accounted for by including the participant's assigned number as a random effect in the model. LMM results showed that the interaction between hazard light configuration and the attention level of participants approached significance, as shown in Table 10.

Table 8: Test of Fixed Effects for full factorial two-way model using Condition and Attention Level as main effects and Participant as a random effect

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Condition	6	203	0.86	0.5245
Attention Level	1	107	2.44	0.1215
Condition*Attention Level	6	203	2.07	0.0585

Post-Hoc analysis focused on the practical effect each hazard light configuration had on the distraction time of less attentive participants. Figure 20 shows the distraction time results for participants categorized as less attentive (*n=30)*. Again, the attentional behavior of participants was categorized based on their frequency to naturally look forward during the distraction task even when the experimental hazard lighting vehicle was not present. By evaluating the effects of the hazard configurations on the less attentive group, this data is believed to show distraction time changes due to the hazard lights and less due to natural driving behavior. These results show that the 5Hz+Reverse configuration was responsible for the shortest distraction time for less attentive drivers.

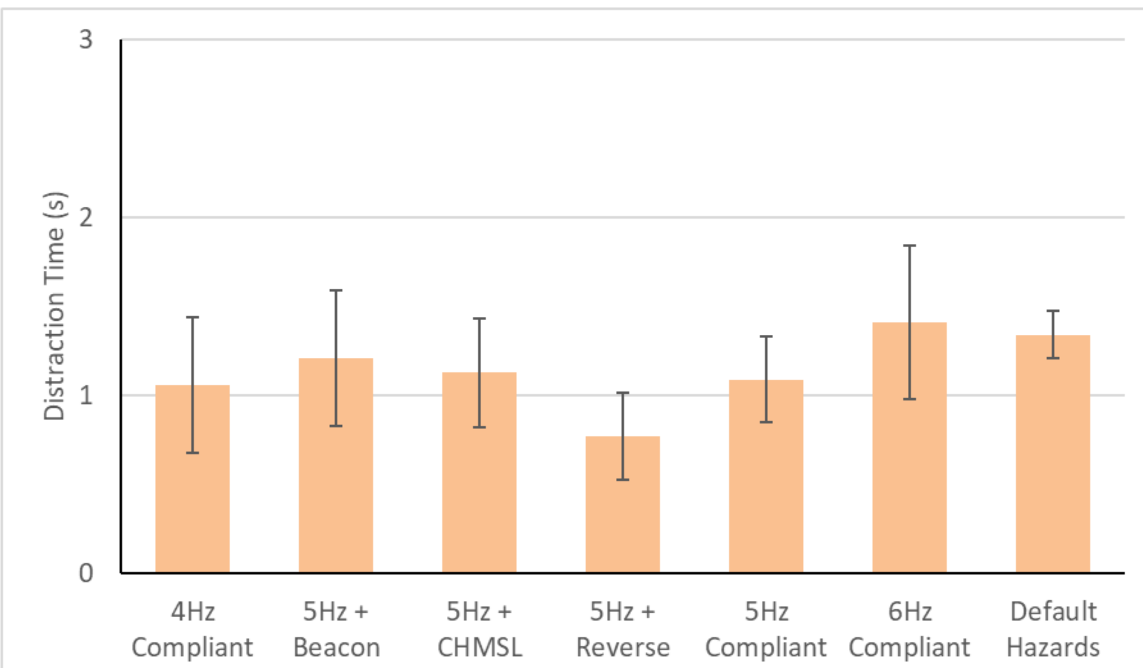


Figure 20: Duration of distraction in seconds for less attentive drivers (shorter bars are favorable). Values denote least square means and error bars denote standard errors.

Figure 21 shows the degree of change in distraction time using the default hazard configuration for less attentive drivers as the reference. The 5Hz+Reverse showed a 40% benefit of over a half-second (47.7 ft at 65 mph). The 6Hz Compliant configuration was the only configuration to not result in a reduction in distraction time when compared to the default hazards.

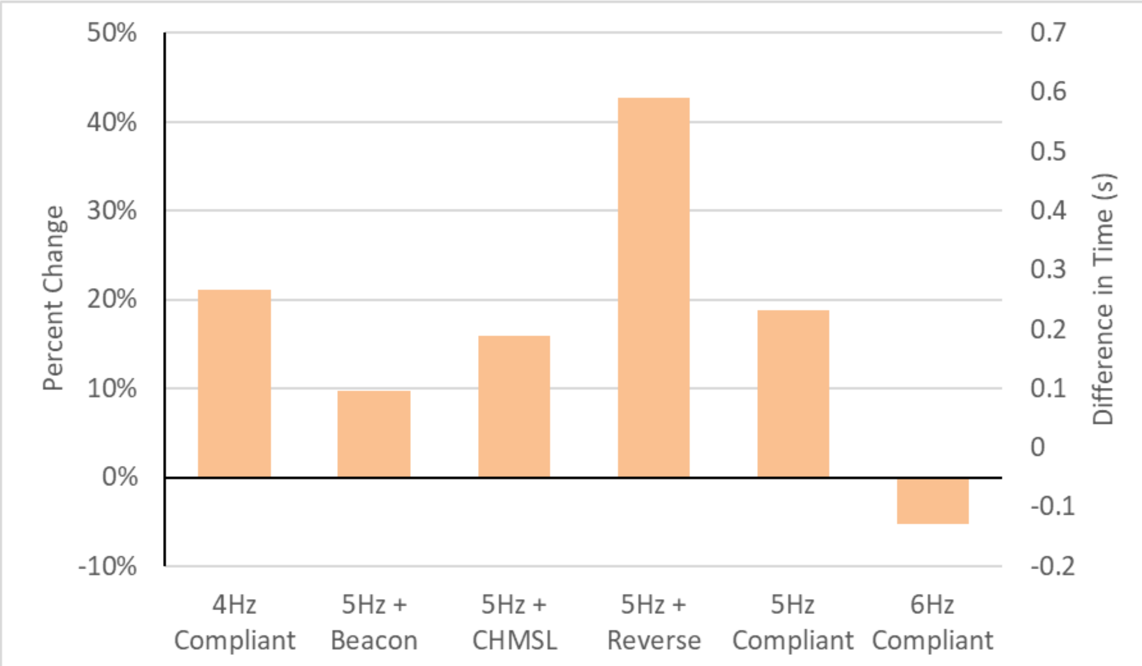


Figure 21: Degree of distraction time difference from default hazard configuration for less attentive drivers

6.1.3 Reaction Time

To explore the interaction between hazard light configuration and time of day on the reaction time of participants a LMM was fit to the data. The data was split into two subsets by the distance from the experimental vehicle that the distraction task was performed at. Subject to subject variability was accounted for by including the participant's assigned number as a random effect in the model. No statistically significant differences in reaction time were observed at either the 200 or 600 ft distances. Reaction times for the 200 ft distance, when reactions to the hazard lighting system would be more urgently required, were over 4 seconds on average. An average reaction time of 4 seconds at 200 ft was determined to be sufficient for drivers to appropriately react, if necessary, at 35 mph. The results of this analysis were not deemed safety critical.

6.2 Static Tasks

Each of the three static tasks were evaluated using a separate methodology. In addition to providing the results from the data collected during those tasks, the ratings and comparison subtasks have content analyzed feedback and selected quotes included.

6.2.1 Ratings

Ratings were evaluated using a five-point Likert-type scale. Figure 22 shows the average rating responses participants assigned each hazard light configuration based on discomfort, annoyance, and urgency.

In general, 5 indicates a high degree of experience and 1, the lowest, indicates no experience (no discomfort, no annoyance, or no urgency). The 5Hz+Beacon generated the highest perception of urgency and the second highest degree of discomfort. The 5hz+Reverse was rated highest for discomfort. 5Hz+Reverse and 5Hz+Beacon were the highest rated for annoyance. The default hazard system was rated lowest for all three factors by a significant margin.

Generally speaking, the research team believes that a desirable configuration would have a low discomfort rating and a high urgency rating. While annoyance is generally considered an undesirable trait for participants, it may provide a benefit for the effectiveness of the hazard light configuration by encouraging drivers to avoid looking at it or potentially merge away from the disabled vehicle. However, this is conjecture and was not part of this project's scope. Using these criteria, the 5Hz+Beacon provided the highest sense of urgency while maintaining a discomfort and annoyance rating that was less than what would be considered "average discomfort" (i.e., a rating of 3).

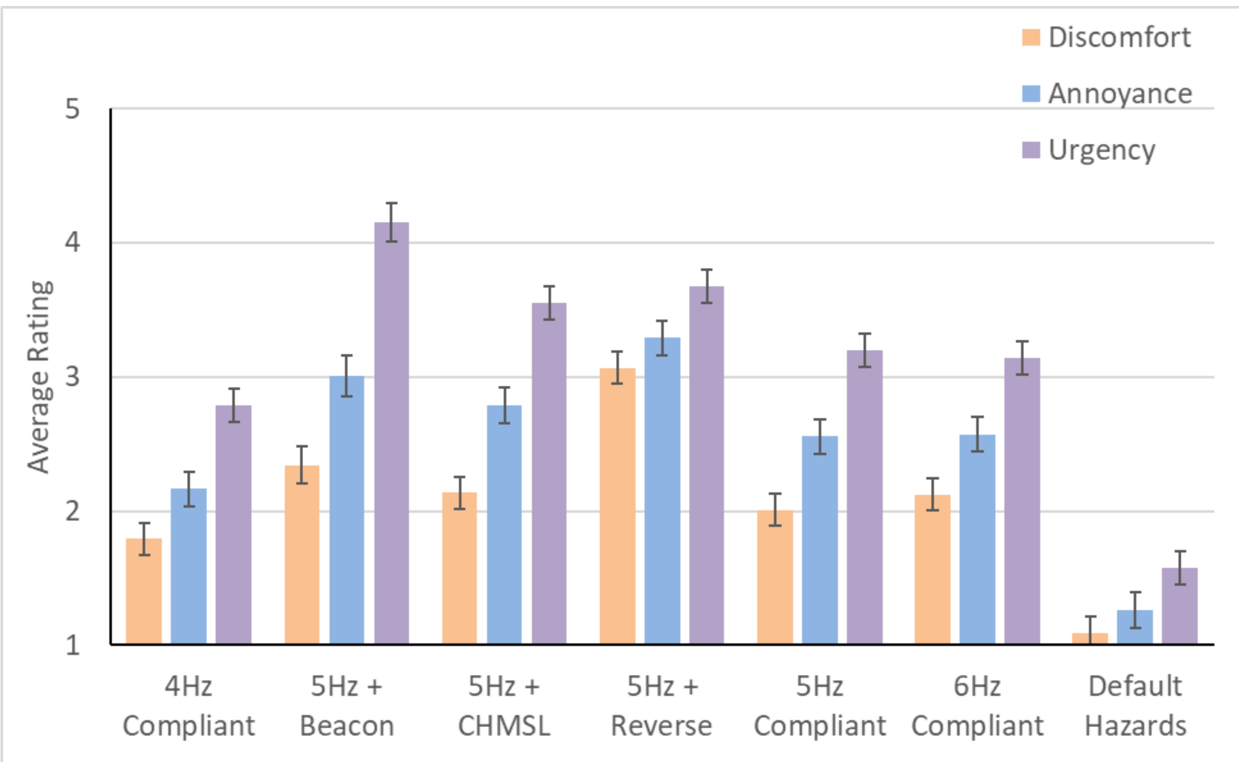


Figure 22: All ratings (discomfort, annoyance, and urgency) by hazard light configuration. Values denote least square means and error bars denote standard errors.

6.2.1.1 Discomfort Rating

To evaluate the effect of hazard light configuration and time of day on the discomfort level due to glare of participants a LMM was fit to the data (Table 6). Subject-to-subject variability was accounted for by including the participant's assigned number as a random effect in the model. Results indicated potential significant differences between the factor levels of condition, time and the interaction between condition and time.

Table 6: Test of Fixed Effects for full factorial two-way model using Condition and Time as main effects and Participant as a random effect

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Condition	6	377	43.78	<.0001
Time	1	71.9	11.42	0.0012
Condition *Time	6	377	3.01	0.0069

Post-Hoc analysis was performed using a difference of least squared means procedure applying Tukey's HSD to account for multiple comparisons. Figure 23 shows the significant differences between the average ratings for discomfort by each hazard lighting configuration. Each single letter above a bar indicates its significance from other single letters. A pair of letters indicates that the bar falls in the range of those two letters and is not significantly different from either.

On its own, the results for the discomfort ratings highlight the significant effect of the 5Hz+Reverse configuration. Its average rating was approximately in the middle of the scale, indicating an overall neutral rating; however, relative to its counterparts it does generate a greater degree of discomfort than other configurations. 5Hz+Beacon and 4Hz Compliant were also significantly different from each other as well as from the default hazards. The default hazard lighting condition generated a discomfort rating approximal to "1" or "No discomfort" which was significantly different than all other hazard light configurations.

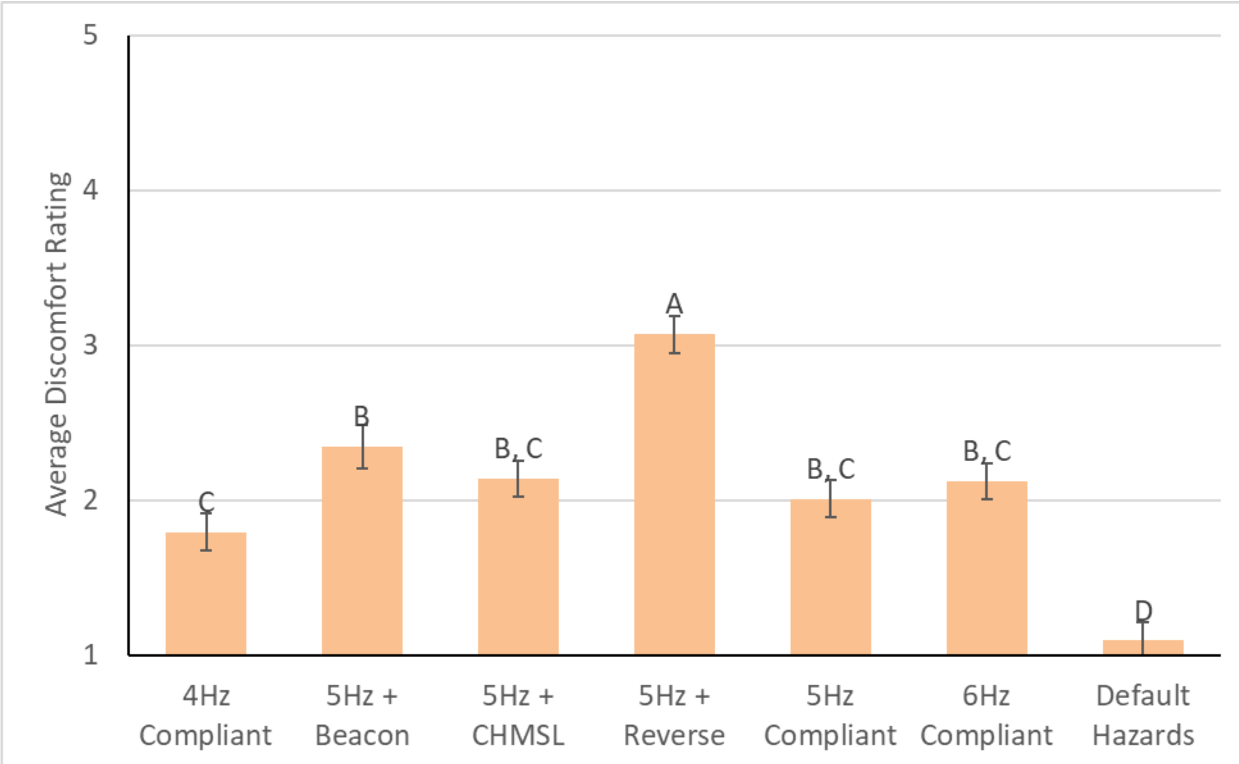


Figure 23: Rating of discomfort by hazard lighting configuration. Upper case letters denote significant differences in post hoc pairwise comparisons ($p < 0.05$). Values denote least square means and error bars denote standard errors.

Figure 24 breaks out the discomfort ratings from Figure 23**Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.** into day and night. As expected, due to lower ambient light levels at night, ratings for experiencing discomfort are higher. Participants experienced increased discomfort at night when exposed to the 5Hz+Reverse configuration (>~3.5), presumably due to the white lights that contain more blue spectrum which can affect brightness perceptions in human eyes. Aside from the default hazard configuration, the other five configurations have similar patterns and are within a consistent range (~1.5 and ~2.5). Once again, the default hazard configuration was rated lowest, day and night, for creating discomfort.

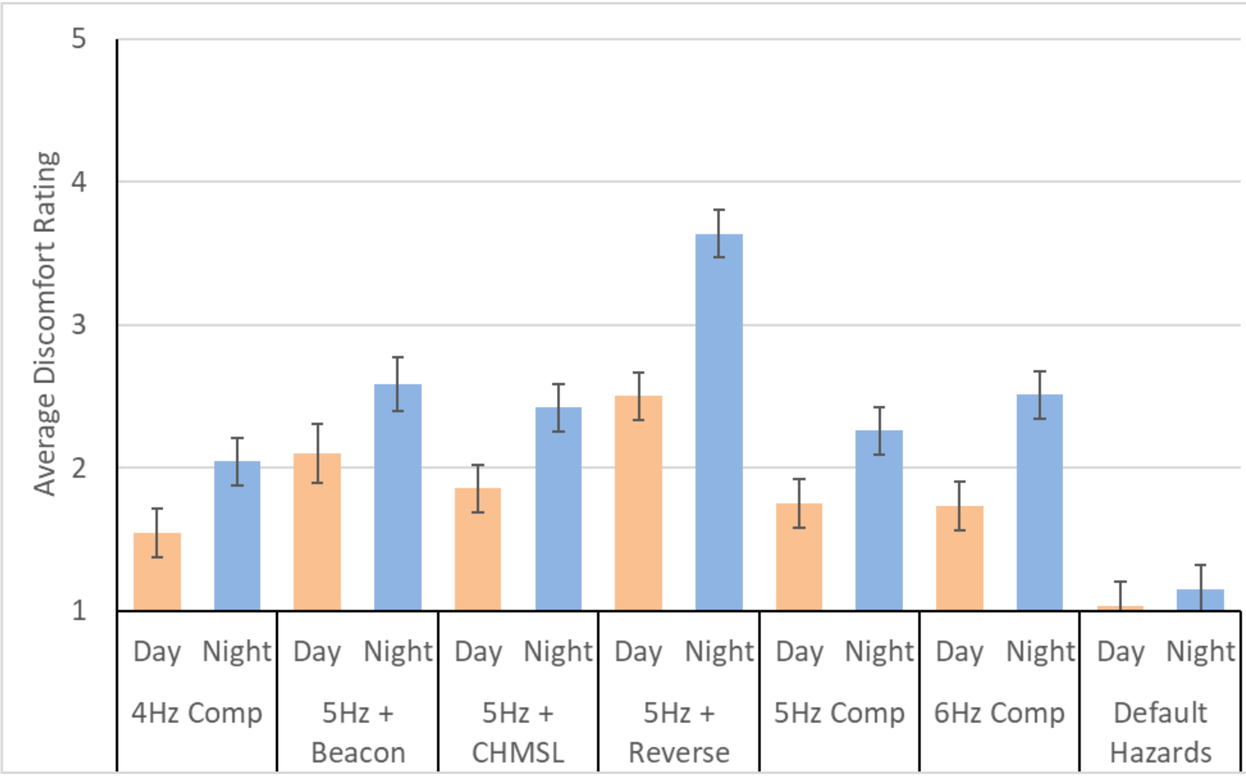


Figure 24: Rating of discomfort by hazard lighting configuration and time of day. Values denote least square means and error bars denote standard errors.

6.2.1.2 Annoyance Rating

To evaluate the effect of hazard light configuration and time of day on the annoyance level of participants a LMM was fit. Subject-to-subject variability was accounted for by including the participant's assigned number as a random effect in the model. Results indicated no significant differences between for the interaction between condition and time (Table 7). Potential significant differences between treatments were found for both time and condition. Post-Hoc analysis was performed using a difference of least squares means procedure utilizing Tukey's HSD to account for multiple comparisons. Subsequent analysis looks at the association between the treatment levels of condition and time on the annoyance rating of participants.

Table 7: Test of Fixed Effects for full factorial two-way model using Condition and Time as main effects and Participant as a random effect

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Condition	6	377	41.43	<.0001
Time	1	71.9	4.13	0.0457
Condition*Time	6	377	1.92	0.0766

Figure 25 highlights the significant differences in annoyance experienced by participants between hazard light configurations. Participants rated the 5Hz+Reverse the highest (labeled "A"). 5Hz+Reverse was found to have a significantly higher annoyance rating than the other configurations save for the 5Hz+Beacon. The default hazard configuration was rated least annoying by a significant margin.

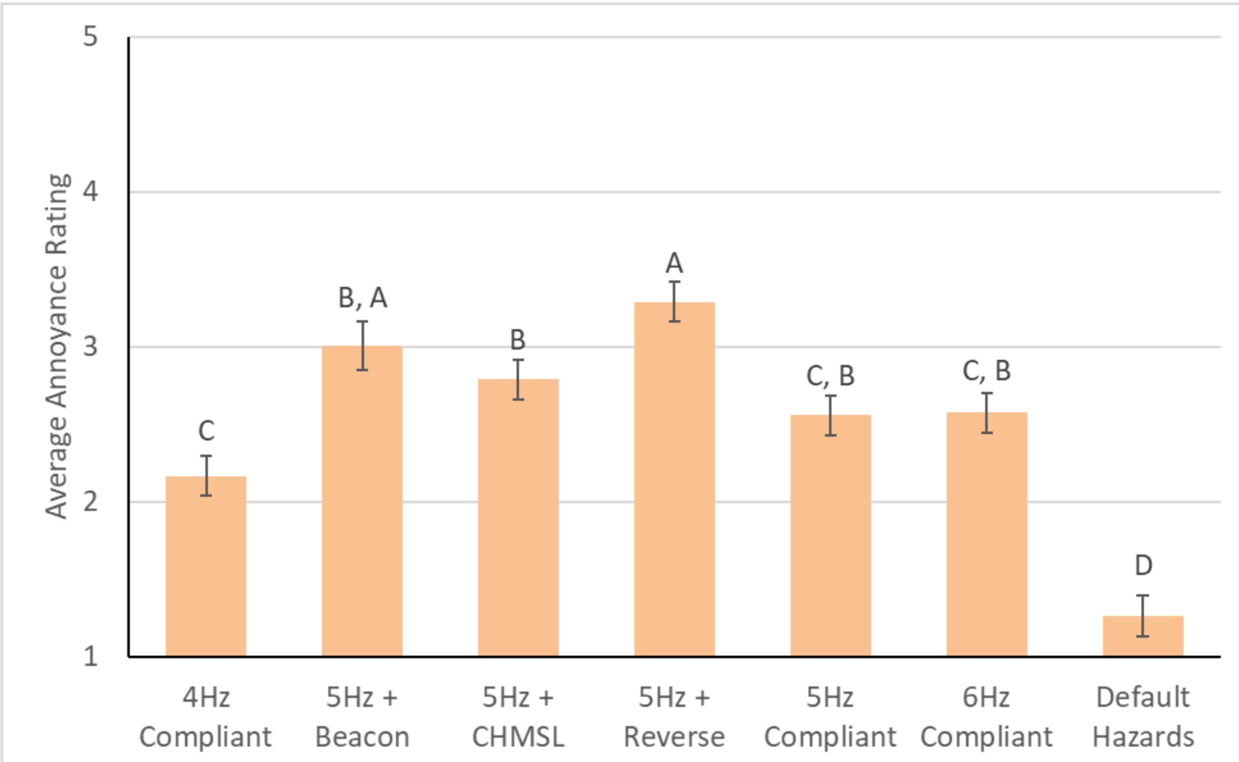


Figure 25: Rating of annoyance by hazard lighting configuration. Upper case letters denote significant differences in post hoc pairwise comparisons ($p < 0.05$). Values denote least square means and error bars denote standard errors.

When divided by time of day, the results for annoyance ratings appear similar to discomfort ratings. Notably, participants did not rate day and night differently for when the 5Hz+Beacon was deployed indicating that time of day may have less of an impact on how people perceive it. The reason for this is unclear from this research but visual angle, with the beacon being placed lower to the ground, could be a factor.

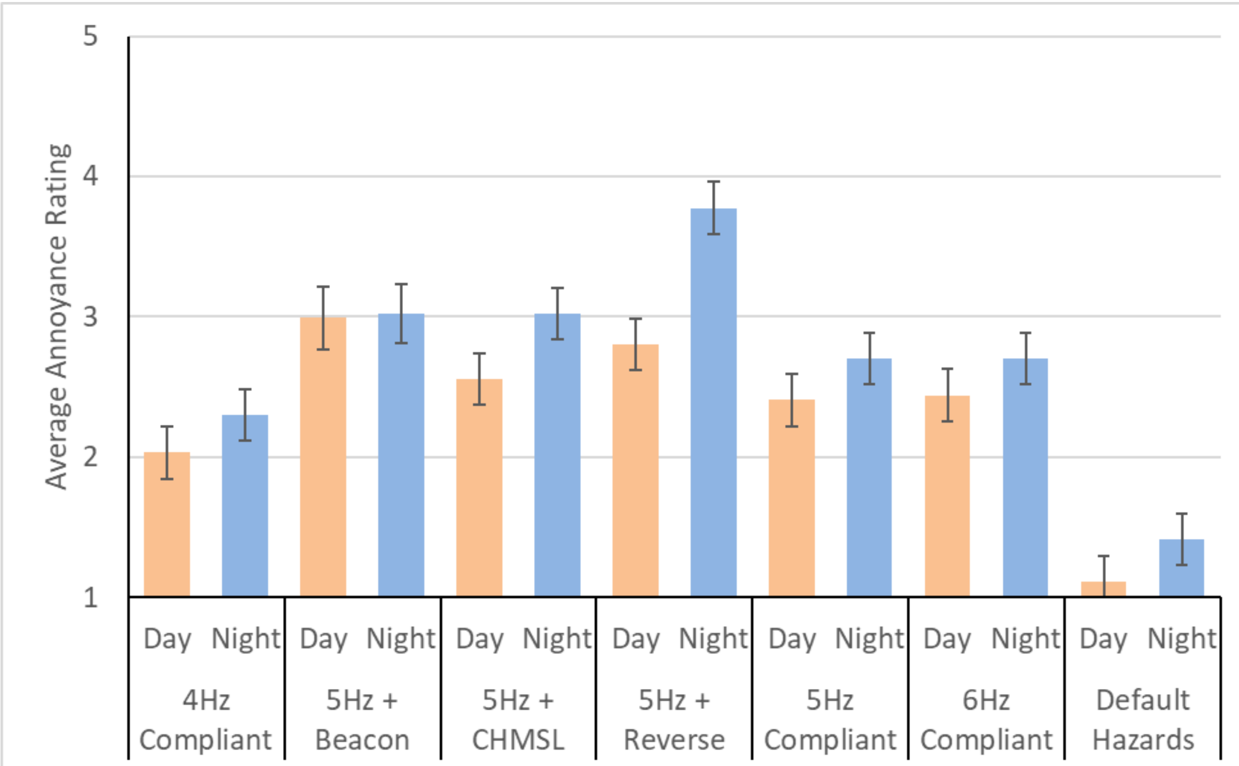


Figure 26: Rating of annoyance by hazard lighting configuration and time of day. Values denote least square means and error bars denote standard errors.

6.2.1.3 Urgency Rating

To evaluate the how the sense of urgency conveyed by the hazard light presentations changed in relation to hazard light configuration and the time of day, a LMM was fit to the data (Table 8). Subject-to-subject variability was accounted for by including the participant's assigned number as a random effect in the model. Results indicated potential significant differences existed amongst the factor level combinations of hazard light condition and time of day. A follow up analysis was performed using a difference of least squares means procedure applying Tukey's HSD to account for multiple comparisons. Further analysis focused on the significant differences between the treatment levels of condition and time.

Table 8: Test of fixed effects for full factorial two-way model using condition and time as main effects and participant as a random effect

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Condition	6	368	64.08	<.0001
Time	1	72.1	2.01	0.1604
Condition*Time	6	368	2.20	0.0427

Results showed the 5Hz+Beacon had significantly higher urgency ratings than all other conditions and was most effective at conveying a sense of urgency to participants. Of the alternative configurations, the 4Hz Compliant configuration was least effective and was the only one to receive an average rating below neutral (3) (Figure 27).

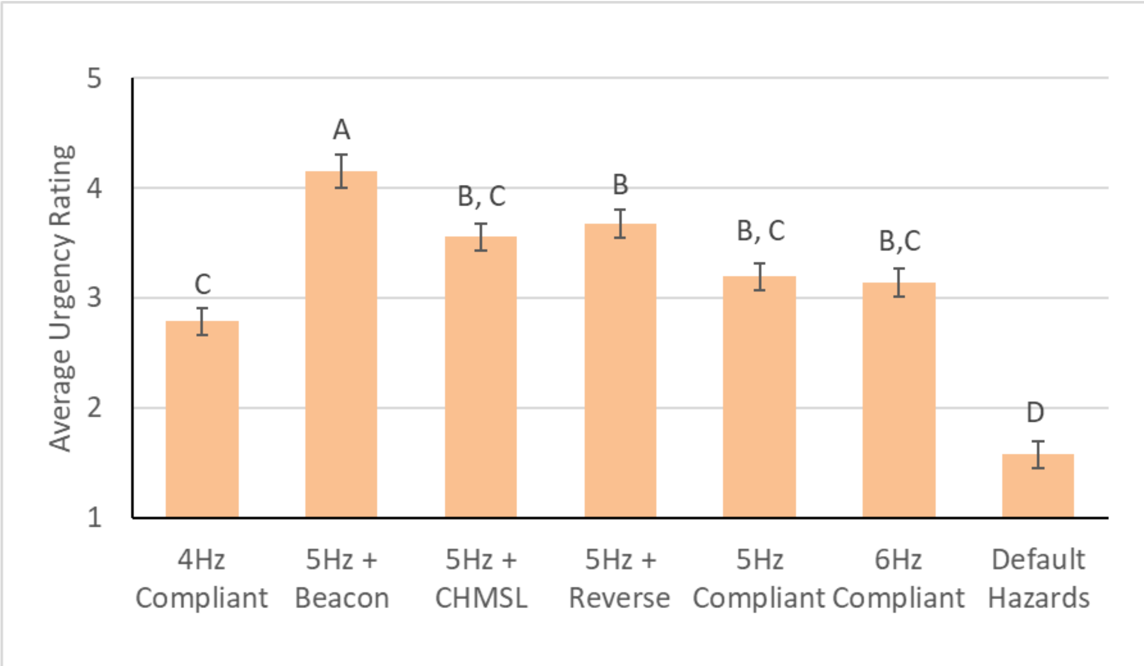


Figure 27: Rating of urgency by hazard lighting configuration. Upper case letters denote significant differences in post hoc pairwise comparisons ($p < 0.05$). Values denote least square means and error bars denote standard errors.

To investigate the effect time of day had on the sense of urgency the data was analyzed by time of day (Figure 28). The results showed that day and night ratings were not significantly different for 5Hz+CHMSL, 5Hz+Beacon, 4Hz Compliant, 5Hz Compliant, 6Hz compliant, and default hazards. Night ratings for urgency were significantly different from day for the 5Hz+Reverse configuration, indicating that the white reverse light was less salient during the day. Overall, the 5Hz+Beacon during both day and night and the 5Hz+Reverse configurations had the largest magnitude of urgency ratings. All the alternative configurations had significantly higher urgency ratings than the default hazard condition.

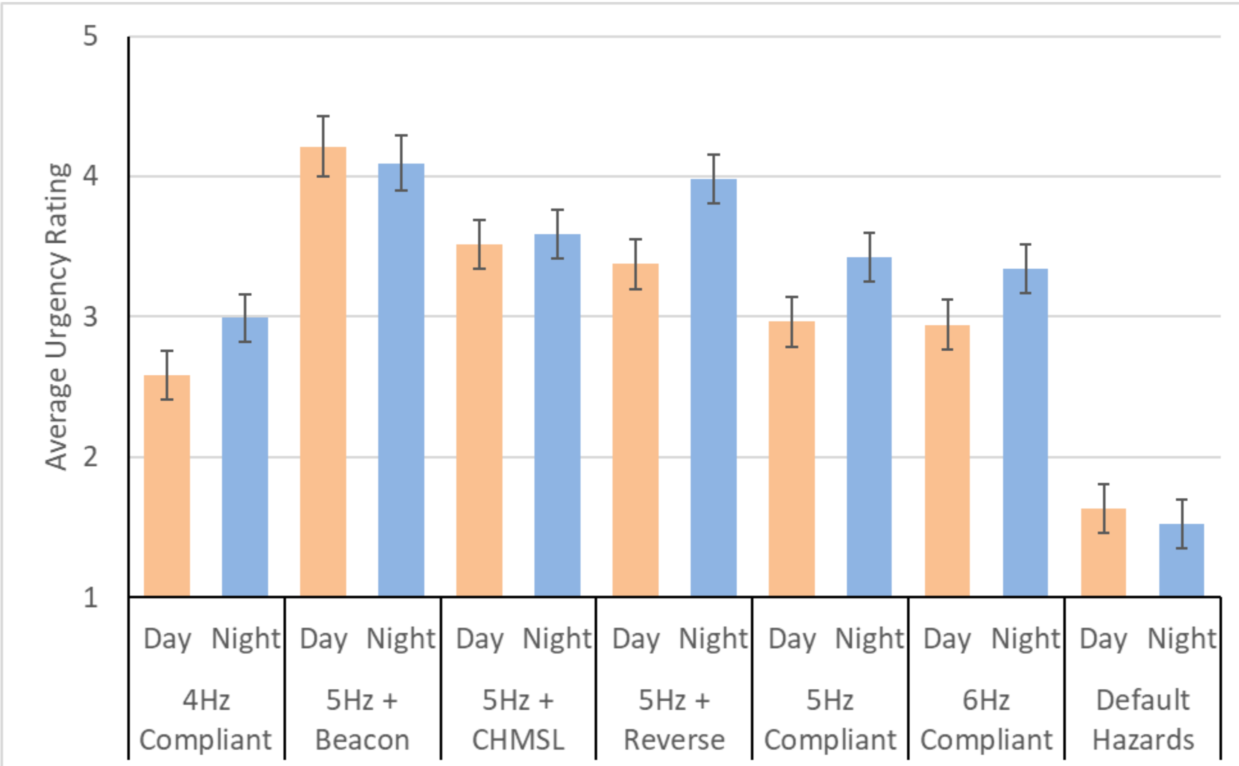


Figure 28: Rating of urgency by hazard lighting configuration and time of day. Values denote least square means and error bars denote standard errors.

6.2.1.4 Participant Feedback on Each Configuration

During the ratings task, after each exposure to a configuration, participants were asked what their thoughts were on the configuration they just experienced. Participants freely provided feedback and were only prompted if no answers were given. Prompts included asking them to provide their thoughts on the flash frequency, pattern, or brightness. Some participants, despite prompting, did not provide any feedback while others openly provided thoughts on their experience.

6.2.1.4.1 Open Ended Thoughts

Table 9 highlights the most common response themes from participant open-ended feedback responses when exposed to each hazard lighting configuration. The coded themes are in the left-most column and each complete the sentence, "Participants responded that "this" (referring to a lighting configuration in the columns to the right) hazard lighting configuration..." For example, "Draws attention", the first theme, was mentioned in reference to the 5Hz+CHMSL and the 5Hz+Beacon 16 and 15 times respectively. Note that the configurations have been abbreviated in the header of each column due to space limitations.

It is worth noting that themes were coded partially on the basis of sentiment. As an example, if a participant indicated that a particular configuration did not effectively draw their attention, that was not coded for "Draws attention" and would have been coded instead for "Would not be effective" located further down the table.

The table is also colored in conditionally to represent higher and lower values. Red cells indicate a popular response for a specific configuration and blue cells indicate that a particular light received few comments centered on that row's theme.

Much of the data gathered here is also indicated in other ways such as via the ratings subtask previously described. Themes such as "Annoying", for example, were rated separately but were also captured here if participants used that word, or similar word such as "obnoxious" to describe a configuration.

Table 9: Response themes from participants when asked to provide feedback on each hazard lighting configuration.

Participants responded that "this" hazard lighting configuration…	4HZ	5HZ	6HZ	CHSML	REV	BEAC	DEF
Draws Attention	6	8	6	16	9	15	2
Flashes noticeably fast	9	11	14	12	2	3	
Flashes TOO fast	2	2	4	3	2		
Does not convey urgency or emergency	9	5	7	4	4	2	31
Appears more urgent or like an emergency	4	6	6	5	6	1	
Does not stand out or appear different than normal	8	7	2	2	1		14
Would not be effective	2		5	3			8
Looks like emergency or police vehicle	3	4	9	15	30	1	
Confuses them or looks broken	2	2	6	1	2		
Is annoying or obnoxious	2	4	3	5	1	5	1
Is disorienting or distracting	1	4	1	3	5	1	1
Is too bright or causes glare	1	2		1	4		

To summarize Table 9, the default hazard configuration was regarded lower for almost all themes save for participants commenting that they did not effectively convey an emergency and that they would not be very effective. Fourteen responses correctly indicated that the default configuration did not stand out from any typical hazard configuration they had ever encountered.

Participants took note of the flash frequency of the configurations and the 6Hz received four responses indicating that it might be "too" fast. Additionally, the 6Hz also received more comments alluding to it creating confusion for the participant or that they believed the rapid flashes made the vehicle appear broken in some way. Ten responses indicated that the 5Hz+Beacon appeared more like an emergency and drew their attention.

Thirty comments were made regarding the 5Hz+Reverse appearing as an emergency or police vehicle and was more commonly labeled "annoying or obnoxious" and "disorienting or distracting”. In addition, 25 comments pointed out the white light on the 5Hz+Reverse configuration. Of those, 14 comments indicated a preference for it and 11 indicated dislike. The 5Hz+CHMSL also received 15 responses that it appeared as an emergency or police vehicle.

6.2.1.4.2 Participant Quotes

Participants did provide some insight as to the potential benefits or their concerns regarding the different configurations. Comments that the research team deemed insightful were pulled and placed below. It is worth noting that when asked for feedback, participants are more likely to offer critiques. These quotes were selected based on the level of content provided and not sentiment.

Regarding 5Hz+Beacon

> *I like the configuration, especially if you are in a blind curve or something like that. If your vehicle is disabled, I think it would be a good feature to have. Give you some extra space. –* ***Male (49), nighttime***

> *The triangle this close to the car has no value to me. I got it already from the lights on the car but if it was 50 yards away, I would interpret it as an early caution so I would move over.* ***– Female (54), nighttime***

> *Well, the triangle reminds me of big rigs on the side of the road when they put them out. So, I always make sure to move to the far lane because the driver might be outside the vehicle.* ***– Female (46), nighttime***

> *It seems a little bit like overkill to have the triangle, but I would assume that means that there's actually an emergency.* ***– Female (21), daytime***

> *I don't have a problem with the triangle. I think for that configuration it's appropriate because those lights seem very small, but personally I wouldn't want to have to put a triangle out behind my car. So, I personally would want the first one [5Hz+CHMSL] on my car, and probably for other people too. Like one time I had a flat tire and I had to pull over on the side of the road, and I just came from a conference and I was in heels, in a dress and I was like "I don't want to get out of the car! I'm on the side of the highway." I wouldn't want to deal with that. –* ***Female (25), daytime***

> *I like the beacon for others, but I like the reverse lights for me****. – Female (36), daytime***

Regarding 5Hz+CHMSL

> *This is a good one. I like this one. It's just like your attention is more drawn to it because of more lights and more frequency. This one I'm like "oh yeah, there's something wrong with this person".* ***– Female (25), daytime***

The bar light that goes across the back windshield, it definitely catches my attention, and the added light would make me want to slow down more. ***– Male (18), daytime***

I feel like it makes me think more of a police vehicle, because of the middle one. Like an undercover cop trying to pull me over. ***– Female (21), daytime***

I notice that there's more light. The top lights on now. I think having the top light on really makes it stand out more. I think I would be less likely to mistake it for a turn signal or anything like that. I mean it's going really fast; I probably wouldn't mistake it for a turn signal anyway, but with the top light, I definitely won't mistake it for a turn signal. ***– Male (29), nighttime***

That reminds me a lot of a fire truck, or a responder signal more than a car. I run rescue, so I would get over and get by them to get out of their way ***– Female (20), nighttime***

Regarding 5Hz+Reverse

I like the two colors. It catches my attention more. I would notice it faster. And probably react, like want to change lanes quicker. Just to get out of their way if they're in trouble. I wouldn't stop because that's not something I should do. Being a girl a know I shouldn't. I would feel more urgency to move over. ***– Female (22), daytime***

I don't like it. If I was driving down the road, and this was on the side of the road, I would mistake it probably for some type of police vehicle at first. And then the white light really kind of blurs out the red sometimes, and I imagine if I was going pretty quick it would probably would even more. So it almost looks like the car is facing me, and the headlights are just flashing. I think maybe if it wasn't so rapid, maybe it wouldn't be as bad, and as annoying. ***– Male (29), nighttime***

It looks like police lights or an emergency vehicle lights. Particularly when you get the white strobe in there, and I'm assuming they're LEDs because I feel like I see a little - something about LEDs you get kinda that blue color from it, but yeah if I was coming up to it I'd assume it's an emergency vehicle. ***– Male (24), nighttime***

It's bright. It definitely looks like a car accident, ambulance, police, something. It would definitely get my attention. ***– Female (43), nighttime***

It reminds me of a European cop car. Since I am seeing white, I would think they are backing up to some extent so I would move over. ***– Male (37), nighttime***

Regarding 6Hz Compliant

It just seems like the car is not working. Not an emergency. They are blinking wrong or something, glitching. It doesn't seem like anything important. At first look, it's very fast. It just doesn't make me want to look at it. ***– Female (22), daytime***

Makes me think there is something wrong with the vehicle. ***– Female (50), daytime***

I don't think of a service vehicle, I think someone has a shorted-out caution system or hazard light. I think their hazard lights aren't working right. ***– Male (45) daytime***

I like the fact that it's a little more solid, so the blinking is happening faster so it's kind of pulsing vs blinking. It catches your attention, but it's not necessarily a police siren, so there's definitely a difference in the frequency of the flashing so it makes it look like less of a police car. ***– Male (42), nighttime***

That one, depending on the rate of speed traveling past it, it seems to me, I think it's a lot more annoying. More distracting. It could be, like, when you put your eyes back on the road, you still see those flashes. ***– Male (49), nighttime***

For the open-ended feedback portion of the ratings task, there were no notable insights in the opinion of the research team offered for the default, 4Hz Compliant or 5Hz Compliant configurations.

6.2.1.4.3 Participant Reactions

The next question posed to participants inquired how they might react if they encountered the hazard lighting configuration they were experiencing while driving. Most participants responded with the actions they would take as drivers, often alluding to slowing down or merging over one lane to provide a safety buffer for the hazard lighted vehicle (Table 10). Significantly fewer participants opted to provide their emotional response.

Most responses indicated that merging away from the vehicle with active hazard lights engaged would be their primary action. Fewer responses pointed out that they would also slow down while passing the vehicle. Of note, while fewer comments for the 5Hz+Beacon referenced merging and slowing down, compared to other configurations, six comments were to stop and help the person on the side of the road. When exposed to the default configuration, more comments indicated that they would change nothing about their driving behavior compared to other configurations although the difference is minimal.

Table 10: Response themes from participants when asked how they would react to each hazard light configuration

If I encountered this hazard lighting configuration, I would…	4HZ	5HZ	6HZ	5Hz CHSML	5Hz REV	5Hz BEAC	DEF
Merge	39	46	44	46	49	29	35
Slow down	26	27	28	28	26	13	27
Continue driving	6	6	4	2	4	2	8
Stop to help	2	3	2	2	2	6	3
Call non-emergency responders			1		1	2	

Table 11 shows the common response themes for comments made that were not considered action-based reactions, as they were in Table 10. Of note, the 5Hz+Reverse light created two curiosity responses. One response indicated that encountering the 5Hz+Reverse configuration would make them feel frightened. No further clarification was provided.

Table 11: Response themes from participants who responded with an emotional or thought-based reaction

If I encountered this hazard lighting configuration…	4HZ	5HZ	6HZ	5Hz CHSML	5Hz REV	5Hz BEAC	DEF
I would be curious			1	1	2		1
I would think something important is happening	1	1		1	1		
I would think it was impressive	1		1				
I would feel frightened					1		

6.2.1.4.4 Participant Quotes

The following quotes were selected from responses given regarding how they would react if they encountered a given hazard light configuration.

6 Hz Compliant

> *So, I'm noticing that the lights are alternating. And that reminds me of a police officer. Makes me think of some sort of law enforcement officer. And so I would change lanes to make sure I didn't hit him if he was pulling somebody over.* **– *Male (33), daytime***

5 Hz+Reverse

> *Probably change lanes, thinking it's an emergency or police related. Give them more space. **– Female (50), daytime***

> *I think I would definitely be moving over. So it would do the job. It would really distract me, like a lot. **– Female (40), daytime***

> *I would definitely be curious about it, and probably distracted while I was driving. Not in a "oh, I'm in trouble and you should notice I'm in trouble", but more of like, "I'm going to have an accident" distracted. **– Male (29), nighttime***

5 Hz+Beacon

> *I would definitely slow down and move over to the next lane. I do think it's more beneficial that there's another hazard light out a little bit more away from the vehicle because a lot of times, people are pretty oblivious to the first set of lights and by seeing an extra set of lights that allows them to have some sort of notification of slowing down and be on their guard. And again, my other answer is, unless it's somebody I know or family for that matter, I would not offer my assistance because you just don't know. **– Male (33), nighttime***

> *I would get over because of the triangle. To me that shows they don't want anyone there, they want you to move. But to me it's signaling there is a mess move out of the way. **– Female (20), nighttime***

5 Hz+CHMSL

> *Honestly, I would think they are pumping their brakes. I wouldn't change lanes if I saw this for the first time. **– Male (37), nighttime***

6.2.2 Comparison Tasks

During the comparison task, participants were shown two hazard light configurations and asked which one they preferred, and which one they felt would be safer to use if it were on their own vehicle. For this task, the experimental configurations were divided into a frequency cohort (Default Hazards, 4Hz Compliant, 5Hz Compliant, and 6Hz Compliant), and a volume cohort (5Hz Compliant, 5Hz+Beacon, 5Hz+CHMSL, and 5Hz+Reverse). Figure 29 shows the number of times a configuration from the frequency cohort was selected to be both safer and preferred to its counterpart. Figure 30 shows the same information but for the volume cohort.

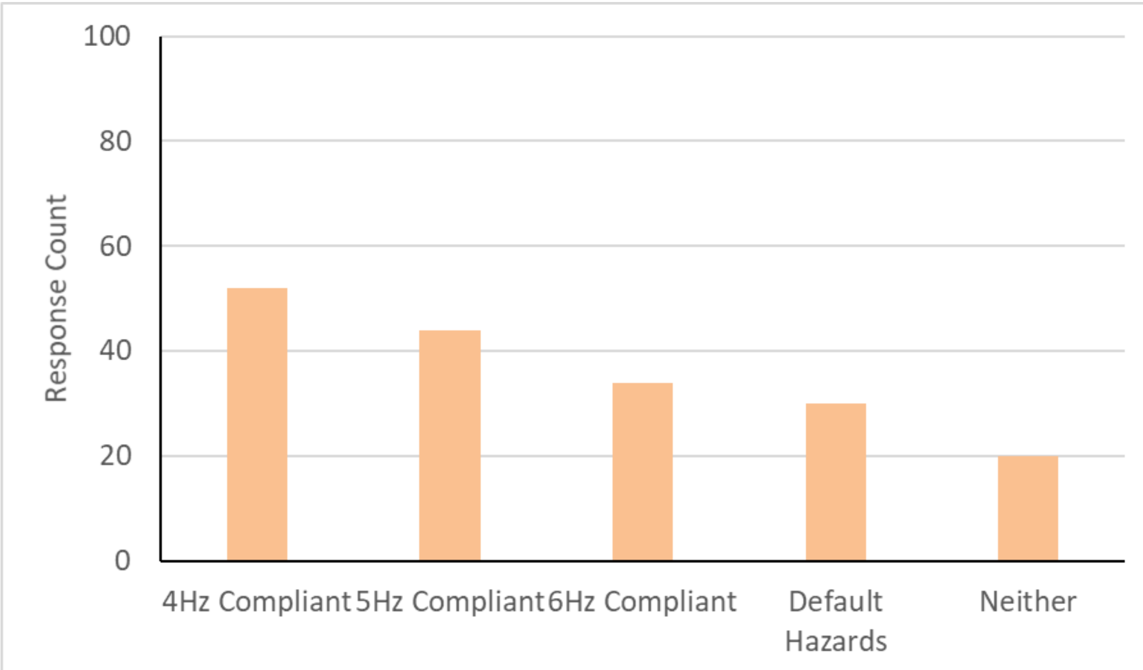


Figure 29: Total responses indicating that a configuration was both "Safer" and "Preferred" over its counterpart within the frequency cohort

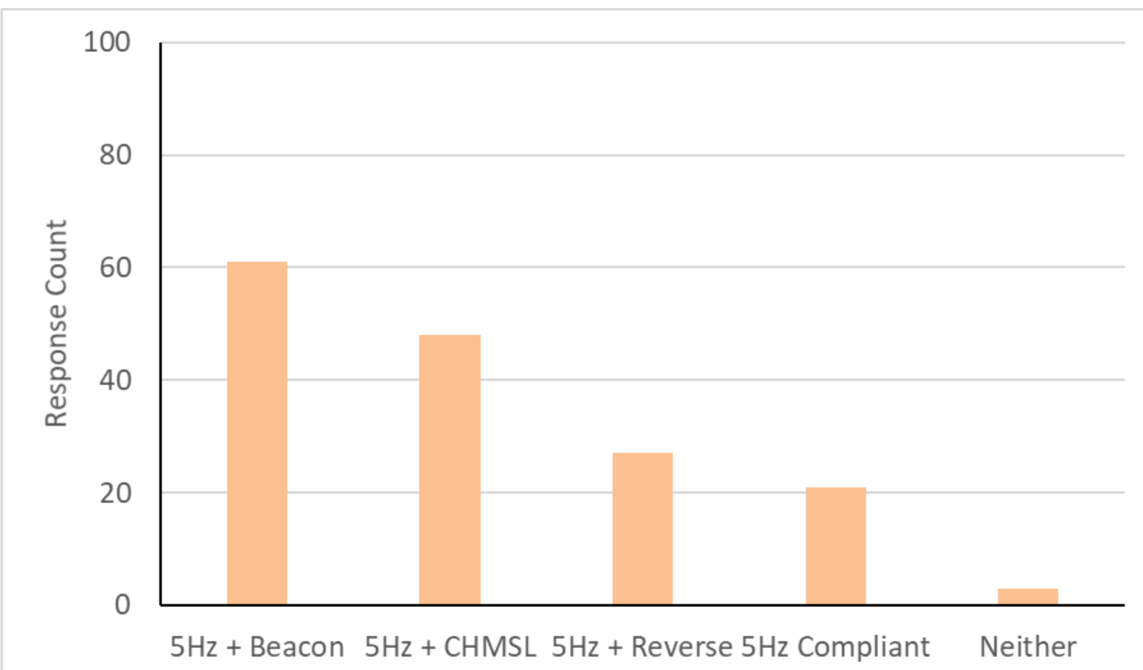


Figure 30: Total responses indicating that a configuration was both "Safer" and "Preferred" over its counterpart within the volume cohort

6.2.2.1 Frequency Cohort for Preference

Table 12 presents the percentage of times each configuration in the frequency cohort was preferred over another. Once again, the frequency cohort included 4Hz, 5Hz, and 6Hz compliant configurations as well as the default configuration. The 4Hz Compliant was the most preferred configuration, being selected as the preferred configuration 61% of the time or more. The 6Hz Compliant was the least preferred configuration, and the only configuration which was preferred less than the Default Hazards.

Table 12: Percentage of preferences from comparisons between flash frequency cohort

	Compared Configuration			
Preferred Configuration	4Hz Compliant	5Hz Compliant	6Hz Compliant	Default Hazards
4Hz Compliant		61%	65%	61%
5Hz Compliant	39%		61%	57%
6Hz Compliant	35%	39%		46%
Default Hazards	39%	43%	54%	

6.2.2.2 Frequency Cohort for Safety

Table 13 presents the percentage of times each configuration in the frequency cohort was selected as safer than another configuration. When compared to the default hazards, the alternative configurations were preferred a majority of the time (61% to 73%). Among the alternative frequency configurations, 57% of participants considered 4Hz safer than 5Hz, and 56% considered 5Hz safer than 6Hz. Participants were evenly split between 4Hz and 6Hz with each being selected by 50% of participants.

Table 13: Percentage of safest configuration from comparisons between flash frequency cohort

	Compared Configuration			
Safer Configuration	4Hz Compliant	5Hz Compliant	6Hz Compliant	Default Hazards
4Hz Compliant		57%	50%	73%
5Hz Compliant	43%		56%	70%
6Hz Compliant	50%	44%		61%
Default Hazards	27%	30%	39%	

6.2.2.3 Light Volume Cohort for Preference

Table 14 shows the percentage of times a configuration within the volume cohort was selected as the preferred configuration when compared to one of the others. The Beacon and CHMSL configurations were both highly preferred over the Reverse and Compliant configurations being chosen by 74% to 76% of participants. When compared to each other, the Beacon was selected as the preferred configuration over the CHMSL by 65% of participants. The Reverse configuration was the least preferred.

Table 14: Summation of preferences for comparisons between light volume cohort

	Compared Configuration			
Preferred Configuration	5Hz+Beacon	5Hz+CHMSL	5Hz+Reverse	5Hz Compliant
5Hz+Beacon		65%	76%	74%
5Hz+CHMSL	35%		74%	74%
5Hz+Reverse	24%	26%		43%
5Hz Compliant	26%	26%	57%	

6.2.2.4 Light Volume Cohort for Safety

Table 15 shows the percentage of times a configuration in the volume cohort was selected as the safer option when compared to another configuration. Each of the configurations which include additional light sources were preferred more often than the Compliant configuration. An overwhelming 82% of participants selected the Beacon and CHMSL configurations as being safer than the Compliant configuration. The Beacon was considered safer more often than any other configuration.

Table 15: Summation of safest configuration from comparisons between light volume cohort

	Compared Configuration			
Safer Configuration	5Hz+Beacon	5Hz+CHMSL	5Hz+Reverse	5Hz Compliant
5Hz+Beacon		77%	65%	82%
5Hz+CHMSL	23%		62%	82%
5Hz+Reverse	35%	38%		60%
5Hz Compliant	18%	18%	40%	

6.2.2.5 Participant Responses During the Comparison Task

6.2.2.5.1 Frequency Cohort Themes

For the Comparison Task, participants' verbal responses were transcribed, and similar comments were binned into general themes. Themes were further categorized as either being positive, negative, or neutral. Table 16 shows the number of comments which fell into each theme for the frequency cohort comparisons.

Table 16: Number of responses by theme for the frequency cohort comparisons.

Reaction	Sentiment	Default Hazards	4Hz Compliant	5Hz Compliant	6Hz Compliant
Neutral	Looks like an emergency vehicle or police car		1	1	
	Seems brighter	2	5	1	1
	Seems aggressive				1
	Indicates an emergency				3
	Can't tell the difference		28	37	25
Positive	Comfortable to look at / Less discomfort	4	1	1	
	Draws your attention / More noticeable	1	3	8	9
	The frequency is a good/better speed	1	3	1	
	Seems more "URGENT"	1		5	5
	Recognizable as hazard lights	4	1		
	Would be visible in bad weather			1	
	Would make me/others stay away				1
Negative	It's annoying		3	2	9
	I want to look away		1		1
	Distracting		3	1	1
	Confusing				3
	Frequency is too slow	2			
	Could cause an accident				1
	Too bright / glaring				1
	Less noticeable	1			

6.2.2.5.1.1 Neutral Themes (Frequency Cohort)

When comparing the 4Hz, 5Hz, and 6Hz compliant configurations, a large number of responses indicated difficulty discerning the difference among them. When a participant indicated that they could not see any difference between the two configurations being shown, that comment was counted for both configurations. Because the 5Hz frequency was always just +/- 1Hz from the configuration it was being compared to, more responses indicated difficulty discerning the difference for that frequency. In contrast, when the 4Hz and 6Hz lights were compared, the larger 2 Hz difference was more noticeable; however, several responses still indicated a difficulty in discerning this difference. Five responses indicated that the 4Hz Compliant configuration appeared brighter when compared to the other configurations.

6.2.2.5.1.2 Positive Themes (Frequency Cohort)

More responses indicated that the 5Hz and 6Hz Compliant configurations were better at drawing attention and seemed more urgent than they did for the 4Hz Compliant and Default Hazard configurations.

6.2.2.5.1.3 Negative Themes (Frequency Cohort)

Participants had more negative comments about the 6Hz Compliant configuration than all the other configurations combined. Many participants indicated that the 6Hz frequency was annoying. Several responses indicated that it caused confusion, was distracting or glaring.

6.2.2.5.1.4 Participant Quotes

Comparing 4Hz Compliant and Default Hazards

> *I'm going to say the [Default Hazards are safer], although I assume a lot of people think differently on that one. You hear a lot about police cars on the side of the road, I think in VA it's the law that if you can move over you're supposed to, but plenty of times people plow into cars on the side of the road even if they have bright flashing lights. So if I was on the side of the road, I'd want people to know I was there, but not be distracted and crash into me because of it*. **– Male (24), nighttime**

Comparing 4Hz and 5Hz Compliant

> *The [4Hz Compliant] was a little bit slower, so I found that one to be a good middle ground between the really slow flashing and the really fast flashing. That one felt like a pretty good middle ground. But I felt like it had a good balance of being noticeable without being overwhelmingly noticeable*. **– Male (29), nighttime**

Comparing 6Hz Compliant and Default Hazards

> *Probably the [6Hz Compliant is safer]. I'd be a little bit concerned about, like if I'm on the side of the road with it, I'd be a little bit concerned that I'd distract somebody and they'd hit me because of how rapid it is, but I would feel like they'd be more likely to see me than with the (Default Hazards)*. **– Male (29), nighttime**

> *[The Default Hazards are] more like a generic hazard light that's on normal cars. I would recognize that. Other people would also recognize that.* **– Female (28), nighttime**

> *The [6Hz Compliant] pattern was a lot quicker so it reminded me of an emergency vehicle already pulled over so that would lead me to pass it up because I would feel like someone has already taken care of the problem.* **– Female (44), nighttime**

6.2.2.5.2 Volume Cohort Themes

Table 17 shows the number of comments that fell into each theme for the volume cohort.

Table 17. Number of responses by theme for the volume cohort comparisons.

Reaction	Sentiment	5Hz Compliant	5Hz + Beacon	5Hz + CHMSL	5Hz + Reverse
Neutral	Looks like an emergency vehicle or police car			1	3
	Seems brighter		4		5
	Seems aggressive				
	Indicates an emergency		1		
	Indicates they are OK		1		
Positive	Comfortable to look at / Less discomfort		1	1	1
	Draws your attention / More noticeable		6	7	6
	The frequency is a good/better speed	1			1
	Seems more "URGENT"	1	2	1	3
	Would be visible in bad weather		1		
	Would make me/others stay away			1	1
	Indicates there's a problem / they need help		3		
	Helpful		1		
	I "like" it. / It makes a difference.			4	
	Adds safety		2	4	1
Negative	It's annoying				1
	I want to look away				1
	Distracting				6
	Confusing				2
	Frequency is too fast	1	2		
	Too burdensome / dangerous to use		4		
	Too bright / glaring				2
	Unsafe	1	1		

6.2.2.5.2.1 Neutral Themes (Volume Cohort)

Several participants indicated that the addition of the beacon or the reverse lights resulted in a noticeable increase in the overall brightness of the configurations. Three participants indicated that the addition of the reverse lights made the configuration look like an emergency vehicle or police car.

6.2.2.5.2.2 Positive Themes (Volume Cohort)

Several participants indicated that the configurations with additional light sources were better at drawing attention. The 5Hz+CHMSL received the most positive responses with a total of 18, with the 5Hz+Beacon receiving 16 positive responses. The 5Hz only received 2 positive responses.

6.2.2.5.2.3 Negative Themes (Volume Cohort)

Participants had the most negative comments (12 total) about the 5Hz+Reverse configuration. Several participants indicated that it was distracting. Others thought that it was annoying, confusing, or glaring. A few participants indicated that the 5Hz+Beacon configuration would be too burdensome or dangerous due to the need to keep track of extra equipment and to get out of the vehicle to set it up. The 5Hz+CHMSL configuration received no negative comments.

6.2.2.5.2.4 Participant Quotes

Comparing 5Hz+Beacon and 5Hz+CHMSL

> *If I was in trouble I'd have to get out and place the [beacon] on the highway; that's kind of dangerous. It's kind of a toss-up. I get what you guys are saying with that [beacon], but probably the three lights on the [5Hz+CHMSL are safer].* **– Male (42), nighttime**

> *I think the rear windshield light does better than the [beacon] because number 1) that'd be a pain in the [expletive] to keep attention of, and it's probably gonna have to be stored and I would probably forget about it after a while, because how often do you use your hazard lights? I prefer the [5Hz+CHMSL] because I think that rear windshield light makes a big difference.* **– Male (38), daytime**

Comparing 5Hz+Beacon and 5Hz+Reverse

> *I like the look of the [beacon] better. But the reverse lights would really key me in to get out of the way. A lot more than any of the others would. I hated looking at it, but there is a lot more urgency for that one.* **– Female (40), daytime**

Comparing 5Hz+Beacon and 5Hz Compliant

> *I prefer the [5Hz+Beacon], but the triangle would be a pain in the [expletive] to deal with. Now if it popped up from the hood of the trunk, that'd be pretty cool.* **– Male (38), daytime**

> *I think the [5Hz+Beacon] is the best for both answers. […] If someone made the effort to set out the [beacon] then they need help. So I really like the [beacon]. […] I know they need help. I know somethings wrong, and they're not just pulled over checking email on*

their phone. Because they got out. It made them get the effort to get out of the vehicle and set up the [beacon]. **– Male (49), daytime**

Comparing 5Hz+Reverse and 5Hz Compliant

I can see the white lights better at nighttime, but I'd worry that people wouldn't know what that means unless it's on more cars, so that's the tricky part. The white lights could signal backing up. **– Male (42), nighttime**

[The 5Hz Compliant is safer because] the bright flashing white lights could almost distract someone and possibly make them react differently than they would if they didn't have bright lights in their eyes. **– Male (50), nighttime**

6.2.3 Confusion Task

A mixed effects logistic regression was performed to evaluate the interaction between condition and time on the ability of participants to correctly distinguish between emergency and hazard lights (Table 18). Subject-to-subject variability was accounted for by including the participant's assigned number as a random effect in the model. No statistically significant results were found for the interaction between hazard light condition and time of day. The main effect of hazard light condition was found to have statistically significant differences between the different treatments. Post-Hoc analysis was performed using a least squares means procedure employing Tukey's HSD to account for multiple comparisons. Further discussion focuses on the rate at which participants were able to correctly identify the light condition presented.

Table 18: Test of Fixed Effects for full factorial two-way model using Condition and Time as main effects and Participant as a random effect

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Condition	2	90	17.23	<.0001
Time	1	90	0.74	0.3925
Condition*Time	2	90	1.18	0.3126

Table 19 contains the responses participants provided when presented with the configuration shown in the left column. Participants were positioned 0.6 miles from the experimental vehicle during this task. When the 5Hz Compliant hazard configuration was presented, participants correctly responded that they were seeing a hazard light 71.1% of the time. Five participants responded that they were seeing both an emergency light and a hazard light and eight thought they were seeing an emergency light. Participants were more accurate when presented with an emergency light and correctly responded 82.9% of the time. When both the 5Hz Compliant and emergency light bar were active, participants were least accurate (19.1%) and assumed they were viewing an emergency light by itself 76.6% of the time.

Table 19: Number of responses and percentage of correct answers per configuration presentation

	Response			
Configuration Presented	Hazard	Both	Emergency	% Correct
5Hz Compliant (Hazard)	32	5	8	71.1%
Both	2	9	36	19.1%
Emergency Light Bar	2	6	39	82.9%

When split by time of day (Figure 31), participants were slightly more accurate at night when viewing both the hazard light and the emergency light bar, but not by a statistically significant margin. Participants were more accurate during the day when viewing either the hazard light or the emergency light independently, indicating that the emergency light may overpower the visibility of the hazard lighting during the day but less so at night.

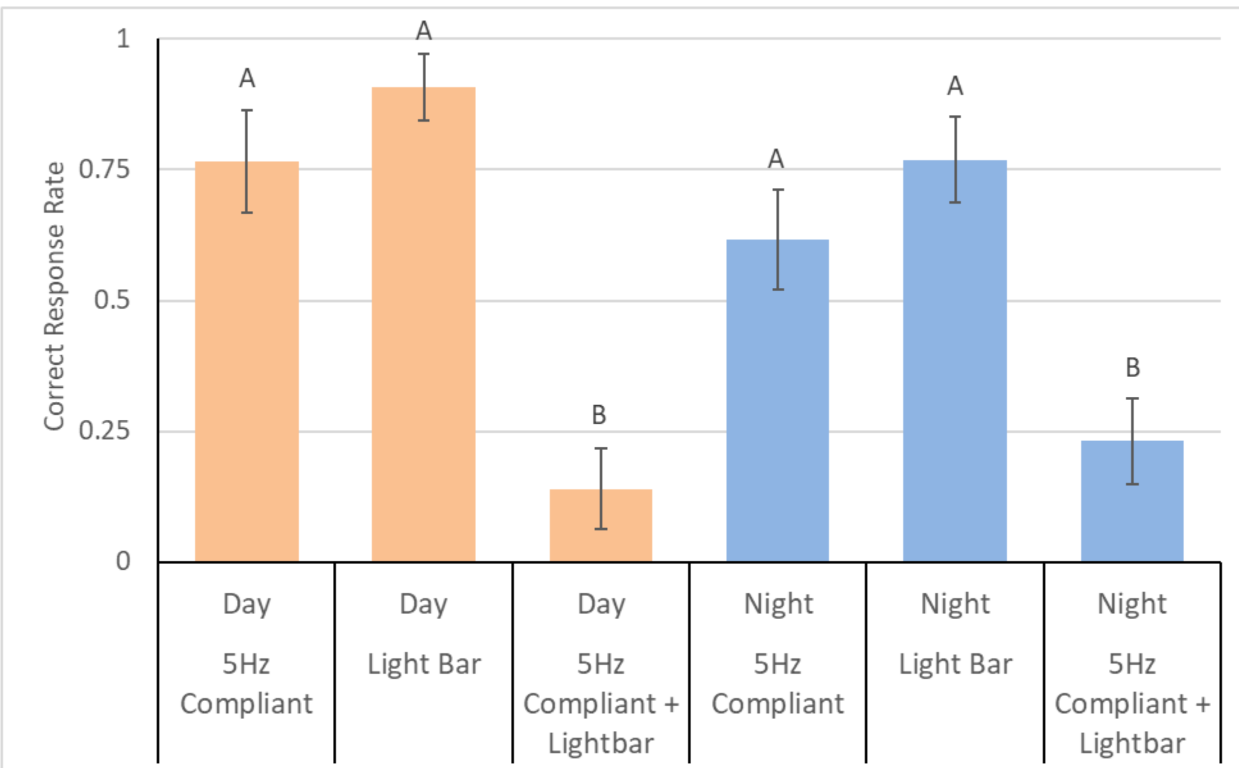


Figure 31: Rate of correct responses in confusion task split by time of day. Values denote least square means and error bars denote standard errors.

7 DISCUSSION

The experiments were designed to answer if the alternative lighting configurations provided a benefit over the default hazard lighting systems in terms of refocusing driver attention forward.

Additionally, researchers wanted to know how drivers perceived the lighting systems, their safety and overall preference, as well as if the enhanced systems were distinguishable from an emergency lightbar. The following section is broken down into general observations which includes insights noted by researchers throughout the course of the study as well as limitations of the research. Following sections of this chapter will focus on each alternative configuration and provide a summary of key findings across the different experimental tasks.

7.1 General Observations

The default hazard system on the Tesla Model 3 was regularly outperformed in both the dynamic and static trials indicating that room for improvements to conventional hazard lighting systems exists. This study evaluated six alternatives that included increased frequency (4, 5, and 6 Hz), added color (reverse), more light (CHMSL), and an external implement (beacon). The overall results indicate that each of these alternatives provide benefit over the default hazard system in terms of redirecting driver attention forward and conveying urgency. The results of the dynamic task do not provide a statistically definitive separation among the alternative configurations in order to establish a best choice although statistical trends did emerge. The static trials and participant feedback offer substantial insight into how each configuration is interpreted and how a driver may react differently to being exposed to the configurations in a real-world situation.

Due to the nature of the dynamic driving task, researchers could not control for the proclivity of a participant to look back toward the roadway at any given moment during the distraction task. However, the experimental design is believed to be a valid measure due to the overall day and night trend. At night, participants' attention was redirected toward the roadway sooner due the salience of the lighting systems in a dark environment, as expected.

Dynamic task results found no statistically significant effects; however, trends were observed when split by time of day and by level of attention. The minimal differences observed in this experiment are comparable to similar studies, such as that of Li et al. (2014), who used a similar methodology in a driving simulator for evaluating alternative brake light patterns and braking response times. Results of that research were not statistically significant, and response times between different conditions averaged under one second apart.

While the dynamic task represented a worst-case scenario in which the hazard lights were activated when a distracted driver was already within 600 ft. of the vehicle, the static tasks, represented a more realistic look at how a driver could have more time observe the hazard lights of a disabled vehicle as they approached and make behavioral changes based on their observations. For this reason, the static results provide valuable insight into how drivers perceive each of the hazard light configurations.

As expected, many participants found the lights to be annoying either by rating them as annoying during the ratings task or by stating that the lights annoyed them while providing feedback. In this case of an alert system, annoyance should not be considered a negative despite the connotation of the word. The hazard lighting systems are not meant to be stared at or fixated upon but are meant to alert motorists so they can recognize the vehicle and make an appropriate action to avoid it. In determining the better hazard lighting system, annoyance can be an effective attentional draw.

The creation of discomfort is not a benefit. Drivers who experience discomfort from a lighting system either due to the rate of flash or intensity may react by swerving or looking away from the roadway and thus create a worse scenario. These tradeoffs must be considered when taking the results of this research into account. Only the 5Hz+Reverse configuration received an average rating above neutral for discomfort and annoyance indicating that it may have crossed the threshold from being effective into not providing a safety benefit. Annoyance and discomfort ratings were correlated, as expected, and their relationship possibly indicates the narrow threshold between beneficial and not.

7.2 4Hz Compliant

The 4Hz Compliant configuration was the most preferred and considered the safest configuration within the frequency cohort. Participant's response themes indicated that the configuration was not noticeably different or unique and that it did not do well at indicating an emergency. Among the alternative configurations, it was considered to produce the least annoyance and discomfort. Comparatively fewer comments were made regarding this configuration than others, either positive or negative.

- Did not reduce distraction times overall compared to default in dynamic task (24.8% benefit during day, 120% worse at night)
- Reduced distraction time of less attentive drivers 20% more than default
- Most preferred frequency according to participants
- Most safe frequency according to participants
- Medium annoyance (M = 2.16, SD = 1.05)
- Low discomfort (M = 1.81, SD = 0.97)
- Medium urgency (M = 2.78, SD = 1.15)
- No noteworthy concerns

7.3 5Hz Compliant

While slightly outperforming other configurations in the dynamic task, the 5Hz Compliant configuration was considered the least safe configuration in the volume cohort and was second safest to the 4Hz Compliant configuration in the frequency cohort. Participant ratings for urgency, annoyance, and discomfort ranked it in the middle with annoyance and discomfort both averaging below neutral.

Feedback on the 5Hz Compliant configuration was mostly positive. Participants felt it drew their attention and would be effective at alerting them. Comment themes for this configuration did not stand out from other configurations, indicating that it was either well received or was not unique compared to conventional hazard configurations participants had been exposed and therefore generated fewer opinions.

- Showed greatest benefit in dynamic trial (20.7% improvement over default hazards overall, 41% improvement at night)
- Second most preferred frequency according to participants
- Second most safe frequency according to participants
- Third preferred volume according to participants
- Least safe volume according to participants
- Medium discomfort (M = 2.03, SD = 0.99)
- Medium annoyance (M = 2.57, SD = 1.05)
- High urgency (M = 3.24, SD = 1.03)
- Feedback mostly positive

7.4 6Hz Compliant

Results for the 6Hz Compliant configuration show a threshold of perception and preference exist between 5 and 6Hz. The 6Hz was outperformed by the slower frequencies (default, 4Hz and 5Hz) in the dynamic task and was the least preferred frequency per feedback. It was considered to be safer than the default hazards likely due to the perception of urgency the higher flash rate created, also according to feedback. This is in line with the ratings results which show participants felt the 6Hz Compliant conveyed urgency better than the default hazards by a significant margin (M = 3.14, SD = 1.08 for 6Hz and M = 1.60, SD = 0.78 for default). Fifteen responses specified the configuration effectively conveyed urgency; however, seven more responses stated otherwise.

In the dynamic trials, participants considered to be less attentive looked up slightly later for 6Hz Compliant than the default hazards, although the separation is small and not statistically significant. It is notable that the 6Hz Compliant configuration was the only one of the alternatives to not improve the look-up time of participants versus the default hazards. This may suggest that the 6Hz frequency may not be as salient in a driver's periphery than 4Hz or 5Hz frequencies.

Participant feedback suggested that the flash rate was noticeably fast and possibly too fast (14). There were nine responses (third most behind 5Hz+CHMSL (15) and 5Hz+Reverse (30)) that indicated the configuration appeared similar to an emergency or police vehicle. Six responses indicated that the configuration appeared confusing or that the vehicle's lighting system appeared broken. Compared to other frequencies, participants more regularly considered (10 responses) the 6Hz configuration difficult to look at and it made them want to look away.

- Small improvement (5%) compared to default hazards overall in dynamic task
- Did not reduce distraction time of less attentive drivers compared to default hazards
- Least effective against less attentive drivers
- Third most preferred frequency according to participants
- Third most safe frequency according to participants
- Medium discomfort (M = 2.12, SD = 1.21)
- Medium annoyance (M = 2.58, SD = 1.26)

- High urgency (M = 3.14, SD = 1.08)
- Potentially confusing and difficult to look at

7.5 5Hz+Beacon

In the dynamic trials, overall, participants responded to the 5Hz+Beacon similar to the default hazard lighting system. While this may seem counterintuitive provided the advanced warning (by 10 ft.) and increased light level from the beacon compared to the 5Hz Compliant, participants driving toward the experimental vehicle could see the beacon placed out from the vehicle prior to the beginning of the distraction task and may have been less surprised by its initiation.

The 5Hz+Beacon's annoyance rating was less influenced by day or night and was the only configuration not impacted. All other configurations were considered more annoying at night, although the margins of separation were often smaller. In general, these results may show that the deployment of a beacon has the potential to improve visibility to rear approaching drivers particularly during the day.

Notably, the beacon, or "triangle" as many participants referred to it, was rated as providing the highest sense of urgency (M = 4.07, SD = 1.10), the only rating to average above 4 on a five-point scale. The annoyance and discomfort ratings were similar to ratings received for the 5Hz+CHMSL, 5Hz Compliant, and 6Hz Compliant conditions. Feedback (number of responses) stated that the configuration was effective at drawing attention (15) and stated that the beacon made the situation appear to be more of an emergency situation ahead (10). In fact, less participants stated that they would move over and slow down if they encountered the beacon than other configurations (-6) but received the most responses stating they would stop to help (6).

Compared to other configurations in the volume cohort, the 5Hz+Beacon was more often rated both preferred and safer to its counterpart. However, four participants indicated that while they saw the value of the beacon, they were not likely to use it themselves for fear of their own safety outside the vehicle or the inconvenience it might present while positioning it themselves.

Compared to the other hazard lights, the 5Hz+Beacon was the only one to utilize a light source which was not attached to the vehicle. While this functionality could potentially provide added safety by providing a buffer between the first warning light and the vehicle, the distance of the beacon was limited in this study. In order to sync the flashing of the beacon with that of the vehicle, the beacon had to remain within proximity of a Wi-Fi signal generated by the HELP system or be tethered to the vehicle through the trailer hitch light connection. If the Wi-Fi signal were adapted to provide a longer range, or if the beacon flashed on its' own, the advanced warning distance could be increased, alerting drivers to the vehicle much earlier.

- Showed no benefit in dynamic trials overall
- Most preferred volume according to participants
- Most safe volume according to participants
- Medium discomfort (M = 2.46, SD = 1.19)
- High annoyance (M = 3.00, SD = 1.28)
- Very High urgency (M = 4.07, SD = 1.10)

- Conveyed an emergency situation
- Safety concerns regarding deploying a device
- Largest potential for advanced warning with increased range of beacon

7.6 5Hz+CHMSL

In the dynamic tasks, the 5Hz+CHMSL performed least favorably during the day and was similar to the default hazards at night. Among less attentive participants, the 5Hz+CHMSL showed improvement over default hazards by 15.9%. Overall, the configuration did not standout as an effective means of drawing attention during the dynamic task.

The 5Hz+CHSML received the most open feedback regarding how it effectively draws attention (16), and the second most responses indicating that it appeared as an emergency or police vehicle (15). During the comparison trials, there was no negative feedback provided for the CHMSL and it received the only comments (4) themed that the participant actively liked the configuration and felt it made a difference.

Comparatively, participants preferred only the 5Hz+Beacon to the 5Hz+CHMSL in the volume cohort. The 5Hz+CHMSL and 5Hz+Beacon equally outperformed the 5Hz+Reverse and the 5Hz+Compliant configuration on the basis of preference and safety, but the 5Hz+Beacon was preferred directly over the 5Hz+CHMSL 22 of 34 times (64.7%) and considered safer 27 of 35 times (77.1%).

One observation from the research team notes the use of the CHMSL as a non-steady light within a hazard lighting system may indicate to other motorists that the vehicle is actively braking and not completely stopped. Similarly, issues might arise if a driver activates the hazards while driving and the CHMSL is flashing as it is most familiar to drivers as accompanying a braking action.

- Least effective during daytime dynamic trials
- Second most preferred volume according to participants
- Second most safe volume according to participants
- Medium discomfort ($M = 2.14$, $SD = 1.06$)
- Medium annoyance ($M = 2.79$, $SD = 1.25$)
- High urgency ($M = 3.52$, $SD = 1.06$)
- No noteworthy concerns from participants

7.7 5Hz+Reverse

The 5Hz+Reverse configuration trended toward the second most effective at redirecting driver's attention during the dynamic task and was effective day and night compared to default hazards.

Participants rated the 5Hz+Reverse configuration highest for annoyance and discomfort, both averaging slightly above neutral ($M = 3.29$, $SD = 1.28$ for annoyance and $M = 3.07$, $SD = 1.41$ for discomfort). At night, the configuration was rated an average of $M = 3.64$, $SD = 1.05$ for discomfort. The next highest average discomfort rating at night and overall was 2.59 for

5Hz+Beacon. Participants shared feedback that the configuration created discomfort by referring to it as disorienting or distracting (5). Feedback indicated the configuration was effective at drawing attention (9) as well as annoying or obnoxious (10).

The most common feedback regarding the configuration was that it could be mistaken as an emergency or police vehicle due to the white light (reverse light) that flashed in tandem (30). Three additional comments to the emergency or police vehicle theme arose when compared to other configurations. The configuration received the most comments (5) relating to it seeming brighter than other volume cohort configurations. Participants more often stated that this configuration, compared to other volume cohort configurations, was distracting (6), was confusing (2), was too bright or caused glare (2) and caused them to want to look away (1)

In terms of preference compared to the other volume cohort configurations, the 5Hz+Reverse configuration was least preferred. In terms of safety, however, participants selected it as a safer configuration than 5Hz Compliant in head-to-head comparisons 21 of 35 times (60%).

- Second most effective during dynamic trials according to averages
- Least preferred volume according to participants
- Third safest volume according to participants
- High discomfort (M = 3.07, SD = 1.41)
- Highest discomfort at night (M = 3.64, SD = 1.05)
- High annoyance (M = 3.29, SD = 1.28)
- High urgency (M = 3.66, SD = 1.24)
- Regarded as appearing similar to emergency or police vehicle
- Regarded as distracting, glaring, and obnoxious

8 CONCLUSIONS

- Participants favored all six alternative configurations compared to the default hazards signifying that alterations can be made to the conventional hazard lighting system to better suit drivers' needs and concerns. Lighting systems such as hazards are passive systems unable of preventing crashes and therefore the perception of safety and comfort is valuable to the confidence of users.
- Participants narrowly favored 4 Hz Compliant over 5 Hz Compliant for overall preference and safety; however, the 5 Hz Compliant showed 0.6 s benefit over 4 Hz in shortening the distraction time of drivers. In terms of frequency, 5 Hz produced the greatest benefit to drivers according to the trends observed in the dynamic results. This shows that, overall, 5 HZ Compliant could be the most viable configuration.
- Participants indicated a preference to higher volume configurations despite a greater number of negative response themes and concerns toward them. When factoring in the concerns specified according to participants in their feedback, the 5Hz+CHMSL may be the most optimal choice of the volume cohort (not considering the 5Hz Compliant baseline) as the 5Hz+Beacon was often seen as an impractical option for some and the

5Hz+Reverse raised concerns regarding its creation of visual discomfort and its reported resemblance to an emergency or police vehicle.

- While dynamic testing showed no statistically significant differences among the alternative configurations and the default hazards, the results suggest that using frequencies and light volumes that are outside of FMVSS compliance are viable options as no ill effects in driver behavior were observed. This supports the idea that higher frequencies and additional light sources could be used to enhance perception (e.g., a higher sense of urgency) without negatively affecting safety.

9 REFERENCES

American Automotive Association, A. (2020). Hazard Light Use. Retrieved from https://drivinglaws.aaa.com/tag/hazard-light-use/

Driver Training, L. (2020). When should you use your hazard lights? Retrieved from https://www.drivingtests.co.nz/roadcode-questions/car/emergencies/when-should-you-use-your-hazard-lights-c/

Greenwell, N. (2013). *Effectiveness of LED Stop Lamps for Reducing Rear-End Crashes: Analyses of State Crash Data*. Retrieved from

Li, G., Wang, W., Li, S. E., Cheng, B., & Green, P. (2014). *Effectiveness of Flashing Brake and Hazard Systems in Avoiding Rear-End Crashes*. Retrieved from

Llaneras, R., Neurauter, L., & Perez, M. (2010). *Evaluation of Enhanced Brake Lights Using Surrogate Safety Metrics*. Retrieved from

National Highway Traffic Safety Administration, N. (2007). FMVSS 108. In.

National Highway Traffic Safety Administration, N. (2009). *Initial On-Road Evaluation of Candidate Rear Lighting Configurations*. Retrieved from

Phelan, M. (2020). Your car's emergency flashers could get a major upgrade soon — and here's why. Retrieved from https://www.freep.com/story/money/cars/mark-phelan/2020/12/05/car-emergency-flashers-upgrade-help/3821201001/

Spicer, R., Bahouth, G., Vahabaghaie, A., & Drayer, R. (2021). Frequency and cost of crashes, fatalities, and injuries involving disabled vehicles. *Accident Analysis and Prevention, 152*.

Terry, T., Fitchett, V., & Gibbons, R. (2020). Evaluation of traffic behavior in response to alternative police lighting. *Accident Analysis and Prevention, 144*. Retrieved from https://www.sciencedirect.com/science/article/pii/S0001457519318561?casa_token=IUwm3HR1BOQAAAAA:bWw0O6UULyLeEE6gPk_h4JQni0mVq9ttHIqidj7pCfY2mVFGp4pf2_jT440jiywn6nE5Ze-OYw

United Nations Economic Commission for Europe, U. (2019). Acts Adopted By Bodies Created By International Agreements. *Official Journal of the European Union*.

Wierwille, W., Lee, S., & DeHart, M. (2003). *Enhanced Rear Lighting and Signaling Systems Task 2 Report Testing and Optimization of High-Level and Stopped/Slowly-Moving Vehicle Rear Signaling Systems*.

Wierwille, W., Llaneras, R., & Neurauter, L. (2009). *Evaluation of Enhanced Brake Lights Using Surrogate Safety Metrics Task 1 Report Further Characterization and Development of Rear Brake Light Signals*. Retrieved from https://one.nhtsa.gov/Research/Human-Factors/Rear-signaling

e

10 APPENDIX

10.1 Appendix A: Participant Screening Criteria

- Must have a valid driver's license.
- Must drive at least 2 times per week.
- Must be a U.S. citizen or hold a green card and be willing to complete a W9 tax form which includes providing their SSN.
- Must have normal (or corrected to normal) vision.
- Must be able to drive without sunglasses or lenses that darken while inside a vehicle.
- Must not be sensitive to bright lights.
- Must not have a history of eye injury or eye surgery other than cataract surgery.
- Must not have participated in a previous surprise/deception study at VTTI.
- Must not have any mobility limitations, and must be able to drive an automatic transmission without assistive devices.
- Must not have a heart condition which limits their ability to participate in certain activities.
- Must not have a history of neck or back conditions which limit their ability to participate in certain activities.
- Must not have a history of brain damage from stroke, tumor, head injury, recent concussion, or disease or infection of the brain.
- Must not have uncontrolled diabetes.
- Must not have current respiratory disorder/disease requiring oxygen.
- Must not suffer from light-induced migraines, or have, on average, more than one migraine or severe headache per month during the past year.
- Must not have epilepsy or have had seizures or lapses of consciousness in the past 12 months.
- Must not have current problems with inner ear, dizziness, vertigo, or balance problems.
- Must not have had any major surgery within the past 6 months including eye surgery.
- Cannot currently be taking any substances that may interfere with driving ability or cause drowsiness.
- Pregnant women will be encouraged to speak to their physician about participation before being schedule to participate. They will be emailed a copy of the consent form to show to their physician.
- Must have normal or corrected to normal hearing, and must be able to hear and follow researcher's verbal directions while driving.
- Must not have caused an injurious accident in the past 3 years.
- Must not have been convicted of more than two driving violations in the past 3 years.

10.2 Appendix B: Static Survey Sample Sheet

Condition 1

1) On a scale from 1 to 5 where 1 is "no discomfort" and 5 is "high discomfort", how would you rate the amount of discomfort you are experiencing due to the glare from the hazard lights?

1	**2**	**3**	**4**	**5**
No discomfort				High Discomfort

2) On a scale from 1 to 5 where 1 is "no annoyance" and 5 is "high annoyance", how would you rate the level of annoyance you are currently experiencing due to the hazard lights?

1	**2**	**3**	**4**	**5**
No annoyance				High Annoyance

3) On a scale from 1 to 5 where 1 is "no urgency" and 5 is "high urgency", how would you rate the urgency being conveyed by the hazard lights?

1	**2**	**3**	**4**	**5**
No urgency				High Urgency

4) Do you have any other impressions of the current hazard light pattern?

   ☐ Frequency
   ☐ Color
   ☐ Pattern
   ☐ Location on the vehicle

   Others (please specify): _______________

5) How do you think you would react if you happened upon a vehicle with this hazard light pattern while you were driving?

☐ Merge behind vehicle
☐ Slow down
☐ Move over to the lane furthest from the parked vehicle
Others (please specify):______________________________

10.3 Appendix C: Alternative Charts for Preference and Safety

An alternate visualization of the data in Table 12 is shown in Figure 32**Error! Reference source not found.**.**Error! Reference source not found.**.**Error! Reference source not found.**. The colors of each horizontal bar represent the pairing between the configuration listed to the left and that configuration. The number and length of the bar indicate the number of times the configuration listed to the left was preferred to the configuration indicated by the color. In other words, the longer the bar, the more times the configuration listed to the left was preferred. The results show that the 4Hz Compliant configuration was preferred more often than other frequency configurations, but the difference is small.

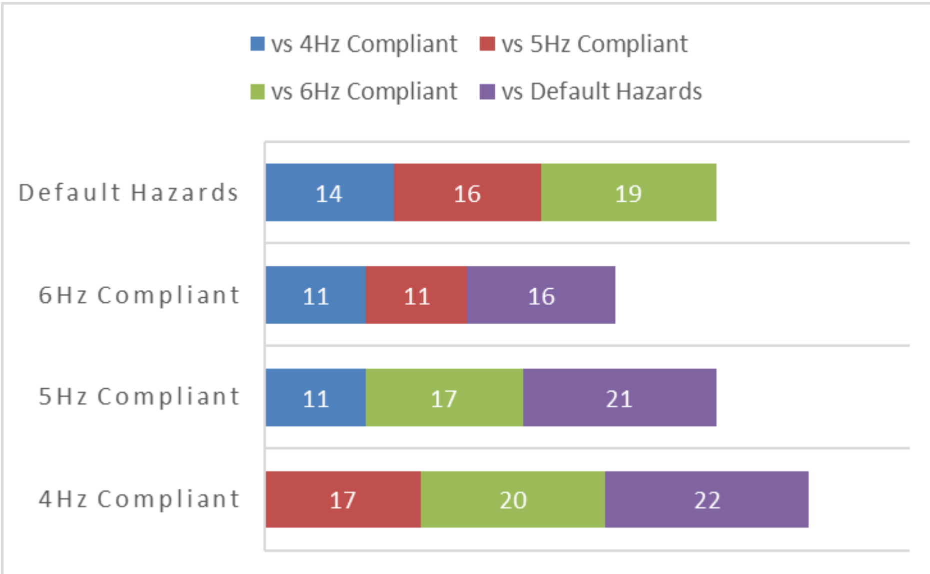


Figure 32: Flash frequency comparisons for preference shown via horizontal bars

Figure 33 shows the actual number of responses for each comparison shown in Table 13. Overall, the 4Hz Compliant configuration was selected more often as a safer configuration but by a narrow margin. The default hazard system was considered the safer option the fewest number of times.

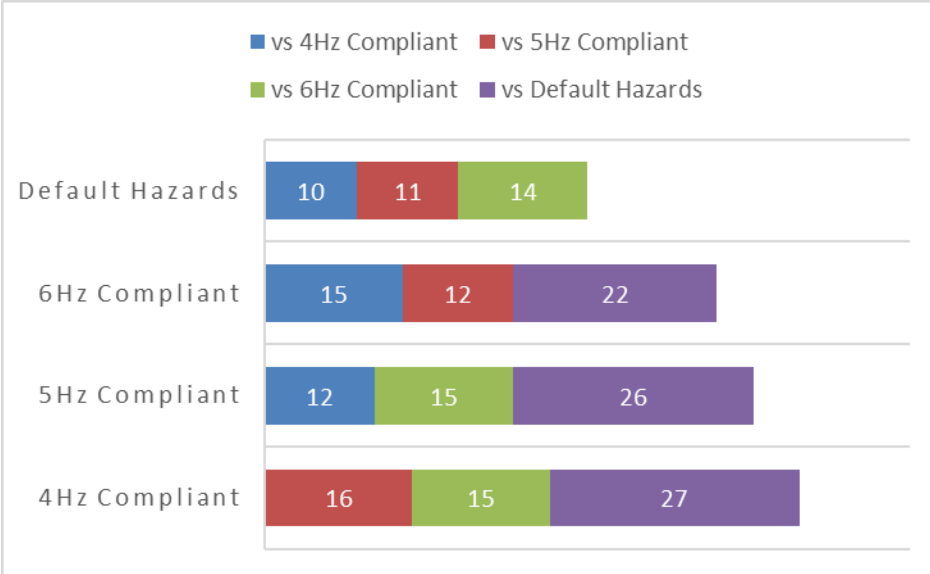


Figure 33: Flash frequency comparisons for safety shown via horizontal bars

Figure 34 shows the overall relationship among the cohort for data presented in Table 14. In general, the 5Hz+Beacon configuration was most preferred and performed similarly to the 5Hz+CHMSL. In head-to-head comparisons, the 5Hz+Beacon was preferred to the 5Hz+CHMSL 22 of 34 trials. The 5Hz+Reverse configuration was least preferred.

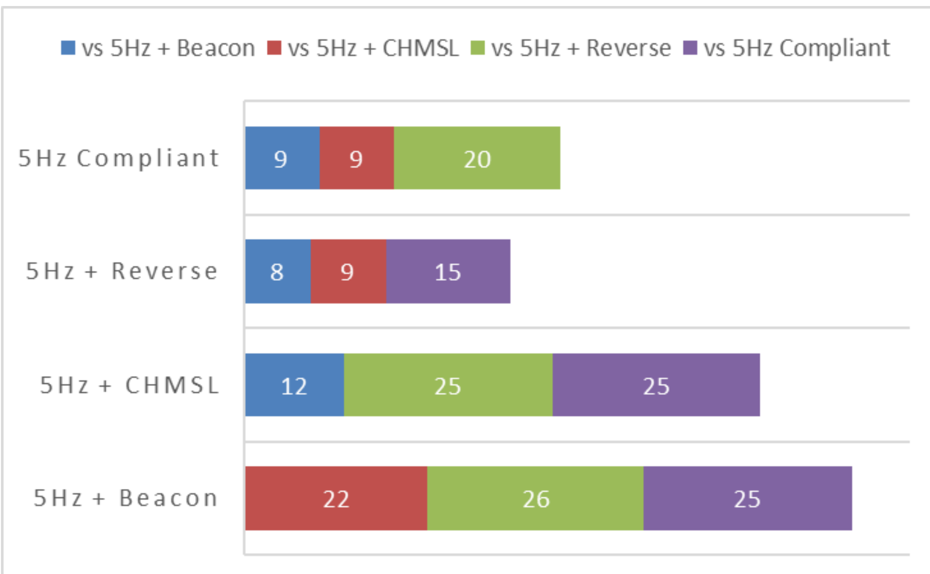


Figure 34: Light volume comparisons for preference shown via horizontal bars

Figure 35 shows the overall relationship among the cohort for data presented in Table 15. The 5Hz+Beacon was considered the safest configuration overall. Once again, the 5Hz+CHMSL and 5Hz+Beacon configurations performed similarly until their head-to-head comparison. Like the results previously shown for preference, the 5Hz+Beacon was considered the safer option to the

5Hz+CHMSL, 27 of 35 trials. The 5Hz Compliant configuration was considered the least safe overall.

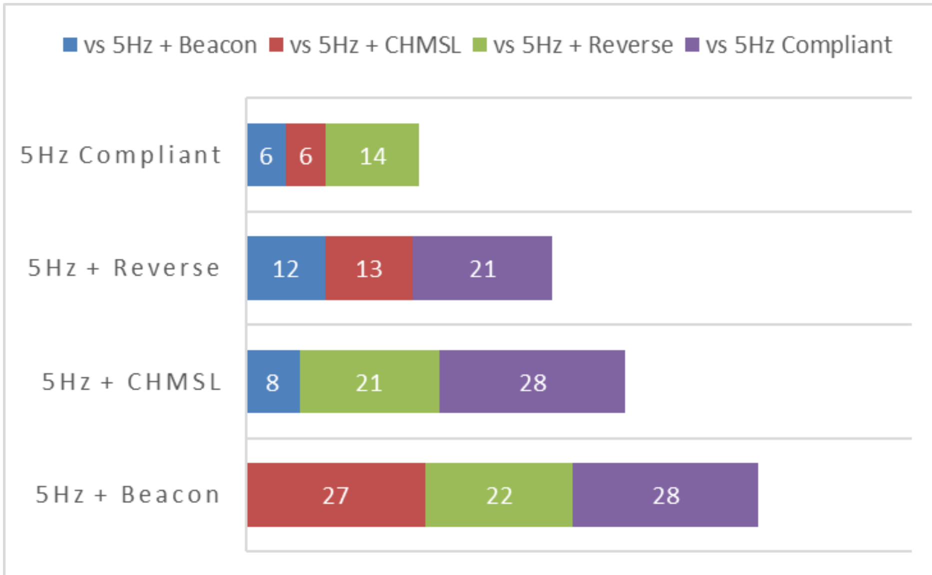


Figure 35: Light volume comparisons for safety shown via horizontal bars

10.4 Appendix D: Sample Order Sheet

Dynamic					
Lap	**Direction**	**Distance**	**Condition**	**Preset**	**Task**
1 (Practice)	Down		Parking Lights		
	Up		Parking Lights	98.1	102.1
2	Down	200	Default Hazards	102.1	96.7
	Up		Parking Lights	96.7	89.1
3	Down	600	Default Hazards	89.1	96.3
	Up		Parking Lights	96.3	105.3
4	Down	200	4Hz Compliant	105.3	99.1
	Up		Parking Lights	99.1	102.3
5	Down	600	4Hz Compliant	102.3	94.9
	Up		Parking Lights		

Ratings	
Condition	**Configuration**
1	5Hz+Beacon
2	4Hz Compliant
3	5Hz+Reverse
4	6Hz Compliant
5	Default Hazards
6	5Hz Compliant
7	5Hz+CHMSL

Comparisons		
Condition	**Config 1**	**Config 2**
1	5Hz+CHMSL	5Hz+Beacon
2	5Hz Compliant	5Hz+Reverse
3	5Hz+Reverse	5Hz+Beacon
4	5Hz+Beacon	5Hz Compliant
5	5Hz+CHMSL	5Hz+Reverse
6	5Hz Compliant	5Hz+CHMSL

Confusion	
Condition	**Config**
1	5Hz Compliant
2	5Hz Comp + Lightbar
3	Light Bar