Study to Understand the Influence of Emergency Vehicle Color, Reflectance, Signing/Arrow Boards, and Lighting Configurations in Reducing Responder-Involved Crashes

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This study aimed to reduce responder-involved crashes by improving the visibility and conspicuity of Road Ranger Service Patrol (RRSP) vehicles. The research combined a comprehensive literature review, a national survey of 44 agencies, and field testing of 16 distinct scenarios across three Florida highways (I-4, SR 429, and Florida Turnpike). Scenarios tested various combinations of emergency lighting colors, flash patterns, mounting heights, arrow/message board messages, and cone placements to evaluate their impact on driver compliance with the Move Over law. Red/white and red lights, higher light placements, directional arrow boards, and cone deployments were found to significantly improve move-over rates, in some cases by over 30%. In parallel, three vehicle marking designs were developed, focusing on maximizing visibility and public recognition through strategic use of color, reflectivity, and FDOT branding. A design featuring a fluorescent yellow-green base and retroreflective chevron markings received the highest preference in stakeholder evaluations. The recommended marking strategy divides vehicle surfaces into three zones: Safety (rear chevrons), Information (service messages and contacts), and Identity (FDOT and program branding). The study also highlighted the importance of uniform vehicle design to improve compliance, public perception, and integration with emerging vehicle technologies. FDOT is encouraged to adopt these recommendations incrementally through vehicle procurement and attrition cycles to enhance safety outcomes for RRSP operators statewide.</td></tr>
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"The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Florida Department of Transportation."

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Executive Summary

The Florida Road Ranger Service Patrol (RRSP) plays a fundamental role in enhancing highway safety by assisting motorists, detecting incidents, and supporting other emergency responders. However, the unique nature of their roadside operations places them at high risk. Between 2014 and 2021, 247 RRSP vehicles were struck, resulting in 47 injuries and eight fatalities since 2001. Recognizing the urgent need for improved safety, the Florida Department of Transportation (FDOT) partnered with the University of Florida to investigate enhancements to RRSP vehicle design to improve driver compliance with Florida's "Move Over" law.

This research evaluated the impact of multiple countermeasures including emergency lighting configurations, arrow/message boards, vehicle color schemes, markings, and graphic placements. The project began with an extensive literature review and a national survey of 44 agencies across 30 states to capture current best practices and agency-level standards for emergency lighting, color, flash pattern, intensity, mounting height, and supplementary devices like cones and message boards.

An observational study was then conducted with FDOT District 5, AutoBase (RRSP contractor), and the Florida Turnpike Enterprise. Testing at three locations (I-4, SR 429, and Florida Turnpike) involved 16 unique scenarios that combined different lighting colors, flash patterns, mounting heights, arrow board messages, and cone deployment. Results indicated that red/white and red lights, higher mounting positions, and directional arrow board messages significantly increased driver compliance. The presence of cones also enhanced move-over behavior by as much as 34% compared to no-treatment scenarios.

In parallel, the research team developed improved RRSP vehicle markings. Existing vehicles use a white base with reflective decals, but the study introduced three new high-visibility designs. Through stakeholder engagement, the design featuring a fluorescent yellow-green base with bold retroreflective lettering and chevron patterns (Design Option C) emerged as the most preferred. The team also developed a functional layout categorizing vehicle surfaces into three zones: Safety (rear markings), Information (service and contact details), and Identity (FDOT and program branding).

This report synthesizes all findings, from technical evaluation to stakeholder input, into practical design recommendations. FDOT is encouraged to adopt these changes incrementally during new vehicle procurement cycles. These enhancements have the potential to significantly reduce responder-involved crashes, elevate public awareness, and strengthen compliance with Florida's Move Over law.

Chapter 1. Introduction

1.1 Background

Ensuring the safety of Florida's Road Ranger Service Patrol (RRSP) operators is of utmost importance due to the challenges they encounter while monitoring and patrolling the state's roadways. Incidents such as vehicle collisions, injuries, and tragic loss of lives highlight the critical need to address safety concerns promptly. With 247 RRSP vehicles struck, and 47 Road Ranger injuries reported since 2014 (FDOT, n.d.-b), the Florida Department of Transportation (FDOT) is steadfast in prioritizing research and implementing safety measures to enhance the well-being of Road Ranger operators.

Carrick et al. (Carrick et al., 2018) report on a project sponsored by the FDOT Research Center which focused on RRSP safety. Traffic crash reports and surveys of Road Ranger operators were utilized. The findings highlighted the heightened risk faced by Road Rangers, especially in struck-by crashes involving parked RRSP vehicles. Responding to these findings, FDOT is taking proactive steps to address the issue by improving RRSP vehicle visibility and conspicuity through the incorporation of emergency lights and markings.

The ongoing study, sponsored by FDOT, aimed to enhance RRSP vehicle visibility and conspicuity to improve overall RRSP safety. The primary objective was to develop recommendations on emergency lighting, vehicle colors, markings, the use of dynamic message boards, and graphic placement to influence driver compliance with Florida's "Move Over" law. The main goal was to understand the effects of different emergency light colors and flash patterns on human eyes, with the aim of enhancing the conspicuity, visibility, and reflectivity of RRSP vehicles in varying light and weather conditions.

1.2 Road Ranger Service Patrol in Florida

The Florida Road Ranger program, operated by the FDOT, is dedicated to enhancing safety and traffic flow on major highways and interstates. It provides incident management response services and complimentary highway assistance, aiming to prioritize the safety of both emergency responders and motorists. The program's mission is to offer services during incidents, minimizing delays, and improving safety for everyone on the road. Road Rangers, operating in mobile units, patrol congested areas and high-incident zones along freeways, providing direct assistance to motorists in various scenarios, including vehicle breakdowns, fuel delivery, debris clearing, crash assistance, and addressing minor mechanical issues.

Funded by FDOT and its partners, the program's services are contractually arranged by individual FDOT districts, the Turnpike Enterprise, Expressway Authorities, and construction contractors on major projects. These contractors own and maintain the Road Ranger vehicles, adhering to established standards for vehicles, equipment, tools, and expendables used within the program. The approximately 150 vehicles statewide, collectively working to improve roadway safety and assist stranded motorists, are typically white with the Road Rangers logo affixed to the rear and sides as observed in Figure 1.

Figure 1: Florida Road Ranger Vehicle

While each contractor may have a different make of vehicle, the vehicles uniformly follow established standards (FDOT, 2019). Road Ranger services are provided by all seven Florida Department of Transportation Districts and Florida Turnpike. The operational hours vary, with Districts 1, 4, 5, 6, and 7 operating 24/7, District 2 operating from 5:30 am to 7:30 pm, and Florida Turnpike operating from 6:00 am to 10:00 am and from 4:00 pm to 8:00 pm.

Established two decades ago, the Road Rangers program's standard vehicle requirements were developed over time. However, no scientific study has been conducted to evaluate the optimal standards for the vehicles, including lighting and markings, to reduce crashes involving

Road Ranger personnel.

1.3 Current Practices and Vehicle Requirements

The minimum standards for Road Ranger vehicles encompass several key criteria (FDOT, n.d.-a). These include the requirement for a 3/4-ton, full-size pickup truck featuring an extended cab with four doors and a long bed designed to accommodate equipment. Furthermore, each vehicle must be equipped with functioning seat belts for all passengers and an automated vehicle location (AVL) system, providing essential information such as latitude, longitude, vehicle number, speed, and direction. The vehicles must maintain a white color and be distinctly marked with approved FDOT markings that include the FDOT logo, SunGuide® logo, "ROAD RANGERS," and "FREE SERVICE". Additionally, the vehicles must display "Dial *FHP" in white letters on a blue background, and a three-digit number for vehicle identification following a specific numbering sequence.

By Administrative Rule, the Secretary of the FDOT has designated RRSP as "Emergency Vehicles" under Florida Statutes section 316.072(5), specifically for purposes of stopping and turning, irrespective of the law and for Move Over purposes. Any variations to the specified vehicle standards necessitate approval from the State Traffic Operations Engineer. Each vehicle must be equipped with specific items at the start of each shift. In the event of malfunction or depletion during the shift, the Road Ranger operator is responsible for promptly replenishing or replacing these items to ensure the maintenance of required quantities.

The existing vehicle design as shown in Figure 1 integrates a roof-mounted emergency light. The rear-facing lights on the bar display red and white colors, while amber is employed at the front. A vehicle-mounted arrow/message board showcases six standard approved messages, including directional arrows. The common lane blocking display is an arrow that directs drivers to the available lane and a “caution” mode for shoulder incidents. The intensity of the arrow board adjusts for day and night conditions and operations independent of other vehicle lighting systems. While the Road Rangers are engaged at an event, the cones are placed in a tapered structure in order to guide the oncoming traffic away from the incident. However, adequate fine tuning of the placement distance is required for optimum results.

1.4 Scope and Objective

This project aimed to improve Road Ranger safety by understanding RRSP vehicle visibility and conspicuity with emergency lights and markings. It aimed to explore human reactions and responses to different emergency lighting configurations in daytime conditions and to develop enhanced vehicle marking designs resting on the principles of visibility and conspicuity.

The main objective of this project was to develop a set of recommendations on emergency lighting, vehicle colors, markings, use of dynamic message boards, and placement of graphics to influence driver compliance with Florida's Move Over law. These laws serve as a tactic in safeguarding roadside workers. It is important to investigate ways to improve compliance and explore additional approaches to achieve the overarching goal of ensuring that drivers maintain a more considerable buffer zone between their vehicles and road service workers.

The research team conducted observational research and a detailed emergency vehicle marking design to come up with a vehicle design resting on the principles of visibility and conspicuity. The project began with identification of the best practices for lighting and marking through an extensive literature review. As a part of this task, the research team also conducted a nationwide survey spanning to 44 agencies across 30 states to understand agencies wise standards and processes of state service patrol operations. The conducted survey and results can be found in Appendix B. This was followed by an observational study conducted at three distinct locations in Florida. In the study, the research team deployed 16 pre-designed scenarios and measured the Move over Compliance (MOR) across each of them to come up with effectiveness of different safety countermeasures such as cones, emergency vehicle lighting and message boards. The study was followed by a marking design effort where the team designed the base RRSP vehicle resting on design principles of zones related to safety, recognition and branding. Finally, the developed designs were evaluated through a stakeholder survey.

All of this effort is presented in each chapter of this report. Following chapters discuss the literature review, the observational study and the marking design process in detail.

Chapter 2. Literature Review

This section of the report illustrates effectiveness of different countermeasures such as emergency vehicle lighting systems, arrow/message boards and markings on increasing move-over compliance resting on the principles of visibility and conspicuity. As a part of this effort, a nation-wide agency survey was also conducted to understand the state service patrol practices across the US, which can be found in Appendix – B.

2.1 Principles of Visibility and Conspicuity

Over the past decade, numerous law enforcement officers, firefighters, and emergency responders were killed or injured in roadside crashes. This explains the importance of addressing the interrelationship between humans, vehicles, and the environment while designing any strategy. Two of the most fundamental principles that are critical and must be addressed are visibility and conspicuity.

According to a study by FEMA (FEMA, 2009), visibility can be defined as the degree to which the vehicles are detectable by other drivers and pedestrians, influenced by various factors like vehicle size, color scheme, conspicuity features, warning devices, and environmental conditions. Likewise, Cook et al. (Cook et al., 1999) define conspicuity as "the ability of a vehicle to draw attention to its presence, even when other road users are not actively looking for it." This study also talks about how the conspicuity of large vehicles and the perception of closing speed to them are contributory factors in incident or crash causation. This can be improved by providing appropriate luminance and color contrast and outlining the vehicle form (J. Bullough et al., 2021).

It is recognized that the human visual system does not detect the absolute luminance levels of various areas in a visual scene, but rather the contrast between the luminance levels of adjacent areas (Gibbons et al., 2008b). The human eye emphasizes the regions of differences in illumination because they possess the most information. As a result, these areas are the most conspicuous. Contrast sensitivity is a main determinant of one's ability to detect objects of interest in the visual scene. Therefore, simple photometry is not enough to reveal light conspicuity. Other fundamental factors include the ratio of light between adjacent locations, times of day, and colors that allow the human visual nervous system (Gibbons et al., 2008b). Two types of conspicuities were explored by Cole and Hughes (Cole & Hughes, 1984):

> **Attention Conspicuity:** This can be defined as the capacity of an object to attract attention, which might be measured by the probability of the object being noticed when the observer has not had his or her attention directed to its likely occurrence.
>
> **Search Conspicuity:** This can be defined as the property of an object that enables it to be quickly and reliably located by search.

To improve conspicuity on the road, emergency vehicles are often painted with light colors (e.g., white, yellow, or lime) and marked with retroreflective materials and/or fluorescent colors. Nevertheless, detecting emergency vehicles on the road remains a challenge for other road users because the efficacy of the emergency vehicle colors and markings is usually a function of environmental conditions. In general, light vehicle colors (e.g., white, yellow-lime, or yellow) are more visible during daytime under clear weather (Fire Administration, 2014). The influence of vehicle color on visibility is significantly reduced in adverse light conditions (Lardelli-Claret et al., 2002), particularly on small emergency vehicles at night. Similarly, retroreflective markings are only effective at night and rely on an external light source (FEMA, n.d.). Fluorescent materials enhance the conspicuity of an object during the daytime (Buonarosa & Sayer, 2007), but they offer no additional benefit at night because fluorescent colors only interact with ultraviolet radiation (Thomas J. Connelly, n.d.).

2.2 Lighting

The influence of lighting configurations in RRSP crashes involves a multitude of strategies in innovative vehicle design and road safety. Besides, the safety of RRSP vehicles during stationary operations is a concern that requires a comprehensive examination of various factors, with lighting playing a pivotal role. In particular, the introduction of light-emitting diode (LED) sources and advanced control systems–provides a wide range of options (Hiebner et al., 2022). This comprehensive literature review aspires to provide an in-depth analysis of studies related to lighting for RRSP vehicles emphasizing stationary scenarios. The focus areas include color coding; flash type, rates, and patterns; intensity; shape; and placement guidelines. The study spans the effect across different times during the day, vehicle motion types, and how individual bias can influence the overall effect. Finally, we have explored prevailing practices and standards to analyze how they differ across different emergency services domestically and in the international domain. Finally, all the literature, guidelines, and prevalent practices were gauged with the fundamental concepts of "visibility" and "conspicuity" that have been explained. The following sections delve deeper into different aspects of lighting and how they impact several aspects related to RRSP vehicle safety.

2.2.1 Color

The color of the RRSP vehicle lighting can have a direct impact on safety. The effect largely revolves around visibility and psychological impact. In general, emergency vehicles typically use five main colors of lighting (JTIC, n.d.). Red is the most common color used to denote an emergency vehicle. It is widely used across different emergency services like police and fire, with some exceptions in law enforcement vehicles in certain states. Likewise, amber is usually used as a cautionary warning light whereas white color is used to provide contrast to other colors. These colors are well known in the public domain, and as a result, compliance is generally on the higher side. Furthermore, the green color is usually limited to fire service or emergency management applications (Carrick & Washburn, 2012). They commonly signal the dedicated position of an incident command post (ICP).

However, the blue color probably has the widest variety of uses in the U.S. In many states, blue color serves as a contrasting color with red. A study conducted by Carrick and Washburn (Carrick & Washburn, 2012) mentioned that the overall compliance in Florida with the Move Over law was around 80% when red and blue colors were used, compared to 68.8% when only amber lights were used in a field study involving more than 9000 right-lane vehicles passing staged police stops in Florida. Likewise, some states use all blue lighting in their emergency vehicle platoons (JTIC, n.d.). A study by Bullough et al. (J. Bullough et al., 2021) recruited volunteers to drive a closed-course traffic incident scene at night under various experimental conditions. Four colors: blue, red, white, and yellow were used for the controlled experiment. As per the findings, the blue and red lights were rated as most visible, while the white and yellow lights were rated as least visible. Differently from the visibility ratings for the lights, the blue and white lights were rated as most glaring (lowest numerical rating values) while the red and yellow lights were least glaring. The results of this study suggest that when a flashing light is judged as highly visible, it does not necessarily directly follow that the more visible light will be judged as more glaring. Similarly, in the study by Flannagan and Devonshire (M. J. Flannagan & Devonshire, 2007a) they used red and blue lamps to compare the visibility and glare of the vehicles across different conditions. As per their findings, the blue lamps showed higher conspicuity and had a lesser glare effect. In general, the color also resulted in longer detection distances and better overall performance in nighttime conditions. Similarly, Flanagan et al. (M. Flannagan, 2008) recommend using bluer colors in general and using color coding for indicating traffic blockages. The New York State Police also began using blue lamps visible to the rear of their vehicles in 2006 as a countermeasure for the vehicles being rear-ended, partly based on indications that the blue lamps had a visibility advantage over red at night (M. J. Flannagan & Devonshire, 2007a). Florida Statutes (Florida Administrative Code 33-602.701, n.d.; Florida Statutes 316.2397, 316.2398, 316.241, n.d.) have special guidelines on the use of different colors for different types of emergency vehicles.

Table 1 presents different Florida statutes and how different colored lighting is used in different emergency vehicles (Extreme Tactical Dynamics, n.d.; Guardian Angel, n.d.).

Table 1. Florida Statutes Commentary on Lighting (Extreme Tactical Dynamics, n.d.; Guardian Angel, n.d.)

<table>
<tr><th>Vehicle</th><th>Florida statutes</th><th>Remarks</th></tr>
<tr><td rowspan="2">Police</td><td rowspan="2">Police; probation; parole officer; state-licensed law enforcement equipment sales and repair staff (while working); FDOC; county corrections
FS 316.2397(2)
FS 843.081
FAC 33-602.701</td><td>Blue lights; sirens in emergencies</td></tr>
<tr><td>Amber lights, at scene only</td></tr>
<tr><td rowspan="3">Fire</td><td rowspan="2">Fire department; fire patrol
FS 316.2397(3)
FS 316.2398</td><td>Red or red and white; must be visible from front and rear; sirens</td></tr>
<tr><td>Amber lights, at scene only</td></tr>
<tr><td>Volunteer firefighter – Only active members authorized by fire chief: and
Only en route to station or scene
FS 316.2398</td><td>Red or red and white; must be visible from front and rear</td></tr>
<tr><td>Ambulance</td><td>Medical staff physicians or technicians of state-</td><td>Red; sirens</td></tr>
</table>

Vehicle	Florida statutes	Remarks
	licensed medical facilities; volunteer ambulance services; ambulances FS 316.2398 FS 316.2399	Amber lights, at scene only
Bus	In emergency only FS 316.2397(3) FS 316.2398 FS 316.2399	Red, front and rear, shines on roadway to signal an in-vehicle emergency
Taxicab	In emergency only FS 316.2397(3) FS 316.2398 FS 316.2399	Red, front and rear, shines on the roadway to signal an in-vehicle emergency
Wreckers (towing)	During roadside recovery. During return if the operator deems it necessary. FS 316.2397(3)	Amber rotating or flashing lights, day or night
Wrecker (carrying)	No lights unless protrusion create a hazard FS 316.2397(3)	Amber rotating or flashing lights, day or night
Construction and road maintenance	Road or street maintenance equipment, road or street maintenance	Amber lights

Vehicle	Florida statutes	Remarks
	vehicles, road service vehicles, refuse collection vehicles, petroleum tankers, and mail carrier vehicles FS 316.2397(4)	
	When in operation and where a hazard exists: Road maintenance and construction equipment and vehicles FS 316.2397(5)	Flashing white lights; Flashing white strobe lights
	When workers are present: Construction equipment in a work zone on roadways with a posted speed limit of 55 miles per hour or higher FS 316.2397(5)	A combination of flashing green, amber, and red lights
	Commercial motor vehicle or trailer designed to transport unprocessed logs or pulpwood. FS 316.2397(4)	Amber light affixed to rearmost point of vehicle or trailer
Farmworker transport	School buses and vehicles	Flashing white strobe

Vehicle	Florida statutes	Remarks
	transporting farm workers. FS 316.2397(5)	lights
Utility vehicle	Vehicles of private service corporations FS 316.2397(3)	Amber lights, at the scene only
Escort vehicle	During escort FS 316.2397(3)	Amber lights
Municipal agencies	Mosquito control, emergency vehicles FS 316.2397(3)	Amber lights, at the scene only
State agencies	FWC, FDEP, FDOT, FDACS, FDOC, FDOH as authorized by agency, sheriff, or chief of police. FS 316.2397(3), (9)	lights and sirens
	Emergency Response function of FWC, DEP, and DOH while responding to an emergency.FS 316.2397(9)	Red lights
Private security vehicle lights	While engaged in security duties FS 316.2397(3)	Green and amber lights, 1:1
Construction contractor		

In some situations, different color combinations can be used for improvement in conspicuity. Brown et al. (Brown et al., 2018) evaluated the impact of four-color combinations, amber/white, green only, green/amber, and green/white on truck-mounted attenuators (TMAs) to get the optimum light bar configuration. Green/amber TMA lighting was the most preferred option in both daytime and nighttime conditions whereas green only TMA lighting was the least preferred. Similarly, some studies used flares as an addition to cones to increase the visibility of the responder vehicles. A three-part study (Blomberg et al., 2023a) examined various strategies to enhance the safety of towing and incident responder vehicles. The study concluded that, for the daytime movements, the flares in combination with cones decreased the occupancy of the adjacent lane. Furthermore, for nighttime movements, this arrangement showed a statistically significant reduction in speeds. The authors also mention developing standards for the use of various lighting systems at various intensities. They explain how the same intensity of light with the same color could enhance visibility in daytime conditions but could cause glare in nighttime conditions.

Similarly, a study by Gibbons et al. (Gibbons et al., 2008a) mentions different guidelines that can be used for the selection and application of warning lights for different operations along a roadway. The literature mentions that the vehicle emergency lighting serves two fundamental functions: the first is to signal the approach of an oncoming vehicle, and the next is to warn the drivers regarding any stoppage of the emergency vehicles along the roadway. They are pivotal when it comes to drawing the attention of the roadway user in high-speed traffic (Vos, 1971). Likewise, they can also be used to create awareness regarding the locations of Road Ranger Service Patrol (RRSP) vehicles along any road segment (Kamyab & Mcdonald, 2003). Five principal types of coloring patterns exist:

- Red: Known to be mostly associated with emergency vehicles
- Amber: Generally used as cautionary warning lights
- White: Used in contrast with other colors
- Green: Largely limited to fire services or emergency management applications
- Blue: Used largely in various law enforcement vehicles.

Different parameters related to lighting have been studied in the past. Ullman and Lewis

(Ullman & Lewis, n.d.) studied different combinations of amber with blue and red and quoted that these combinations "may have some incremental benefit." Furthermore, in his study in 1971, Cox (Cox, 1971) emphasized that the brightness level of a flashing light is perceived as greater than a fixed light with the same lumen output. This led to a study by Hargroves in 1971 (Hargroves, 1971) where he explored how flashing lights on vehicles and roads work best for catching road user attention. The study concluded that during daylight hours, blinking amber lights and mechanical signaling arms are equally visible. However, during nighttime, amber lights significantly outperform, becoming the preferred method for visibility. Consequently, it is advised for vehicles to utilize blinking amber lights for signaling, ensuring they emit a brightness of 100 to 500 candelas for optimal nighttime visibility. Additionally, for enhanced safety, particularly in urban driving situations where proximity to other vehicles is a concern, these flashing lights should be mounted at the sides of the vehicle at a height level with the driver's head to facilitate easier detection by fellow motorists.

Similarly, Cox (Cox, 1971) further explored how our ability to perceive colors changes as we age, from 20 to 60 years old. The findings indicate a decline in color perception, varying from a 20% decrease in seeing red to an 80% decrease in seeing blue. Based on this, they claimed that red light serves as a more reliable signal for people within this age range when looking directly at it. On the other hand, blue light turns out to be more noticeable when it is in the corner of our vision. Finally, to improve the visibility of the railway-crossing flashing lights from different vantage points, they proposed using a mix of traffic-red and lunar-white lights as an effective yet inexpensive method. In the same way, he claimed that a person with normal vision can detect objects 1.5 times further than someone who is colorblind. Subsequently, they suggest implementing a flashing light system with adequate brightness to assist those individuals. This could also be achieved by incorporating blue or lunar-white lights alongside traditional red signals.

2.2.2 Flash Pattern and Rates

The flash pattern and rate of vehicle lighting play a crucial role in capturing attention and conveying urgency to other road users. Different patterns and rates can influence how quickly responders are visible and how an individual driver reacts to them. This directly impacts safety during emergencies. Holmes (Holmes, 1971) suggests that repetitive flashing signals with a maximum interval of 5 seconds retain observers' attention effectively. Similarly, Cook et al. (Cook, n.d.) and Hargroves (Hargroves, 1971) investigate the impact of flash frequencies on warning-beacon detection time, emphasizing the practicality of certain frequencies. This aspect explores the temporal dynamics of signaling for optimal attention retention. He cites the work of Cohen and Dinnerstein (J. Cohen & J. Dinnerstein, 1958), who investigated the number of flash frequencies that people can discriminate. They suggest that three or four flash frequencies could be used to code information. Besides, they also emphasize that reaction times for correctly identifying flash frequencies are less for higher frequencies-but still very long in terms of the time required in driving. Subsequently, they recommend 3 Hz as a practical maximum and state that the most suitable single flash frequency for vehicle flashing lights is 90±30 cycles per minute, or 1 to 2 Hz. Similarly, different patterns, like steady burning, flash-together, and flash-alternate patterns, were tested by Flannagan and Devonshire (M. J. Flannagan & Devonshire, 2007b) in their study. As per the findings, the flash-together pattern was rated as the most conspicuous. However, for pedestrian visibility, steady-burning lamps had better performance. A study by Bullough et al. (ERSI, 2021) used different types of random, alternating, on/off, and X-pattern lighting patterns in their vehicles and recommended a low flashing rate of 60 flashes per minute. Likewise, flashing lights can cause seizures in people with photosensitive epilepsy. Specifically, lights that flash 10 to 20 Hz are the most risky. Even lights as dim as 20 cd/m² can trigger seizures. It is safer to avoid using lights that flash more than 5 Hz. Also, lights flashing directly in front of someone are more dangerous than those off to the side (Gibbons et al., 2008b).

2.2.3 Type of Lighting

The type of lighting used in emergency vehicles can affect visibility, energy consumption, and maintenance needs. Selecting the appropriate lighting technology ensures that emergency responders are seen clearly in all conditions, enhancing their safety and operational efficiency. Differently colored lighting can be further grouped into four main types based on their characteristics (Gibbons et al., 2008a):

- Rotating Lights: Traditionally used but now less common in favor of newer technologies

- Fixed Flashers: Flash in a single direction, attracting attention through flashing on and off
- Strobe Lights: Flash in only one direction, used either individually or within a light bar arrangement
- Light-emitting Diode (LED) Lights: This] is preferred due to their efficiency, brightness, and reduced strain.

In a collaborative effort between U.S. Fire Administration (USFA) and the Society of Automotive Engineers (SAE), Wieder et al. investigated the use of non-blinding emergency vehicle warning lighting systems (FEMA, 2014). The report aimed to understand the relationship between warning lamps and safety by examining multiple variables related to the design and usage of these lights. Wieder et al. emphasize that the effectiveness of warning lamps depends on several factors such as light intensity, flash rate, color, and configuration of lamps. These variables are crucial in determining how drivers perceive and respond to emergency vehicles. The analysis suggests that the intensity of warning lamps plays a critical role in balancing their conspicuity against potential negative effects, such as glare and distraction.

Additionally, the research examines various types of crashes involving emergency vehicles, including those where an emergency vehicle is involved in the crash and pedestrian-related incidents near emergency vehicles. Concerns exist that warning lamps, due to factors like distraction or glare, might increase the risk of these types of crashes, particularly where a firefighter is involved as a pedestrian. Analyses based on multiple sources of crash data help categorize and understand the effects of warning lamps on various types of crashes. Similarly, Cook (Cook, n.d.) investigated the conspicuity of warning beacons according to flash type. He found that strobe warning beacons were subjectively considered to convey greater urgency, while rotating warning beacons were less annoying and minimized the effects of disability glare (Gibbons et al., 2008b).

Similarly, different sources of light have gained popularity over the years. From the tungsten filament lamps to the more recent LEDs, lights have been used for a multitude of applications. LED sources possess several characteristics that make them highly suitable for signal applications, including swift onset and offset times, simple temporal control of luminous intensity via current or voltage adjustment, vibrant saturated colors offering greater perceived brightness, and durable performance leading to extended useful lifespans when accompanied by adequate thermal design (J. D. Bullough et al., 2012). Table 2 presents various light sources and their several characteristics.

Table 2: Different light sources (J. D. Bullough et al., 2012)

Light Source	Efficacy (lm/W)	Life (hours)	Correlated Color Temperature (K)	Onset Time*
Tungsten filament lamp	12–20	750–4000	2700–3200	0.1-0.3 s
Fluorescen (incl. compact)	60–100	10,000–30,000	2700–7500	1-60 s
Metal halide	80–110	10,000–20,000	2800–5000	60-300 s
Xenon	30–60	1000–5000	5000–6000	1 μs
Light-emitting diode (white)	90–130	50,000–100,000	3000–8000	10-20 ns

** The onset time is marked to indicate the time it takes for each light source to reach 90% of its maximum light output.*

Furthermore, previous research has advocated for the standardization of warning signals to avoid confusion among motorists. However, achieving this standardization has been a challenge due to the lack of empirical safety data regarding warning lamps' impact on crashes. The report by Wieder et al. (FEMA, 2014) aimed to address this gap by leveraging crash data to draw inferences about warning lamp performance, drawing from existing research on vehicle lighting, signaling, and glare effects on driver visibility. This prior work helps provide insights into the potential effectiveness of warning lamps and their role in ensuring roadway safety for emergency responders. The subsequent phase of this research project focused on mitigating the disorientation of motorists caused by emergency warning lights. It delved into aspects such as lighting design, colors, flash rates, and the visibility and conspicuity of emergency vehicles, as well as strategies for operational mitigation. The project identified substantial differences in detection distances for pedestrians and emergency responders on roadways at night, emphasizing the importance of retroreflective markings for enhanced visibility.

2.2.4 Intensity Modulation and Wavelength

Modulating the intensity and choosing the right wavelength of light can significantly affect visibility, especially in diverse environmental conditions. Adjustments to these factors can help in minimizing glare and improve recognition, which is vital for the safety of emergency responders and the public. Cook (Cook, n.d.) found that high flash intensities minimize warning-beacon detection times for both day and night conditions (Gibbons et al., 2008b). The flash duration can be defined as the time period for which the light is turned on during a flashing cycle. As mentioned in Gibbons et al. (Gibbons et al., 2008b), Gerathewohl (GERATHEWOHL, 1953) and Brown and Gibbs (I. D. Brown & C. B. Gibbs, 1958) investigated reaction times with respect to several parameters like flash frequencies, durations, and on-off ratios. Similarly, the report also mentions that Brown and Gibbs found that as the flash frequency decreased in the range of 1.5 to 3 Hz, there was a corresponding decrease in reaction times, and Gerathewohl found a decrease in reaction time for signals with frequencies of 3 Hz. However, for signals with frequencies of 1 Hz and 0.33 Hz, he obtained shorter reaction times for longer flash durations.

Likewise, the flash wave pattern refers to the temporal distribution of light in the flash cycle. In his study Gibbons et al. (Gibbons et al., 2008b), mention the work done by Howard and Finch (J. Howard & D. M. Finch, 1960), who state that when flashes are present for longer than 50 ms, a square wave pattern is in general more effective compared to a triangular wave pattern. Another study in the report mentions the work done by Hargroves (Hargroves, 1971), which states that it is not practical to use multiple flashes as seen in marine buoys as the time taken to decipher these patterns will be longer, which may complicate the driving task. Furthermore, different literature talks about the standardization of lighting patterns to promote a uniform understanding of the topic. Kersavage et al. (Kersavage et al., 2018) and Bullough et al. (J. Bullough et al., 2019) have also reported that increasing the intensity of flashing lights at night can make pedestrians near vehicles more challenging to detect and identify in nighttime conditions. These findings imply that reducing nighttime intensities for flashing lights or establishing maximum limits, could potentially enhance first responder safety (ERSI, 2021).

Finally, the intensity and modulation of light within a practical time period must communicate its message in a period that is practical for driver perception (awareness and recognition).

2.2.5 Shape of Light

The physical design and shape of vehicular lights play a crucial role in determining the visibility of ERSP vehicles and the distance from which they can be observed. An effectively designed light shape can greatly enhance its overall effectiveness, ensuring that both the vehicles and the Road Rangers are easily noticeable from various angles and at significant distances. Regarding steady lights at threshold levels, several investigations, such as the one by Gibbons et al. (Gibbons et al., 2008b) have concluded that the size of the lamp does not significantly affect its conspicuity. Similarly, another study by Cole and Brown (Cole & Brown, 1968) highlighted that when the lamp achieves optimal luminance, its size becomes irrelevant in determining its visibility. Additionally, the number of warning beacons used also impacts conspicuity, as observed in research done by Cook et al. (Cook, n.d.). They found that the more warning beacons employed, the greater the perceived conspicuity. Specifically, four warning beacons were significantly more conspicuous than using just one, although they were significantly less conspicuous than using eight. However, it's important to note that the use of eight beacons resulted in more discomfort glare, although no clear relationship between the number of beacons and discomfort glare was identified (Gibbons et al., 2008b). These findings underscore the importance of both design and quantity when considering the visibility and safety of ERSP vehicles.

2.2.6 Placement of Lights and Light Bars

Emergency responder vehicle safety is of paramount importance, with visibility and conspicuity being critical factors. The placement of lights and light bars on these vehicles is a key consideration in enhancing safety and alerting nearby motorists. Studies by Hanscom and Pain (Hanscom & Pain, 1990) suggest that specific placement distances, such as 1,500, 1,000, and 500 feet in advance of a taper, significantly influence the effectiveness of warning lights. However, it's worth noting that additional signs at distances like 1 mile or 4 miles did not confer any advantage (Hanscom & Pain, 1990). Furthermore, the type of light and the method of flashing were found to have the most significant impact on driver response and lane-change time, with the number and placement of lights having a comparatively smaller effect (Gibbons et al., 2008b). The crucial factor, according to researchers, is ensuring that the lights are visible from all angles of approach. This comprehensive approach to light placement can significantly contribute to the safety and conspicuity of emergency responder vehicles on the road.

2.3 Arrow Boards

Arrow boards, vital elements in traffic control, play a crucial role in enhancing road safety by utilizing a matrix of elements capable of flashing or displaying sequences. These directional arrow boards provide essential warning and directional information, guiding drivers effectively. Various studies investigating arrow displays in the context of traffic management in work zones have yielded significant insights into their effectiveness (Graham et al., 1978)(Schrock et al., 2008)(Yin et al., 2016). Graham et al. (Graham et al., 1978) focused on the placement of arrow devices in long-term work zones, particularly at merge tapers. Their findings emphasized the effectiveness of arrow boards in guiding traffic out of closed lanes, especially when positioned at the start of the merge taper. However, the study identified limitations in diverse scenarios, such as route diversions or shoulder closures, suggesting that drivers may associate arrow displays more with leaving a lane than leaving the roadway.

Wieder et al. (FEMA, 2014) highlight the increasing adoption of directional arrow boards on fire department apparatus, underlining the importance of compliance with MUTCD requirements outlined in Section 6L.06 when integrating arrow boards into fire department vehicles. On fire department vehicles, arrow boards are expected to operate in three modes as shown in Figure 2 flashing arrow, sequential arrow, or sequential chevron; flashing double arrow; and flashing caution or alternating diamond mode. For effective nighttime operation, the boards must be capable of at least a 50 percent dimming from full brilliance to avoid adversely affecting oncoming driver vision. Apparatus-mounted arrow boards are subject to specific size requirements, emphasizing a 48-inch length for the arrow and a 24-inch width for the arrowhead, ensuring visibility at a minimum distance of 0.5 miles. The study (FEMA, n.d.) underscores concern about existing arrow boards and directional light bars potentially not meeting standards, diminishing their effectiveness. Recommendations include advising that vehicle-mounted arrow boards be placed as high as practical and equipped with remote controls and the vehicle itself feature high-intensity rotating, flashing, oscillating, or strobe lights.

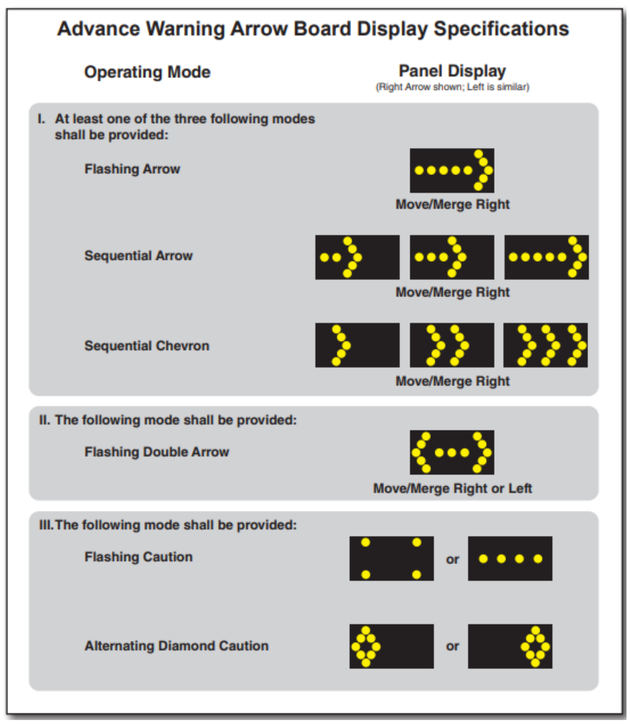


Figure 2: This diagram shows various advanced directional arrow positions (FEMA, 2014)

In a previous Texas-based study (Finley et al., 2006), the comprehension of information presented on trucks in a moving work convoy was evaluated using various signaling methods. The study revealed that a flashing arrow display directing traffic to move right was understood by only 66 percent of participants, contrasting with text-based CMS messages that achieved higher comprehension rates. This finding aligns with previous research, suggesting reduced effectiveness of flashing arrow displays when directing drivers beyond moving into an adjacent travel lane.

Wooldridge et al. (Wooldridge et al., n.d.) delved into the brightness levels of arrow panels and changeable message signs (CMSs) and their impact on driver behavior. Their investigation involved varying luminous intensity levels during daytime operations at long-term work zones, establishing a link between luminous intensity and lane-changing behavior. This emphasized the importance of considering the distance from which drivers perceive arrow panels, particularly during bright daytime conditions. The study concluded with recommended minimum luminous intensity values, providing valuable insights for improving the visibility and effectiveness of arrow displays in traffic management.

Schrock et al. (Schrock et al., 2008) conducted surveys with a focus group across multiple states to analyze the effectiveness of different arrow board types, including flashing arrow, sequential arrow, and sequential chevron. Preferences leaned towards sequential displays over flashing ones, perceiving sequential movement as indicative of a more critical situation. The study questioned the inclusion of the flashing chevron in future versions of the MUTCD. Examining multiple arrow displays in a work convoy, participants generally understood them to indicate a single lane closure, with a preference for staggered work vehicles. However, there was unanimous disapproval of mixing different arrow displays within the same work convoy, indicating potential credibility issues. Participants expressed interest in additional information via static signing on the back of shadow vehicles, emphasizing the need for clearer and more effective traffic control in short-duration, mobile, and moving work zones.

2.4 Markings

Numerous studies have delved into various facets of lighting systems for maintenance vehicles, ranging from color selection to configuration. However, a comprehensive guideline encompassing all relevant aspects of marking these vehicles is lacking. There exist no national laws or standards relative to vehicle lighting or reflective markings on law enforcement vehicles. For RRSP in Florida, the areas of investigation include retroreflectivity, placement strategies, patterns, utilization of arrow boards, and the incorporation of contour marking. Despite the individual insights provided by these studies, a unified and comprehensive framework that integrates findings across these diverse aspects remains an unexplored territory in the current body of research.

2.4.1 Retroreflective Tape

Retroreflective tape's primary purpose is to enhance the visibility of heavy trailers, particularly in dark conditions. Without the tape, many trailers remain virtually invisible to other road users until they are dangerously close, making tape crucial for safety. Studies have shown that the use of retroreflective agency logos or emblems could help improve emergency vehicle visibility and conspicuity.

Morgan (Morgan, 2001) demonstrated the effectiveness of retroreflective tape in increasing the visibility of heavy trailers and reducing side and rear impacts during dark conditions. Based on a statistical analysis of 10,959 crash cases from 1997 to 1999 by the Florida Highway Patrol and the Pennsylvania State Police, the tape reduced side and rear impacts in dark conditions by 29%. In "dark-not-lighted" situations, the reduction was 41%, and for injury crashes during dark conditions, there was a significant reduction of 44%. Retroreflective tape emerges as particularly effective in enhancing safety and reducing the severity of crashes involving heavy trailers.

Nevertheless, Gibbons et al. (Gibbons et al., 2008b) indicate that the retroreflective tape is not suitable as the only marking option on maintenance vehicles; however, this tape seemed to provide an additional benefit at night. During winter months, snowplow detection can be challenging due to the snow clouds they produce, covering taillights and hindering recognition, especially at night. Gibbons et al. [3] suggested considering the use of retroreflective strips on snowplows. A study by Stidger (Stidger, 2003) found that 8-inch-wide orange and fluorescent-orange magnetic strips, though having an insignificant impact on daytime driving, could improve vehicle visibility during nighttime or low-visibility winter weather.

2.4.2 Patterns and Chevron Marking

A recent study by Bullough et al. in 2021 (J. D. , S. A. P. A. S. E. Hiebner. Bullough, 2021) shows that retroreflective panels consisting of red and yellow reflective chevron markings meeting ASTM Type V specifications, commonly denoted as "super high intensity" material, when positioned near flashing lights, resulted in shorter distances to detect a simulated firefighter compared to scenarios where the markings were absent. Although the impact of the retroreflective markings alone did not show a statistically significant difference, an interesting finding was noted when considering their interaction with the intensity of the flashing lights (J. D. , S. A. P. A. S. E. Hiebner. Bullough, 2021). Notably, the difference in detection distances between scenarios with and without retroreflective markings was most noticeable when the intensity of the lights was at its highest level (J. D. , S. A. P. A. S. E. Hiebner. Bullough, 2021).

Similar results were observed in other studies as well. Some studies indicated that the presence of reflective markings with a retroreflectivity level exceeding the minimum (ASTM Type I) (American Society for Testing and Materials., 2019) requirements specified by NFPA might hamper drivers' ability to see emergency responders around their vehicles.

As previously mentioned, the chevron markings on the rear of the fire apparatus can take the form of alternating red and yellow or fluorescent-yellow or fluorescent-yellow-green stripes or stripes featuring "different and high-contrasting colors." However, there is limited published evidence supporting the specific color combinations or patterns for chevron-style markings on vehicles–and even less guidance on the optimal pattern or coverage area for retroreflective vehicle markings on emergency vehicles.

A study conducted by Harrison (Harrison, 2004) used photographs and video footage of vehicles, implementing marking schemes derived from principles found in existing literature. The goal was to showcase these schemes as being perceived as conspicuous by members of U.K. police agencies and the driving public in that country. The study concluded that a Battenburg (checkerboard) pattern presented a distinctive and attention-grabbing visual cue.

It is crucial to note, however, that the Harrison study did not include comparisons of various colors or patterns. Consequently, while the Battenburg pattern was recommended for police vehicles in the U.K., it is not necessarily deemed the optimal choice for both driver visibility and comprehension, as the study did not delve into such comparative analyses.

2.4.3 Contour Marking

Contour marking, utilizing retroreflective tape to outline the shape of heavy vehicles, has emerged as a valuable strategy for enhancing visibility and conspicuity on the road. The primary objective is to provide other road users with clear visibility of the vehicle ahead, enabling them to accurately perceive distance and closing rates. This is achieved through the implementation of full contour marking, indicating the vehicle's outline with a continuous line, or partial contour marking, which highlights the horizontal dimension with a continuous line and marks the upper corners for the vertical dimension.

To ensure the effectiveness of contour markings, the Australian Trucking Association has established specific criteria (Heavy Vehicle Visibility, 2003). These guidelines dictate that the total minimum length of retroreflective markings should cover at least 80% of the combined length of the vehicle, bumper to bumper, to ensure comprehensive visibility. When employing non-continuous stripes, their distribution and spacing must adhere to regulated standards to maximize their effectiveness. Additionally, the recommended installation height ranges from a minimum of 250 mm to a maximum of 1.5 m from the ground, with allowances made for certain vehicle designs. Adhering to these standards requires careful selection of materials. It is recommended to use tape that complies with UN ECE R104 (United Nations, 2010), ensuring that its dimensions meet specified standards. The choice of tape color should be customized according to the location and surface type, with a preference for Class 1A material, typically e-marked for quality assurance.

The efficacy of contour marking in enhancing vehicle visibility and safety has been extensively documented in research literature spanning several decades. Early studies, such as those conducted by Henderson et al. (Henderson et al., 1983) laid the groundwork for understanding the benefits of contour markings. Subsequent research by Schmidt-Clausen (Schmidt, 2000) further emphasized the significant role of contour markings in improving both side and rear visibility. Additional studies by Langham and Rillie (M. Langham & L. Rillie, 2002) and Tijerina et al. (L. Tijerina et al., 2003) have corroborated these findings, highlighting the comprehensive projection of a vehicle's shape facilitated by contour markings. Such visibility enhancements contribute significantly to overall safety, particularly in traffic incident management scenarios.

However, despite the proven effectiveness of contour markings, it is essential to recognize their inherent limitations, notably their finite lifespan. Research indicates that retroreflective contour markings typically experience a significant decrease in effectiveness after three years, with up to a 50% reduction in visibility. This underscores the importance of proactive measures, including regular compliance checks and scheduled maintenance, to ensure the sustained efficacy of contour markings on traffic incident management vehicles.

2.5 Other

2.5.1 Use of Cones

Cones emerge as a cost-effective and promising solution to prompt motorists to slow down or change lanes when encountering a traffic incident management vehicle. In our assessment of various technology readiness levels capable of eliciting the desired motorist behavior, cones were given due consideration. Despite their potential effectiveness, it's crucial to note that cones are not universally embraced or implemented on a broader scale.

Blomberg et al. (Blomberg et al., 2023b) conducted a study testing the implementation of three 28-inch tall retroreflective and fluorescent cones positioned at specific distances (11 ft, 29 ft, and 43 ft) behind a client car. The on-road experiment demonstrated that the addition of cones with the daytime light pattern at night resulted in a marginal reduction in Lane 1 occupancy, which was statistically insignificant. Daytime use of cones was associated with slight increases in Lane 1 vehicle speeds, with statistical reliability. The study's findings indicate that the incorporation of cones as part of broader countermeasures proved effective, especially in nocturnal conditions when combined with specific light patterns.

To delve further into industry perspectives, Blomberg et al. (Blomberg et al., 2023b) conducted an online survey targeting workers in the road service industry. The survey revealed favorable attitudes towards cones, with respondents expressing a readiness to use them, particularly when supported by research evidence. This suggests that the potential implementation of cones was contemplated based on the positive outcomes discerned during the field test.

Previous research by Allpress and Leland in 2005 (Allpress & Leland, 2010) found that cone arrangements at the entry points to roadwork sites effectively slowed traffic. The findings indicated that parallel rows of cones produced the greatest reduction in mean vehicle speeds. Subsequently, they suggested that the implementation of traffic cones, especially when arranged unevenly, results in significant speed-reduction effects. They recommended a specific arrangement of at least 16 cones spaced at decreasing intervals, emphasizing the effectiveness of this strategy against speeding within roadwork sites. The study concluded that traffic cones, due to their affordability, mobility, reusability, and ease of arrangement, are not only highly effective but also likely to be more convenient and cost-effective than alternative countermeasures. The adoption of unevenly spaced cones, as demonstrated in the present experiment, could play a pivotal role in reducing speed-related accidents within roadwork zones.

2.5.2 Use of Safety Vests

Arditi et al. (Arditi, n.d.) investigated highway construction and maintenance professionals' perceptions of the effects of night-time construction conditions on worker visibility and of issues associated with safety vests in night-time activities. Workers not wearing safety vests appear to be a small problem as are weather conditions. Respondents appear to have high confidence in safety vests as very few suggested that accidents were caused by the performance of safety vests. The design of safety vests should adhere to existing ANSI standards that specify the brightness and quantity of retroreflective materials but should particularly ensure adequate performance in wet weather conditions. If safety vests perform well under different lighting and weather conditions and if they are perceived by workers to be effective, all workers will be motivated to always wear them. Consequently, the frequency and severity of night-time accidents can be reduced, and labor productivity can be enhanced.

The summary table for this section can be found in Appendix A. The upcoming sections explain the observational study and vehicle marking design process that rest on the findings from this literature review process.

Chapter 3. Observational Study

3.1 Research Goal

The goal of this task was the testing of emergency lighting and message board use in Road Ranger Service Patrol (RRSP) vehicles in the furtherance of identifying characteristics that positively influence driver compliance with Florida's Move Over law.

3.2 Objectives

The objectives of the study can be grouped as follows:

- Identification of visual characteristics related to emergency lighting on RRSP vehicles that can positively influence driver compliance with Florida's Move Over law.
- Identification of visual characteristics associated with the use of dynamic message signs (DMSs) on RRSP vehicles that can positively influence driver compliance with Florida's Move Over law.

3.3 Methodology

The research team collaborated with a Florida Department of Transportation (FDOT) RRSP contractor, AutoBase, the FDOT District 5 in Central Florida, and the Florida Turnpike Enterprise in South Florida in an observational experiment. The goal was to simulate a realistic roadside event involving a disabled vehicle, an RRSP vehicle, and an RRSP operator. The scenario was designed according to the example scenarios for shoulder disabled vehicles (DAV) created by FDOT for the training purposes because the Manual for Uniform Traffic Control Devices (MUTCD) does not provide typical applications for traffic incidents, which are considered emergency events. Figure 3 provides an example of the typical shoulder event.

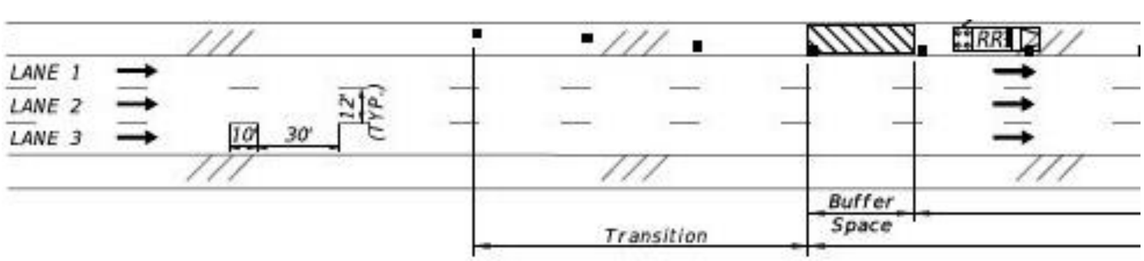


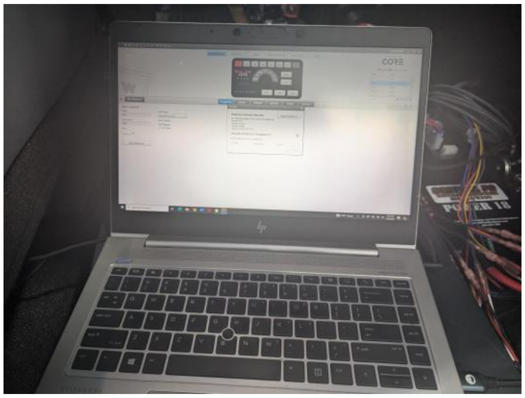
Figure 3: Example shoulder event with a Road Ranger present on an inside roadway shoulder.

At a typical response scene, the RRSP vehicle is positioned on the shoulder, parallel to the roadway. An attempt is made to position the vehicle to provide the driver with a safe exit from the the vehicle onto the shoulder. Parallel positioning maximizes the effective visibility of vehicle-mounted arrow/message boards, which have a limited field of view.

Standard operating procedure for the Florida RRSP is to deploy 5–7 traffic cones for all incidents immediately upon arrival. For longer duration incidents, additional temporary traffic control is required, and additional cones (up to 15) are commonly used. Channelizing devices are typically deployed at the edge line near the rear of the vehicle, spaced approximately 40 feet apart and aligned upstream in a diagonal pattern. Roadway skip lines provide a good approximation of spacing and are generally used. Figure 4 presents the image of the experiment layout at SR-429.

Figure 4: Experiment Layout at SR-429

Given the objective, the experiment assessed various variables, including messages displayed on arrow boards, color, pattern, and placement height of the lighting system. A description of these testing variables is presented in subsequent sections. Each scenario represented a distinct combination of variables, with each variable varied while keeping others constant to evaluate the marginal effect. A total of 16 scenarios was designed. A baseline scenario in which no treatment measures were applied was also included for comparison purposes. All scenarios were programmed using the **Whelen Core System** and implemented on the controllers for lighting systems and arrow boards. The description of the core system is presented in a subsequent subsection. Figure 5 illustrates the different components involved in the process, while Table 3 provides a comprehensive list of the scenarios.



(a)

(b)

(c)

Figure 5: Whelen core system components: (a) programming interface; (b) controller for lighting system; and (c) controller for arrow boards

Table 3: List of the experiment scenarios

Test	Configuration of Rear-facing Lights				Setup Summary		
	Arrow board (4)	Color (3)	Pattern (4)	Height (3)	Notes	Variable	Program
1	Blank/Down	None	None	None	4-Way Only	None	0
2	Blank/Down	None	None	None	4-Way Only With Cones	Cones	0
3	"Move Over" "It's the Law"	Red Only	Left/Right	Roof Mount	With Cones	VMS	1
4	"Caution" text + "Slow Down"	Red Only	Left/Right	Roof Mount	With Cones	VMS	1
5	Arrow	Red Only	Left/Right	Roof Mount	With Cones	VMS	1
6	Caution (4 Dots)	Red Only	Left/Right	Roof Mount	With Cone	VMS and Height	1
7	Caution (4 Dots)	Red Only	Left/Right	Utility Box Only	With Cones	Height	2
8	Caution (4 Dots)	Red Only	Left/Right	Top of Arrow Only	With Cones	Height	3
9	Caution (4 Dots)	Red Only	Left/Right	Roof Mount & Utility	With Cones	Color 1 Pattern 1	4
10	Caution (4 Dots)	Red Only	Inside/Outside	Roof Mount & Utility	With Cones	Color 1 Pattern 2	5
11	Caution (4 Dots)	Amber Only	Left/Right	Roof Mount & Utility	With Cones	Color 2 Pattern 1	6
12	Caution (4 Dots)	Amber Only	Inside/Outside	Roof Mount & Utility	With Cones	Color 2 Pattern 2	7
13	Caution (4 Dots)	Red/White	Left/Right	Roof Mount & Utility	With Cones	Color 3 Pattern 1	8
14	Caution (4 Dots)	Red/White	Inside/Outside	Roof Mount & Utility	With Cones	Color 3 Pattern 2	9
15	Caution (4 Dots)	Red Only	Direction Sequence	Roof Mount & Utility	With Cones	Color 1 Pattern 3	10
16	Caution (4 Dots)	Red Only	Full Pulse	Roof Mount & Utility	With Cones	Color 1 Pattern 4	11

3.4 Testing Parameters

Testing parameters describe the independent variables related to lighting device color, pattern, and placement, as well as the message board configuration. The following illustrations show how the RRSP lighting, arrow board, and use of temporary traffic control were used to alter the independent variables.

3.4.1 Base condition

For the base condition, the vehicle on the shoulder displayed no lights or warnings of any kind, other than the statutorily required hazard lights that are standard equipment on all vehicles and typical of a vehicle on the shoulder. The RRSP message board was dark, no traffic cones were deployed, and no emergency lights were activated or visible. As already mentioned, only vehicle hazard lights were used, as would be legally required for any vehicle on the roadway shoulder. This established a baseline for measuring approaching vehicle behavior. Figure 6 shows the graphical diagram of the base condition.

Figure 6: Base Condition

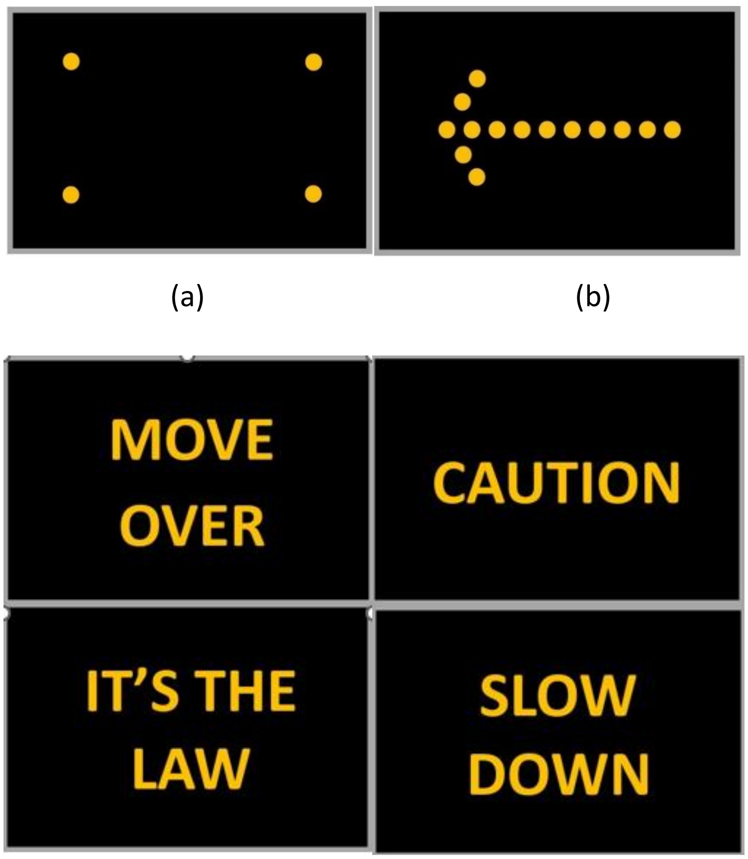
3.4.2 Test Condition

The test condition added different lighting components (colors, flash patterns, mounting height), arrow board displays (caution; arrow; “Move Over”/“It’s the Law”; and “Caution”/“Slow Down”) and the deployment of traffic cones. Figure 7 presents a visualization of a typical test condition.

Figure 7: Test Condition

3.4.3 Arrow/message Board as Independent Variable

Different configurations were tested, including caution (4 dots), arrow, two-phased text message “Move Over”/“It’s the Law,” and “Caution”/“Slow down” as shown in Figure 8.



(a) (b)

(c) (d)

Figure 8: Different arrow board messages used: (a) caution (4 dots); (b) arrow; (c) “Move over”/“It’s the law”; and (d) “Caution”/“ Slow Down”

3.4.4 Emergency Lighting Height Independent Variable

In the emergency lighting height evaluation, the arrow board was set to caution mode (4 dots). Traffic control devices remained deployed. Lights were mounted at three heights: on top of the arrow/message board; traditional roof mounting; and on top of the utility box. Lights at each height were tested in separate study periods to determine their impact on move-over behavior. To ensure consistency, the same color and flash pattern—alternating red and amber lights in a left/right sequence—was used across all heights. This combination also allowed for evaluating the impact of color and pattern, particularly with the roof-mounted configuration. Figure 9 presents an image depicting the height of emergency lights on the RRSP test vehicle.

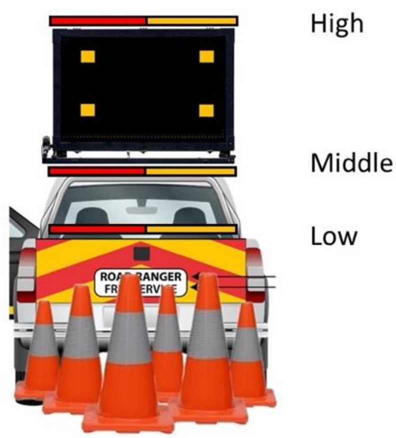


Figure 9: Example of emergency lighting mounting locations to be tested; above the arrow board; roof mounted; and on top of the utility box. Left/right flash and red/amber color were used for all height tests.

3.4.5 Emergency Lighting Color and Pattern as Independent Variables

The combination of colors and flash patterns for emergency vehicle lighting is practically limitless because of the sophistication associated with the technology. For this evaluation, the research team limited the color selection to red, amber, and red/white combination only.

To evaluate the impact of light patterns, four distinct flash patterns were chosen for the field test: inside/outside, left/right, full pulse, and sequential.

1. The inside/outside pattern alternated one flash of the light bar's center two lamps with one flash on the outer lamps.
2. The left/right pattern alternated one flash on one half of the light bar with one flash on the other half.
3. The full pulse configuration used the entire light bar and pulsed on and off.
4. In the sequential pattern, each of the six segments of the light bar flashes once in turn, from the outside lamp to the inside lamp and then repeats. This pattern can complement a directional arrow on the message board when one is used to direct motorists to vacate the lane adjacent to the response scene.

Table 4 depicts the combination of colors and patterns that were used in the configuration of the lighting systems used in the field test.

Table 4: Lighting colors and patterns to be tested

Color(s)	**Pattern**		
Red Only	Inside/Outside	Left/Right	Full pulse, Sequential
Amber Only	Inside/Outside	Left/Right	
Red/White	Inside/Outside	Left/Right	

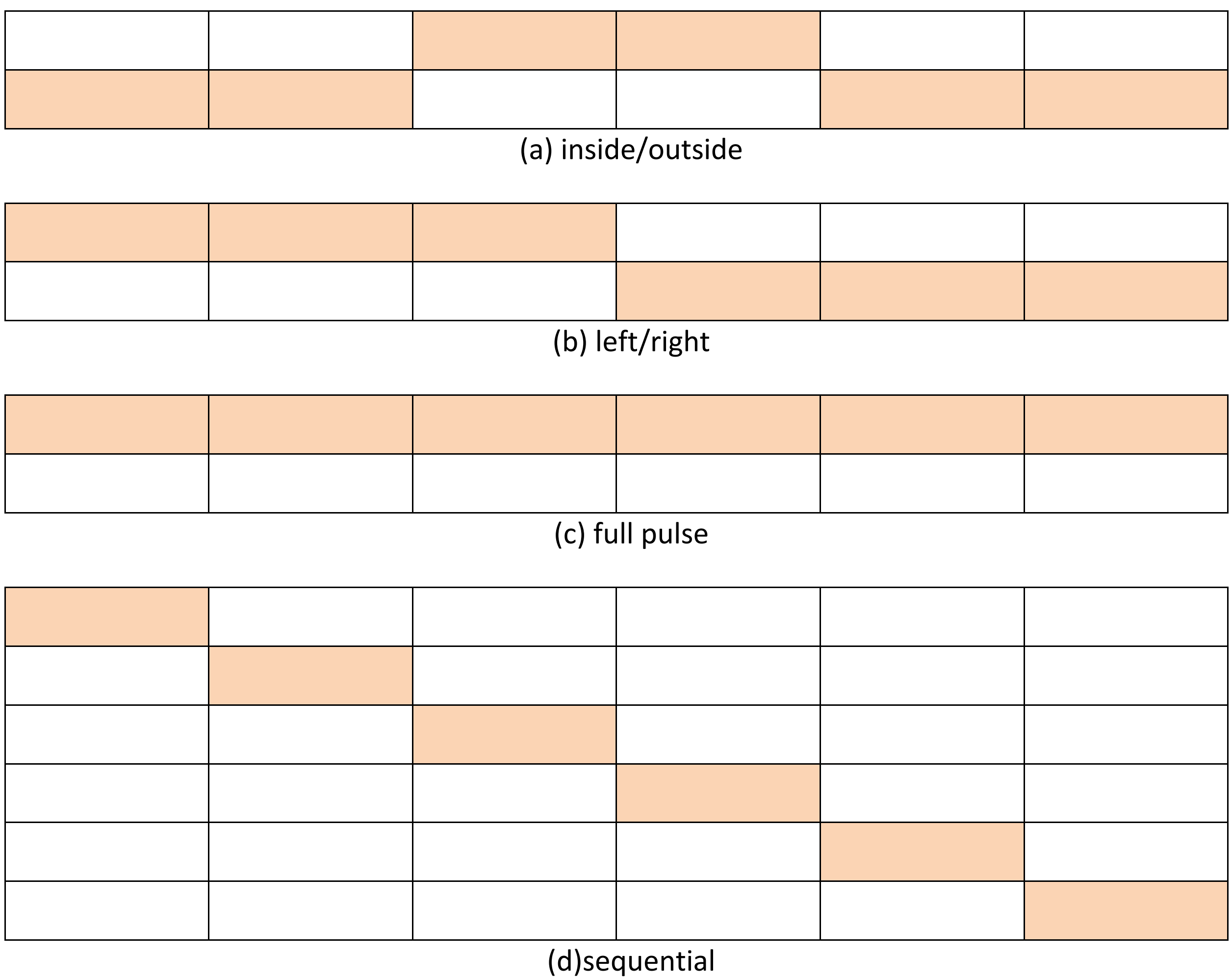


Figure 10: Different flash patterns used: (a) inside/outside; (b) left/right; (c) full pulse; and (d) sequential

3.5 Programming with the Whelen Core System

Central Pennsylvania Truck & Equipment Sales (Central PA Truck hereafter) provides RRSP vehicles for the FDOT District 5 (D5) Road Ranger contractor, AutoBase Inc. As part of the standard truck configuration, each vehicle is equipped with emergency lighting and a digital message board. To tailor the test vehicle for this project, the research team engaged in several telephone consultations with representatives from AutoBase and Central PA Truck to understand the lighting systems installed on D5 RRSP vehicles. These discussions helped determine how the existing systems could be modified to meet the specific requirements of the University of Florida team's field testing and experimental design.

During the summer of 2024, Central PA Truck was delivering new RRSP vehicles weekly to AutoBase for their D5 contract. Central PA Truck agreed to configure one of these newly delivered vehicles according to the research project's specifications. Since the testing would occur before the vehicle's deployment into regular RRSP service, this arrangement allowed for the customization of the vehicle to fit the project's needs, while minimizing any disruption to AutoBase's RRSP operations.

3Echo Emergency Solutions, the emergency lighting contractor for Central PA Truck, programmed the vehicle's lighting systems in Pennsylvania prior to delivery to AutoBase in Florida. The research team provided detailed specifications for 16 distinct lighting scenarios, including the use of the message board and variations in light height, color, and flash pattern. Upon delivery to Apopka, Florida, a 3Echo technician remained on-site for an additional day to ensure that the programming and lighting systems were fully aligned with the research team's requirements.

The Whelen CORE lighting system, widely used by emergency service providers, including safety service patrols, was employed for this project. The system is highly advanced and customizable, allowing each light to be programmed to operate individually or in coordination with the others. Dual and triple light heads were used, offering flexibility in light color selection. This technology enables a single LED light head to display two or three different colors, depending on programming and user preference, which was particularly advantageous as the research team was evaluating amber, red, and white lights.

The CenCom CORE controller is the brains of the emergency vehicle lighting system. This controller integrates all emergency lighting components and interfaces with the vehicle's CAN bus, enabling communication between the various devices in the CORE system. The CAN bus allows the Whelen lights to respond dynamically to vehicle conditions, such as motion, braking, and door operations.

Programming the various lights and the controller is accomplished using the Whelen Command software, which allows for the identification of all installed emergency lighting equipment and the assignment of flash patterns, intensity, color, and other parameters. Figure 9 provides a screenshot of the Command software's user interface. The software is a robust tool for setting up emergency vehicle lighting, and multiple programs can be stored as presets for later selection by the user.

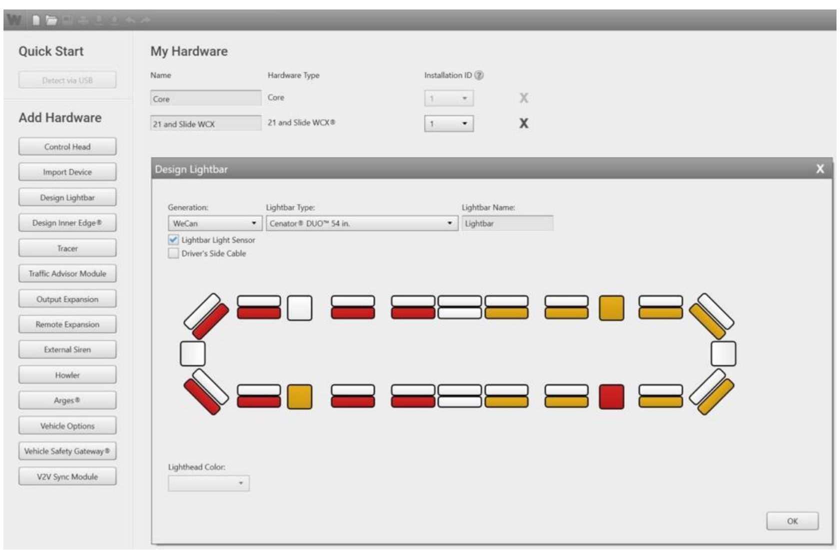


Figure 11: Whelen command software interface

Once installed in the vehicle and programmed, the vehicle operator used the control head (Figure 5b) mounted in the vehicle cab on the center console, to configure the lighting system. Pre-sets are an important part of emergency lighting. This allows operator to use pre-programmed patterns for the lighting system, that can be easily selected via an array of onetouch buttons and a slider switch. The system supports up to several dozen combinations of lighting programs, with each slider position corresponding to unique button modes.

These programmed lighting modes enable the operator to quickly choose appropriate colors and patterns for various situations and operational conditions. For the purposes of this research, the pre-programmed buttons were customized using the Command software, allowing the research team to switch between different lighting scenarios outlined in the field test evaluation plan. The combination of programming and pre-set control head buttons greatly simplified the execution of the lighting field tests, ensuring smooth transitions between the various test conditions.

3.6 Data Collection

Study locations were strategically selected to ensure free-flowing traffic conditions and the availability of sufficient lane-changing gaps, thereby minimizing the potential impact of congestion on observations of vehicles not adhering to the move-over law. Furthermore, locations near upstream and downstream interchanges, as well as ramps within several miles, were deliberately avoided to reduce the influence of weaving and lane selection associated with vehicles entering or exiting the roadway. Figure 12 depicts the location of all the study locations.

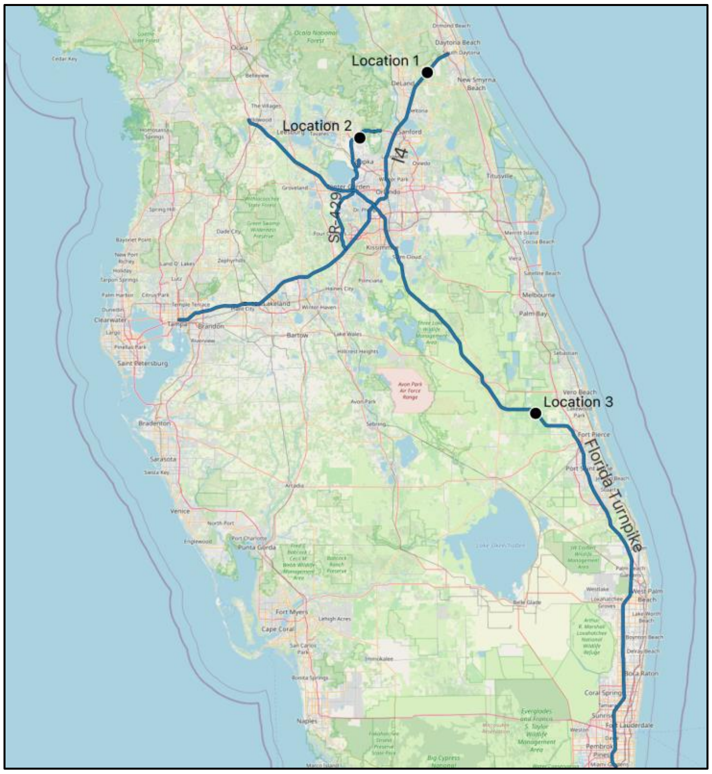


Figure 12: Testing locations for the study

The specific testing locations chosen were Interstate 4 (I-4) south of Daytona, Florida, the southbound approach of SR-429, and the Florida Turnpike near Fort Pierce. I-4 is characterized as a six-lane divided rural highway, while the SR-429 and Turnpike sections are four-lane divided rural highways. The posted speed limit for both segments is 70 miles per hour (mph). Table 5 provides detailed information on the selected testing locations, and Figure 13 presents the images of the research team conducting experiments at the testing location on I-4.

Table 5: Date, times, and locations of the experiment

Location	Road	Direction	Section	Testing Date	Testing Time
1	I-4	East Bound (EB)	MM 123.6	06/26/2024	12:30–16:30
2	SR-429	South Bound (SB)	MM 41.9	06/27/2024	15:15–19:15
3	SR-91	SB	MM 171.0	06/28/2024	11:00–15:00

Figure 13: Research team at the test location at I-4

The Florida Department of Transportation (FDOT) facilitated the field tests by granting access to their Road Ranger Service Patrol (RRSP) contractor, AutoBase Corporation. The research team ensured that the RRSP contractor was compensated for the use of the vehicle and operator, separately from regular patrol duties, to prevent any disruption to daily operations. The research design underwent thorough review by both the FDOT and the RRSP contractor to ensure technical and operational accuracy. Each test scenario was conducted over a 15-minute period.

Given the prolonged nature of the field study, it was essential to video record the traffic at the study locations. Detailed notes were documented in the field, and the message and lighting configurations of the vehicle were verified, enabling the research team to accurately correlate test conditions with the video footage during the analysis phase.

3.6.1 Sources of Data Collection

The FDOT's extensive network of Intelligent Transportation Systems (ITS) cameras, including closed-circuit television (CCTV) cameras and microwave vehicle detection systems, provided a robust means of traffic monitoring on the state's limited-access highways. Figure 4 presents an example of an FDOT camera image capturing an RRSP vehicle at the testing location at SR-429. Additionally, three GoPro cameras and three in-vehicle cameras were employed to supplement the traffic recordings obtained from the ITS cameras. Figure 14 illustrates the roadside camera setup used during the study. The entire camera setup underwent extensive pre-testing on SR-429 before the actual field deployment and experiments. More details about the pre-testing can be found in subsequent subsections. Table 6 summarizes the various sources of video data collected along with the corresponding data volumes.

Figure 14: Roadside camera setup

Table 6: Different data sources and volume of data collected

Source	**Location**	**Size**
TMC Video Footage	1, 2, 3	19.87 GB + Location 3 (over 1 TB)
GoPro Videos (3 cameras)	1 (3 cameras), 2(2 cameras), 3 (2 cameras partial, 1 camera full)	553.66 GB
In-vehicle Cameras (3 cameras)	2,3	13.6 GB

3.7 Study Pre-testing

To ensure a robust and effective data collection methodology, our team undertook an extensive pre-testing phase, which spanned multiple locations (shop, on-site, and in Gainesville) and focused on both technical coordination and equipment testing. This pre-testing work was crucial for identifying and mitigating potential issues ahead of the actual testing day. The pre-testing was carried out in several stages, which are described below.

3.7.1 Coordination with the Traffic Management Center (TMC)

The first step in our pre-testing involved a visit to the TMC, where we coordinated efforts to figure out the best way to record camera footage. During this visit, we explored several options for capturing the video feed, some of which initially failed. After thorough exploration, we successfully identified two viable solutions: remote recording and at-location screen recording. These methods ensured that we could reliably capture the necessary footage without interruption during the actual test.

3.7.2 Bench Testing for Optimal Camera Setup

The team then conducted a series of bench tests at the AutoBase shop in Apopka and SR-429 to determine the optimal camera configurations, focusing on variables such as height, angle, frame rates, and zoom levels. These tests were essential to ensure that the GoPro cameras could accurately capture the move-over behavior of oncoming traffic without overheating or other technical issues. The objective was to identify the most suitable setup that would provide clear, reliable data for analysis.

3.7.3 Equipment Testing for Uninterrupted Recording

Alongside the bench testing, we also rigorously tested all the cameras and other recording equipment to ensure that they would function seamlessly during the actual data collection. This included trial runs with the equipment to check for any potential issues, such as overheating, connectivity problems, or power failures, which could disrupt the recording process. By addressing these concerns during pre-testing, we minimized the risk of encountering technical difficulties on the test day.

3.7.4 Second Round of Testing in Gainesville

After addressing the initial challenges and refining our setup, we conducted a second round of testing in Gainesville. This additional testing phase allowed us to validate our solutions in a different environment, ensuring that our methodologies were sound, and that all equipment was adequately prepared for the actual experiment. This final round of pre-testing was crucial for confirming that our strategies would work effectively under real-world conditions.

By the end of these pre-testing activities, the team had established a well-coordinated and reliable methodology for the actual test day. This thorough preparation was instrumental in ensuring that the data collection process would proceed smoothly, with minimal risk of unexpected issues.

3.8 Average Weekday vs. Test Day Traffic Volume and Occupancy

The SunGuide® software is a sophisticated Advanced Traffic Management System (ATMS) utilized in Traffic Management Centers (TMCs) across the state of Florida. Within SunGuide, the Transportation Sensor System Interface delivers reports from numerous roadway sensors, which monitor occupancy and average speeds by lane on all limited-access roadways within the state. Traffic data are aggregated and presented in 15-minute intervals, making it well-suited for research purposes. The dataset was used to compare the occupancy of the right lane on an average weekday in comparison to the test day. This was crucial to study the move behavior at the site in terms of traffic volume.

In the dataset, lanes are sequentially numbered from the inside to the outside; for instance, Lane 3 refers to the rightmost lane adjacent to the incident location, which was on the right shoulder for the tests. Traffic counts recorded on the test day at the designated testing locations are detailed in Tables 7, 9, and 10. This was used to compute the traffic occupancy as shown in Table 8 and Table 11. Similarly, Tables 12 and 13 provide the average weekday traffic volumes and traffic occupancy respectively at the I-4 and the Turnpike section.

Table 7: Traffic counts for test at I-4

Time of Day	Lane 1	Lane 2	Lane 3	Total
12:30	260	275	55	590
12:45	235	273	72	580
13:00	245	281	46	572
13:15	241	267	37	545
13:30	257	281	37	575
13:45	273	296	12	581
14:00	256	282	47	585
14:15	297	285	33	615
14:30	277	287	31	595
14:45	272	291	23	586
15:00	247	269	22	538
15:15	256	258	20	534
15:30	258	294	42	594
15:45	274	249	12	535
16:00	281	276	10	567
16:15	251	259	14	524
Total	**4,180**	**4,423**	**513**	**9,116**

Table 8: Occupancy of lanes on the test day at I-4

Time of Day	Lane 1	Lane 2	Lane 3
12:30	0.441	0.466	0.093
12:45	0.405	0.471	0.124
13:00	0.428	0.491	0.080
13:15	0.442	0.490	0.068

Time of Day	Lane 1	Lane 2	Lane 3
13:30	0.447	0.489	0.064
13:45	0.470	0.509	0.021
14:00	0.438	0.482	0.080
14:15	0.483	0.463	0.054
14:30	0.466	0.482	0.052
14:45	0.464	0.497	0.039
15:00	0.459	0.500	0.041
15:15	0.479	0.483	0.037
15:30	0.434	0.495	0.071
15:45	0.512	0.465	0.022
16:00	0.496	0.487	0.018
16:15	0.479	0.494	0.027
Average	**0.459**	**0.485**	**0.056**

Table 9: Traffic counts on the test day at SR-429

Time of Day	Lane 1	Total
15:15	74	74
15:30	95	95
15:45	88	88
16:00	90	90
16:15	65	65
16:30	95	95
16:45	87	87
17:00	85	85
17:15	79	79
17:30	94	94

Time of Day	Lane 1	Total
17:45	84	84
18:00	65	65
18:15	60	60
18:30	50	50
18:45	50	50
19:00	43	43
19:15	40	40
Total	**1,244**	**1,244**

Table 10: Traffic counts on the test day at the Florida Turnpike

Time of Day	Lane 1	Lane 2	Total
11:00	218	90	308
11:15	193	98	291
11:30	221	113	334
11:45	266	99	365
12:00	253	77	330
12:15	275	97	372
12:30	261	105	366
12:45	299	111	410
13:00	264	104	368
13:15	260	92	352
13:30	238	108	346
13:45	226	87	313
14:00	254	123	377
14:15	259	101	360
14:30	254	89	343
14:45	274	134	408

Time of Day	Lane 1	Lane 2	Total
15:00	266	106	372
15:15	235	91	326
Total	**4,516**	**1,825**	**6,341**

Table 11: Occupancy of lanes on the test day at the Florida Turnpike

Time of Day	Lane 1	Lane 2
11:00	0.708	0.292
11:15	0.663	0.337
11:30	0.662	0.338
11:45	0.729	0.271
12:00	0.767	0.233
12:15	0.739	0.261
12:30	0.713	0.287
12:45	0.729	0.271
13:00	0.717	0.283
13:15	0.739	0.261
13:30	0.688	0.312
13:45	0.722	0.278
14:00	0.674	0.326
14:15	0.719	0.281
14:30	0.741	0.259
14:45	0.672	0.328
15:00	0.715	0.285
15:15	0.721	0.279
Average	**0.712**	**0.288**

Table 12: Average weekday traffic volume at I-4 and Turnpike

Location	Average weekday traffic		
	Lane 1	Lane 2	Lane 3
1	3,690	3,678	1912
3	2,258	2,155	

Table 13: Average weekday traffic occupancy at I-4 and Turnpike

Location	Average weekday Occupancy		
	Lane 1	Lane 2	Lane 3
1	0.398	0.396	0.206
3	0.512	0.488	

It can be clearly observed that the right lane traffic volume and traffic occupancy is consistency lower in the rightmost lane at test locations, indicating the move-over behavior of oncoming traffic. This trend is further illustrated in Figures 15 and 16.

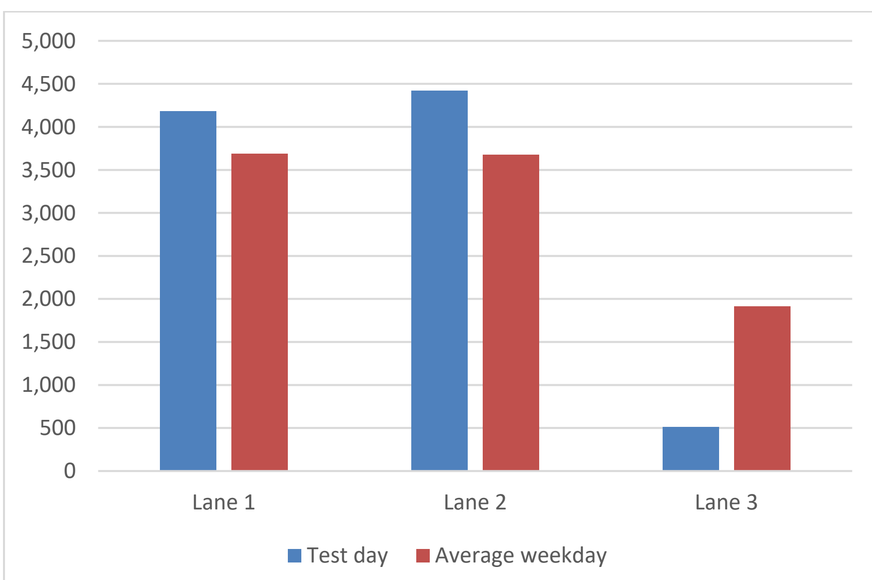


Figure 15: Average weekday vs. test day traffic volume at I-4

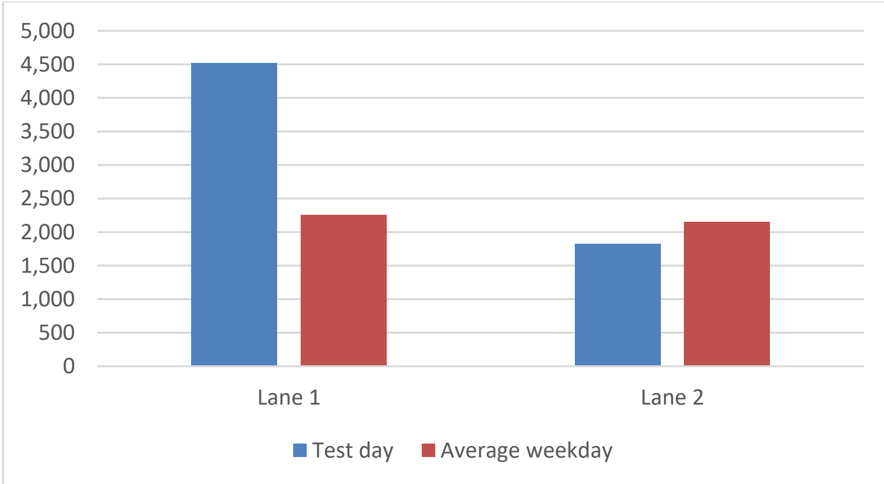


Figure 16: Average weekday vs. test day traffic volume at the Florida Turnpike

Additionally, speed is another critical factor in vehicles approaching an incident scene. In compliance with move-over laws, drivers should vacate the lane nearest the roadside incident or, if unable to do so, slow to a speed that is at least 20 miles per hour below the posted speed limit. However, speed data from detectors represent the average speeds over the sample period (15 minutes), which would not be suitable for determining whether individual vehicles slow down. Therefore, volumetric measurements have been used to analyze the move-over compliance rate in the subsequent sections.

3.9 Post-processing of the Video Data

3.9.1 Data Sources

The video data for analysis were gathered from three primary sources: TMC video footage, GoPro cameras, and in-vehicle cameras. The supplementary recordings from the GoPro and in-vehicle cameras were particularly useful in covering areas or angles that the TMC footage missed, providing a more comprehensive assessment of vehicle behavior.

3.9.2 Method and Assumptions

The post-processing of the video data was completed manually in five weeks. The primary task during this phase was to count the number of vehicles that changed lanes from the rightmost lane to the adjacent lane upstream of the testing site. At the testing site, the experiment time was recorded for each scenario, which made it easy to tally and count the number of vehicles that moved over for each specific scenario. Only vehicles traveling in the right lane were considered for analysis. Additionally, only vehicles that were clearly discernible within the camera's field of view were included.

Besides, the analysis was conducted through multiple passes of the video footage. In the first pass, the team focused on counting vehicles that did not comply with the move-over law by not changing lanes. For the subsequent passes, the video screen was divided into multiple segments, and for each pass, the number of vehicles moving over in each segment was counted separately. Finally, some vehicles were observed to perform partial move-overs, where they began to change lanes but did not fully comply with the move-over law. These vehicles were counted as non-moving-over vehicles, as they did not meet the legal requirements for lane change behavior under the move-over law.

3.10 Data Analysis

A total of 16 scenarios was classified into distinct cases for analysis. Table 14 provides a summary of the results across all locations. For the entire experiment, 6,940 vehicles in the right lane were observed, of which 5,180 vehicles complied with the move-over requirement, resulting in an average move-over rate (MOR) of 74.64% across all locations.

Table 14: Summary of move-over rates at various locations

Behavior Category	Deployed Locations			
	I-4	SR-429	Florida Turnpike	Total
Overall				
Right-lane Vehicles	1,672	1,993	3,275	6,940
Moved-over Vehicles	1,215	1,832	2,133	5,180
MOR	**72.67%**	**91.92%**	**65.13%**	**74.64%**
Scenario 1				
Right-lane Vehicles	131	124	135	390
Moved-over Vehicles	59	78	64	201
MOR	**45.04%**	**62.90%**	**47.41%**	**51.54%**
Scenario 2				
Right-lane Vehicles	132	137	177	446
Moved-over Vehicles	82	127	97	306
MOR	**62.12%**	**92.70%**	**54.80%**	**68.61%**
Scenario 3				
Right-lane Vehicles	103	144	178	425
Moved-over Vehicles	70	130	117	317
MOR	**67.96%**	**90.28%**	**65.73%**	**74.59%**
Scenario 4				
Right-lane Vehicles	117	122	180	419
Moved-over Vehicles	75	108	126	309
MOR	**64.10%**	**88.52%**	**70.00%**	**73.75%**
Scenario 5				
Right-lane Vehicles	102	156	181	439
Moved-over Vehicles	76	144	142	362
MOR	**74.51%**	**92.31%**	**78.45%**	**82.46%**
Scenario 6				

Behavior Category	Deployed Locations			
	I-4	**SR-429**	**Florida Turnpike**	**Total**
Right-lane Vehicles	101	150	180	431
Moved-over Vehicles	64	134	111	309
MOR	**63.37%**	**89.33%**	**61.67%**	**71.69%**
Scenario 7				
Right-lane Vehicles	95	149	200	444
Moved-over Vehicles	58	140	140	338
MOR	**61.05%**	**93.96%**	**70.00%**	**76.13%**
Scenario 8				
Right-lane Vehicles	111	156	201	468
Moved-over Vehicles	86	147	131	364
MOR	**77.48%**	**94.23%**	**65.17%**	**77.78%**
Scenario 9				
Right-lane Vehicles	60	168	178	406
Moved-over Vehicles	50	157	130	337
MOR	**83.33%**	**93.45%**	**73.03%**	**83.00%**
Scenario 10				
Right-lane Vehicles	118	126	168	412
Moved-over Vehicles	96	121	119	336
MOR	**81.36%**	**96.03%**	**70.83%**	**81.55%**
Scenario 11				
Right-lane Vehicles	105	114	171	390
Moved-over Vehicles	89	111	122	322
MOR	**84.76%**	**97.37%**	**71.35%**	**82.56%**
Scenario 12				
Right-lane Vehicles	110	104	181	395
Moved-over Vehicles	72	100	108	280

Behavior Category	Deployed Locations			
	I-4	**SR-429**	**Florida Turnpike**	**Total**
MOR	**65.45%**	**96.15%**	**59.67%**	**70.89%**
Scenario 13				
Right-lane Vehicles	83	97	208	388
Moved-over Vehicles	73	94	142	309
MOR	**87.95%**	**96.91%**	**68.27%**	**79.64%**
Scenario 14				
Right-lane Vehicles	95	97	184	376
Moved-over Vehicles	87	96	133	316
MOR	**91.58%**	**98.97%**	**72.28%**	**84.04%**
Scenario 15				
Right-lane Vehicles	100	79	189	368
Moved-over Vehicles	85	78	82	245
MOR	**85.00%**	**98.73%**	**43.39%**	**66.58%**
Scenario 16				
Right-lane Vehicles	109	70	170	349
Moved-over Vehicles	93	67	113	273
MOR	**85.32%**	**95.71%**	**66.47%**	**78.22%**

Figure 17 offers a visual representation of the results in Table 14. The observations indicate that the MOR was highest for SR-429, at 91.92%, and lowest for the Florida Turnpike section, at 65.13%. The following subsections present a detailed analysis of the various scenarios. Additionally, due to the limited spatial sample size, an observational approach was employed for aggregate-level analysis rather than extensive statistical methods.

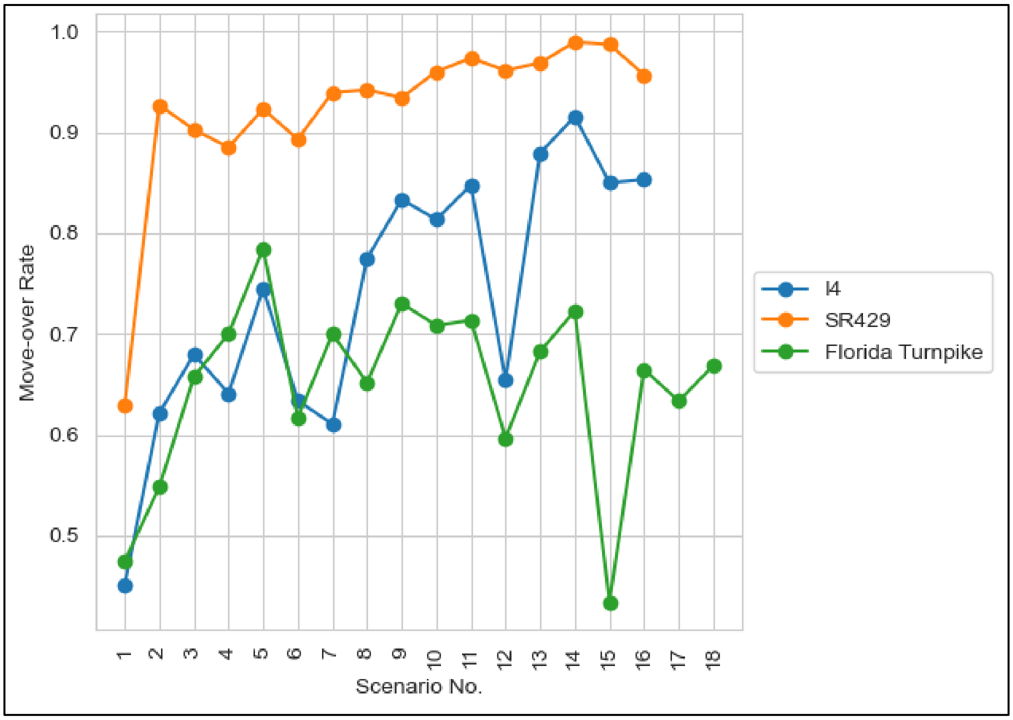


Figure 17: MOR at test locations

The following subsections present a detailed analysis of the various scenarios. Additionally, due to the limited spatial sample size, an observational approach was employed for aggregate-level analysis rather than extensive statistical methods.

3.10.1 Traffic Volume and Move-over behavior

The relationship between traffic volume and move-over behavior is illustrated in the graphs presented in Figures 18 through 20. These plots depict the correlation between right-lane volume and MOR. Various scenarios are represented by rectangles within the graphs, highlighting the observed behavior. The variations in these metrics offer insights into how traffic volume affects the ability of vehicles to comply with move-over laws. These figures collectively suggest that as traffic volume increases, it becomes more challenging to change lanes due to congested traffic conditions.

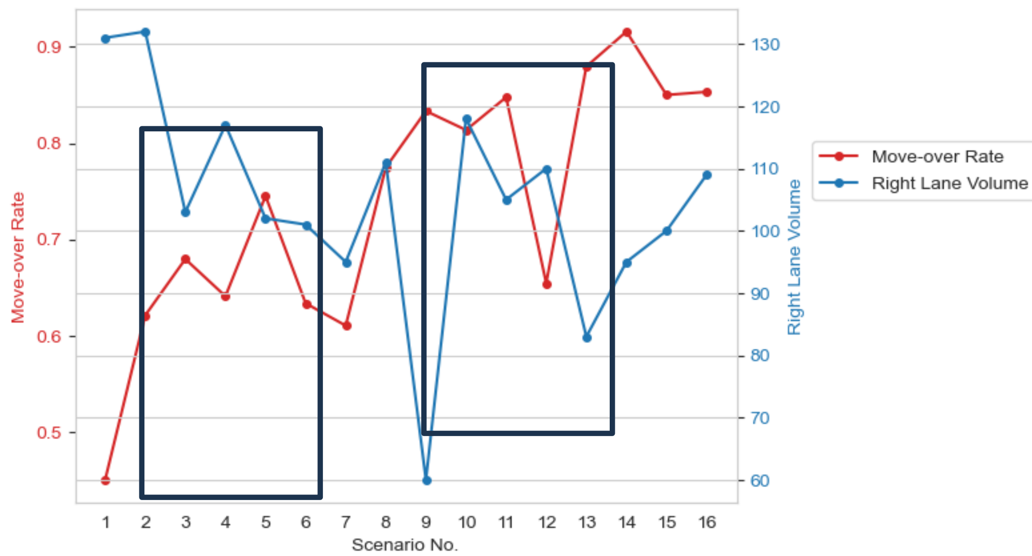


Figure 18: Right-lane volume vs. MOR at I-4

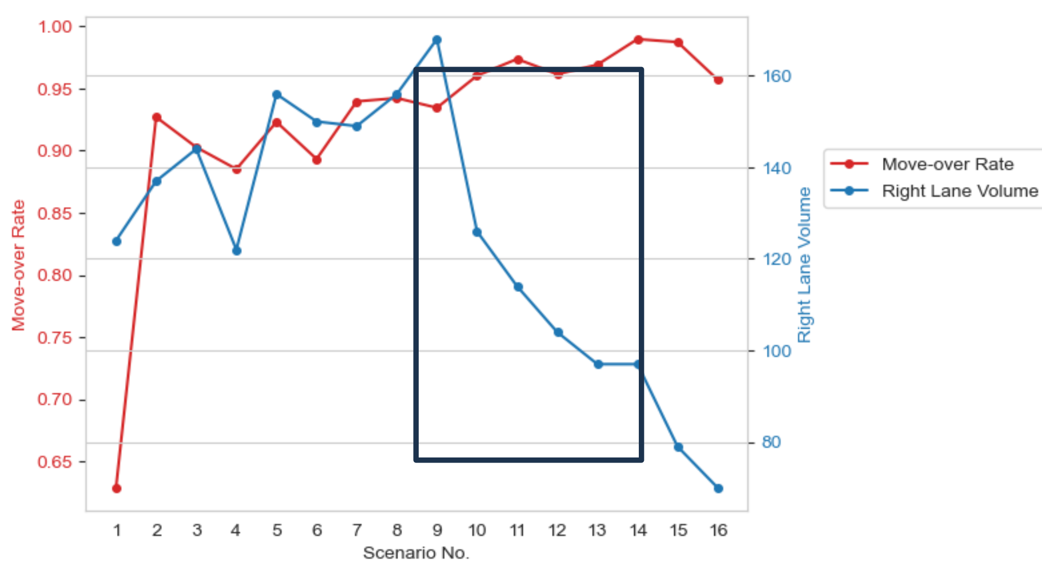


Figure 19: Right-lane volume vs. MOR at SR-429

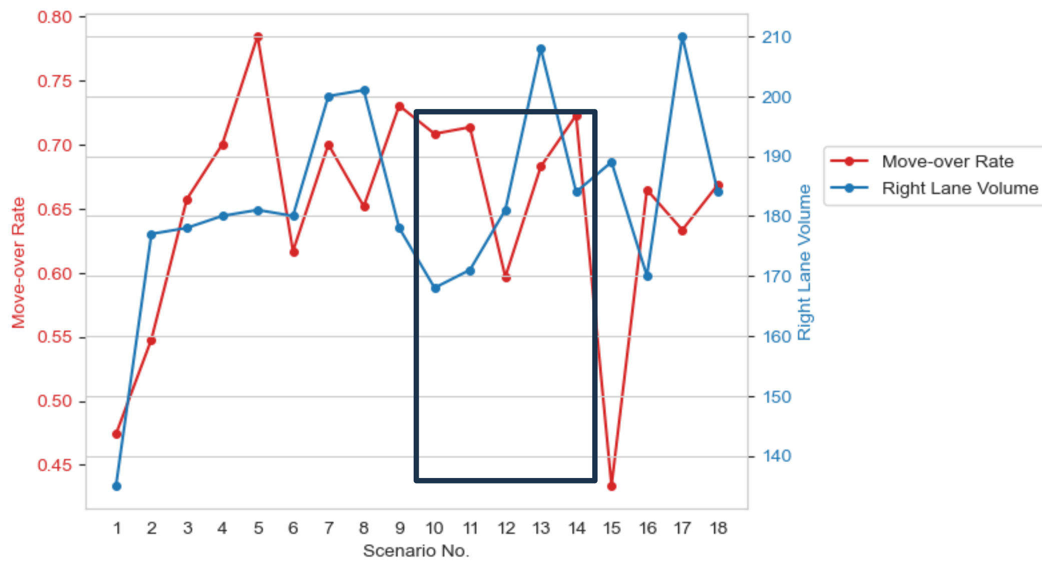


Figure 20: Right-lane volume vs. MOR at Florida Turnpike

<u>3.10.2 Treatment vs. No-Treatment and Do-Nothing vs. Using Cones</u>

Figure 21 presents the results of MOR in regard to treatment and no-treatment conditions. For this analysis, the scenarios were categorized into two groups. Scenario 1 represented the baseline condition where no treatment measures were applied to influence move-over compliance. Conversely, the remaining scenarios were grouped to aggregate the MOR under conditions where some treatment measures (such as cones or other devices) were employed. The results indicated that, on average, the MOR increased by 54% when treatment measures were applied. Furthermore, the use of cones alone increased the MOR by 34% in comparison to the scenario where no treatment measures are employed. This underscores the importance of cones, lighting systems, and arrow boards in enhancing responder safety.

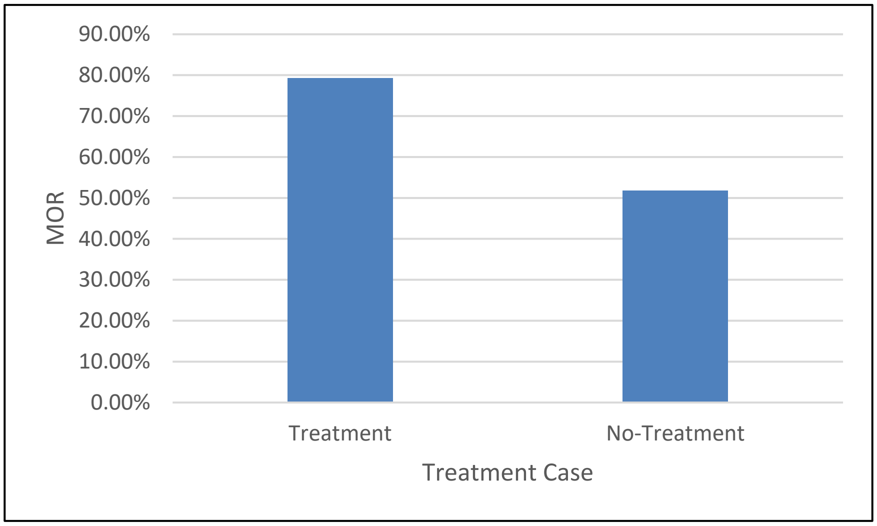


Figure 21: MOR with different treatment vs. non-treatment scenarios

3.10.3 Changeable Message Signs

Table 15 presents the MOR for cases utilizing various messages on message boards compared to the caution mode (4 dots). Additionally, at the Florida Turnpike, an opportunity was taken (Scenarios 17 and 18) to evaluate the impact of using an upstream changeable message sign (CMS) in conjunction with the caution mode on compliance rates.

Table 15: Summary of move-over compliance for different message scenarios

Scenario	**CMS**	**I-4**		**Move-over Percent**	**SR-429**		**Move-over Percent**	**Turnpike**		**Move-over Percent**
		Move	**No Move**		**Move**	**No Move**		**Move**	**No Move**	
3	"Move Over, It's the Law"	70	33	67.96%	130	14	65.73%	117	61	65.73%
4	"Caution, Slow Down"	75	42	64.10%	108	14	70.00%	126	54	70.00%
5	Left Arrow	76	26	74.51%	144	12	78.45%	142	39	78.45%

Scenario	CMS	I-4		Move-over Percent	SR-429		Move-over Percent	Turnpike		Move-over Percent
		Move	No Move		Move	No Move		Move	No Move	
17,18	Upstream CMS							256	138	64.97%
6	Four-dot Caution Mode	64	37	63.37%	134	16	61.67%	111	69	61.67%
	Total	**285**	**138**	**67.38%**	**516**	**56**	**90.21%**	**752**	**361**	**67.57%**

On average, when a message was displayed on the arrow board, the MOR increased to 67.86%, which is 10% higher than 61.67% observed when only the caution mode was used. Notably, the average MOR for the arrow sign was 78.45%, marking the highest among all the scenarios and representing a 27.2% increase over the caution mode. This indicates that message boards enhance the perception of the incident scene, thereby improving move-over compliance rates.

Furthermore, the use of an upstream CMS sign also contributes to increased MOR, as indicated in Table 15, by providing oncoming drivers with advance notice of the presence of responder vehicles. It should be noted that the upstream CMS sign was placed 4 miles upstream of the incident scene, and the impact of the sign could potentially be more pronounced if it had been placed closer to the scene.

3.10.4 Height

Figure 22 illustrates the MOR associated with the placement of lighting systems at various heights. The placement height of these systems can significantly affect the perception of oncoming drivers. The highest MOR (83.27%) was observed in scenarios where the lighting systems were mounted on the roof and utility boxes. This indicates that elevated placement of lighting systems enhances their visibility and effectiveness, thereby improving driver awareness and increasing MOR.

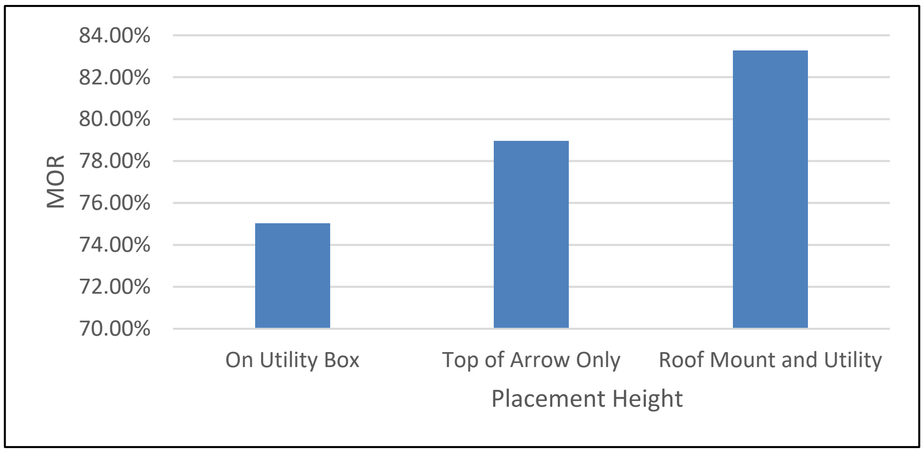


Figure 22: Compliance rate at different placement heights of the lighting systems

3.10.5 Color

Figure 23 presents the impact of different colors tested on MOR. Three color combinations were tested: red, amber, and red/white. The highest MOR, 86%, was observed when the red/white lighting systems were employed. This was followed by an 83% for the red lighting system. Amber lighting system demonstrated the lowest MOR at 79.13%. These findings corroborate the information obtained from the literature review, which indicated that the color red, whether used alone or in combination with white, was deemed more visible.

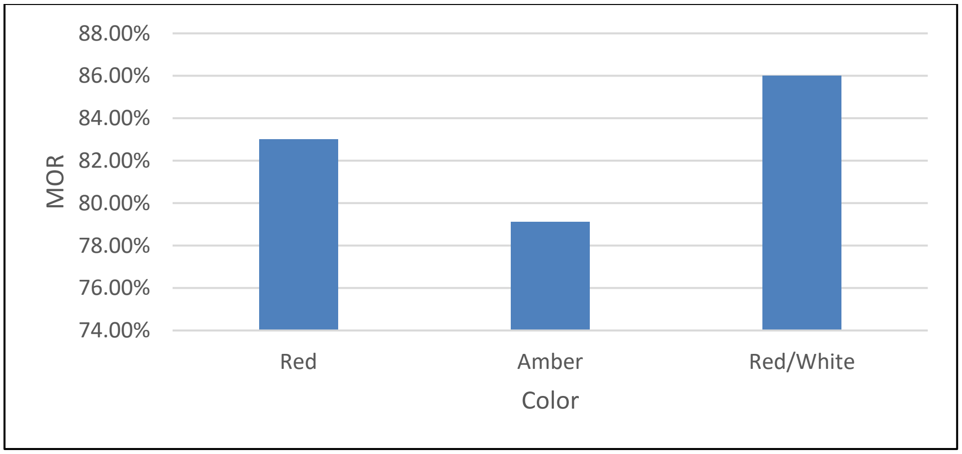


Figure 23: Compliance rate for different colored lighting systems

3.10.6 Pattern

Figure 24 presents the findings related to the impact of various flash patterns on move-over compliance. Four types of flash patterns were implemented across all test locations. However, as illustrated in Figure 17, the MOR for Scenario 15, which corresponds to the directional sequence, was the lowest at 43.39%. This anomaly can be attributed to poor visibility conditions at the site. Consequently, only data from I-4 and SR-429 were used for analysis. The highest compliance rate, 92%, was observed when the directional sequence flash patterns were employed. This suggests that these flash patterns may enhance the perception of the scene for oncoming drivers by providing a clearer indication of the appropriate action to take when approaching the scene.

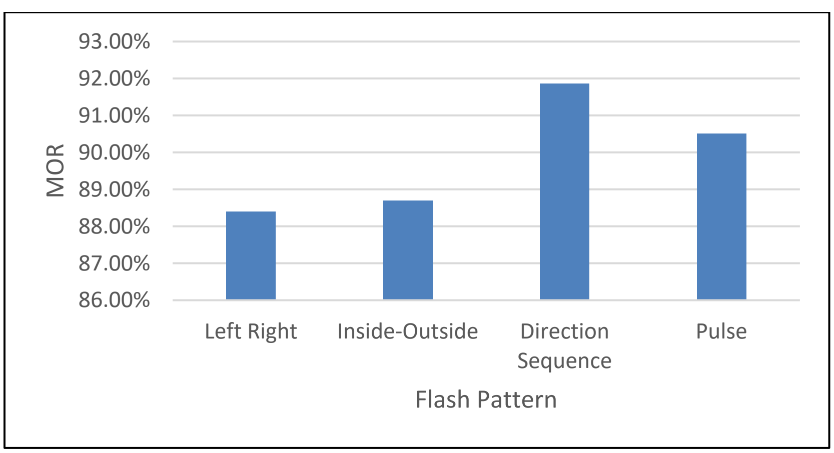


Figure 24: Compliance rate with different flash patterns (average I-4 and SR-429)

3.11 Qualitative Findings

3.11.1 Gap Acceptance

The study suggests that the availability of a gap in the adjacent lane may have a significant impact on move-over compliance. However, due to the perspective limitations of the video recordings, accurately estimating these gaps was challenging. As a result, this study approaches the analysis of gap acceptance from a qualitative perspective. Observations suggest that move-over law compliance decreased in scenarios where congestion in adjacent lanes, especially due to platooning, reduced the availability of gaps for lane changes.

In high-density traffic situations, the reduced availability of such gaps likely discourages drivers from attempting the maneuver, thereby reducing overall compliance. Furthermore, the psychological pressure of driving in a congested environment, where lane changes can be perceived as risky or challenging, may further contribute to lower compliance rates.

3.11.2 Car-following Nature of Traffic and Presence of Heavy Vehicles

The analysis also revealed a car-following behavior, where vehicles tend to replicate the actions of the car directly in front of them. Specifically, if a lead vehicle executes a move-over maneuver, the following vehicle is more likely to do the same. This behavior underscores the importance of leader influence in traffic streams, suggesting that the actions of a single vehicle can significantly affect the compliance behavior of those following.

Moreover, the presence of heavy vehicles was found to negatively impact the move-over rate. Due to the obstructed view caused by these larger vehicles, oncoming drivers following closely behind may not have a clear sight of the emergency scene until the last moment. This reduced visibility led to delayed or incomplete lane changes, as drivers are unable to assess the situation in time. The effect of heavy vehicles highlights the critical role that visibility plays in move-over compliance, particularly in congested traffic environments.

3.11.3 Late and Partial Merges

The occurrence of late or partial merges is a critical factor impacting responder safety, as it represents the portion of traffic that fails to fully comply with the move-over law. Our study indicated that the frequency and nature of these maneuvers can be influenced by several parameters, which include:

- **Location of Testing Site and Driver Demographics:** The characteristics of the testing location along with the demographic profile of drivers, might play a significant role in compliance rates. Factors such as local driving culture, familiarity with move-over laws, and the presence of signage or law enforcement may all contribute to varying levels of adherence. For instance, at SR-429, where higher move-over compliance rates were observed, fewer instances of late or partial merges occurred compared to locations such as the Turnpike, where these maneuvers were more frequent.
- **Vehicle Type:** The study indicates that the type of vehicle significantly affects move-over behavior. Notably, trucks and other large vehicles often did not completely move-overs, likely due to their size, reduced maneuverability, and limited visibility of the scene ahead. This behavior poses a heightened risk to responders, as these vehicles can obstruct the view and delay the reaction time of following traffic.
- **Visibility of the Scene:** The ability of drivers to clearly see the emergency scene plays a crucial role in their decision to comply with the move-over law. Poor visibility, whether due to obstructions by other vehicles, adverse weather conditions, or inadequate lighting, can lead to delayed or partial maneuvers, increasing the danger to both responders and other road users. For example, in Figure 17, a significant drop in compliance is noted in Scenario 15 at the Turnpike location, likely due to reduced visibility from cloud cover during that time.
- **Car-Following Behavior:** The tendency of drivers to follow the actions of the vehicle ahead, as discussed earlier, further influences the occurrence of late or partial merges. If the lead vehicle does not execute a full move-over, the following vehicles are likely to replicate this incomplete action, perpetuating a cycle of non-compliance.

The observational study was followed by an exhaustive vehicle marking design process which will discussed in the subsequent section of the report.

Chapter 4. Marking Design

4.1 Research Approach

To evaluate potential improvements to the RRSP vehicle color scheme and markings, the research team adopted a structured approach. This involved analyzing past research, assessing current national practices, and incorporating stakeholder feedback to ensure practical and institutionally viable design solutions.

By understanding best practices, the research team identified key design objectives to enhance visibility, recognition, and safety. Stakeholder engagement played a crucial role, ensuring that proposed modifications reflected real-world operational needs while aligning with institutional guidelines.

Key design attributes such as color schemes, logos, and legends formed the foundation for developing new concepts. Using photographic enhancement techniques, the team iteratively created candidate designs. These were reviewed by Central Office and District Program Managers, who provided qualitative feedback, allowing for a collaborative selection of a recommended RRSP vehicle design.

Figure 25 illustrates the Road Ranger vehicle design process, summarizing the steps taken to refine and select the most effective modifications.

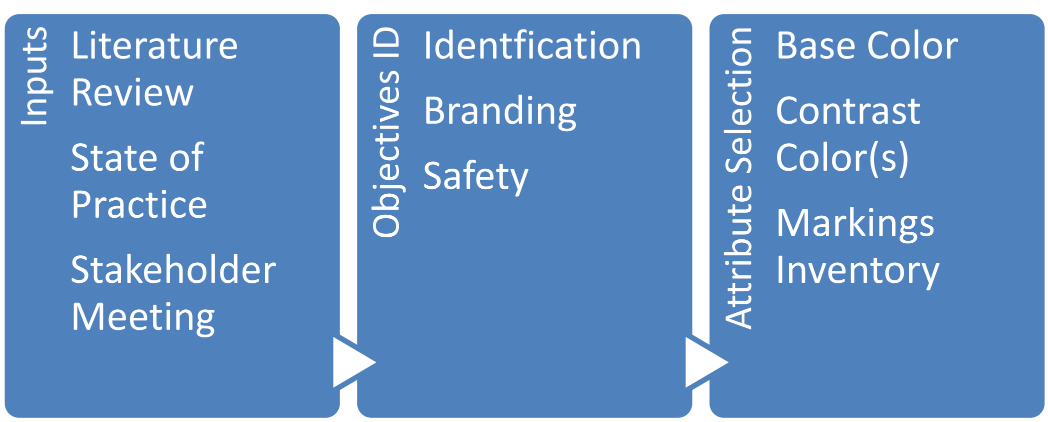


Figure 25: Road Ranger Vehicle Design Process

4.2 Insights from literature review

The literature review revealed that emergency vehicle design has continuously evolved to enhance visibility and recognition, ultimately improving roadside safety.

4.2.1 Global Best Practices:

Several countries have established visibility standards for emergency vehicles:

- *Europe:* Countries have widely adopted the Battenburg pattern, which features alternating high-visibility colors. This design enhances recognition in both daytime and nighttime conditions, ensuring emergency vehicles remain distinct from service and maintenance vehicles.
- *Australia & Japan:* These countries have integrated retroreflective materials and strategic color schemes to improve vehicle conspicuity in various lighting and weather conditions.

4.2.2 U.S. Emergency Vehicle Marking Practices:

Unlike in Europe, the United States lacks a unified industry standard for emergency vehicle markings. However, various agencies—including police, fire, EMS, and transportation departments—have implemented their own best practices.

- *National Fire Protection Association (NFPA) Standards:*
  - NFPA 1901 mandates retroreflective chevrons on the rear of fire apparatus.
  - NFPA 1917 sets similar visibility standards for ambulances.
  - These guidelines emphasize fluorescent red/orange and yellow/green patterns, which enhance conspicuity and help reduce collision risks.
  - Despite these standards, color selection and implementation remain flexible, leading to variations across agencies.
- *Regulatory Framework & Federal Guidelines:*
  - The NFPA 1901 standard aligns with ASTM D4956, which defines performance criteria for retroreflective sheeting.
  - The U.S. General Services Administration (GSA) provides non-governmental ambulance marking standards under the Triple K Standard (KKK-A-1822F).

- These guidelines emphasize reflective tape usage and feature distinctive emblems, such as the "Star of Life" symbol, to improve vehicle recognition.

Despite these efforts, inconsistencies remain across agencies regarding color choices, reflectivity levels, and integration with existing vehicle aesthetics. The ongoing lack of standardization highlights the need for clearer federal guidance in emergency vehicle design.

Figure 26 presents examples of safety service patrol vehicle designs from various U.S. states. While many designs incorporate visibility-enhancing elements, there is a clear lack of consistency in how these features are applied nationwide.

(a)

(b)

(c)

(d)

(e)

Figure 26: State Service Patrol vehicles across the US: a) Alabama b) Maryland c) Connecticut d) Minnesota e) New Mexico

4.3 Insights from a national level survey

The research team conducted a nationwide survey (Appendix B) targeting state safety service patrol (SSP) program managers. The survey, designed to gather insights into emergency vehicle lighting, vehicle-mounted arrow boards, vehicle markings, and other safety treatment, consisted of 24 questions aimed at understanding SSP operations across the United States.

The survey was distributed to traffic incident management (TIM) contact in all 50 states, the District of Columbia, and Puerto Rico. A total of 44 agencies across 30 states responded, providing valuable data on emergency vehicle design and markings.

Key findings of the survey are as follows:

- The majority of agencies use white as the base vehicle color.
- Most agencies have retroreflective rear-facing conspicuity markings, with several indicating ongoing efforts to install them.
- Common marking color combinations include red, blue, green, and yellow, while white is used only in combination with blue –never as a standalone marking color.

4.4 Design Priniciples

The research team developed overarching design principles to guide the evaluation and enhancements of FDOT's RRSP vehicle markings. These principles prioritize safety, visibility, and public recognition, while reinforcing the branding of the Road Ranger program. Stakeholder engagement played a key role in shaping these principles, ensuring alignment with operational needs and FDOT best practices.

The design principles are categorized into three key areas: enhancing safety, improving motorist recognition, and strengthening branding.

4.4.1 Enhancing Safety

The safety of Road Rangers and motorists is the highest priority. To improve visibility and reduce collision risks, the following measures were emphasized:

- *Retroreflective Materials:* All rear markings, logos, and lettering should incorporate retroreflective materials to enhance visibility in low-light and nighttime conditions.
- *Color Contrast:* Rear markings should feature high-contrast colors against the base vehicle color to maximize visibility.
- *High-Visibility Colors:* Fluorescent red/orange and yellow/green should be used to improve daytime visibility and attract driver attention.
- *Chevron Pattern:* A downward-oriented chevron pattern should be applied to the rear vertical surfaces and rear-facing door openings to enhance visibility and guide driver focus.

4.4.2 Improving Motorist Recognition

Ensuring RRSP vehicles are easily identifiable as an official FDOT service vehicle is essential. Key principles include:

- *Statewide Consistency:* Vehicle markings should be uniform across all FDOT districts to maintain consistent recognition.
- *Distinctive Identity:* The design should distinguish Road Ranger vehicles from FDOT maintenance trucks and private asset maintenance (AM) contractor vehicles.
- *Official Appearance:* Unique FDOT logos and official Road Ranger legends should be prominently displayed.
- *Service Messaging:* Legends should clearly indicate that the service is free of charge, along with *FHP emergency contact information and an “Incident Response” designation.

- *Identification Markings:* Each RRSP vehicle should have a unique ID number clearly visible on the sides and rear.

4.4.3 Strengthening Branding

A strong, consistent brand identity reinforces the credibility of the Road Ranger program. The key branding elements include:

- *FDOT and Road Ranger Logos:* These logos should be prominently placed to build public trust and ensure clear identification.
- *Consistent Color Palette:* Standardized colors should enhance visibility while supporting FDOT's branding identity.
- *Graphics and Legends:* All lettering and graphics should align with FDOT design standards, ensuring a professional and cohesive vehicle appearance.

These design principles serve as the foundation for developing new RRSP vehicle designs, ensuring that they address safety, operational efficiency, and public perception while supporting FDOT's strategic goals.

4.5 Stakeholder Engagement and Feedback

To refine the RRSP vehicle design, the research team conducted a stakeholder meeting on November 22, 2024 via Zoom. The meeting was attended by RRSP program managers from multiple FDOT districts and Central Office representatives. Participants were provided with preliminary design documents ahead of the meeting and were asked to provide feedback through a live stakeholder poll.

The discussions were held on three topics: motorist recognition, safety considerations, branding and public recognition. Key findings include:

4.5.1 Motorist Recognition

- *Uniformity in Markings:* Stakeholders emphasized the need for a consistent vehicle marking system to distinguish RRSP trucks from FDOT maintenance and AM contractor vehicles.

- *High-Visibility Colors:* A preference emerged for lime green and fluorescent yellow over white, as white tends to blend into the environment.
- *Funding Considerations:* Concerns about costs for transitioning vehicle colors were addressed, with assurances that changes would occur gradually through attrition and new contracts.
- *Public Perception:* Stakeholders agreed that clear identification and emergency contact information should reinforce the public image of RRSP as an official FDOT service, distinct from private towing companies.

4.5.2 Safety Considerations

- *Chevron Markings:* Participants supported the addition of chevron patterns on the rear to enhance visibility. European chevron designs were discussed as potential references.
- *Retroreflective Materials:* Strong support emerged for retroreflective lettering and logos to improve nighttime visibility.
- *Standardization for AI Recognition:* The group discussed AI-driven vehicle technology and how standardized markings could improve recognition by autonomous and connected vehicles.
- *Poll Results:* 11 out of 12 participants agreed that rear chevron markings improve safety.

4.5.3 Branding & Public Recognition

- *Larger Lettering & Graphics:* Stakeholders supported larger text and graphics to improve vehicle recognition from a distance.
- *Multilingual Messaging:* Some participants proposed adding Spanish translations (e.g., "Servicio gratuito") to enhance public understanding. However, concerns were raised about overloading the design with excessive text.
- *Preferred Branding Elements:* The group agreed that logos and distinct symbols should be used to establish a recognizable Road Ranger brand.
- *Poll Results:* 12 out of 13 stakeholders agreed that stripes, graphics, and logos improve vehicle recognition.

Based on stakeholder feedback, the research team proceeded with developing initial renderings for further review and discussion.

4.6 Design concept and vehicle zoning

Following the stakeholder meeting, the research team refined the RRSP vehicle design concept, incorporating feedback from internal discussions. Figure 27 illustrates the schematic layout of the new design concept, which divides the vehicle into three distinct zones: an Identity Zone (Branding), an Information Zone, and a Safety Zone. The structured approach helps ensure that critical information is presented clearly while maintaining a professional and consistent appearance across the fleet. Additionally, the design must be appropriate for two key operational conditions: (1) when the vehicle is stationary and assisting motorists and (2) when the vehicle is actively moving in the traffic stream. This distinction ensures that visibility, messaging, and safety elements remain effective in both scenarios.

4.6.1 Identity Zone

The Identity Zone (Branding) is dedicated to establishing the vehicle's association with FDOT and the Road Ranger program. This section includes key branding elements such as the FDOT and Road Ranger identifiers, ensuring that motorists and responders can easily recognize the vehicle as part of an official service. The thought process behind this section is to increase public awareness by distinguishing the RRSP vehicle from other FDOT maintenance or private contractor service trucks.

4.6.2 Information Zone

The Information Zone focuses on providing essential operational details for motorists and responders. This includes the "Incident Response" designation, a contact number (*FHP), and the truck identification number. This section ensures that motorists can quickly access relevant information when assistance is needed. The designation of a "Free Service" was considered important to help drivers understand that no payment is required for assistance.

Furthermore, the team discussed different operational states and potential adjustments to rear messaging when the vehicle is in motion versus when it is stationary. This included the possible removal of the "Move Over, Slow Down – It's the Law" lettering on the bumper, as it may not be effective when the vehicle is actively assisting, given the small size. When on patrol, this messaging may be confusing to motorists, being interpreted as a requirement to act. The team felt this kind of promotion is best left to bumper stickers that leave no ambiguity about purpose. Similarly, the team also discussed about various adjustments, such as optimizing tailgate positioning and signage placement, that could enhance visibility and improve compliance with safety regulations.

4.6.3 Safety Zone

The Safety Zone is designed with high-visibility elements to enhance vehicle conspicuity, especially in low-light conditions. The rear of the RRSP vehicle is the most visible and also the most vulnerable to approaching drivers. This vehicle section incorporates alternating high-visibility red/orange and yellow/green reflective markings, improving motorist awareness and promoting safer interactions on roadways. To ensure effectiveness in both stationary and moving conditions, the placement of rear markings and messaging must be carefully considered, particularly when the tailgate is up or down, to maintain consistent visibility of critical safety warnings. This would apply to both the pickup bed and utility bed vehicles. These designated zones collectively contribute to improved recognition, operational clarity, and enhanced safety for both responders and the public. The words "Road Ranger" is an essential part of the rear vehicle markings, helping inform other responders who may approach.

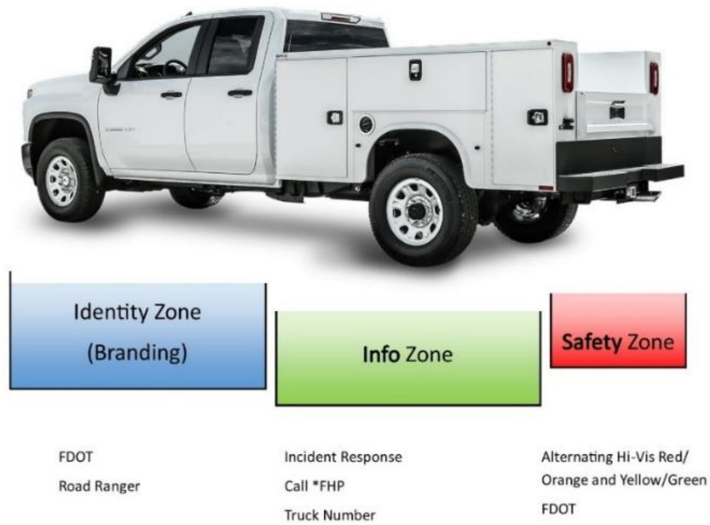


Figure 27: Design Concept Schematics of the Vehicle

4.7 Vehicle Design Renderings

Based on the research approach, the team developed three new vehicle marking designs, created using graphic software. Figure 28 presents the designs.

(A)

(B)

(C)

Figure 28: A) Design A B) Design B C) Design C

4.7.1 Design Specifications

The designed vehicle option exhibit following characteristics:

- Option A features a DOT Yellow base color with blue accents along the rocker and upper beltline.
- Option B utilizes a fluorescent orange base color with blue accents on the rocker and upper beltline.
- Option C adopts a fluorescent yellow-green base color, also with blue accents along the rocker and upper beltline.

All three designs incorporate high-contrast, retroreflective lettering to enhance visibility and recognition:

- "ROAD RANGER" is prominently displayed in bold blue font on the sides and rear, with "FREE SERVICE" to emphasize the public nature of the assistance.
- A vehicle identification number is positioned on the front fender.
- "INCIDENT RESPONSE" is marked in retroreflective red lettering on the side of the vehicle bed for quick identification.
- The FDOT logo appears on the side, along with “*FHP”, directing motorists to the statewide emergency contact number.

To improve conspicuity, visibility, and compliance with Florida's Move Over law, the rear of the vehicle incorporates:

- High-visibility red and yellow-green chevron striping, both fluorescent and retroreflective.
- "ROAD RANGER" is centered on the rear against a solid background of yellow-green, ensuring it remains highly visible.
- A large vehicle-mounted message/arrow board is installed on the roof of each RRSP vehicle, providing real-time directional guidance for drivers.

When in the "up" position, the reverse (non-electronic) side of the digital board features "FDOT" in a contrasting, non-retroreflective material.

4.8 Program manager survey on vehicle designs

To assess feedback on the proposed vehicle designs, the research team conducted a survey with 18 program managers across different FDOT districts. The 16-question survey was divided into four key evaluation areas:

1. Safety
2. Recognition
3. Branding
4. Design Evaluation

The findings for each subsection are presented below:

4.8.1 Safety

Most program managers indicated that Option C best promoted safety, particularly in terms of: Color contrast and Daytime and nighttime visibility. Figure 29 presents the visualization of these results.

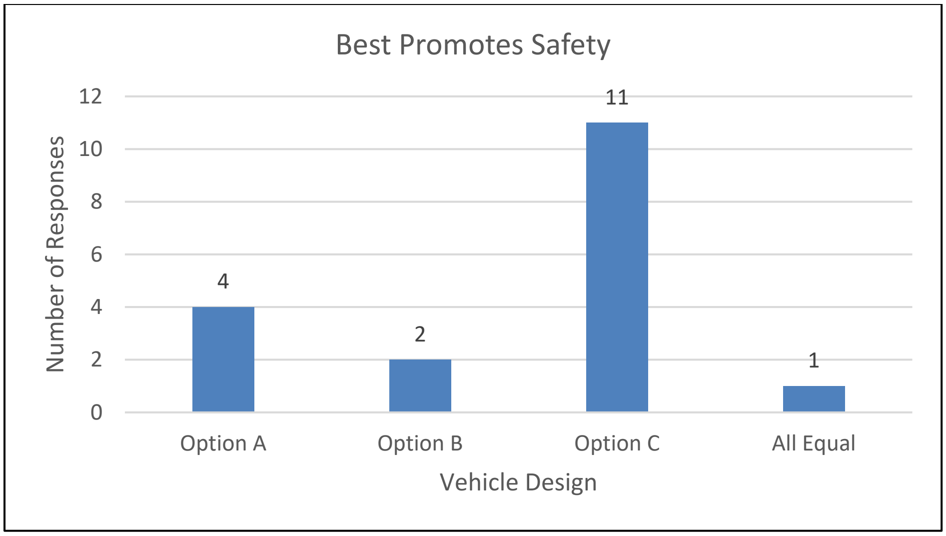


Figure 29: Designs and promotion of safety

Other recommendations from program managers can be grouped into following categories:

- *Enhancing Visibility:*
  - Preferred colors: Bright green, yellow-green, or high-visibility yellow.
  - Some suggested a fully yellow or lime-green vehicle for maximum conspicuity.
  - A few preferred a white vehicle with contrasting graphics for better recognition.
- *Reflectivity Improvements:*
  - Suggested adding reflective materials on the sides for better side visibility.
  - Maintaining the red/white "DOT" conspicuity stripe along the fenders and side panels was emphasized.
- *Lighting Enhancements:*
  - Installing strobe lights on the signboard pillars to increase visibility.
  - Adding LED lights on the rear bumper, activated when the vehicle is stopped, similar to transit vehicles.
  - Flashing lights underneath the vehicle to improve nighttime recognition.

4.8.2 Recognition

Most program managers agreed that Option C clearly identifies the vehicle as part of FDOT's RRSP program. Figure 30 presents a visualization of these results.

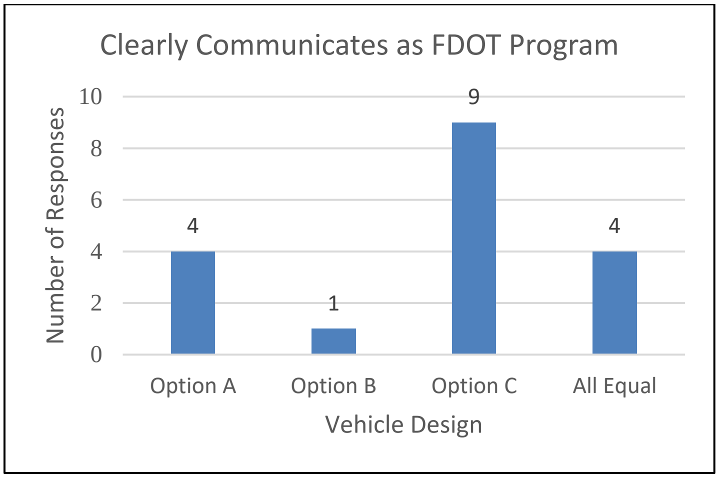


Figure 30: Designs and Recognition

Other recommendations from mangers for better recognition of the designed vehicle can be grouped into following categories:

- *Color Differentiation:*
    - Yellow-green (hi-vis) or FDOT Yellow was recommended preferred for better visibility.
- *Text & Labeling Adjustments:*
    - Suggested replacing "Road Ranger" with "Incident Response" on the rear tailgate to reinforce its first responder role.
    - Recommended adding "FDOT" or "Incident Response" above "Road Ranger" for better identification.
    - Including district-specific labeling (e.g., FDOT D7) was suggested for improved clarity.
- *Reflectivity Enhancements:*
    - Using 3M high-visibility reflective tape on all sides to enhance recognition.

- *Bilingual Messaging:*
  - Some suggested adding Spanish translations (e.g., "Servicio gratuito") to improve communication with Spanish-speaking motorists.

4.8.3 Branding

Most program managers approved of the current placement of FDOT and Road Ranger logos, stating they effectively distinguish RRSP vehicles from FDOT maintenance trucks. Figures 31 and 32 present a visualization of these results.

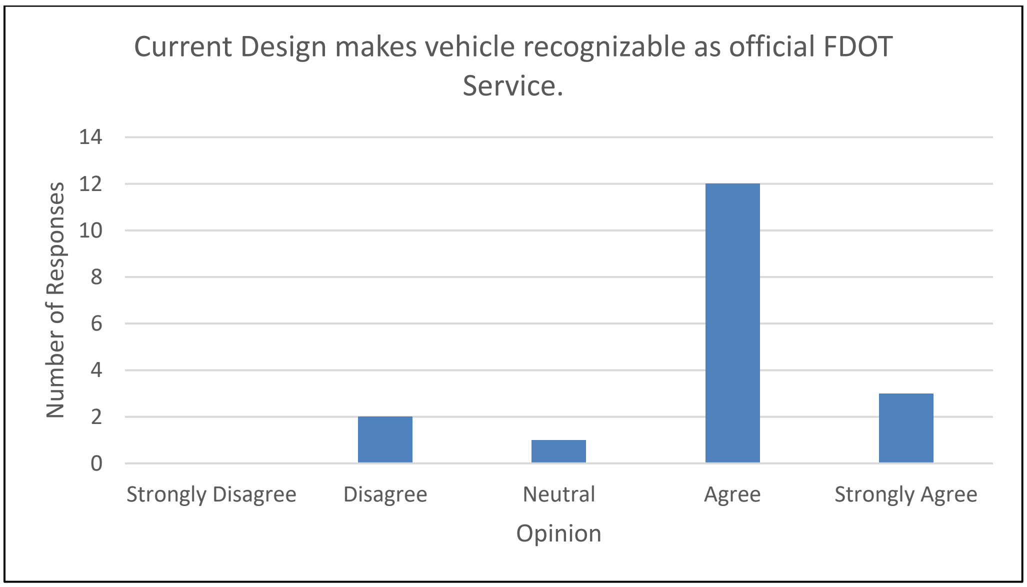


Figure 31: Design options and branding

Other recommendations from program managers for better branding can be grouped into following categories:

- *Enhancing Logo Visibility:*
  - Increasing the size of the FDOT logo, especially on the rear and back of the arrow board.
  - Adding "FDOT" on the door for better side visibility.
- *Adjusting Text Placement:*
  - Replacing "Incident Response" with "Emergency Response" for clarity.
  - Displaying "Road Ranger" on the push bumper and in mirrored lettering on the front.

- *Ensuring Unique Branding:*
  - Recommended restricting non-RRSP vehicles from using similar markings and colors.

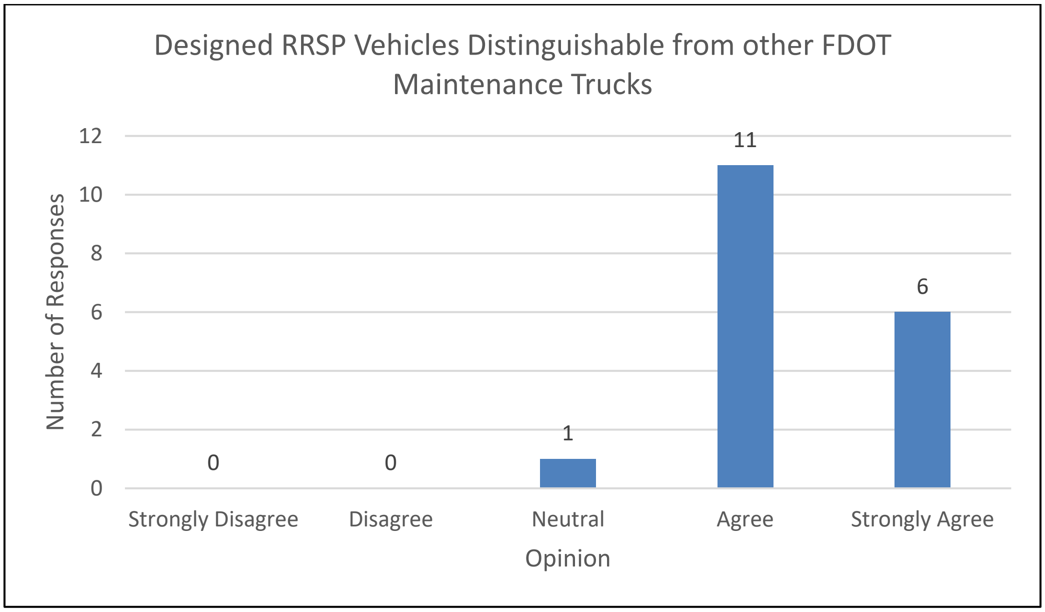


Figure 32: Design Options and Distinction from FDOT Maintenance Trucks

4.8.4 Design Evaluation

Most program managers agreed that:

- The Identity Zone (Branding section) effectively communicates FDOT's identity and Road Ranger branding (Figure 33).
- The Information Zone (*FHP, vehicle ID, purpose, etc.) is effective in conveying relevant information** (Figure 34).
- The Safety Zone (high-visibility markings and chevrons) improves emergency vehicle recognition (Figure 35).

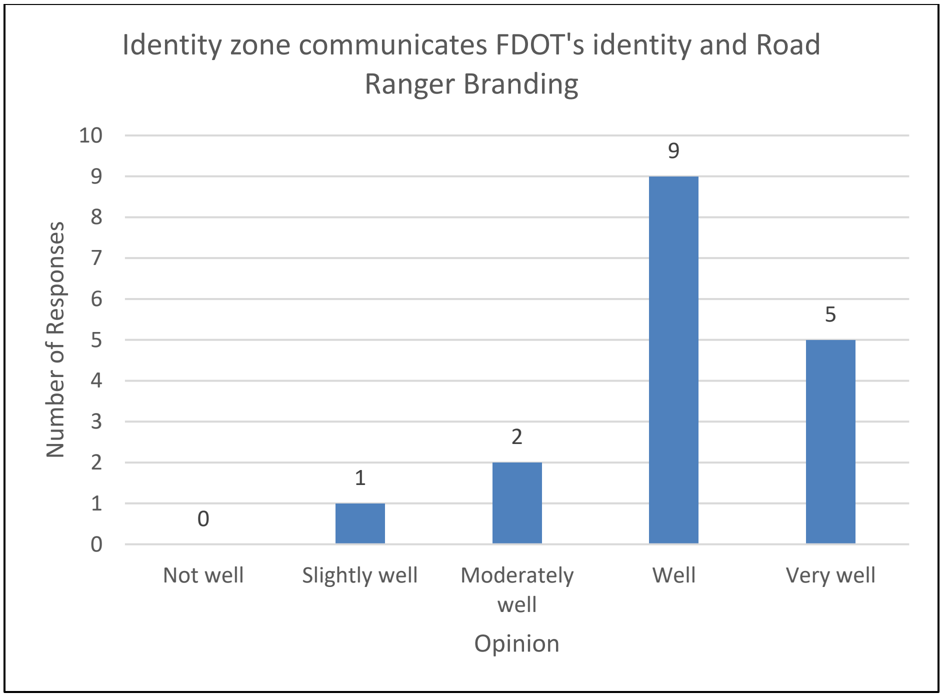


Figure 33: Identity zone and FDOT identity

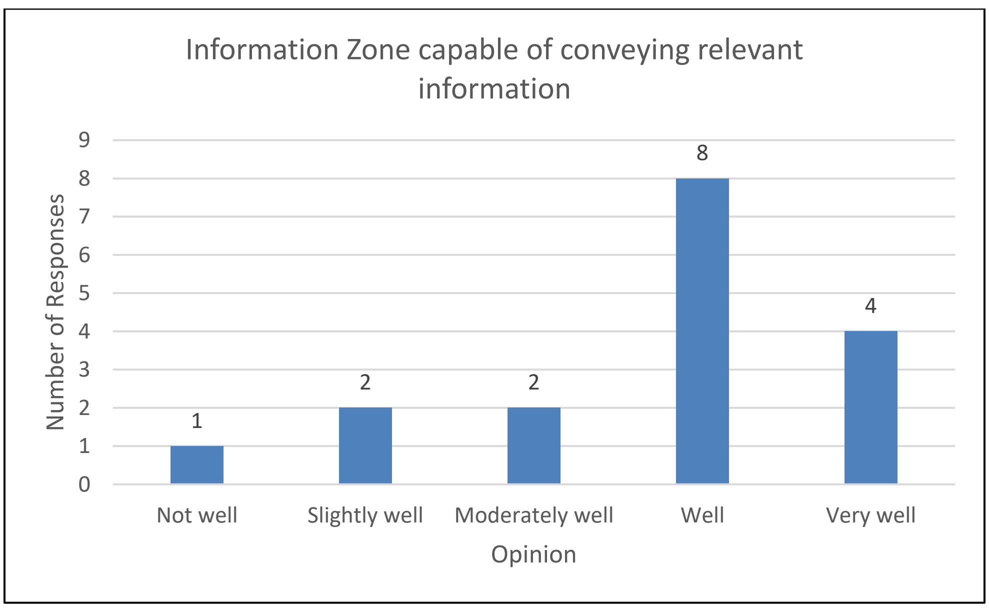


Figure 34: Information zone and conveyance of information

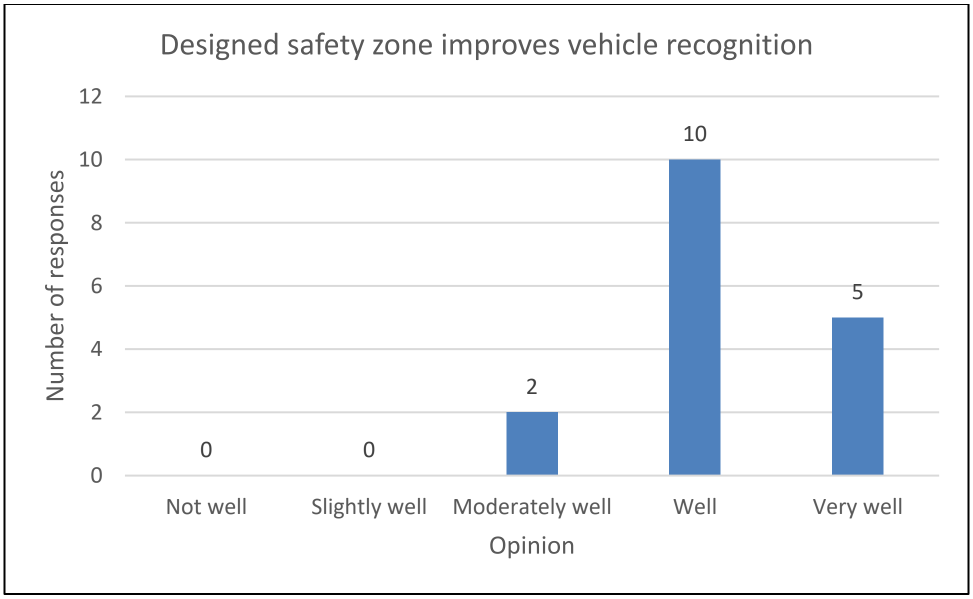


Figure 35: Safety zone and vehicle recognition

Other recommendations from program managers in regard to the design approach can be grouped into following categories:

- *Identity Zone Enhancements:*
- Increase the size of the FDOT logo above the "ROAD RANGER" text.
- Move "FREE SERVICE" to the Information Zone for better clarity.
- *Information Zone Refinements:*
- Replace "*FHP" with "*347" for easier dialing.
- Use "Dial **FHP"* instead of just *"*FHP"* for better clarity.
- Add "FREE SERVICE" to reinforce that assistance is free of charge.
- *Safety Zone Adjustments:*
- Consider blue/yellow chevrons for greater contrast.
- Add reflective tape along the vehicle's sides for increased recognition at night.
- Increase LED lighting for nighttime visibility.

4.9 Key Findings

The color and markings of emergency vehicles play a crucial role in visibility, recognition, and safety. Given the multiple RRSP vehicle collisions while assisting motorists, improving conspicuity is critical.

Key takeaways from this study are as follows:

- **Best Practices:** The study incorporated literature reviews and national benchmarking on emergency vehicle design.
- **Stakeholder-Driven Approach:** FDOT program managers, RRSP contractors, and safety experts contributed valuable insights.
- **Clear & Effective Zoning:** The three-zone vehicle layout enhances branding, recognition, and safety.
- **Survey-Driven Refinements:** Option C was the most preferred design, with recommended enhancements in:
    - FDOT logo placement
    - Reflective materials
    - Lighting improvements

4.10 Final Recommendation

The proposed designs incorporate high-visibility color schemes, standardized chevron patterns, and retroreflective materials to improve compliance with Florida's Move Over law. By implementing these refinements through vehicle attrition and contract updates, FDOT can enhance Road Ranger safety while ensuring uniform branding across districts.

Chapter 5. Conclusion

This research examined the influence of emergency vehicle lighting, arrow/message boards, and visual markings on driver compliance with the Move Over law. The need for this study was underscored by 247 reported RRSP vehicle strikes and 47 operator injuries between 2014 and 2021.

A combination of literature review, national survey, and field testing at three Florida highway locations produced robust findings. The use of red/white lighting and elevated light bar placement demonstrated the highest driver compliance. Additionally, clear directional arrow boards and message-based signage outperformed caution-only modes in signaling urgency. Cone deployment also proved effective in increasing lane-change behavior at incident scenes.

Following the field study, the team developed and evaluated new RRSP vehicle designs featuring three key zones—Safety, Information, and Identity. These zones help ensure consistency in vehicle visibility, operational messaging, and branding. Stakeholder feedback supported the adoption of high-visibility materials, standardized chevron markings, and consistent FDOT identifiers.

Key recommendations include:

- Use of red/amber light combinations and elevated light bar placements.
- Incorporation of text-based message boards with actionable warnings.
- Adoption of consistent vehicle markings to reinforce public and driver recognition.
- Systematic integration of stakeholder-informed design refinements.

The proposed changes, when implemented through vehicle attrition and future procurement cycles, are expected to significantly reduce responder-involved crashes by increasing driver awareness and compliance with roadway safety laws.

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APPENDIX A – Literature Review Tables

Table 16: Summary of Literature for Different Lighting Colors

Title	Author(s)	Lighting Color	
		Color Tested	Selected
Effects of Emergency Vehicle Lighting Characteristics on Driver Perception and Behavior	Bullough et al. (J. Bullough et al., 2021)	Blue, red, white, yellow	Blue and red
Effects of Warning Lamps on Pedestrian Visibility and Driver Behavior	Flannagan and Devonshire (M. J. Flannagan & Devonshire, 2007a)	Red and blue lamps	Blue lamps showed higher conspicuity ratings and longer detection distances.
Evaluation of Green Lights on TMAs	Brown et al. (Brown et al., 2018)	In simulator: amber/white, green only, green/amber, green/white; in field test: amber/white, green only	Green/amber TMA was the most preferred option in both daytime and nighttime conditions whereas green-only TMA was the least preferred.
Effects of Warning Lamp Color and Intensity on Driver Vision	Flannagan et al. (M. Flannagan, 2008)	White, yellow, red, blue	Recommends adopting blue overall, day and night, and using color coding for indicating traffic blockages
Law Enforcement Vehicle Lighting and Reflectivity Studies: An Overview	JTIC (JTIC, n.d.)	——	• Red lights – More visible in the daytime • Blue lights – More visible at night; serves as a contrasting color with red on emergency vehicles
Guidelines for the Selection and Application of Warning Lights on Roadway Operations Equipment	Gibbons et al. (Gibbons et al., 2008a)	Amber, blue, red, white	In terms of detection, amber and white light performed equivalently and best in terms of attention and conspicuity. Red and blue performed worse.

Title	Author(s)	Lighting Color	
		Color Tested	Selected
Texas DOT Vehicle Fleet Warning Light Policy Research	Ullman and Lewis (Ullman & Lewis, n.d.)	Red-blue-yellow configuration, blue-yellow configuration, all-yellow configuration, yellow and blue strobes	• Research at two sites showed a 5–6 mph reduction in average speeds with the yellow-blue light setup compared to yellow lights alone. • No significant speed differences were noted between these configurations at the other three sites. • Across all five sites, average speeds with the red-yellow-blue light configuration matched those of the yellow-light-only setup. • The yellow-blue-red taillight strobe configuration resulted in lower average speeds at one site relative to the yellow-only setup but did not affect speeds at the other two sites where it was tested.
		——	Lane choice performance measures inconclusive, however, increased brake usage trend towards yellow-blue light configuration relative to yellow light only configuration.
		Perception study of red, blue, yellow, and different colors	Motorists commonly link yellow lights with vehicles related to highway construction and maintenance, as well as tow trucks. On the other hand, light

Title	Author(s)	Lighting Color	
		Color Tested	Selected
			combinations that include red (such as red and blue, red and white, and red with other colors) are typically associated with different kinds of emergency vehicles.
		——	Motorists tend to view yellow-only warning lights as signaling less critical situations compared to when vehicles display a mix of yellow with either blue or red lights. A greater number of drivers believe that these more hazardous scenarios require a level of braking action, unlike situations where only yellow lights are used.
The Move Over Law: Effect of Emergency Vehicle Lighting on Driver Compliance on Florida Freeways	Carrick and Washburn (Carrick & Washburn, 2012)	1. Configuration A: Emergency top lights only 2. Configuration B: Emergency top lights plus amber directional lights 3. Configuration C: Amber directional lights with no emergency top lights	Lighting Configuration A: 78.3% compliance, B: 80.1%, C: 64.7% overall compliance
Survey of the Use of Flashing Lights on Roads and Road Vehicles	Hargroves (Hargroves, 1971)	——	In daylight, flashing amber lights and mechanical signaling arms offer similar levels of visibility, but at night, amber lights significantly surpass in performance, making them the preferred choice for visibility.

Title	Author(s)	Lighting Color	
		Color Tested	Selected
Motor Vehicle Conspicuity: Warning Beacons	Cook et al. (Cook, n.d.)	Amber, blue, green, red	When intensity was held constant, • Amber: Poor detection time, • Blue: Minimize glare and gives rise to least discomfort during day, • Green: Quickest detection time (day) but bad glare, • Red: Quickest detection least glare. In real world conditions, • Amber: Quickest Detection Times, greatest glare, • Blue: Least Discomfort glare, • Green: Least glare, poorest detection time, • Red: Minimum glare at night, enables pedestrian detection at night

Table 17: Summary of Literature for Different Lighting Type and Intensity

Title	Author(s)	Lighting Type		Lighting Intensity	
		Type of Lighting Tested	Selected	Intensity Levels Tested	Selected
Effects of Emergency Vehicle Lighting Characteristics on Driver Perception and Behavior	Bullough et al. (J. Bullough et al., 2021)	——	——	Two intensity levels were tested.	Higher intensity resulted in higher visibility ratings.
Effects of Warning Lamp Color and Intensity on Driver Vision	Flannagan et al. (M. Flannagan, 2008)	——	——	Low, high	Higher intensity improved performance
Fire Apparatus Emergency Lighting	Bullough et al. (ERSI, 2021)	——	——	• Level 1 (Typical full intensity) • Level 2 (Minimum per current standard) • Level 3 (50% Minimum) • Level 4 (10% Minimum) • Level 5 (5% Minimum) Minimum per current standard (NFPA) for rear of vehicle when blocking right-of-way	For blocking-the-right-of-way at night, the lighting intensity in each upper zone should be in a range of 400,000 to 1,600,000 cd·s/min. For blocking-the-right-of-way at night, the lighting intensity in each lower zone should be in a range of 150,000 to 600,000 cd·s/min
Guidelines for the Selection and Application of Warning Lights on Roadway Operations Equipment	Gibbons et al. (Gibbons et al., 2008a)	Halogen, LED, Strobe	For detection, LED was the best performer.	High and low	Lower intensity resulted into poor detection. A higher effective intensity of light source provides a greater conspicuity both during daytime and night.

Title	Author(s)	Lighting Type		Lighting Intensity	
		Type of Lighting Tested	Selected	Intensity Levels Tested	Selected
Viewing of Railway Flashing Light Signals	Cox (Cox, 1971)	——	Brightness level of a flashing light is perceived as greater than a fixed light with the same lumen output.	——	Drivers may overlook distant low-intensity lights due to their focus on proximal events, downward gaze, and potential colorblindness or poor visual acuity.
Survey of the Use of Flashing Lights on Roads and Road Vehicles	Hargroves (Hargroves, 1971)	——	——	——	Utilize blinking amber lights for signaling, ensuring they emit a brightness of 100 to 500 candelas for optimal nighttime visibility. Additionally, for enhanced safety, particularly in urban driving situations where proximity to other vehicles is a concern, these flashing lights should be mounted at the sides of the vehicle at a height level with the driver's head to facilitate easier detection by fellow motorists.

Title	Author(s)	Lighting Type		Lighting Intensity	
		Type of Lighting Tested	Selected	Intensity Levels Tested	Selected
Motor Vehicle Conspicuity: Warning Beacons	Cook et al. (Cook, n.d.)	——	Strobe warning beacons were subjectively considered to convey greater urgency, while rotating warning beacons were less annoying and minimized the effects of disability glare.	——	High flash intensities minimize warning beacon detection times (day and night).

Table 18: Summary of Literature for Different Flashing Patterns

Title	Author(s)	Flashing Pattern	
		Patterns Tested	**Selected**
Effects of Warning Lamps on Pedestrian Visibility and Driver Behavior	Flannagan and Devonshire (M. J. Flannagan & Devonshire, 2007a)	Steady burning, flash-together, and flash-alternating	Flash-together pattern rated as most conspicuous. Flashing patterns (flash-together and flash-alternating) had less impact on pedestrian visibility than steady-burning lamps.
Fire Apparatus Emergency Lighting	Bullough et al. (ERSI, 2021)	Random, alternating, on/off, X pattern	Low flashing rate: 60 flashes per minute
Guidelines for the Selection and Application of Warning Lights on Roadway Operations Equipment	Gibbons et al. (Gibbons et al., 2008a)	Steady, synchronous at 1 Hz, asynchronous at 1 Hz, asynchronous at 4 Hz	Synchronous better than asynchronous for detection
Language of Flashing Lights	Holmes (Holmes, 1971)	——	Repetitive flashing signals with a maximum interval of 5 seconds retain observers' attention effectively.

Title	Author(s)	Flashing Pattern	
		Patterns Tested	Selected
Flash Rate as a Visual Coding Dimension for Information	Cohen and Dinnerstein (J. Cohen & J. Dinnerstein, 1958)	——	Suggested that using three or four flash frequencies could serve as a method for coding information. Importantly, while reaction times for correctly identifying these flash frequencies decrease at higher frequencies, they remain significantly extended in the context of driving times. A practical maximum flash frequency of 3 Hz is recommended for effectiveness and safety. Furthermore, the most appropriate single flash frequency for vehicle flashing lights is identified as 90±30 cycles per minute, equating to 1 to 2 Hz. This range balances the need for visibility and the ability for motorists to accurately perceive and react to the signals.

Title	Author(s)	Flashing Pattern	
		Patterns Tested	**Selected**
Motor Vehicle Conspicuity: Warning Beacons	Cook et al. (Cook, n.d.)	——	High flash rates, such as 4 Hz, enhance the detection time of warning beacons and are more effective in conveying a sense of urgency, both during the day and at night. Conversely, low flash rates, around 1 Hz, reduce discomfort glare and disability glare at night, as well as minimize perceived annoyance throughout the day and night. Additionally, when multiple warning beacons are used on a vehicle, those that flash simultaneously are detected significantly faster than beacons that flash alternately. Beacons flashing in unison are also subjectively considered more attention-grabbing, both during the day and at night. However, beacons that flash alternately are better at minimizing discomfort glare in both lighting conditions.

Table 19: Summary of Literature for the Use of Arrow Boards

Title	Author(s)	Arrow Boards
		Key Findings
Guidelines for the Application of Arrow Boards in Work Zones	Graham et al. (Graham et al., 1978)	Placement of arrow devices in long-term work zones, particularly at merge tapers. Arrow boards effectively guide traffic out of closed lanes, especially when positioned at the start of the merge taper. Diverse scenarios like route diversions or shoulder closures may limit the effectiveness of arrow displays, as drivers may associate them more with leaving a lane than leaving the roadway.
Public Opinion and Understanding of Advance Warning Arrow Displays Used in Short-Term, Mobile, and Moving Work Zones	Schrock et al. (Schrock et al., 2008)	Analysis of the effectiveness of different arrow board types, including flashing arrow, sequential arrow, and sequential chevron, through surveys with a focus group across multiple states. Preferences leaned towards sequential displays over flashing ones, perceiving sequential movement as indicative of a more critical or important situation. There were doubts about including the flashing chevron in future versions of the Manual on Uniform Traffic Control Devices (MUTCD). Participants preferred staggered work vehicles but disapproved of mixing different arrow displays within the same work convoy. They expressed interest in additional information via static signing on the back of shadow vehicles for clearer and more effective traffic control in short-duration, mobile, and moving work zones.

Title	Author(s)	Arrow Boards Key Findings
Motorist Comprehension of Traffic Control Devices for Mobile Operations	Finley et al. (Finley et al., 2006)	Evaluation of comprehension of information presented on trucks in a moving work convoy using various signing methods. The study found that a flashing arrow display directing traffic to move right was understood by only 66 percent of participants, contrasting with text-based CMS messages that achieved higher comprehension rates. This aligns with previous research, suggesting reduced effectiveness of flashing arrow displays when directing drivers beyond moving into an adjacent travel lane.
Project Summary Report 4940-S Project 0-4940: Photometric Requirements for Arrow Panels and Portable Changeable Message Signs	Wooldridge et al. (Wooldridge et al., n.d.)	Investigation into the brightness levels of arrow panels and changeable message signs (CMSs) and their impact on driver behavior. The study varied luminous intensity levels during daytime operations at long-term work zones, establishing a link between luminous intensity and lane-changing behavior. It emphasized the importance of considering the distance from which drivers perceive arrow panels, particularly during bright daytime conditions. The study concluded with recommended minimum luminous intensity values, providing valuable insights for improving the visibility and effectiveness of arrow displays in traffic management.
Emergency Vehicle Safety Initiative	Wieder et al. (FEMA, 2014)	Arrow boards on fire department vehicles are expected to operate in three modes: flashing arrow, sequential arrow, or sequential chevron; flashing double arrow; and flashing caution or alternating diamond mode. Arrow boards must be capable of at least a 50 percent dimming from full brilliance to

Title	Author(s)	Arrow Boards
		Key Findings
		avoid adversely affecting oncoming driver vision during nighttime operation. Apparatus-mounted arrow boards should have a 48-inch length for the arrow and a 24-inch width for the arrowhead, ensuring visibility at a minimum distance of 0.5 miles.
Safe Operation of Fire Tankers	USFA (FEMA, n.d.)	Concern about existing arrow boards and directional light bars potentially not meeting standards, reducing their effectiveness. Recommendations include advising vehicle-mounted arrow boards to be positioned as high as practical and equipped with remote controls. Additionally, the vehicle itself should feature high-intensity rotating, flashing, oscillating, or strobe lights for improved effectiveness.

Table 20: Summary of Literature for the Use of Markings and Safety Vests

Title	Author(s)	Marking	Other (Cones or Safety vests)
		Key findings	Key Findings
The Effectiveness of Retroreflective Tape on Heavy Trailers	Morgan (Morgan, 2001)	Retroreflective tape significantly reduces side and rear impacts of heavy trailers during dark conditions, based on a statistical analysis of crash cases.	——
Selection and Application of Warning Lights on Roadway Operations Equipment	Gibbons et al. (Gibbons et al., 2008c)	Retroreflective tape provides additional benefits for marking maintenance vehicles at night, particularly during winter months when snowplow detection is challenging.	——
Safer Winter Maintenance	Stidger (Stidger, 2003)	Orange magnetic strips improve vehicle visibility at night and in low-visibility weather conditions, enhancing safety during winter months.	——
Effects of Emergency Vehicle Lighting Characteristics on Driver Perception and Behavior Study Report Emergency Responder Safety Institute	Bullough et al. (J. D. , S. A. P. A. S. E. Hiebner. Bullough, 2021)	Retroreflective panels with chevron markings meeting ASTM Type V specifications, when combined with flashing lights, result in shorter detection distances to simulated firefighters.	——

Title	Author(s)	Marking	Other (Cones or Safety vests)
		Key findings	Key Findings
High Conspicuity Livery for Police Vehicles	Harrison (Harrison, 2004)	A Battenburg pattern is recommended for police vehicles in the U.K., as it presents a distinctive and attention-grabbing visual cue.	——
Worker Safety Issues in Night-Time Highway Construction	Arditi et al. (Arditi, n.d.)		Safety vests have high approval among highway construction/maintenance professionals and are perceived as effective in enhancing worker visibility during nighttime activities. Adherence to ANSI standards for safety vest design ensures adequate performance in various lighting and weather conditions. Effective safety vest usage can reduce the frequency and severity of nighttime accidents, thereby enhancing labor productivity.

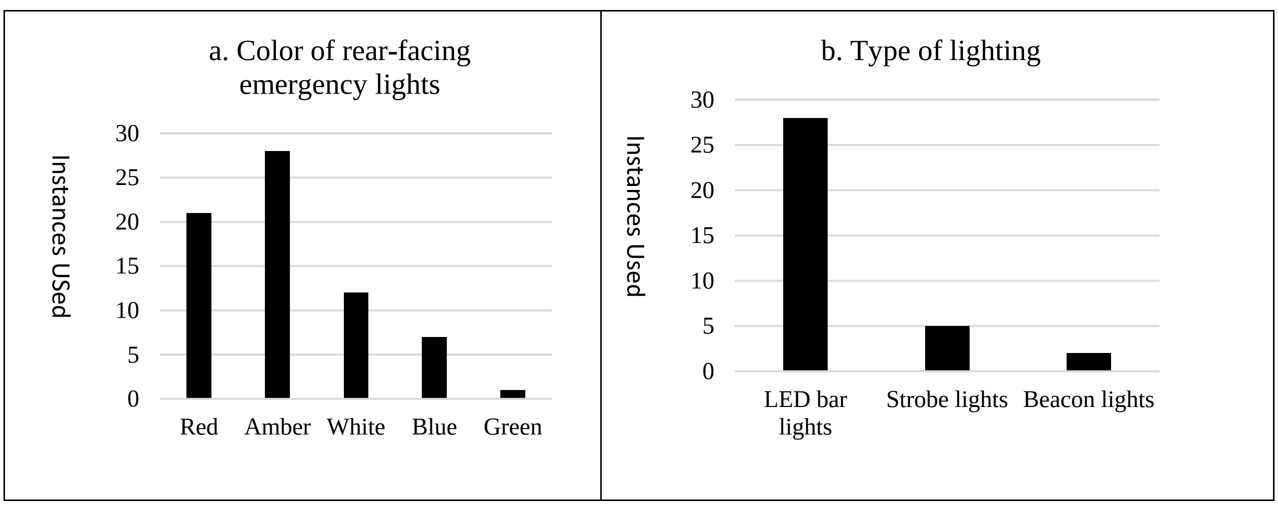
Title	Author(s)	Marking	Other (Cones or Safety vests)
		Key findings	Key Findings
Protecting Roadside Workers: Field Evaluation of Flares, Cones, and Tow Truck Light Patterns	Blomberg et al. (Blomberg et al., 2023a)		Cones, when combined with specific light patterns at night, are effective in prompting motorists to slow down or change lanes near traffic incident management vehicles. Previous research demonstrates that parallel rows of cones reduce mean vehicle speeds, with uneven arrangements further reducing speed-related accidents within roadwork zones. Cones are highly effective, affordable, and convenient compared to alternative countermeasures, making them a practical choice for traffic management.

APPENDIX B – State Safety Service Patrol Survey

Building on a firm understanding of past lighting research, the opportunity arose to use that information to evaluate current practices in safety service patrol (SSP) operations. A nationwide targeted survey, consisting of 24 questions about SSP emergency lighting, arrow boards, markings and miscellaneous treatment methods was conducted to understand the operations of SSP programs across the United States. The survey was distributed to traffic incident management (TIM) points of contact in all 50 states, the District of Columbia, and Puerto Rico We received responses from 44 agencies across 30 states, and their responses were analyzed.

A.1. Lighting Systems

Among the various questions about program elements, specific questions focused on the lighting system design of the SSP vehicles. Figures 36 and 37 provide an overview of the results. Most vehicles use red- and amber-colored LED bar lights, noted for their high visibility and minimal glare. Roof-mounted systems are the most common, but agencies also use mounting points on utility boxes, bumpers, or on the supporting structure of arrow/message boards for additional lights.



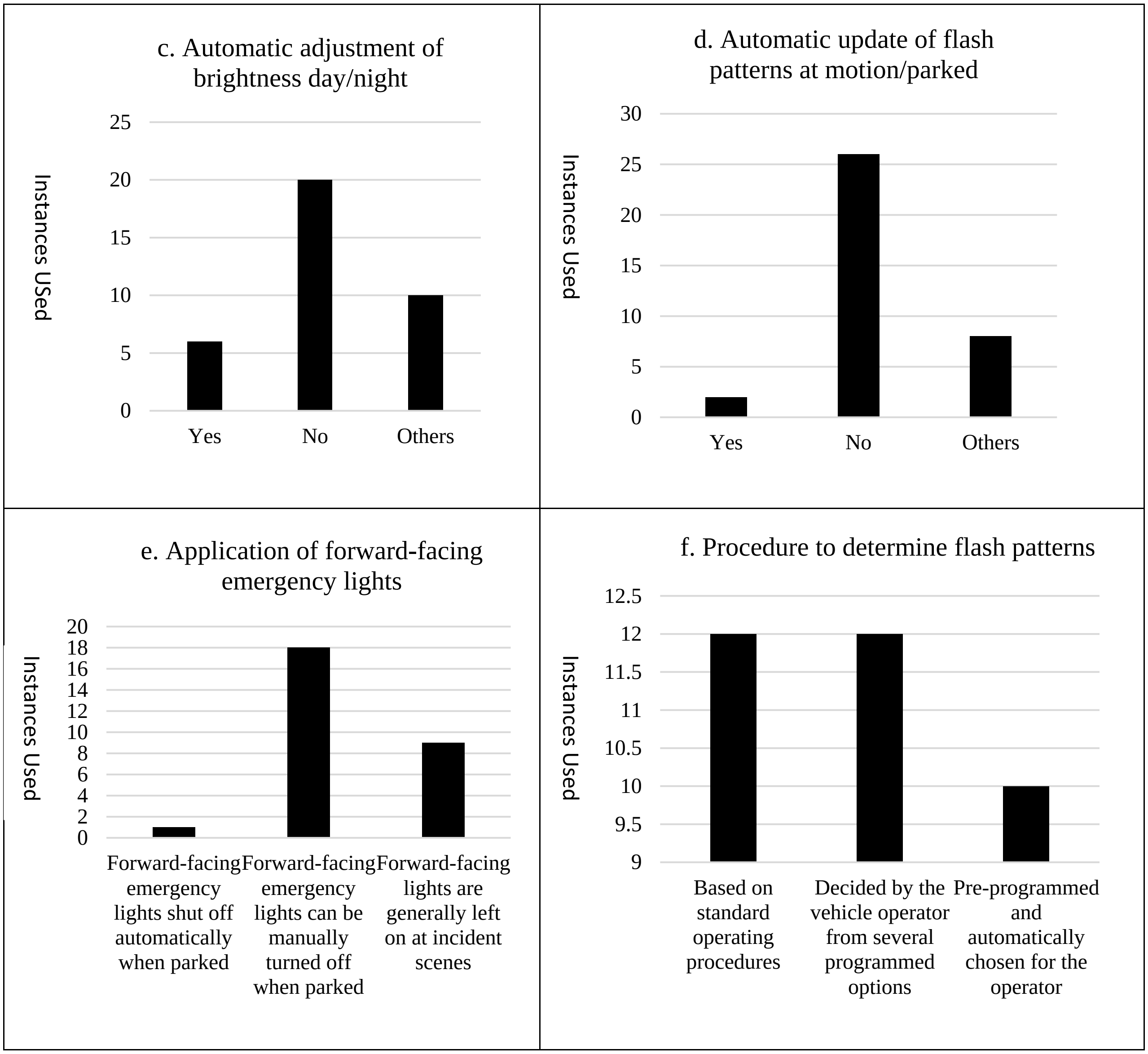


Figure 36: Lighting system design of SSP vehicles

Most lighting systems do not automatically adjust brightness for daylight conditions. Additionally, there is no automatic or preprogrammed change in flash patterns when vehicles are stopped or in motion. Instead, the flash pattern is selected based on standard operating procedures or by the vehicle operator from pre-programmed options.

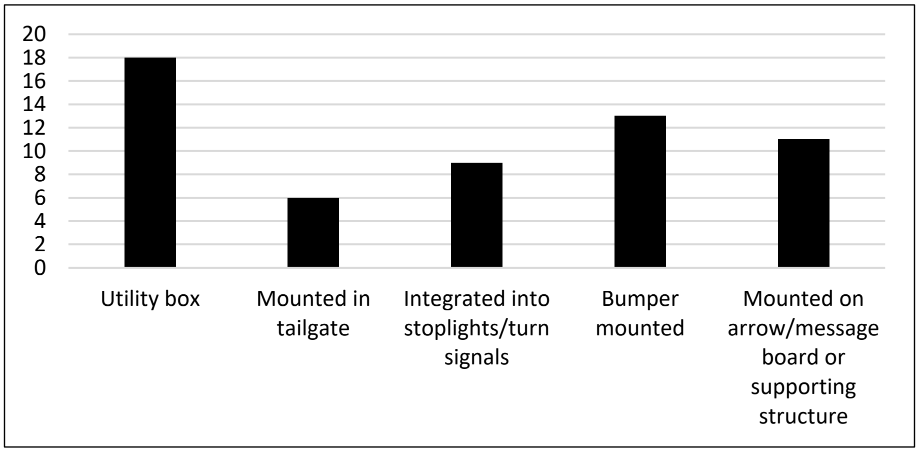
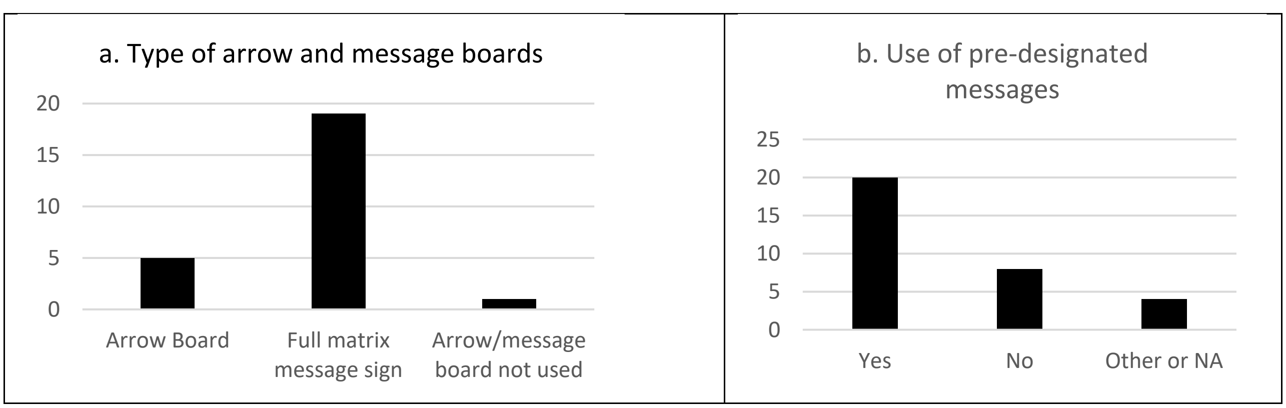


Figure 37: Mounting positions of other emergency lights

A.2. Arrow Boards

Four questions were asked to assess the usage of arrow boards across the United States. The majority of agencies reported the utilization of full matrix message signs in their arrow boards, with the displayed messages being pre-designated. Similarly, most agencies indicated the use of caution mode (4 corners) and confirmed that both the emergency lights and arrow board are operational at a scene. Figure 38 provides an overview of the results. The usage of the message boards varied across the agencies. Certain agencies mentioned that they were not allowed to use their vehicle with the message board whereas certain agencies commented that the selection of message depended on the operator choice based on call type, roadway geometry and traffic density.



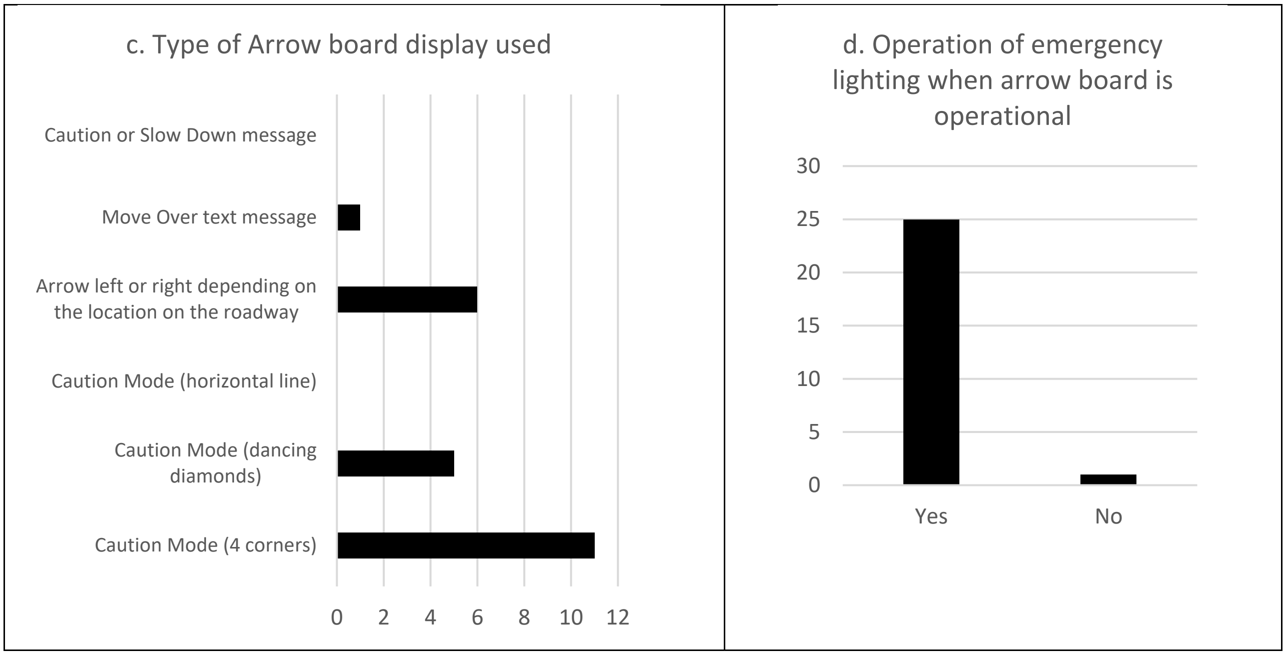


Figure 38: Arrow board design of SSP vehicles

A.3. Markings

A set of three questions was asked to understand the characteristics of the markings used on SSP vehicles. Figure 39 provides an overview of the results. The majority of agencies indicated that their vehicles are equipped with retroreflective rear-facing conspicuity markings, with some agencies commenting that they are in the process of installing them. Various color combinations are being used, with red, blue, green, and yellow being the primary colors. White is also used but only in combination with blue, not in isolation.

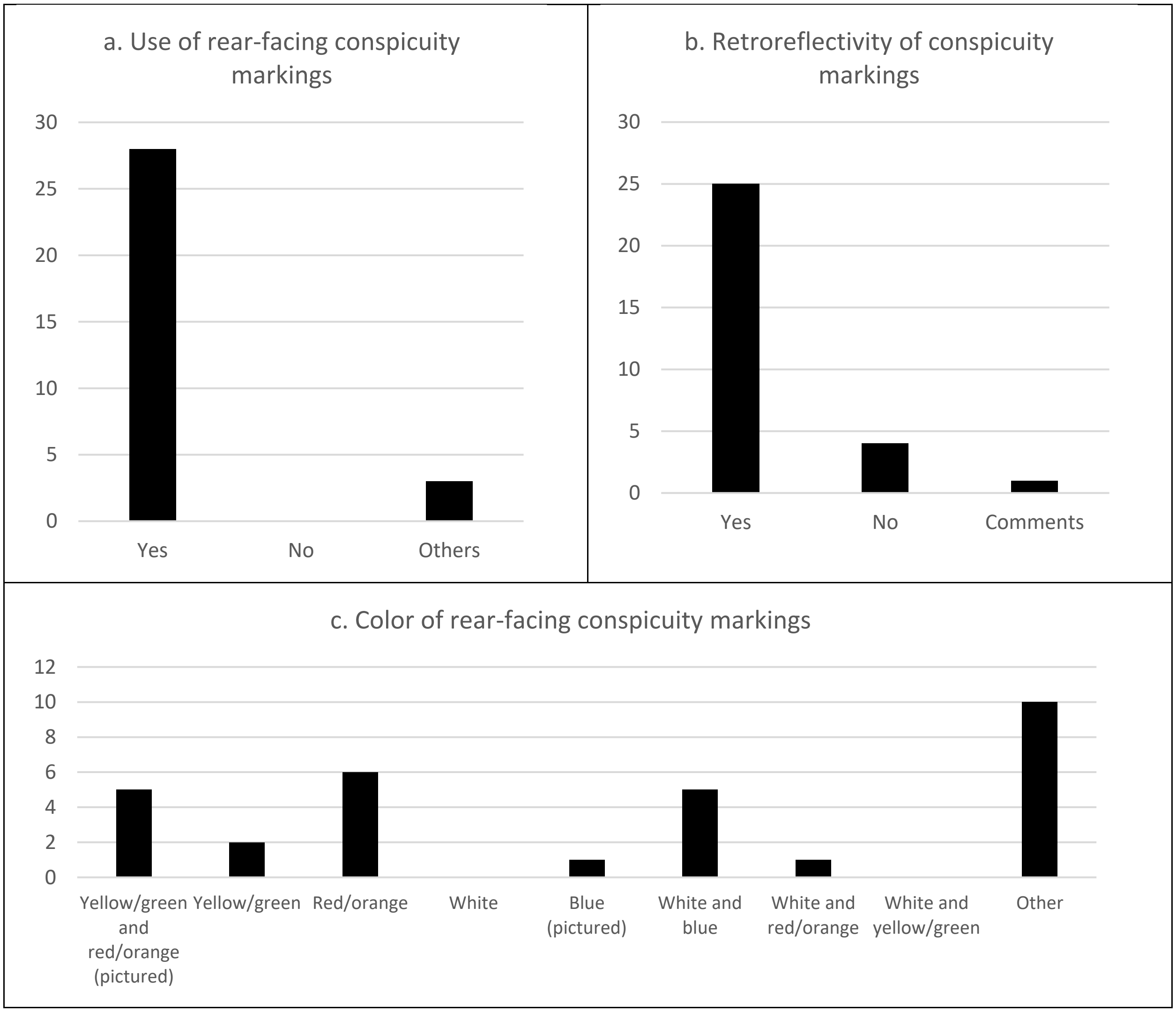


Figure 39: Marking design of SSP vehicles

A.4. Cones and Miscellaneous

Three questions were asked to understand the usage of other treatment methods such as cones, digital alerts, decals and logos. Most agencies mentioned that they used cones for only long-term shoulder incidents. Certain agencies commented that they were used generally when traffic lane closure was required, and it depended on the call type and the decision of the operator. Similarly, majority of agencies commented that the decals and logos present in their vehicles were retroreflective. However, the usage of digital alerts was divided. Certain agencies mentioned they were using or in the process of installing the HAAS emergency vehicle warning system. Figure 40 presents the overview of the results.

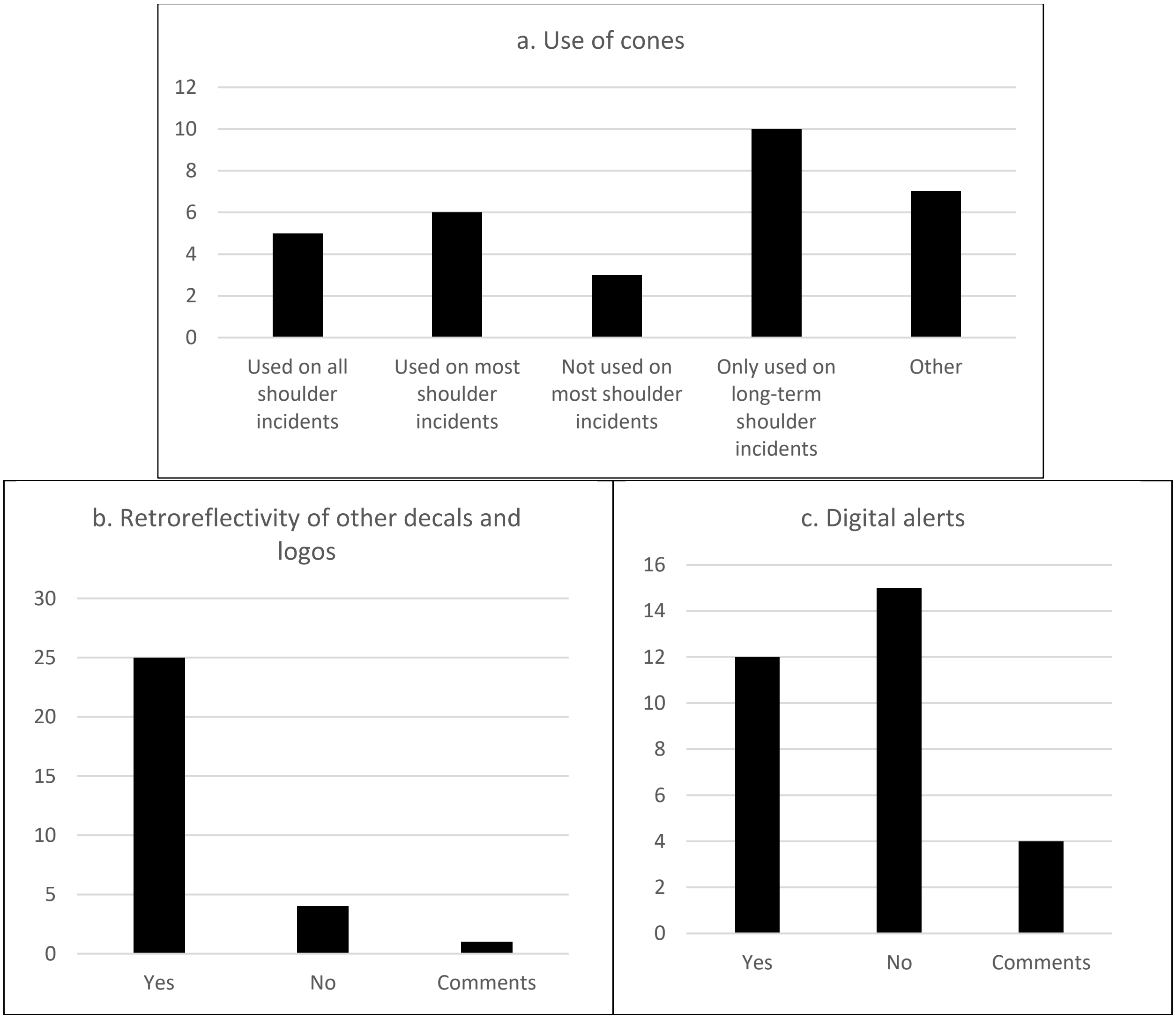


Figure 40: Miscellaneous design element of SSP vehicles

A.5. Ratings and Possibility of Improvement

Most agencies commented the existing arrangements were good but required improvement. Some agencies are exploring modifications in lighting. Certain agencies commented that they would like to have automation in their rear-facing lights so they could have different types of flash patterns for the vehicles when parked in comparison to when in motion.

Figure 41: Rating of the SSP Vehicles

A.6. Feedback from the Agencies

In the survey, two questions focused on exploring innovative approaches to lighting, i.e., opportunities and challenges.

A.6.1. Opportunities

The North Texas Tollway Authority (NTTA) lighting programs interface with vehicle systems to make adjustments based on conditions. For instance, the alley light turns off when the door is open, preventing the operator from being blinded upon exiting the vehicle. Additionally, side lighting synchronizes with traffic advisory lights when the vehicle is angled to block traffic. Applying the brakes activates a flashing pattern on the rear advisory lights to alert approaching drivers.

The Minnesota Department of Transportation (MNDOT) has implemented rear utility box LED flashers on their vehicles, providing a three-dimensional balance to the rear-facing lights, and enhancing visibility and safety. In Kansas, the Highway Patrol SSP employs CMS to increase conspicuity. Some agencies identified synchronized lights as a potentially useful feature, with plans to integrate them into future vehicle acquisitions. Additionally, several agencies mentioned that current lighting systems needed more automation to reduce operator's burden and were excessively bright.

A.6.2. Challenges

Agencies reported several challenges, such as rear lights positioned high on the back of the utility box, which occasionally washes out the message board display. They also highlighted the significant challenge posed by the absence of national standards for emergency vehicle lighting. For instance, Texas state law restricts the use of red lights on SSP trucks, permitting them only on wheel lifts and flatbeds. Some agencies allow only amber lights and prohibit the use of red lights. Lighting the rear of SSP trucks presented difficulties due to bed length, current conspicuity standards, and the message board rotator frame. Additionally, training operators to turn off front-facing lights during extended incidents remains a notable operational challenge.

Agencies explained that motorists frequently fail to respond appropriately to emergency vehicle lighting, disregarding the Move Over law's requirement to slow down and move over. In some cases, the public exhibited indifference to amber and red lights, responding more consistently to blue lights. Some agencies pointed out that rear amber lights create confusion between SSP vehicles and tow trucks. Despite advanced lighting packages or traffic control devices, driver inattention remains as a persistent issue, resulting in vehicles being struck from behind.

APPENDIX C – Guiding Principles for the Design of the RRSP Vehicle Markings

We, the research team at the University of Florida working on the project titled **"Study to Understand the Influence of Emergency Vehicle Color, Reflectance, Signing/Arrow Boards, and Lighting Configurations in Reducing Responder-Involved Crashes"** (BED31-977-24; UF AWD15234/ P0314148) invite you to participate in a discussion focused on developing guiding principles for the design of Road Ranger Service Patrol (RRSP) vehicle markings.

The primary goal of this discussion is to gather your perspectives and insights on a set of proposed guiding principles. These principles are intended to enhance the safety, recognition, and branding of RRSP vehicles. Your valuable input will help ensure that the design of vehicle markings aligns with operational needs and best practices across FDOT districts. Below are the key principles we would like you to consider and provide feedback on during the discussion:

Enhance Safety

The following safety principles will be discussed:

- Markings on the rear of the vehicle should be retroreflective for nighttime visibility.
- All logos and lettering should be made from retroreflective materials.
- Rear markings should contrast with body color of vehicle.
- Use of high-visibility fluorescent red/orange and yellow/green for daytime visibility.
- Orient vehicle-rear chevron pattern from the centerline downward to each side.
- Markings should promotes “Move Over” behavior with markings or legend.

Motorist Recognition

The following points regarding motorist recognition will be discussed:

- Road Ranger vehicle markings are consistent statewide.
- Road Ranger vehicles are easily distinguishable from FDOT maintenance and AM trucks.
- Motorists understand the vehicle to be “official” and FDOT, not a “for hire” service.

- Marking promotes “free service” with conspicuous legends.
- Marking promotes “*FHP” as a way to contact FDOT/Road Ranger with conspicuous legends.
- Each truck should have a unique identifier or number.
- Use front, sides, and rear for identification, including back of the message board.
- Vehicles should not be cluttered with additional logos, messages, etc.

Promote Branding

Key points for consideration include:

- Vehicles are clearly identified as FDOT.
- Vehicles are clearly identified as Road Ranger Service Patrol.
- Uses a palette of colors that is consistent with FDOT or Road Ranger
  - Base vehicle color(s) (white, yellow, orange, lime, etc.)
  - Stripes and graphics
  - Legends and lettering
  - Logos

We kindly request that you review these principles ahead of the discussion. Your feedback on these topics will be critical to ensuring that the final design guidelines meet safety standards, enhance service recognition, and help further establish the Road Ranger vehicles as part of the FDOT brand. It would be valuable to hear your perspectives on what design elements have been effective in the past, as well as areas where improvements could be made, based on your experiences and observations.

APPENDIX D – Vehicle Design Survey

The University of Florida (UF), in collaboration with the Florida Department of Transportation (FDOT), is conducting research to enhance the visibility, recognition, and safety of Road Ranger Service Patrol (RRSP) vehicles. As part of this effort, we have developed a new vehicle design incorporating improved emergency lighting, markings, and branding elements to enhance compliance to the "Move Over" law and overall roadside safety. To ensure the effectiveness of this design, we are seeking feedback from District Road Ranger Program Managers on the proposed approach and design renderings. Your insights will help refine the design to align with best practices and operational needs across FDOT districts.   If you have any questions about this survey, please contact the principal investigator, Dr. Nithin Agarwal, at nithin.agarwal@ufl.edu or the FDOT project manager, Shawn Kinney, at Shawn.Kinney@dot.state.fl.us.   If you want to participate in this survey, click the "Yes" button below. If you do not want to participate, you may simply close this window or click "No" button.

Q1 Would you like to participate in this survey?

- ◯ Yes (1)
- ◯ No (2)

Details of the Participant:

Q2 Name of individual completing survey (Fname, Lname):

____

Q3 District:

____

Q4 Contact email address:

____

The following designs were created from a review of past research on emergency vehicle conspicuity, a national survey of state service patrols, and a small-group meeting with Florida District Road Ranger Managers. Your survey responses will focus on these designs.

Safety:
Q5 Which option best promotes safety concepts such as contrast, and daytime/nighttime visibility?

- ○ Option A (1)
- ○ Option B (2)
- ○ Option C (3)
- ○ All are equal (5)

Q6 Are there any additional visibility and conspicuity improvements you would recommend for the vehicle design?

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Recognition:
Q7 Which new design most clearly communicates that the vehicle is part of an official FDOT RRSP program?

- ○ Option A (1)
- ○ Option B (2)
- ○ Option C (3)
- ○ All are equal (5)

Q8 What additional elements, if any, would help motorists more easily recognize the vehicle's function?

____

Branding

Q9 The current placement of the FDOT and Road Ranger logos make the vehicle recognizable as an official FDOT service.

	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
Opinion (6)	○	○	○	○	○

Q10 In your opinion, does the current placement of the FDOT and Road Ranger logos make the vehicle recognizable as an official FDOT service? Any additional comments?

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____

Q11 The branding elements (logos, color scheme, graphics) distinguish RRSP vehicles from other FDOT maintenance trucks.

	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
Opinion (6)	○	○	○	○	○

Q12 In your opinion, do the branding elements (logos, color scheme, graphics) distinguish RRSP vehicles from other FDOT maintenance trucks? Any additional comments?

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Q13 Which additional branding elements should be considered?

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Design Approach Evaluation:
The research team employed a three-zone design approach for vehicle design. The zones are illustrated in the schematic diagram below. Please respond to the questions based on the diagram. Option A: Option B: Option C:

Q14 How well does the Identity Zone (Branding section) communicate FDOT's identity and Road Ranger branding?

	Not well (1)	Slightly well (2)	Moderately Well (3)	Well (4)	Very Well (5)
Opinion (1)	o	o	o	o	o

Q15 How well does the Identity Zone (Branding section) communicate FDOT's identity and Road Ranger branding? Any additional comments?

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____

Q16 How effective is the Information Zone (*FHP, vehicle identification, purpose, etc.) in conveying relevant information to motorists?

	Not well (1)	Slightly well (2)	Moderately Well (3)	Well (4)	Very Well (5)
Opinion (1)	o	o	o	o	o

Q17 How effective is the Information Zone (*FHP, vehicle identification, purpose, etc.) in conveying relevant information to motorists? Any additional comments?

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____

Q18 How well does the Safety Zone (high-visibility markings and chevrons) improve emergency vehicle recognition?

	Not well (1)	Slightly well (2)	Moderately Well (3)	Well (4)	Very Well (5)
Opinion (1)	o	o	o	o	o

Q19 How well does the Safety Zone (high-visibility markings and chevrons) improve emergency vehicle recognition? Any additional comments?

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Q20 Do you have any additional feedback or recommendations regarding the overall design approach?

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