EFFECTS OF EMERGENCY VEHICLE WARNING LIGHTING SYSTEM CHARACHTERISTICS ON DRIVER PERCEPTION AND BEHAVIOR

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ABSTRACT

Secondary crashes, including struck-by incidents are a leading cause of line-of-duty deaths among emergency responders, such as firefighters, law enforcement officers, and emergency medical service providers. The introduction of light emitting diode (LED) sources and advanced lighting control systems, provides a wide range of options for emergency lighting configurations. This study investigated the impact of lighting color, intensity, modulation, and flash rate on driver behavior while traversing a traffic incident scene at night. The impact of retroreflective chevron markings in combination with lighting configurations, as well as the measurement of "moth-to-flame" effects of emergency lighting on drivers was also investigated. The results indicate that higher intensity lights were judged consistently as more glaring, but were only rated as marginally more visible. This finding may suggest that dimming emergency lights at night could results in near equal visibility, but with significantly less glare. The rated visibility of the lights appears to be related to the perceived saturation of the color, while discomfort glare is related to the amount of short-wavelength spectral content. This suggest colors at the extreme ends of the light spectrum (red and blue) are more visible. However, the results indicate that blue lights, with their shorter wavelength are more glaring than red lights. Therefore, red may be a better choice for emergency vehicle lighting at night. The results also suggest that the presence of very highly reflective markings may decrease drivers' ability to see first responders working adjacent to their vehicles. This is likely because the retro-reflective sheeting is compounding the emergency lighting visible to the drivers as well as the reflection of the driver's headlights against the sheeting. Taking the study in its totality, it is likely that national standards are needed which specify the maximum intensities for emergency vehicle lighting at night. Further research is needed to identify these levels and likewise investigate the maximum luminance for retro-reflective sheeting.

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1 INTRODUCTION

Transportation systems struggle to remain reliable during times of disruption (i.e. work zones, evacuations, and incidents). Actions practiced by emergency responders following an incident or event can enhance the systems performance during times of uncertainty. Traffic incident management (TIM) provides transportation systems flexibility and resiliency, during the facility's disruption. Emergency responders fill a vital role in preserving the lives and safety of the public on the Nation's roadways. These responders come from a diverse group of agencies and jurisdictional arrangements from police, fire, and emergency medical service (EMS), to towing, motorist assistance personnel, and other roadside workers. Emergency responders and their vehicles often operate in ways that are different from other travelers, including being stop on or next to the roadway (USFA, 2014). Many of these methods require using the transportation system in a manner for which it was not designed. Historically, this has led to a disproportionate number of emergency responder injuries and fatalities on or near the roadway. Motor vehicle-related incidents are a leading cause of line-of-duty deaths for emergency responders in the United States. Between 2009 and 2018, 531 police officers died while working on or near the roadway. That includes the 122 officers that were killed in struck-by incidents (NLEMF, 2019). Similarly, firefighters experienced 200 fatalities related to motor vehicle incidents during this same period (USFA, 2020). Prior research has also found that approximately 57 percent of EMS line-of-duty deaths resulted from motor vehicle crashes and struck-by incidents (Reichard et al., 2019).

Vehicles accumulating within a relatively small geographic area, and often at high speeds unavoidably leads to conflict. In 2015 the United States experienced over 35,000 deaths and 2.4 million injuries attributed to motor vehicles and in 2016 these numbers rose with over 37,000 deaths (NHTSA, 2019). When there is a crash on a highway there is an immediate and significant impact on mobility of people and goods that are traveling within the area. Directly following a crash, drivers in the vicinity must react and respond quickly to an unpredictable and dynamic environment. As vehicles then approach the incident location, they tend to slow and a queue on this section of highway builds. Furthermore, the crash scene itself is a distraction to drivers traveling in both directions. This situation often increases the likelihood of yet another crash (USFA, 2014).

A crash that occurs as a result of an initial or primary crash is known as a secondary crash. Secondary crashes are often resulting from what is known as D drivers, drunk, drugged, drowsy, distracted, and/or “dumb” (Avsec, 2018). These drivers are known to be on the road; therefore, the question is what can be done to better protect the first responders. Estimates suggest that approximately ten present of freeway crashes are classified as secondary crashes (Goodall, 2017). Secondary crashes are extremely dangerous to both victims and first responders dispatched to support them. Because there is already a queue built up from the first crash, this second crash is even more difficult to respond to.

The understanding of why secondary crashes occur, where they occur, and when they occur, can help improve the safety of emergency responders and protect road users including the crash victims and the emergency responders. Legislative tools, such as the adoption of “move over” laws and traffic incident management (TIM) training initiatives, have been enacted to help reduce secondary crashes and in particular, responder struck-by incidents (AAA, 2020). Many organizations have platforms encouraging the education of drivers on the importance of “move over” laws, to help protect the individuals working on the side of the road. The law requires drives to change lanes and/or reduce speed when passing emergency vehicle or personnel along a roadway, with the goal of these laws being to reduce the number and severity of the responders and roadside workers struck-by-vehicles. The move over law has been put into place to help reduce both struck-by and secondary crashes. In the United States variations of the move over law have been passed in all 50 states and in the District of Columbia.

The National Firefighters Association (NFA) has reported 61 firefighters killed between 2000 and 2013 from vehicle struck-by crashes. Operating an emergency vehicle such as a firetruck in and near a roadway tends to draw driver's attention, often times leading to distraction. A distracted driver can result in vehicles operating erratically, drifting from the roadway, or failing to stop. Fundamental traffic incident management techniques to minimize risk need to be taken into consideration including time, distance, and management, and shielding. One of the goals of TIM is to minimize the time that responders operate in and around active roadways. Another goal is to increase the distance between drivers and the incident as well as increasing the distance at which drivers become aware of the incident. These may be accomplished by using cones, flares, signs, arrow boards, or other devices to alert drivers. Shielding drivers or otherwise providing cover for the incident area where responders are present is another effective technique of TIM. This is often accomplished by using the fire apparatus as a shielding vehicle. This blocks the incident from the drivers to protect first responders and people involved in the incident (Duckworth, 2018).

TIM programs are an alternative approach to reducing secondary crashes. TIM programs are designed to detect, respond to, and clear the incident scene. Multi-disciplinary efforts aim to clear the wreckage, restore the flow of traffic, and safely and quickly treat the victims. This can be accomplished with a coordinated and planned approach to protect the incident scene, modify the flow of traffic, and separate the first responders and victims from the motorists. Effective TIM programs reduce incident duration and affect and improve safety for the victims, other drivers, and responding emergency personnel. Limiting the exposure of the traffic incident scene and duration individuals are working roadside with quick clearance practices, is a key part of TIM. Roadside workers and emergency responders are required to wear high-visibility apparel. Educating the public about incident management practices, i.e., the importance of the move over law and how to operate a vehicle within a TIM scene, are also important considerations. Responder training has played a significant role in the creation of TIM programs. The second Strategic Highway Research Program (SHRP 2) developed the National Traffic Management Responder Training course, providing responders with an interactive, hands-on training for incident resolution; featuring a multi-disciplinary training to promote a focus on multiagency communication, standards, and best practices. Over 400,000 responders had been trained through this program as of May 2019 (Letteney, 2019).

Technological advancements and temporary traffic control devices have been developed and deployed to reduce secondary crashes. Temporary traffic control devices include movable barriers and blocking vehicles and are designed to physically separate traffic form the incident scene. Pull-over areas in traffic control plans within long stretches of barrier protected work zones provide a safe place for law enforcement. Variable message boards, portable message signs, dynamic messaging boards, and rotating truck mounted signs provide advanced warning for work zones and incidents. Portable speed bumps and rumble strips provide an audible and physical warning to alert drivers of an upcoming change in the road including incidents, work zones, a change in terrain, and more. Applications such as MakeWay and HAAS Alert can communicate directly with a driver’s cellular device to alert them that they are in the path of an oncoming emergency vehicle or entering a TIM scene. Other applications such as Waze, Google Maps, and Apple Maps can notify drivers of the presence of work zones, incidents, and hazards. Some DOTs are also collecting crowdsourced data from drivers to more quickly and efficiently respond to incidents. Emergency vehicles have also been outfitted with retroreflective chevrons and sequential lighting to increase visibility.

The introduction of light emitting diode (LED) sources and computerized wireless controls has given emergency lighting systems more options for how the lighting can behave (Skinner et al., 2011). In recent years, as LED lighting systems have become common, these flashing lights, designed to capture attention and warn drivers of changing conditions, have increased in intensity as the efficacy of LED sources has increased. At the same time, standards that define the minimum photometric performance of flashing emergency lights (SAE, 2014, SAE, 2019, and NFPA, 2016), but no maxima, have not changed substantially. If lights are excessively bright, they could hinder drivers' ability to see first responders working adjacent to their parked vehicles, or create unwanted visual discomfort, potentially reducing first responder safety. The lights at night distracting the drivers can also cause the drivers to veer towards the light, similarly to how a moth would go towards a flame. This is known as the moth effect theory and is defined as a situation when drivers are mesmerized by lights at night and steer towards that light source (Travis, 2018). In the case of first responders, emergency lights on their vehicles can distract the driver at night and the moth effect theory can occur, creating an increased safety risk. There is a need for additional work to investigate the role(s) of lighting intensity, flash rates, color, and other factors in helping to prevent emergency responders from being involved in crashes and being struck while working on the roadway.

The objective of this human factors study was to investigate potential disorientation effects caused by the nighttime use of emergency warning lights. Investigated in this study was the impact of lighting color, intensity, modulation, and flash rate on driver behavior while traversing a traffic incident scene at night. The impact of retroreflective chevron markings in combination with lighting configurations, as well as the measurement of possible “moth-to-flame” effects of emergency lighting on drivers were also investigated.

2 LITERATURE REVIEW

The literature review predominately focused on three broad areas of research: emergency lighting studies, advanced technologies for protected roadside workers and emergency responders, and impact of policies, such as the move over law on responder safety. The literature review is not intended to be exhaustive, but rather a review of relevant works in these areas as they related to the research objects.

2.1 Emergency Lighting Studies

In order to increase safety for front line service workers, it is essential to reduce the potential for crashes involving passing cars and workers in work zones and incident scenes. Warning beacons that flash yellow and are often used to alert drivers that they are approaching a work zone. Kersavage et al. (2018) summarized a nighttime field study using simulated workers with and without high-visibility vests, outside trucks, to evaluate the effects on different warning beacon intensities and flash frequencies. That research found that intensities of 25/2.5cd and 150/15cd (peak/trough intensity) provided the farthest detection distance of the simulated worker compared to an intensity of 700/70cd. It was also found that mean detection distances in response to a flash frequency of 1 Hz were not statistically different from those in response to 4 Hz flashing. The simulated workers that were wearing the high-visibility vests were able to be seen the furthest away from the trucks for all combinations of flashing frequencies.

Flashing lights on emergency vehicles need to be bright enough to alert drivers of their presence on or near the roadway. Anecdotal evidence suggests that public safety agencies select the emergency lights based on their apparent brightness; the brighter the light, the brighter the lights are judged as “better” (Bullough et al., 2018). With the start of light emitting diodes (LEDs), emergency flashing lights are brighter and produce a more saturated color, but this can cause a greater glare and discomfort to the driver, possibly resulting in the first responders being at a higher risk of being injured or killed from a vehicle crash because the driver approaching the incident is not able to see them. In the study conducted by Bullough et al. (2018), participants viewed blue and red flashing lights on a scale model police vehicle with lighting consistent with recommended practices for emergency vehicles. The study investigated the impact of lights varying in intensity and optical power (intensity x duration). The participants were asked to view the modeled police vehicle and determine whether or not an officer was standing beside the vehicle as quickly as possible. The results showed that the blue flashing lights were perceived as brighter and more glaring, than red flashing lights of the same intensity. It was also found that the probability of correctly detecting the police officer figure was affected by intensity, while color had little impact. The presence of low-level white illumination at the side of the model vehicle was also found to significantly improve detection.

The Emergency Responder Safety Institute (ERSI) reported on the history and development of proposed changes for the emergency lighting requirements in NFPA 1901 and NFAP 1906. The existing standards were developed in the early 1990s and were largely designed based on the vehicle electrical system's ability to power the lighting systems. There have been concerns for many years on the blinding effects that emergency vehicle lighting has on the drivers' eyes, in particular when an emergency vehicle is parked at night. This issue has grown exponentially as lighting has transitioned to LED lights. The brighter the LED lights, the greater effect they have on the eye and the brain due to being very narrowband sources, their ability to turn on and off with very sharp temporal edges, and their ability to produce a significantly greater number of flashes per second. These changes may have put responders at risk on the highway because the approaching driver has an increased difficulty recognizing the situation, navigating successfully past the emergency scene, and seeing and avoiding the first responders and/or citizens near the scene or apparatus. From studies using existing research, there is a virtually a universal agreement that the warning lights on vehicles should be less intense at night when stopped on the road, to increase the safety of the responders and citizens on the scene (ERSI, 2019). The NFPA, in response to public input, drafted language for public comment and as a basis for further study. This was used to develop a study to gather evaluations based on observations of 60 configurations by approximately 50 observers, in May of 2019. The observers looked at numerous lighting intensities, flash patterns, and modulation depths and filled out a questionnaire about each configuration. The historical development of flashing light standards was also reviewed. The results of the study determined that the current optical levels were developed based on using limited electrical power, not on the evaluation on how bright the lights should be for optimal safety and performance. With the current usage of LED light sources on emergency vehicles, the current lighting is much brighter then would have ever been possible with previous technologies such as halogen sources. This can result in them being much brighter than they need to be at night, making it difficult and dangerous for drivers to safety navigate past the incident scene. Based upon this study changes were made in NFPA 1901 and NFPA 1906 regarding flashing intensity, flash rate, and pattern and synchronization guidance. Guidance for lighting and apparatus manufacturers was also provided (ERSI, 2019).

Previous research (Kersavage et al., 2018) has found that nighttime visibility of simulated workers adjacent to vehicles equipped with flashing warning lights can be reduced if the intensity is increased. This is crucial because present standards for these lights (SAE, 2014, SAE, 2019, and NFPA, 2016) do not contain upper limits for the intensity the lights should produce, especially at night when glare control would be most important. A recent study from the Emergency Responder

Safety Institute (ERSI) of the Cumberland Valley Volunteer Firemen's Association (ERSI, 2019) confirmed that increasing the intensity of light emitting diode (LED) warning lights results in increased discomfort and reduced visibility. Kersavage et al. (2018) and Bullough et al. (2019) also found that increasing the intensity of flashing lights at night made pedestrians near the vehicle more difficult to detect and identify under nighttime conditions. These findings suggest that reduced nighttime intensities for flashing lights, or maximum limits, could help improve first responder safety. In their study of worker detection, Kersavage et al. (2018) found no difference between lights flashing at 1 Hz or 4 Hz in terms of how far away the workers could be detected by approaching drivers.

The ability to see decreases at night, affecting vision including depth perception, color recognition, and peripheral vision. Glare from headlights, traffic lights, and emergency vehicles interferes with the driving ability. Drivers at night can also be distracted, drowsy, drugged, or drunk. Many nighttime crashes occur when drivers are mesmerized by lights in the dark and amplified when the driver is distracted, drunk, drugged, or drowsy (Avsec,2018). It has been speculated that drivers might become attracted to stationary flashing lights, similar to moths being attracted to a flame and the frequency with which stationary vehicles are struck by a passing motorist is the moth effect theory. According to this theory, vehicle hazard lights create an eye fixation, where the driver is attracted to the flashing lights, increasing the risk of a collision (Nighttime Driving and the Moth Effect, n.d.).

Emergency lighting has the purpose to alert approaching motorists of an emergency vehicle approaching or an emergency vehicle being stopped in the roadway. Red is the most common color used in the United States to indicate an emergency vehicle. Yellow typically has the broadest range of acceptable use and is typically used as a cautionary warning light. White is used in contrast to other colors. Green is limited to the fire service or emergency management applications, the most common being dedicated to Incident Command Post (ICP). Blue has the widest variety and serve as a contrast for red or red and white on all types of emergency vehicles (JTIC, n.d.). Some standards (SAE, 2014 and SAE, 2019) specify different intensities for lights of different colors.

It is well-understood that even when matched for luminous intensity, lights of different colors will not have the same apparent brightness. Blue lights especially are often judged to be substantially brighter (Alman, 1977) and glarier (Bullough, 2019 and Flannagan et al., 2008) than lights of other colors such as yellow or white. Even though blue flashing lights are judged as much more glaring than red lights of the same intensity, they have the same visibility-reducing impact (2019) regardless of color, when matched for intensity, demonstrating the importance of considering both discomfort glare and disability glare in specifications for these lights.

When lights flash and turn completely off during the flash cycle, it can be difficult for drivers to accurately judge their location, speed, and direction of motion. Rea and Bullough (2016) found closure detection times to simulated vehicles were faster when the lights flashed in a "high-low" modulation pattern rather than an "on-off" pattern. Furthermore, ERSI (2019) found that "high-low" flash patterns were judged as somewhat less glaring and easier to navigate past than "on-off" patterns.

Visual and auditory alerts are essential to the transportation industry and more specifically traffic incident management. Research done by Chan focusses on the factors that govern the relative effectiveness of alerting signals involving various combinations of visual and auditory signals. The visual variables consisted of color, flash rate, and flash mode and the auditory signals consisted of with or without sirens. This study showed that a red flashing light was perceived as the most hazardous warning color, with blue and yellow lights indicating a less hazardous scenario.

It was also observed that a flash rate of 240 flashes per minute (fpm) was the most effective and 60 fpm was not as effective. It was also seen that by providing a double or triple flashing pattern there was an increased effectiveness of the signal. When the auditory siren was added in it was found that blue and yellow with an auditory siren were just as effective at warning of a hazard as red was with no auditory siren (Chan, 2009).

Service vehicles use flashing warning lights to alert drivers of their presence. Standards offer ranges of flash frequencies to avoid potential hazarders and risks. But in practice, the flash frequencies are not varied to cater to specific situations (Skinner et al., 2020). In the research of Skinner et al., a study was conducted to identify if drivers are able to use cues from the frequencies of the flashing lights to determine how a service vehicle might behave in work zones or incident scenes. Results showed that even if drivers are not taught about the usage of different flashing frequencies, they are able to differentiate between 1 Hz and 4 Hz and make accurate predictions about their meanings. Results also show that there is no reliable relationship between 1 Hz and 4 Hz and when the vehicle has begun to move.

Skinner et al. (2020) recently found that closure detection for simulated pairs of flashing lights was no easier or more difficult to perform when the lights flashed at either 1 Hz or 4 Hz. People will judge faster flashing speeds as more urgent or dangerous, however (Chan, 2009 and Turner et al., 2014). Further, individuals can readily distinguish flashing at 1 Hz from that at 4 Hz (Skinner et al., 2020), so the flashing rate may be a practical way to communicate to drivers about the status of an emergency vehicle (e.g., parked versus in motion).

Reflective markings on a vehicle can help to make the vehicle more readily visible to approaching drivers, which should assist in closure detection. In addition, the presence of markings might help reduce perceptions of discomfort glare from adjacent flashing lights through two possible mechanisms. First, they increase the relative luminance of the overall background surrounding the lights, which is expected to reduce discomfort (Bullough et. al., 2008). Second, by making the location, size, and motion of the marked vehicle easier to ascertain, reflective markings could reduce the psychological discomfort of drivers approaching them and working out the proper route to pass them by. Reducing task difficulty also has the effect of reducing perceptions of discomfort glare (Sivak et al., 1991 and Bullough and Derlofske, 2004). Studies to identify the optimal light flash frequency using light-emitting diodes (LED) however have not been carried out in a systematic manner. Standards for reflective sheeting materials on the rear of fire trucks (NFAP, 2016) require ASTM Type I materials as a minimum, but materials commonly marketed for this application often have higher ASTM Types (such as Type V).

2.2 Technologies for Protected Roadside Workers and Emergency Responders

According to the American Traffic Safety Organization (ATSSA) in conjunction with the Illinois Department of Transportation (IDOT) approximately 69 percent of work zone crashes were caused by improper driving. Furthermore, 40 percent of fatal and injury-related work zone crashes occurred in work zones that had no traffic signals or rigorous restrictions at the crash scene. These findings may indicate the need for temporary traffic control (TTC) countermeasures at sites to increase the alertness of the driver and provide warning signals that there is a work zone and to slow down. Though often times work zones do have arrow panels, dynamic portable message signs, and temporary pavement markings; an audible and tactical stimulus to improve driver compliance, would be a strong addition to TTC devices. Rumble strips provide both audible and physical warnings to alert drivers (ATSSA ,2013). According to the Federal Highway Administration, the Manual on Uniform Traffic Control Devices (MUTCD) indicates that rumble strips used across multiple lanes are intended to notify road users of an upcoming hazard or change in roadway features. These temporary rumble strips are able to be installed and removed quickly and efficiently and increase the safety of workers (FHWA and U.S. DOT, 2009).

Vehicle placement at the initial response on an incident scene is vital to establish safe and effective traffic control. The blocking vehicle is placed in-between the approaching traffic and the incident scene. An arrow panel can also be used at the scene to direct traffic to move over, accompanied by lane closure taper traffic cones (U.S. DOT, 2020). The strategy of blocking is to protect the incident scene from approaching vehicles, allowing first responders time to gather information visually and verbally that will determine the actions and steps that need to be prioritized, but is one of the least trained on tactics of traffic incident management. The initial action dictates the amount of traffic control and recourses needed and what these measures shall consist of. The goal of the responders is responder safety, safety of the involved motorists, and the safety of the approaching traffic. Different factors determine the placement of the blocking vehicle and the type of block that is going to be utilized. The most common type of block is the parallel block and is primarily used on shoulders, and when staggering Safety Service Patrol (SSP) upstream of responsive vehicles to geode traffic to merge to the right or the left. There is angled blocking that is used for blocking one or more lanes, or the shoulder and an adjacent lane. This is used mostly by fire services and is used as an initial and primary block when responding to roadway incidents. This block is to protect crews attending the pump panel, or accessing tools and equipment, but not to guide traffic. Law enforcement will occasionally use angled blocking for the purpose of shielding and other tactical reasons. Good communications, pre-planning, and training with SSP can allow for better preparedness for initial blocks of the roadway scene (Sullivan, 2016).

Other safety practices have been put into place including sequential flares, rotating truck message signs, smart cones, CCTV, and dynamic messaging signs. Sequential flares or roadside flares are used by safety professionals at an accident site to warn oncoming drivers and guide traffic around an obstacle. Road flares are used because of their consistent source of bright light and help keep the accident scene safe. The flares are over five times brighter then electric alternatives, they do not require an alternative source of energy to use, they are quick and easy to deploy, they do not distract or blind the driver, and they are universally understood (Giarratana, 2019). Rotating truck mounted message boards are typically found on the back of DOT vehicles that assist with highway management and traffic incident management. The signs provide graphic messages and an arrow alerting drivers to move over. Similarly, changeable message signs can be used to alert drivers of a hazarded ahead, but those are used for more long term hazards while the rotating truck mounted message sign provides message for a short term hazard. Closed circuit camera systems (CCTV) assist with road network management. Cameras can be installed at locations that have an increased risk of accidents or traffic incidents. By having the cameras, drivers can be warned ahead of time through dynamic messaging signs (DMS) that there is an upcoming hazarded or accident. These cameras allow an advanced warnings to drivers. Smart cone is a technology connects a workers PPE to a smart cone to ensure the safety of the worker using Bluetooth. A smart cone is equipped with the smart add-on technology, that slides over the top of the cone and when the cone is moved intentionally or not, the workers shoe/boot gets a vibration to alert the cone has moved and there is possibly a car moving towards them (Mdestrian, 2019).

Technology advances have allowed programs that can send an alert to motorists as they are driving that there is an approaching emergency vehicle. The HAAS Alert is a digital alert technology for roadside safety, that is a cloud-based system. When an emergency fleet activates their lights, the Safety Cloud starts to deliver real-time notifications to approaching drivers before the emergency vehicle arrives to them on the roadway. The alerts are received by motorists that are nearby, allowing the driver to slow down and move over (HAAS Alert, 2022). MakeWay technology is a hands-free emergency alert system that sends audible warnings to drivers to alert that they are in the path of an emergency vehicle, similar to that of an amber alert. It uses the driver's mobile device to transmit an audible, emergency alert, notifying the driver that there is an approaching emergency vehicle (MakeWay, n.d.).

Transportation systems management operations (TSMO) programs work to optimize the use of existing roadway facilities through traveler information, incident management, road weather management, arterial management, and other strategies that target the causes of congestion. TSMO programs need real-time, high-quality, and wide-range roadway information, but there can be gaps in the geographic coverage, lags in information and timeliness, and life-cycle costs for equipment. Crowdsource data allows for a cost-effective approach to the application of strategies and better decision making to help with safer and more reliable travel. Crowdsourced data collection provides a new real-time data source, to proactively operate transportation systems. Crowdsource data comes from smartphones and cellular based data sources and enhances law enforcements communication through computer aided dispatch (CAD) systems, helping public agencies increase their situational awareness of traffic conditions. Those conditions include crashes, work zones, and weather events. Information gathered from crowdsource data can include information related to speed, travel time, incident type, travel behavior, vehicular operation, and so on. This data is obtained wherever and whenever people travel and can be accessed at traffic management centers (TMC). This data benefits transportation operations by allowing for a quick assessment of system performance, increased operations, increased safety and reliability, and cost savings (U.S. DOT and FHWA, 2021).

2.3 Policies Targeting Responder Roadside Safety

Police and first responder traffic are hazards that often appear on the roadways. Statistics from the Federal Bureau of Investigation indicate that in a nine year period, from 2000 to 2009, there were 47 U.S. offices that were killed while preforming traffic stops, 73 were killed while directing traffic or assisting motorists, and 101 were killed were killed by violence during traffic stops. To minimize the dangers that these officers face the move over law was put into place (Carrick and Washburn, 2012). The move over law requires drivers to move over a lane for stopped law enforcement, emergency vehicles, sanitation, and utility vehicles, tow trucks and wreckers, and maintenance or construction vehicles, that have displayed warning lights. If you are unable to move over or are on a two-lane roadway the law requires drivers to slow down to a speed that is less than 20 miles per hour (mph) than the posted speed limit or if the posted speed limit is 20 mph or less, slow down to 5 mph (FLHSM, n.d.). These laws have been implemented in all 50 states and the District of Colombia. Research conducted by Carrick and Washburn in 2012 observed 9,000 right-lane vehicles passing staged police stops on central and north Florida freeways. The staged police stop consisted of a civilian research vehicle, a marked police vehicle, a video recording of the passing traffic, and a speed measurement of the passing vehicle. The speed measurement was captured with a laser speed measurement device. There was a 75.9% compliance rate with the Florida's move over law, but only a 5.8% compliance with slowing to 20 mph below the speed limit. Further research was conducted to explore the patrol vehicle lighting configurations. The use of red and blue lights was statistically significant yielding early 80% compliance, versus 68.8% when only amber lights were used. Moreover, when red and blue lights were not used, drivers executed the maneuver to move over closer to that of the staged police stop and the mean speeds of the vehicles that did not move over was higher.

Working near traffic and around construction equipment is dangerous and having these workers remain safe is important. In order to keep these workers safe high-visibility safety apparel is worn to ultimately decrease worker injuries and fatalities. The American National Standards Institute (ANSI)/International Safety Equipment Association (ANSI/ISEA) provides standards on high-visibility safety apparel (ATSSA, 2012). In January 2010, ANSI approved a revised edition of the ANSI/ISEA 107-2010 standard, that was formally known as the ANSI/ISEA 107-2004. This standard a uniform guide for the design and performance specifications of retro-reflective vests, appeal, jackets, coveralls, trousers, and harnesses (U.S. DOT and FHWA, 2020).

A study conducted by Carney, Kubu, and Nisenson, in conjunction with the Institute for Police Research (IPR) and Police Executive Research Forum, regarding the policies, experiences, and perspectives on the use of reflective vests by law enforcement officers in the United States. This study used a survey, developed by the authors and a focus group and a core committee consisting of active-duty law enforcement of various duties and ranks. The participants were street-level officers from five different agencies. The agencies were selected based on varying in geographic size, demographics, locations, and force sizes. These participants were to wear reflective vests and the survey was distributed and collected by the IRP. The results of this study found that the usage of high visibility vests is needed while directing traffic, assisting motorists, stabilizing an accident scene, taking down an accident scene and conducting roadblock. The results of the study also showed that there was not a need found for high visibility vests when conducting traffic stops or during routine patrolling.

For police officers, firefighters, DOT towing, medical personal, and other incident responders, effective traffic incident clearance is important to reducing congestion and delays and improving the safety of the roadway. There is a need for a training to ensure a well-coordinated response to traffic incidents to ensure safety for responders and motorists and achieve faster incident clearance. SHARP2's National Incident Management Responder Training is a training brings theses responders hands-on incident resolution exercises. Classroom training is used for coordination of response activities and optimization of operations, then allowing for effective incident management in the field. This training is endorsed by the International Association of Chiefs of Police, the International Association of Fire Chiefs, and the National Volunteer Fire Council (U.S DOT, n.d.). The National Traffic Incident Management (TIM) Responder Training Program also offers responders the Training-the-Trainer (TtT) Program. This training consists of an 8.5-hour classroom training, a 1.5-hour hands-on and outdoor training, and a 1-hour training wrap-up (U.S. DOT 2021).

Some regulations have been put into place to protect first responders including placement of the vehicle, where they can and cannot walk, and clearing the incident efficiently and safely. The parking of the firetruck at an incident can be done as blocking or linear positioning. Linear positioning being used most often in a disabled vehicle on the shoulder. Blocking is often used when there is a more complex incident, needing the blockage of lanes (Sullivan, 2016). Other protective techniques include the placement of cones on a taper depending on the speed limit of the roadway and number of lanes. Another protection technique is the how and where the first responders stand and approach the emergency vehicle. Advanced warning is another practice used to alert approaching traffic that there is an incident ahead that may be a hazard, allowing the driver time to react, slow down and move over. Advanced warning devices can consist of sings, flares, and or an emergency vehicle that is parked well in advance of a hazarded with its lights on; all used to warn drivers in advance of an incident or hazarded. Traffic Incident Management (TIM) offers nationwide courses, teaching these recommended practices (Sullivan, n.d.).

3 METHODOLOGY

This human factors study recruited volunteers to drive a closed course traffic incident scene, at night under various experimental conditions. The simulated traffic incident was designed to replicate a fire apparatus in the center-block position. The incident scene was complemented with a cone taper extending from the driver-side buffer to the edge of the roadway. This scene was designed and reviewed by the Volusia County Fire Department and can be seen in **Figure 1.** Three experimental researchers were positioned around the course to collect the lateral vehicle offset from the incident scene, the longitudinal distance at which drivers could distinguish the silhouette of a firefighter, and to record drivers' perceptions via survey questionnaire. These locations are shown in **Figure 1.** The remainder of this chapter provide further detail on the test lighting equipment and the experimental conditions and procedures.

Figure 1 – Roadway scene

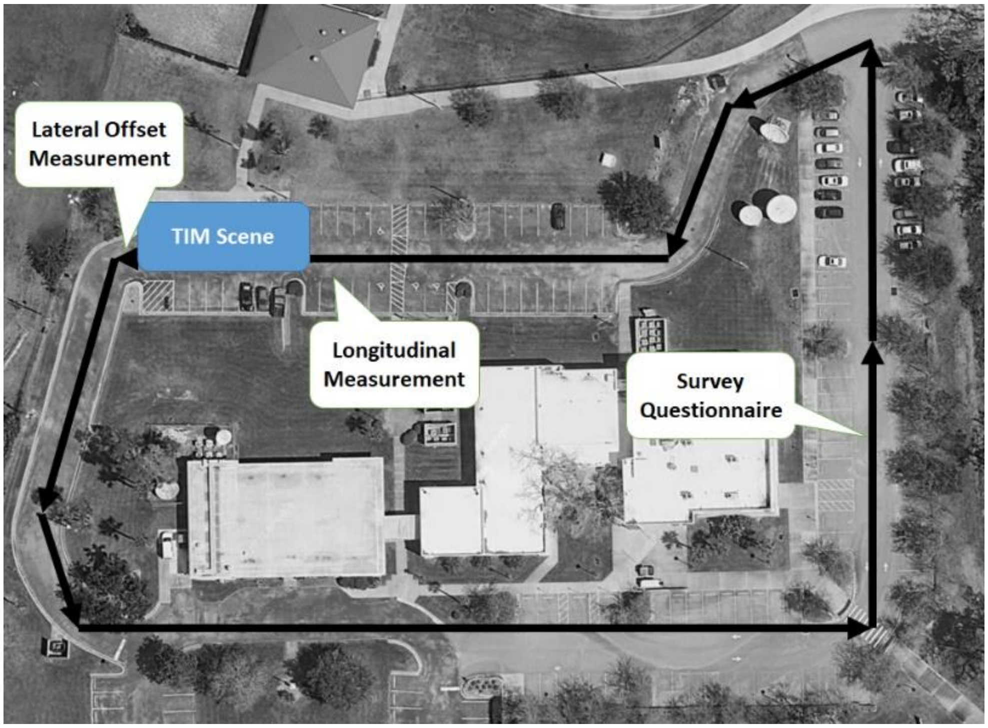

Figure 2 – Plan view of the closed course

3.1 Test Light Equipment

Equipment to conduct the experiment consisted of commercially available lights (blue, white, yellow, and red meeting SAE (2002) requirements for color) mounted on two tripods (**Figure 3**), each representing the approximate location of the left and right edge of the rear of a large fire truck. The color could be switched from red, blue, white, and yellow. Lights were mounted in clusters representing the upper and lower portions of the rear of the vehicle. Lights in the upper clusters produced higher optical power, defined as the time-integrated luminous-intensity energy produced by a flashing light over one minute (cd·s/min), and lights in the lower clusters produced lower optical power. The "high" nominal intensity levels were selected to be approximately 33% higher than the minimum levels specified by the NFPA Standard 1901 (NFPA, 2016) for fire trucks. The "low" nominal intensity level was designed to be about one-third to one-half of the minimum levels. **Table 1** provides the NFPA 1901 standards along with the "high" and "low" settings used in this study.

Figure 3 - Mounting configuration for the flashing emergency lights used in the study; also shown are reflective marking panels behind each set of lights

Flashing Light Location	NFPA 1901 Minimum	High Intensity Level	Low Intensity Level
Upper Location Lights	800,000 cd·s/min	1,065,000 cd·s/min	304,000 cd·s/min
Lower Location Lights	150,000 cd·s/min	204,000 cd·s/min	104,000 cd·s/min

Table 1 - Minimum Optical Power Requirements from NFPA (2016) in Upper and Lower Locations, and Average Optical Power Produced by the Test Lights at Each Level

The lights were also able to be controlled in terms of their modulation so that they could either flash with an "on-off" pattern or a "high-low" pattern with "low" being about 5% of the peak intensity of the lights when fully on. Further, the lights could be flashed with one of two flash rate profiles. The "faster" profile consisted of four short pulses of light followed by one longer pulse, with each train of pulses repeating 72 times/min, a pattern that is typical of use on many fire trucks. The "slower" profile consisted of a single pulse of light repeating 60 times/min. Both flash rate profiles produced the same optical power at the same nominal intensity level.

3.1 Preliminary Site Review

A preliminary review of the crash scene was conducted with Volusia County Fire Rescue, to establish the most realistic set up of the demonstration equipment. The lights were placed in a blocking position, which is a position that protects the incident work area, accomplished by the emergency vehicle parking across a lane or lanes of traffic, allowing for oncoming traffic to recognize the incident and react (Sullivan, 2016). According to the U.S. Department of Transportation Federal Highway Administration (U.S. DOT and FHWA, 2021) incident scenes should be treated as a temporary work zone. The area of impact must be secured, while balancing the flow and control of traffic, and clearing the incident scene efficiently. Regulations can be found in the Manual on Uniform Traffic Control Devices for Streets and Highways, Part 6 (MUTCD, 2009). Traffic cones and barriers "standard" taper amount needed is regulated when the responding transportation agency or personnel arrives on the scene to support the long-term lane closure. The taper length and placement of the cones are dictated by the width of the required shift of the traffic lanes and the speed of the facility and can be seen in **Figure 4** (U.S. DOT and FHWA, 2021).

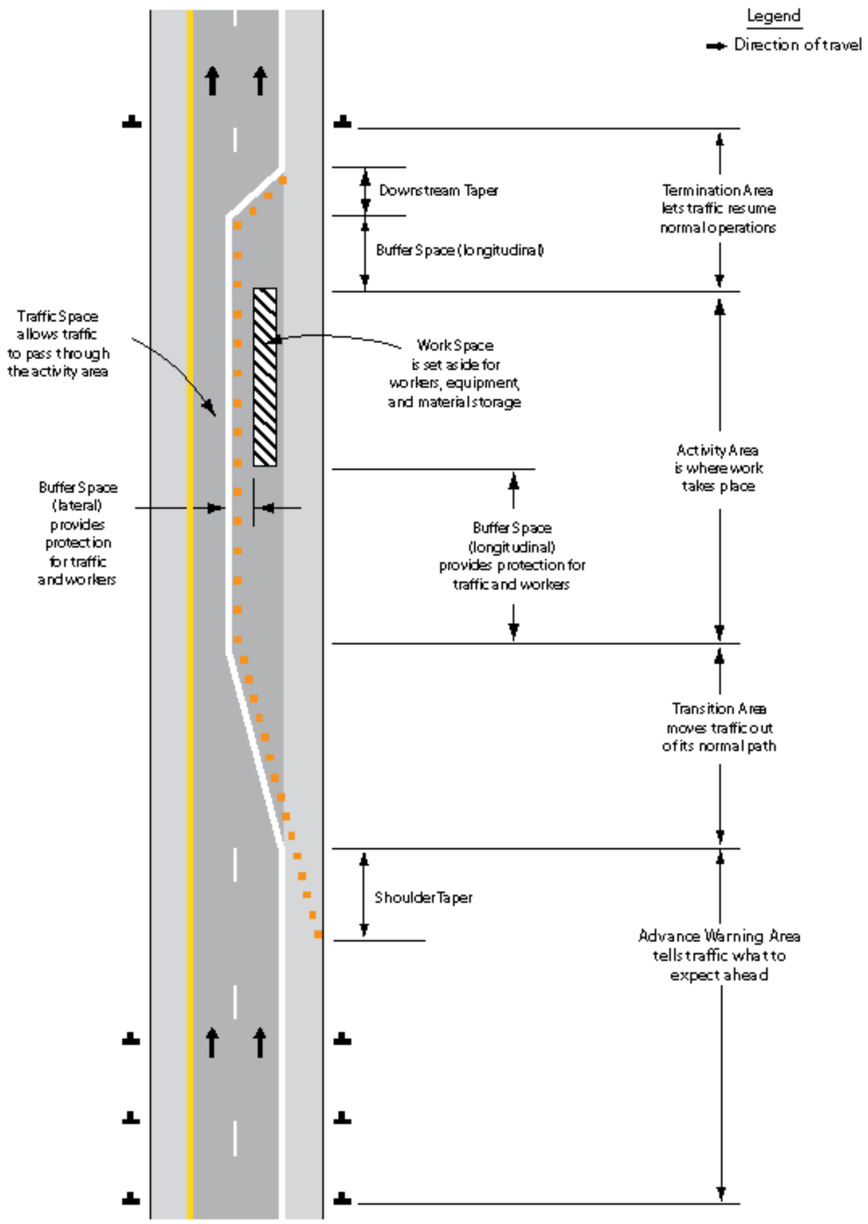

Figure 4 - Diagram of cone taper for incident management response (U.S. DOT and FHWA, 2021)

Some responding agencies, such as North Carolina DOT have developed an Emergency Responder Reference Card, that provides the responders a quick reference on how and where the emergency vehicle should be parked, taper information, and on-scene goals, see **Figure 5** (U.S. DOT and FHWA, 2021).

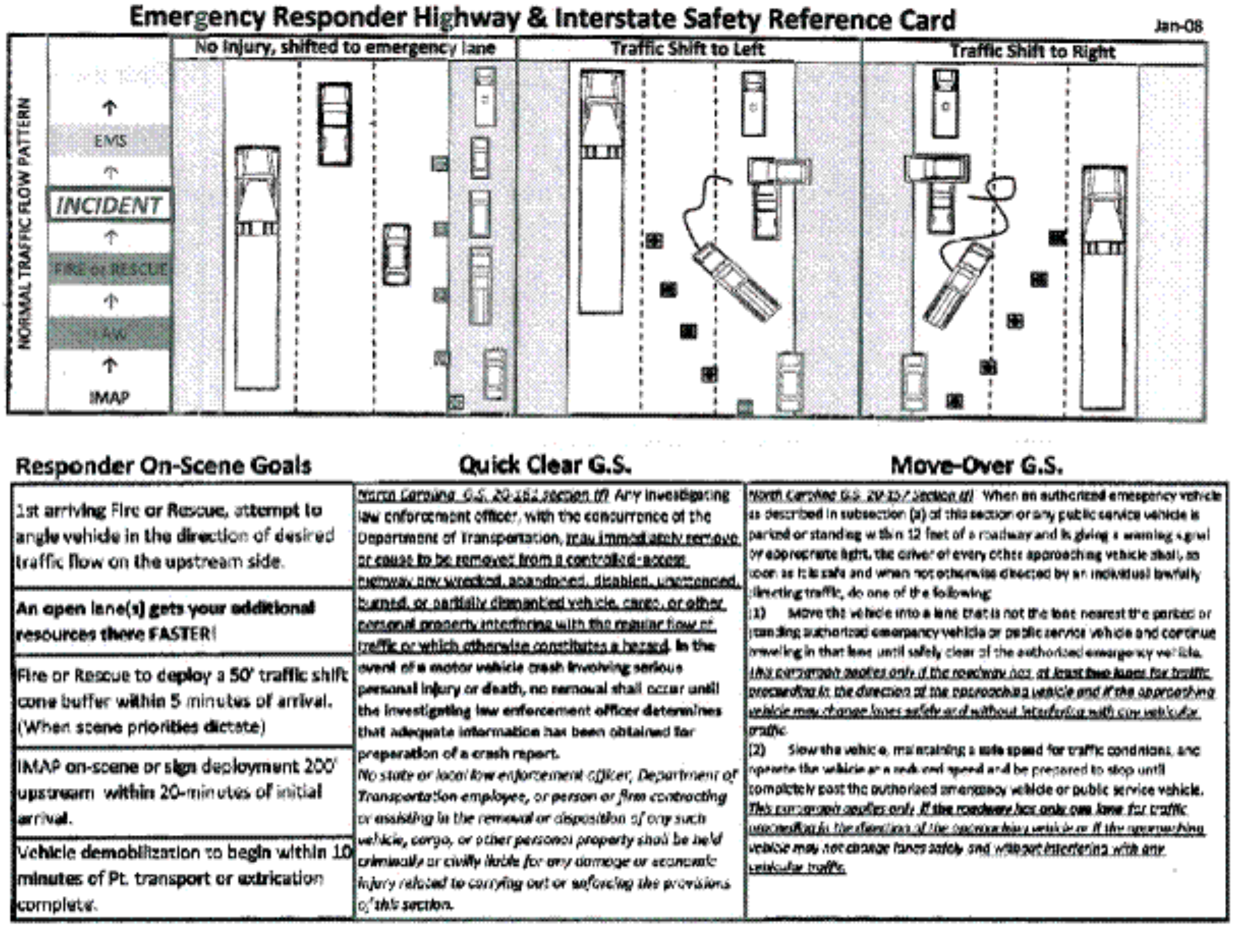

Figure 5 - North Carolina DOT Emergency Responder and Interstate Safety Card Reference (U.S. DOT and FHWA, 2021)

Volusia County Fire Rescue acted as the responding agency and placed the cones and taper as they would on an incident scene. Locations were marked enabling placement during demonstrations. Firefighters are instructed when responding to a scene, that there are certain places they should and should not walk to ensure their safety. The firefighter silhouette was placed in accordance with these instructions. Firefighters must also wear high-visibility clothing that meets requirements of American National Standards Institute (ANSI)/ International Safety Equipment

Association (ISEA). To demonstrate this in the demonstration the firefighter silhouette was equipped with a reflective safety vest.

A demonstration was held for Volusia County Fire Rescue to review the lighting conditions, prior to having the participants drive through the demonstration. Upon review it was learned that the white light conditions, conditions 7 and 8, would not be applicable in real time emergency management. White lights can be used in contrast to other color lights, but are not to be used unaccompanied (JTIC, n.d.). The 2021 Florida Statutes state that firetrucks may display red or red and white lights on the vehicle and police vehicles may display blue lights. Although all four colors are not necessarily allowed at the present time for this type of road situation, the experiment used yellow, red, blue, and white to determine how different colored lights would affect the driver's perception and behavior during nighttime conditions.

3.2 Experimental Conditions and Procedure

There were five independent variables in the experiment: intensity level (high/low), color (blue/white/yellow/red), modulation (on-off/high-low), flash rate (faster/slower), and the presence of ASTM Type V reflective markings (present/none) in a red/yellow chevron pattern mounted on two 5 ft × 2 ft panels that could be located directly behind the flashing lights on each tripod. With this number of independent variables, a parametric experimental design was impractical for a nighttime field study, so a set of 14 combinations of these factors was identified (**Table 2**), resulting in a 2 (intensity) × 4 (color) block, a 2 (intensity) × 2 (modulation) block, a 2 (intensity) × 2 (flash rate) block, and a 2 (intensity) × 2 (reflective markings) block. In each block, factors not included were held constant, and the results could be analyzed using a two-way within-subjects analysis of variance (ANOVA) to assess main effects and interactions. The intensity level was included in each block because this the impacts of this factor should be more highly predictable than the other factors (i.e., higher intensity lights should be easier to see and more glaring), providing an intuitive "calibration" for assessing the impacts of the other factors.

Table 2 - Experimental Conditions in the Present Study

No.	Color	Intensity	Modulation	Flash Rate	Markings	Notes
1	Red	High	On-Off	Faster	None	Parametric Combinations of Color and Intensity
2	Red	Low	On-Off	Faster	None	
3	Blue	High	On-Off	Faster	None	
4	Blue	Low	On-Off	Faster	None	
5	Yellow	High	On-Off	Faster	None	
6	Yellow	Low	On-Off	Faster	None	
7	White	High	On-Off	Faster	None	
8	White	Low	On-Off	Faster	None	
9	Red	High	High-Low	Faster	None	Versus 1, Tests Modulation
10	Red	Low	High-Low	Faster	None	Versus 2, Tests Modulation
11	Red	High	On-Off	Slower	None	Versus 1, Test Flash Rate
12	Red	Low	On-Off	Slower	None	Versus 2, Test Flash Rate
13	Red	High	On-Off	Faster	Yes	Versus 1, Test Markings
14	Red	Low	On-Off	Faster	Yes	Versus 2, Test Markings

Each of the 14 experimental conditions was presented to a subject in a different randomized order to minimize effects of learning or fatigue over the course of the experiment. In each trial, participants drove the test vehicle with low-beam headlights, no faster than 30 mph along a closed test road at night after the end of civil twilight. A full-scale, black-painted silhouette of a firefighter wearing a reflective safety vest was located adjacent to the lights. Subjects were asked to drive past the lights along the side of the road in a safe manner (not to exceed 30 mph).

An experimenter with a video camera recorded the lateral offset distance between the vehicle and the lights as a measure of the "moth-to-flame" effect, and also recorded when subjects indicated that they could readily see the presence of the firefighter silhouette by activating the vehicle's horn. After driving past the lights, an experimenter asked the subject to rate the visibility of the lights (-2: very difficult to see, to +2: very easy to see), the level of discomfort glare they experienced (9: just noticeable glare, to 1: unbearable), and how easy the overall road scene was to see (-2: very difficult to see, to +2: very easy to see), a blank questionnaire can be found in **Appendix A.**

A total of 20 individuals were involved in this Institutional Review Board (IRB) approved human research study. The participant pool consisted of seven females and 13 males. The participants ranged in age between 19 and 61 years, with a mean age of 32 years and a standard deviation of 15 years. All participants held valid driver's licenses at the time of the study. Participants were adults recruited from the greater central Florida area and were compensated $50.00 for their participation.

3.3 Pilot Study

A pilot study was conducted to ensure a smooth run-through of the demonstration prior to the 20 participants going through. A select group of Embry-Riddle Aeronautical University students were brought through the course and simulated the participants. A full run-through of demonstration was run with all 14 conditions.

3.4 Logistic Regression Analysis

A logistic regression analysis was run with the visibility of the roadway scene as the dependent variable, while in the presence of the visibility of the flashing lights and glaring of the lights as the independent variables. The analysis used the XLSTAT, Excel add in.

3.4.1 Logistic Regression Formulation

Logistic regression is a statistical tool which predicts the probability of a discrete outcome given a set input of independent variables. Independent variables are incorporated into a utility function consisting of measured parameters (V_{in}). This formulation is provided in the following equation (Ben-Akiva and Lerman, 1985):

$$P_n(i) = \frac{e^{uVin}}{e^{uvin}+e^{uVjn}}$$

3.4.2 Utility Function

The utility function of logistic regression for representing discrete choice is linear, but the linearity in the parameters do not require the observed attributes to be linear. The attributes functions can take the form of any polynomial, piecewise, linear, logarithmic, exponential or any real transformation of the attributes (Ben-Akiva and Lerman, 1985). To represent this in the visibility of the roadway scene, the independent variable vector x_{in} is modified by the parameter coefficient vector β_k. The utility function takes form by combining the parameter coefficient vector β_k for *k* parameters and the vector of the independent variables in equation (Ben-Akiva and Lerman, 1985):

$$U_{in} = \beta_0 + \beta_1 x_{in1} + \beta_2 x_{in2} + \cdots + \beta_k x_{ink} + \varepsilon_{in}$$

For the utility function U_{in} to accurately represent the observed dependent variable, the parameter coefficient vector β_k adjusts the independent variable vector x_{in}. The parameter coefficient vector β_k is econometrically gathered form a sample of *N* observations. Accomplished by using the highest likelihood estimation procedure that estimated parameter coefficients that predict the highest choice probabilities to match the observed choice behavior within the sample, represented in the following equation (Ben-Akiva and Lerman, 1985):

$$\ell'(\beta_1, \beta_2, \ldots, \beta_k) = \prod_{n=1}^{N} P_n(i)^{yin} P_n(j)^{yjn}$$

Where y_{in} is equal to one if scene visibility was rated between zero and two in the participant survey, and is zero.

Due to the likelihood function being in an exponential form, it is more convenient to maximize the log likelihood function. This function is recognized to be globally concave and by differentiating the function with respect to the parameter coefficient and setting the partial derivative equal to zero. The optimum coefficient values are determined from the following equation (Ben-Akiva and Lerman, 1985):

$$\ell'(\beta_1, \beta_2, \ldots, \beta_k) = \sum_{n=1}^{N} y_{in} \log P_n(i) + y_{jn} \log P_n(j)$$

Subject to,

$$\frac{\partial \ell}{\partial \hat{\beta}_k} = \sum_{n=1}^{N} \left\{ y_{in} \frac{\partial P_n(i)/\partial \widehat{\beta_k}}{P_n(i)} + y_{jn} \frac{\partial P_n(j)/\partial \widehat{\beta_k}}{P_n(j)} \right\} = 0 \forall k$$

These processes estimated the β values, allowing the choice probabilities to accurately represent empirical observations. Using this procedure, it is possible to estimate the probability of the visibility of the roadway scene, given a participant's rating of the visibility of the flashing lights and the glaring of the lights.

3.4.3 Model Goodness-of-Fit

The goodness-of-fit for logit models is how well the predicted model estimates the observed dependent variable; in this application two goodness-of-fit measures were used to evaluate the effectiveness of the logistic regression. The goodness-of-fit test includes the pseudo R-squared (ρ^2) and the area under the Receiver Operation Curve.

The pseudo R-squared (ρ^2) value is the most common goodness-of-fit measure for the logit models. Comparing the performance of the parameter coefficients estimated using only marker shared observed percentage in the sample population and the final coefficients estimated by the maximum likelihood procedure in the following equation:

$$\rho^2 = 1 - \frac{\ell(\hat{\beta})}{\ell(c)}$$

Where ℓ(c) is the log likelihood corresponding to market shares and $\ell(\hat{\beta})$ is the log likelihood corresponding to estimated parameter coefficients.

The value of ρ^2 ranges between zero and one and the later value denotes that the model predicts the observed choice behavior perfectly. A ρ^2 of less than 0.1 signifies "poor" model performance, a ρ^2 between 0.1 and 0.2 signifies an "acceptable" performance, a ρ^2 between 0.2 and 0.3 represents a "good" performance, and any ρ^2 with a value of 0.3 or greater indicates an "excellent" performance (Hosmer and Lemeshow, 1980).

The area under the Receiver Operator Curve (ROC) utilizes two parameters, sensitivity and specificity, to estimate model fit. Sensitivity is the proportion of the sample that was correctly predicted positive. Specificity, is the proportion of the sample that was correctly negatively predicted. The ROC plotted the complementary sample that of the specificity; the probability of a false positive on the x-axis and the sensitivity on the y-axis. The area under the curve is used to determine between correctly predicted true-false pairs as a proportion of the sample population, with values ranging between zero and one. Values between 0.8 and 0.9 are “excellent” and anything above 0.9 is “outstanding” (Hosmer and Lemeshow, 1980).

4 RESULTS

The results focus on the ANOVA analyses of the visibility of the flashing lights, discomfort glare, the visibility of the roadway scene, lateral distance from the flashing lights, and detection distance from the firefighter silhouette, and use box plots to show the average standard error of these results. This is followed by a logistic regression analysis looking at the effect the glaring of the flashing lights and visibility of the flashing lights on the visibility of the roadway scene. The remainder of this chapter goes into detail about each of the findings.

4.1 Visibility of the Flashing Lights

As expected, the intensity level of the flashing lights had a statistically significant effect on ratings of how visible the lights were. In the intensity × color block ANOVA, a significant main effect of intensity ($F_{1,19}$=4.42, $p<0.05$) was identified. The higher intensity level resulted in higher ratings of visibility (**Figure 6**). It should be noted that for both intensity levels, the average visibility ratings were quite high, ranging between +1.5 and +2, and indicating that the subjects judged both intensity levels to be relatively highly visible and easy to see at night.

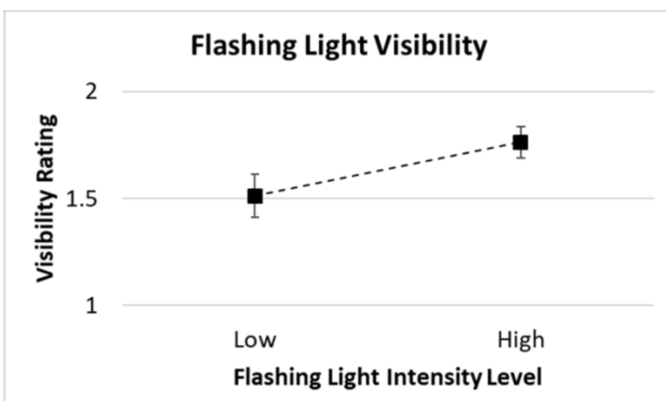

Figure 6 - Average (± standard error of the mean) visibility ratings for each intensity level.

As illustrated in **Figure 7** there was also a statistically significant main effect of color in the intensity × color ANOVA ($F_{3,57}$=5.19, p<0.005). The blue and red lights were rated as most visible, while the white and yellow lights were rated as least visible. The range among the four colors in terms of average visibility rating in this study was larger than the range between the high and low intensity levels.

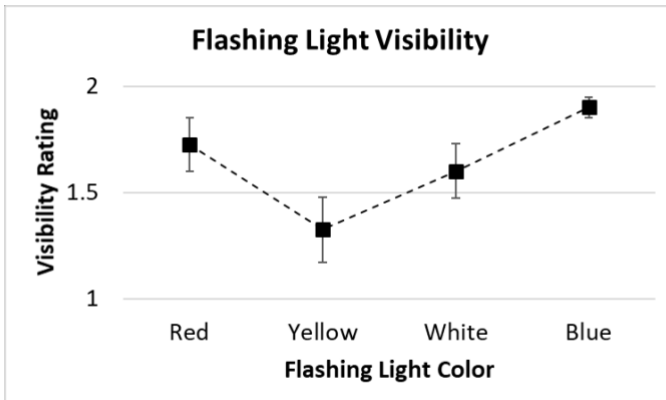

Figure 7 - Average (+/- standard error of the mean) visibility ratings for each color.

None of the other independent variables (modulation, flash rate, or the presence of a reflective background) had a significant main effect (p>0.05) on ratings of visibility for the flashing lights.

4.2 Discomfort Glare

Similar to the expected effect of intensity on rated visibility, the intensity level of the lights had a statistically significant main effect ($F_{1,19}$=15.2, p<0.005) on discomfort glare ratings (**Figure 8**; lower numerical ratings indicate a greater sensation of discomfort glare). The ratings for the low-intensity lights averaged near 7, indicating a “satisfactory” level of discomfort glare, while the higher-intensity lights differed by about one unit on the glare scale.

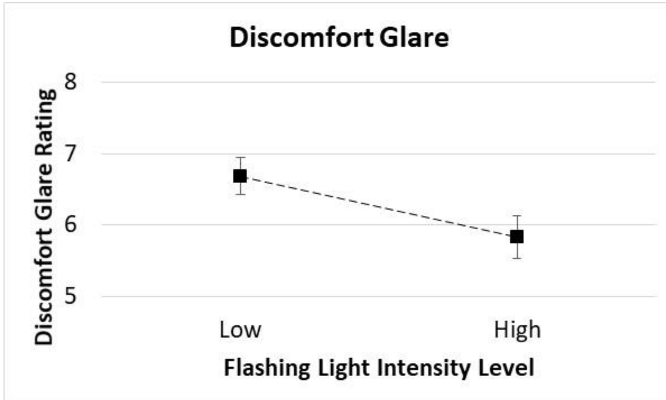

Figure 8 - Average (+/- standard error of the mean) glare ratings for each intensity level

The color of the lights (**Figure 9**) also exhibited a statistically significant main effect ($F_{3,57}$=10.2, p<0.001) on the discomfort glare ratings. 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 range between the least and most glaring color was about twice the range between the low and high intensity levels in this study.

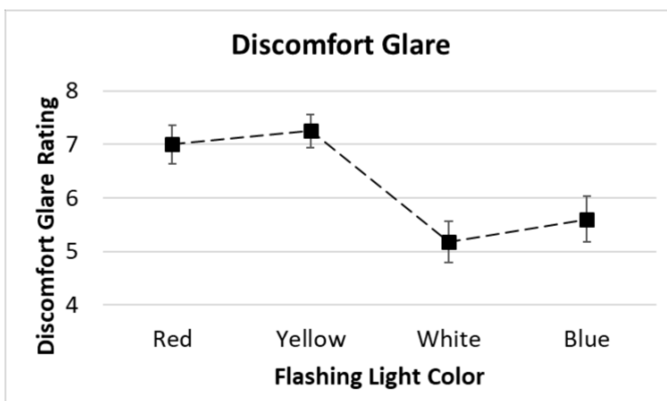

Figure 9 - Average (+/- standard error of the mean) glare ratings for each color

None of the other factors (modulation, flash rate and the presence of reflective markings) had a statistically significant (p>0.05) effect on the glare ratings.

4.3 Visibility of the Roadway Scene

None of the independent variables (intensity level, color, modulation, flash rate or the presence of reflective markings) had a statistically significant ($p>0.05$) effect on ratings of the overall visibility of the road scene.

4.4 Lateral Distance from the Flashing Lights

None of the independent variables (intensity level, color, modulation, flash rate or the presence of reflective markings) had a statistically significant ($p>0.05$) effect on the lateral distance from the flashing lights at which the subjects drove past them.

4.5 Detection Distance for the Firefighter Silhouette

While there were not statistically significant main effects ($p>0.05$) of any of the independent factors on the distance at which drivers could clearly identify the silhouette of the firefighter in the road scene, there was a statistically significant ($F_{1,19}=8.83$, $p<0.01$) interaction between the intensity level and the presence of reflective markings (**Figure 10**). The interaction suggests that although there was a small (although non-significant) difference in average detection distances between the low and high intensity levels (about 4 ft), the potential difference in detection distances between the conditions with and without reflective markings was larger (about 25 ft, but also non-significant). The difference between the distances with and without markings was larger for the higher intensity level, resulting in the significant interaction.

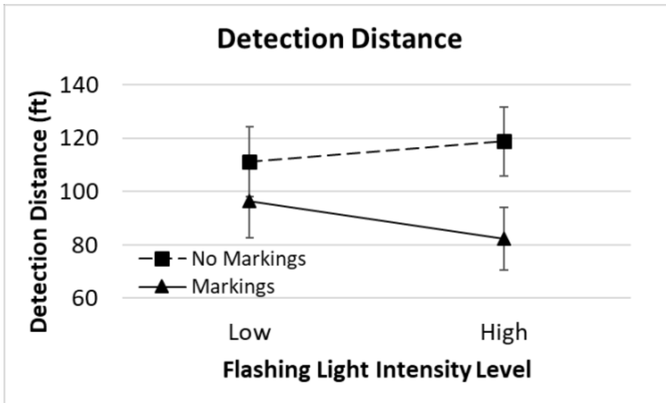

Figure 10 - Average (+/- standard error of the mean) detection distances for each combination of intensity level and the presence of reflective markings

4.6 Logistic Regression Analysis

Logistic regression was undertaken to further investigate the relationship between the visibility of the roadway scene, and the visibility and glaring of the flashing lights. The visibility of the roadway scene was collected on a scale of negative two to positive two, negative two being very difficult to see and positive two being very easy to see. For the logistic regression the response variable needed to be in terms of pass/fail; a zero was assigned to the unacceptable roadway condition/fail (negative two, negative one, or zero) and a one was assigned to the acceptable roadway conditions/pass (positive one and positive two). The visibility of the flashing lights was on a scale from negative two to two while the glare ratings of the flashing lights were collected on a scale nine to one, nine being just noticeable and one being unbearable. Those conditions scales were left untouched.

A logistic regression was run for each of the 14 conditions individually and all the conditions together, resulting in 15 total regression models. **Table 3** provides the goodness-of-fit results for the 15 logistic regression models. The first column shows the condition scenario, the second column provides the pseudo R-squared results, and the third shows the area under the receiver operator curve. For this research, an acceptable model fit was taken to be a pseudo R-squared value greater than 0.30 and an area under the receiver-operator curve of 0.90. Model fits corresponding to Condition 2, Condition 4, Condition 7, and Conditions 11-14 were in the acceptable range. This suggest that for these conditions, the regression model was able to reasonably predict the visibility of the roadway seen. These conditions are shaded within **Table 3**.

Table 3 - Logistic regression goodness-of-fit

	R Squared Value	***Area Under the Curve***
Condition 1	0.093	0.762
Condition 2	0.370	0.917
Condition 3	0.372	0.879
Condition 4	0.914	1.000
Condition 5	0.098	0.641
Condition 6	0.204	0.863
Condition 7	0.441	0.947
Condition 8	0.044	0.627
Condition 9	0.040	0.611
Condition 10	0.283	0.706
Condition 11	0.914	1.000
Condition 12	0.654	0.972
Condition 13	0.615	0.972
Condition 14	0.914	1.000
All	0.174	0.784

Table 4 provides a summary of the 15 logistic regression model results. The first column provides the condition scenario, the next six columns provide the model estimated coefficient values, their standard deviation, and associated p-value. In addition to the two independent variables, (visibility of the flashing lights, and glaring of the lights), an intercept value was estimated based on market shares. Conditions with an acceptable level of model fit are shaded within **Table 4**.

Table 4 – Logistic regression model results summary

Condition	Intercept			Visibility of Flashing Lights			Glaring of the Flashing Lights		
	Coefficient	Standard Error	Pr > Chi²	Coefficient	Standard Error	Pr > Chi²	Coefficient	Standard Error	Pr > Chi²
1	-0.942	1.280	0.462	0.000	0.000	-	0.291	0.201	0.147
2	-7.334	4.049	0.070	1.832	0.827	0.027	0.815	0.478	0.088
3	-2.736	1.511	0.070	0.000	0.000	-	0.812	0.399	0.042
4	2.996	5.382	0.578	0.000	1.110	1.000	0.000	0.463	1.000
5	3.365	2.479	0.175	0.779	0.620	0.209	-0.362	0.356	0.309
6	4.806	3.641	0.187	1.103	0.650	0.090	-0.449	0.474	0.344
7	1.095	2.904	0.706	1.921	2.642	0.467	0.907	0.853	0.288
8	3.222	2.045	0.115	0.091	0.551	0.868	-0.254	0.317	0.422
9	3.723	2.643	0.159	-0.142	0.751	0.851	-0.218	0.386	0.572
10	5.126	3.075	0.096	1.910	1.046	0.068	-0.700	0.483	0.148
11	2.996	5.596	0.596	0.000	1.218	1.000	0.000	0.517	1.000
12	262.732	23735.207	0.991	5.430	662.757	0.993	-30.277	2742.085	0.991
13	247.824	25758.968	0.992	15.942	1725.797	0.993	-30.925	3224.122	0.992
14	2.996	5.395	0.579	0.000	1.077	1.000	0.000	0.459	1.000

An examination of **Table 4** shows only a few instances where the intendent variables' contribution toward the predictive ability of the model were significant, e.g. independent variables having a p-value less than or equal to an alpha of 0.05. Looking exclusively at models with acceptable model fit, only Condition 2, visibility of the flashing lights provided a significant contribution toward the model fit. All other independent variables for models with an acceptable goodness-of-fit did not demonstrate a significant contribution toward predicting the visibility of the roadway scene. It is therefore difficult to draw any meaningful conclusion from the logistic regression analysis. This finding is consistent with ANOVA analysis results, which also found no significant relationship between explanatory variables and the visibility of the roadway scene.

The logistic regression analysis results were likely poor for several reasons. The first likely factor was the low number of participants in the study. Another likely factor was consistency with which participants rated the visibility of the roadway scene as "acceptable", e.g. a rating of one or two in the survey. In total, there were 280 (20 participants x 14 scenarios) scene visibility observations. Of those, only 39 (less than 14 percent), were rated below a score of one. The more "rare" an event is, the more precise the logistic regression must be to accurately estimate the impact of an independent variable. Furthermore, several factors beyond simply the visibility and glare of the flashing lights likely impacted the visibility of the scene. These are likely to include the level of ambient light, use of corrective lenses, age of the participant, and a number of unmeasured contributing factors.

5 CONCLUSION

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. The differences in the trends by color in and **Figure 6** and **Figure 7** (for visibility of the lights and for glare, respectively) are in fact consistent with published literature on the brightness of colored signal lights. Bullough et al. (2001) found red and green signal light colors to be brighter and to result in greater discomfort glare than yellow signal lights of the same intensity, and like blue lights, red and green are perceived as having greater color saturation than yellow lights (as well as white lights).

In comparison, Bullough (2009) and Bullough and Liu (2019) found that light sources with greater short-wavelength ("blue") spectral or color content were consistently judged as more glaring than yellow or red lights of the same intensity. Blue, yellow and red LED sources have peak wavelengths of around 470, 590 and 630 nm, respectively; white LEDs are actually blue LEDs equipped with a phosphor coating that converts some of the blue light into yellow light with the mixture appearing white. Thus, the finding that the blue and white lights were judged as most glaring in the present study is not surprising. Blue lights in particular of high intensities can elicit high levels of discomfort glare.

The ratings for the visibility of the lights and for the discomfort glare elicited by the lights for the two intensity levels used in this study offer some support for the notion that flashing lights meeting existing minimum intensity requirements for emergency vehicles (SAE, 2014, SAE, 2019, and NFPA, 2016) may be higher than needed for nighttime driving conditions, at least when the emergency vehicles were stationary as in the present study. Intensity levels substantially lower than the minimum levels specified for fire trucks (NAFP, 2016) were rated as slightly less visible than higher intensities, yet remained highly visible, but reduced discomfort glare by a significant amount. However, the current results do not identify an optimal level for nighttime flashing light intensity.

The potential, albeit non-significant, for decreased detection distances to the first responder in the present study when the reflective markings were present was unexpected. It was considered that the markings might reduce glare, but not necessarily impact visibility of the first responder silhouette. However, the direction of this non-significant effect suggests that the reflective markings could have contributed to making the responder less visible by contributing to the amount of scattered light entering the eyes of a driver (Fry, 1954). This could have implications for the minimum ASTM Type requirements for reflective markings on the rear of fire trucks. Figure 7 shows the minimum luminance of yellow ASTM Type I and Type V materials as a vehicle with low-beam headlights approaches (Bullough and Skinner, 2018). The Type V luminances exceed those of Type I materials by a factor of 5 to 10. Future work could investigate the impact of retro-reflective materials, chevrons shape, direction, and color. The study findings suggest that there may be an upper limit to luminance which would be appropriate for incident scenes at night. However, more research is needed to verify this and to identify the appropriate levels.

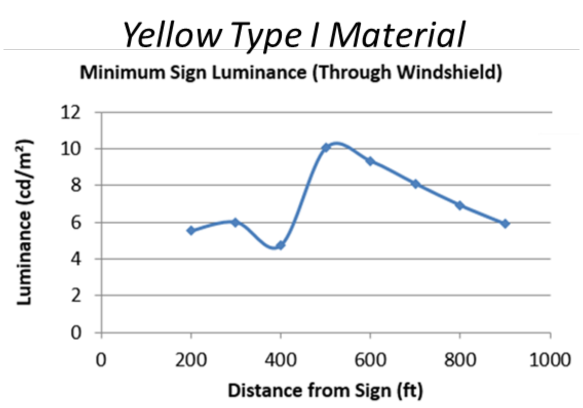

Figure 11 - Minimum luminances of yellow ASTM Type I (a)

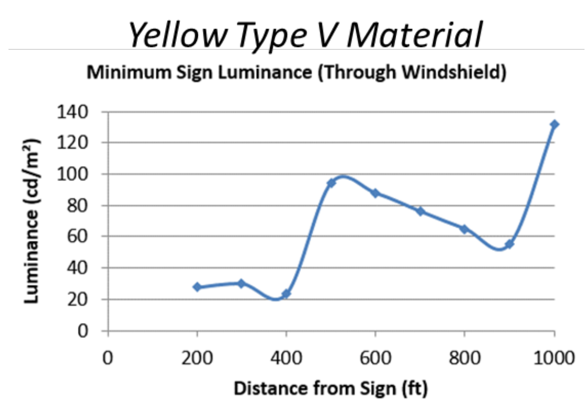

Figure 12 - Type V (b) materials as a passenger vehicle with low-beam headlights approaches

Taken together, the present results help to define a suitable evaluation and analysis methodology for the performance of flashing lights on emergency vehicles, in terms of visibility of the lights, discomfort glare, and the ability of approaching drivers to detect first responders at night. Such data could be used to direct subsequent research efforts as to whether reducing intensity levels of flashing lights at night (or specifying maximum limits to intensity) are beneficial to the safety of first responders.

The study analysis failed to identify a “moth” effect. As vehicles passed by the experimental scene, there was no measurable impact on their lateral offset from the incident. The failure to see any impact on lateral offset may have resulted from the experimental design. Antidotal evidence suggests that during a highway incident, some drivers slow down to view the incident scene and satiate their curiosity. This phenomenon is generally referred to as “rubber-necking”. This was not observed during the experiment because there was nothing to see at the incident. It is likely that participants looked away from the scene to shield their eyes, then directly at it during the experiment. In future studies, it is suggested that the incident scene be more engaging and explicitly require the driver’s attention. This would simulate the “rubber-necking” which occurs during an incident and would better investigate the “moth” effect.

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APPENDICIES

APPENDIX A – DRIVER RESPONSE FORM

FEMA: Study of Emergency Vehicle Warning Lighting Systems

Participant Number: ___________________

Age: _________

Sex: _________

Do you wear corrective lenses while driving: Yes or No

Study Description:
During each trial of this study, you will drive toward a simulated emergency vehicle's flashing lights varying in color, intensity and flash rate. A silhouette of a firefighter will be located adjacent to the lights, and you should indicate as instructed by an experimenter when you can clearly see the silhouette (e.g., honk your horn). After you pass the lights, you will be asked several questions about how visible the lights and the overall roadway scene were, and how glaring the flashing lights were. You will complete 16 trials in this experimental session.

Condition 1:
Lateral offset: _____________ *Distance to target:* ___________

How visible were the flashing lights?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How visible was the roadway scene?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the flashing lights?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 2:
Lateral offset: _____________ *Distance to target:* ___________

How visible were the flashing lights?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How visible was the roadway scene?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the flashing lights?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 3:

Lateral offset: ______________ *Distance to target:* ____________

How <u>visible</u> were the <u>flashing lights</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How <u>visible</u> was the <u>roadway scene</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the <u>flashing lights</u>?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 4:

Lateral offset: ______________ *Distance to target:* ____________

How <u>visible</u> were the <u>flashing lights</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How <u>visible</u> was the <u>roadway scene</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the <u>flashing lights</u>?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 5:

Lateral offset: ______________ *Distance to target:* ____________

How <u>visible</u> were the <u>flashing lights</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How <u>visible</u> was the <u>roadway scene</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the <u>flashing lights</u>?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 6:

Lateral offset: ______________ *Distance to target:* ___________

How <u>visible</u> were the <u>flashing lights</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How <u>visible</u> was the <u>roadway scene</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the <u>flashing lights</u>?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 7:

Lateral offset: ______________ *Distance to target:* ___________

How <u>visible</u> were the <u>flashing lights</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How <u>visible</u> was the <u>roadway scene</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the <u>flashing lights</u>?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 8:

Lateral offset: ______________ *Distance to target:* ___________

How <u>visible</u> were the <u>flashing lights</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How <u>visible</u> was the <u>roadway scene</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the <u>flashing lights</u>?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 9:

Lateral offset: ______________ *Distance to target:* ____________

How visible were the flashing lights?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How visible was the roadway scene?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the flashing lights?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 10:

Lateral offset: ______________ *Distance to target:* ____________

How visible were the flashing lights?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How visible was the roadway scene?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the flashing lights?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 11:

Lateral offset: ______________ *Distance to target:* ____________

How visible were the flashing lights?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How visible was the roadway scene?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the flashing lights?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 12:

Lateral offset: ______________ *Distance to target:* ____________

How <u>visible</u> were the <u>flashing lights</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How <u>visible</u> was the <u>roadway scene</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the <u>flashing lights</u>?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 13:

Lateral offset: ______________ *Distance to target:* ____________

How <u>visible</u> were the <u>flashing lights</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How <u>visible</u> was the <u>roadway scene</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the <u>flashing lights</u>?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

Condition 14:

Lateral offset: ______________ *Distance to target:* ____________

How <u>visible</u> were the <u>flashing lights</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How <u>visible</u> was the <u>roadway scene</u>?

Very difficult to see	Somewhat difficult to see	Neither easy nor difficult	Somewhat easy to see	Very easy to see
-2	-1	0	+1	+2

How glaring were the <u>flashing lights</u>?

Just noticeable		Satisfactory		Just acceptable		Disturbing		Unbearable
9	8	7	6	5	4	3	2	1

APPENDIX B - PARTICIPANT INFORMED CONSENT FORM

INFORMED CONSENT FORM

FEMA: Study of Emergency Vehicle Warning Lighting Systems

Purpose of this Research: I am asking you to take part in a research project for the purpose of measuring your driving response to various flashing warning light configurations. You are being asked to drive carefully along a closed road at a speed of no more than 30 mph toward and past simulated fire engine flashing lights. You will be asked to do this 16 times. An experimenter will observe you from a distance at all times and give any necessary instructions using hand signals. If the experimenter feels that you are driving in a reckless manner, you will be asked to stop the car immediately and the experiment will be concluded. After each trial, you will be asked to answer questions regarding each lighting configuration you observed, including visibility of a simulated firefighter. The total time of your participation is estimated to be about 60 minutes.

Eligibility: To be in this study, you must have a valid Driver's License and insurance, a resident of the U.S., and 18 years of age or older. Participants prone to epilepsy or seizures are not eligible.

Risks or discomforts: The risk of participating in this study include the slight possibility of a vehicle crash and possible epileptic seizure. To mitigate the risk of an accident, the study will be performed on an open flat terrain road that will be closed to all traffic. No heavy objects or equipment will be placed in the roadway during the experiment. The risks are estimated to be lower than when driving through a work zone or adjacent to a police traffic stop, because no other traffic or heavy equipment will be present. All luminous intensities to be used will be no greater than those specified by the National Fire Protection Association for flashing lights used on fire engines. In many cases the intensities will be lower. In accordance with these standards, lights will flash at a frequency no greater than 4 Hz to minimize any risk of interactions with epileptic seizures from flashing lights.

Benefits: While there is no benefit to you as a participant in this study, the information learned by the experiment will benefit society, by potential reducing vehicle crashes near emergency roadside lights. The goal of this study is to identify potential benefits of reducing the nighttime intensities of flashing lights on emergency vehicles over current practices. It is hypothesized that the proposed lighting conditions will allow drivers to experience less glare and better see the road environment while maintaining high conspicuity. Human subjects are necessary to obtain information on the effects of the proposed warning light characteristics on driver response. Documentation of these responses will be needed by public safety agencies who might consider using new lighting approaches on service vehicles.

Confidentiality of records: Your individual information will be protected in all data resulting from this study. While the members of the research team will have access to your personal information, publication of the data will not include any identifying information. You will be assigned a number; the key code will be stored separately from the data. Information collected as part of this research will not be used or distributed for future research studies.

Compensation: You will be compensated $50 for participating in this study. If you begin the study and decide to discontinue during the study, you will still be compensated $50.

Contact: If you have any questions or would like additional information about this study, please contact Emily Hiebner, hiebnere@my.erau.edu, or the faculty member overseeing this project, Dr. Scott Parr, parrs1@erau.edu. For any concerns or questions as a participant in this research, contact the Institutional Review Board (IRB) at 386-226-7179 or via email teri.gabriel@erau.edu.

Voluntary Participation: Your participation in this study is completely voluntary. You may discontinue your participation at any time without penalty or loss of benefits to which you are otherwise entitled. Should you wish to discontinue the research at any time, no information collected will be used.

CONSENT. By signing below, I certify that I am a resident of the US, 18 years of age and older and have a valid Driver's License and insurance. I further verify that I understand the information on this form, that the researcher has answered any and all questions I have about this study, and I voluntarily agree to participate in the study.

Signature of Participant:_____________________________________Date: __________________

Printed Name of Participant: _________________________________

APPENDIX C – PARTICIPANT REINBERSEMNT FORM

PARTICIPANT REIMBURSEMENT RECEIPT

FEMA: Study of Emergency Vehicle Warning Lighting Systems

I, ________________________ have received $50 for my participation in the above titled studied for my participation.

Signature of Participant:_______________________________________Date: ___________________

Printed Name of Participant: ___________________________________