Effects of Emergency Vehicle Lighting Characteristics on Driver Perception and Behavior

Study Report

Emergency Responder Safety Institute

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Acknowledgments

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- John D. Bullough, Ph.D., formerly with RPI, and currently with the Light and Health Research Center in the Icahn School of Medicine at Mount Sinai
- Scott A. Parr, Ph.D., P.E., with Embry-Riddle Aeronautical University
- Alec Sblendorio, with Embry-Riddle Aeronautical University
- Emily Hiebner, with Embry-Riddle Aeronautical University

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Summary

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 any potential “moth-to-flame” effects of emergency lighting on drivers were also investigated. The results indicate that higher intensity lights were judged consistently as more glaring but were only rated as marginally more visible than lights of lower intensity. 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 (“bluish”) spectral content. 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.

Introduction

Emergency responders fill a vital role in preserving the lives and safety of the public on U.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. 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 (National Law Enforcement Memorial Fund, 2019). Similarly, firefighters experienced 200 fatalities related to motor vehicle incidents during this same period (U.S. Fire Administration, 2020). Prior research has also found that approximately 57% of EMS line-of-duty deaths resulted from motor vehicle crashes and struck-by incidents (Reichard et al., 2011).

Secondary crashes are broadly defined as crashes that occur as a result of a prior incident, work zone, or crash. Secondary crashes are a common occurrence because drivers in the vicinity of an initial incident must respond quickly to a dynamic and unpredictable environment. Furthermore, the crash scene itself is a distraction to drivers traveling in both directions. Estimates suggest that nearly 10% of freeway crashes can be classified as secondary (Goodall, 2017). Secondary crashes occurring in or near a work zone or initial crash scene are exceptionally dangerous for roadside workers, responders, and the victims of the initial incident. 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 (American Automobile Association, 2020).

The introduction of LED sources and computerized wireless controls has given emergency lighting systems more options for how the lighting can behave (Skinner et al., 2021). 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 (Society of Automotive Engineers, 2014, 2019; National Fire Protection Association, 2016), but no maxima, have not changed substantially since LED light sources have become widespread (Kersavage et al., 2018). If lights are excessively bright, they could hinder drivers’ ability to see first responders working adjacent to their parked vehicle, or create unwanted visual discomfort, potentially reducing first responder safety. 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 study of human factors is to investigate potential disorientation effects caused by the nighttime use of emergency warning lights. This study investigates the impact of lighting color, intensity, modulation, and flash rate on driver behavior while traversing a traffic incident scene at night. The impacts 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.

Literature Review

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 point is crucial because present standards for these lights (Society of Automotive Engineers, 2014, 2019; National Fire Protection Association, 2016) do not contain upper limits for the intensity of the lights, especially at night when glare control is most important. A recent study from the Emergency Responder Safety Institute (ERSI) of the Cumberland Valley Volunteer Firemen's Association (Emergency Responder Safety Institute, 2019) confirmed that increasing the intensity of 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.

Some standards (Society of Automotive Engineers, 2014, 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 more glaring (Bullough, 2009; 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 (Bullough et al., 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. In the ERSI study of flashing emergency lights (Emergency Responder Safety Institute, 2019), high-low flash patterns were judged as somewhat less glaring and easier to navigate past than on-off patterns.

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. Skinner et al. (2021) 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 and Ng, 2009; Turner et al., 2014). Further, individuals can readily distinguish flashing at 1 Hz from that at 4 Hz (Skinner et al., 2021), 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; Bullough and Van Derlofske, 2004). Studies to identify the optimal light flash frequency using LEDs, however, have not been carried out in a systematic manner. Standards for reflective sheeting materials on the rear of fire trucks (National Fire Protection Association, 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).

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 measure the lateral vehicle offset from the incident scene, the longitudinal distance at which drivers could distinguish the silhouette of a firefighter, and record drivers' perceptions via survey questionnaire. These locations are shown in Figure 2. The remainder of this section provides further detail on the test lighting equipment and the experimental conditions and procedures.

Figure 1. Simulated traffic incident scene.

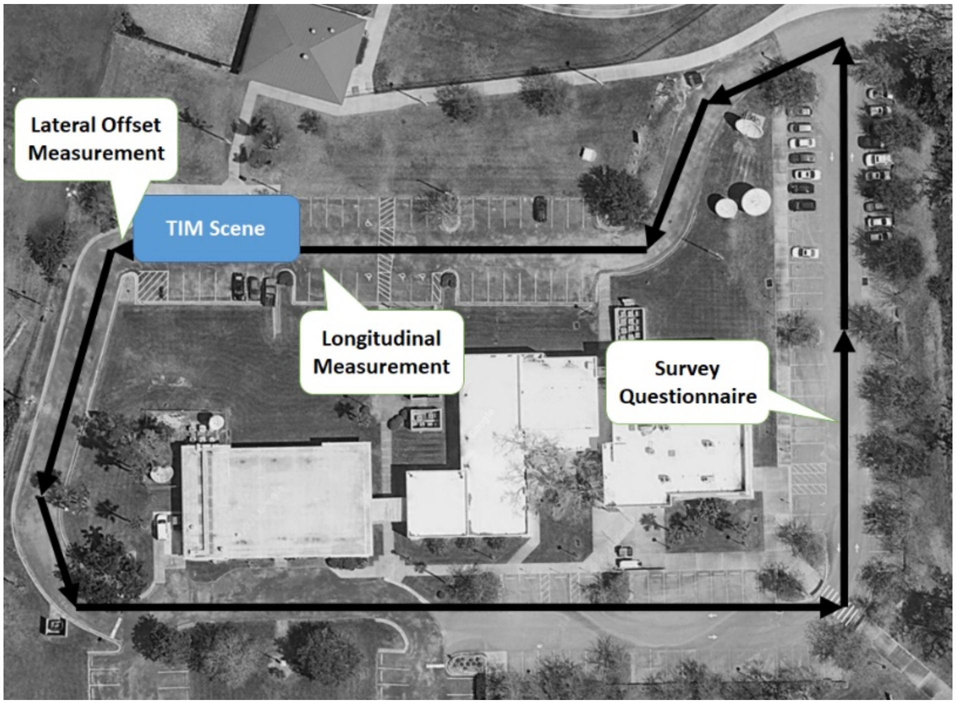


Figure 2. Plan view of closed course.

Test Light Equipment

Equipment to conduct the experiment consisted of commercially available lights that were blue, white, yellow and red, meeting SAE requirements for color (Society of Automotive Engineers, 2002), and 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.


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

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 for large fire trucks (National Fire Protection Association, 2016). The “low” nominal intensity level was designed to be about one-third to one-half of the minimum levels. Table 1 summarizes the relevant NFPA 1901 standards along with the “high” and “low” settings used in this study.

Table 1. Minimum Optical Power Requirements from NFPA (9) in Upper and Lower Locations, and Average Optical Power Produced by the Test Lights at Each Level.

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

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 approximately 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 (30 ms in duration, each separated by 20 ms) of light followed by one longer pulse (200 ms in duration), with each train of pulses repeating 75 times/min, a pattern that is typical of use on many fire trucks. The “slower” profile consisted of a single pulse of light (400 ms in duration) repeating 60 times/min. Both flash rate profiles produced the same optical power at the same nominal intensity level.

Experimental Conditions and Procedure

There were five independent variables in the experiment:

- Intensity level (2 levels: high/low)
- Color (4 levels: blue/white/yellow/red)
- Modulation (2 levels: on-off/high-low)
- Flash rate (2 levels: faster/slower)
- Presence of reflective markings (2 levels: present/none)

The reflective markings consisted of a red/yellow chevron pattern constructed with ASTM Type V sheeting materials (American Society for Testing and Materials, 2019), mounted on two 5 ft × 2 ft panels that were 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.

Table 2. Experimental Conditions in the Present Study.

No.	Color	Intensity	Modulation	Flash Rate	Markings	Notes
1	Red	High	On-Off	Faster	None	
2	Red	Low	On-Off	Faster	None	
3	Blue	High	On-Off	Faster	None	
4	Blue	Low	On-Off	Faster	None	Parametric Combinations of Color and Intensity
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

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 the impact 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.

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 according to the following scale:

- –2: very difficult to see
- –1: somewhat difficult to see
- 0: neither difficult nor easy to see
- +1: somewhat easy to see
- +2: very easy to see

Subjects also rated the level of discomfort glare they experienced, using the following scale (qualitative descriptions for glare are only defined for the odd-numbered scale values, but subjects could provide ratings using even-numbered values corresponding to sensations between the odd-numbered values):

- 9: just noticeable glare or no glare
- 7: satisfactory level of glare
- 5: just permissible glare
- 3: disturbing glare
- 1: unbearable glare

In this scale, lower numerical values correspond to greater sensations of discomfort glare; the rating is therefore a figure of merit for visual comfort.

Finally, the subjects rated how easy or difficult the overall road scene, including the roadway around the lights and the firefighter silhouette, was to see using the same +2 to –2 scale used to rate the visibility of the lights. A total of 20 individuals (7 females/13 males, mean age 32 years, standard deviation 15 years, range 19–61 years) with valid driver's licenses participated in the study. All subjects signed an informed consent form approved by the Institutional Review Board (IRB) at Embry-Riddle Aeronautical University and by the IRB at Rensselaer Polytechnic Institute.

Results

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 4). It should be noted that for both intensity levels, the average visibility ratings were quite high, ranging between +1.5 and +2, which indicates that the subjects judged both intensity levels to be relatively highly visible and easy to see at night.

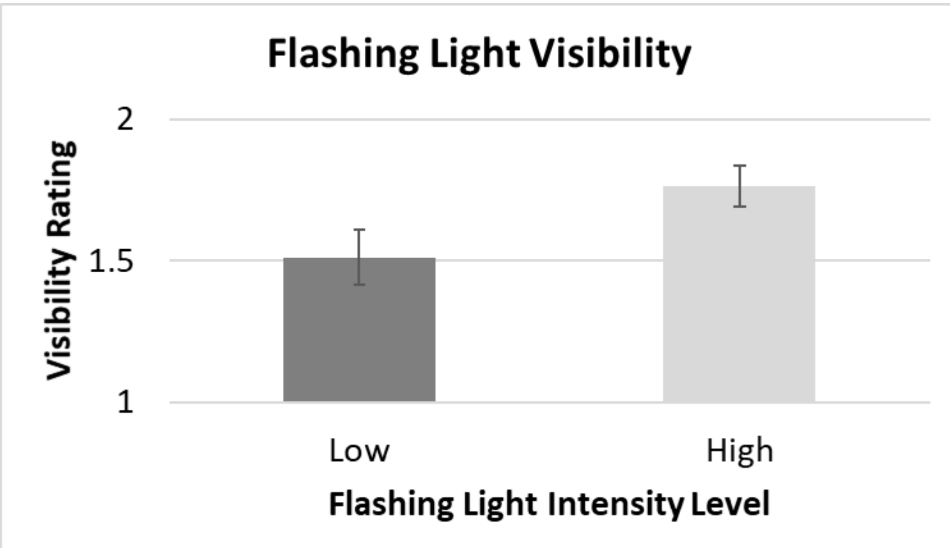


Figure 4. Average (± standard error of the mean) visibility ratings for each intensity level. A rating value of 1 corresponds to somewhat easy to see; a rating value of 2 corresponds to very easy to see.

As illustrated in Figure 5, 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.

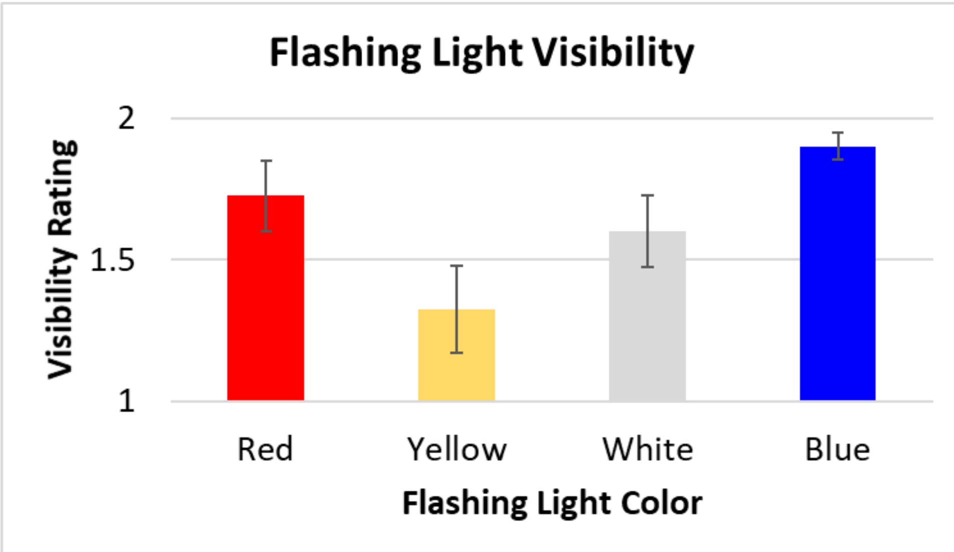


Figure 5. Average (+/- standard error of the mean) visibility ratings for each color. A rating value of 1 corresponds to somewhat easy to see; a rating value of 2 corresponds to very easy to see.

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.

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 6; recall that 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.

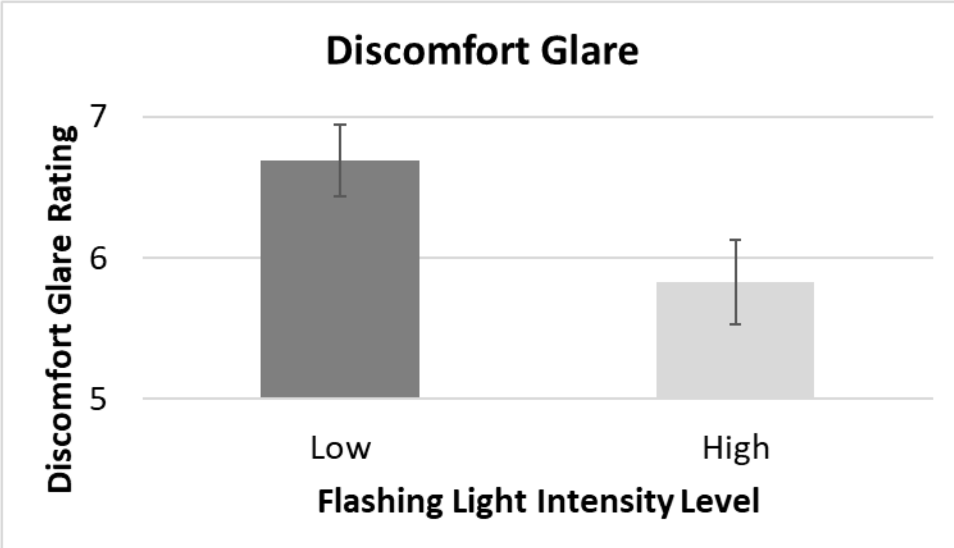


Figure 6. Average (+/- standard error of the mean) glare ratings for each intensity level. A rating value of 5 corresponds to a just permissible level of discomfort glare; a rating value of 7 corresponds to a satisfactory level of discomfort glare.

The color of the lights (Figure 7) also exhibited a statistically significant main effect ($F_{5,37}$=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.

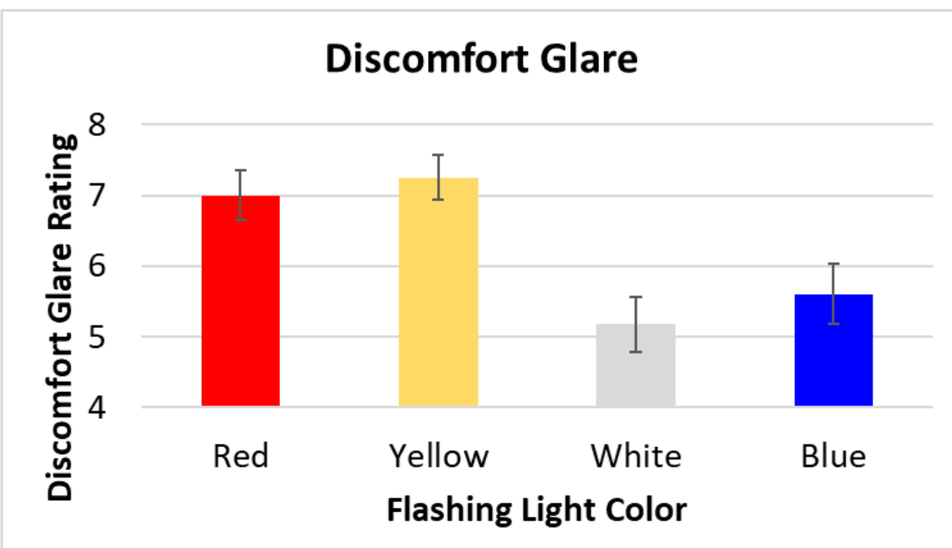


Figure 7. Average (+/- standard error of the mean) glare ratings for each color. A rating value of 5 corresponds to a just permissible level of discomfort glare; a rating value of 7 corresponds to a satisfactory level of discomfort glare.

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.

Visibility of the Road 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.

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.

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 8). The interaction suggests that although there was a small (non-significant) difference in average detection distances between the low and high intensity levels (about 4 feet, corresponding to 0.1 second of driving time at a speed of 30 mph), the potential difference in detection distances between the conditions with and without reflective markings was larger (about 25 ft, but also non-significant, corresponding to about 0.6 s of driving time at a speed of 30 mph). The difference between the distances with and without markings was larger for the higher intensity level, resulting in the significant interaction.

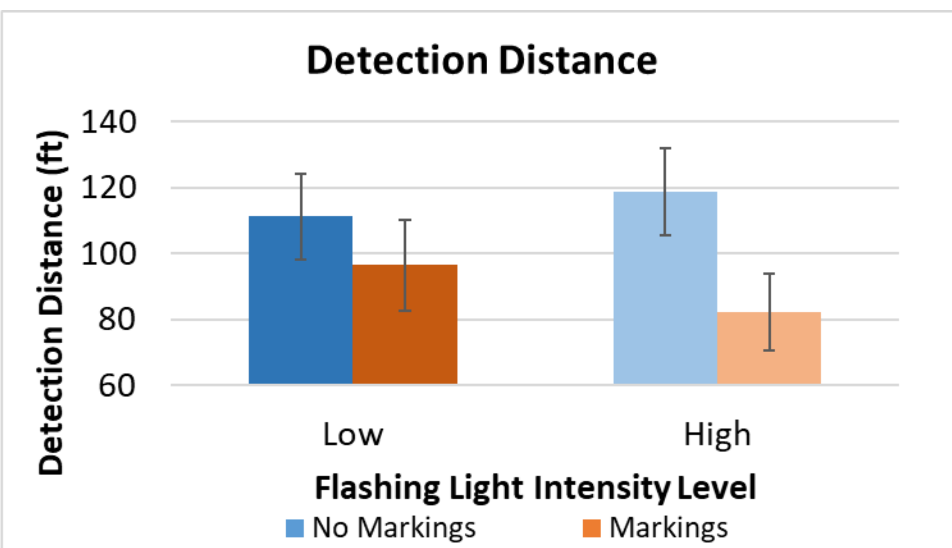


Figure 8. Average (+/- standard error of the mean) detection distances for each combination of intensity level and the presence of reflective markings.

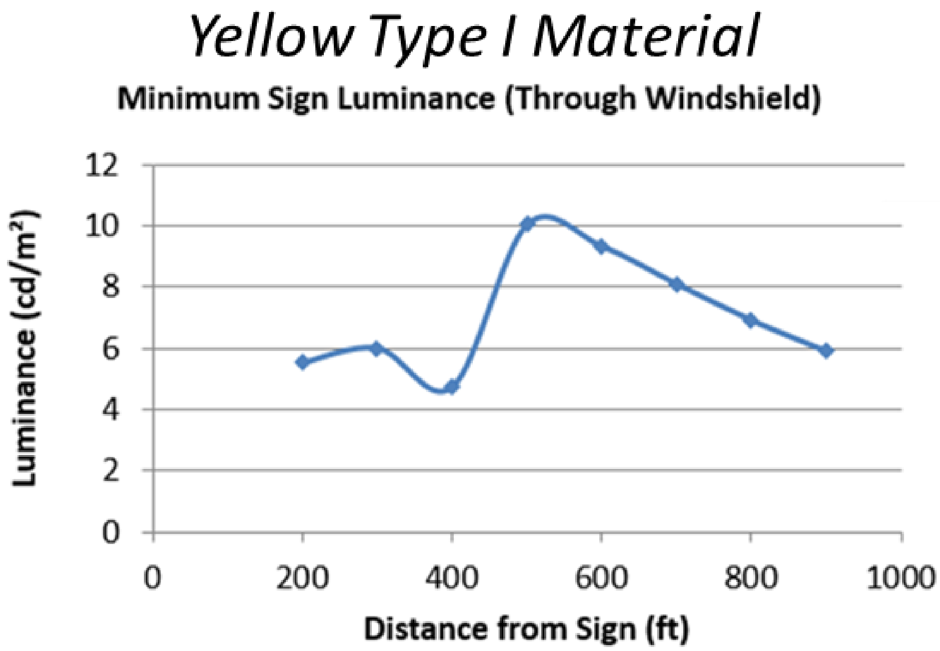
Conclusions

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 Figure 5 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 (Society of Automotive Engineers, 2014, 2019; National Fire Protection Association, 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 large fire trucks (National Fire Protection Association, 2016; see Table 1) were rated as only slightly less visible than higher intensities, yet remained highly visible. Even so, the lower intensities resulted in reduced discomfort glare by a relatively larger amount. However, the current results do not identify an optimal level for nighttime flashing light intensity, nor do they suggest that drivers exhibit a "moth-to-flame" effect in response to bright flashing lights.

The potential for decreased, albeit non-significant, detection distances to the first responder in the present study when the reflective markings were present was unexpected. It was considered that the presence of the markings might reduce discomfort 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. Perhaps a maximum Type specification would be appropriate, if further data to explore this possibility are collected in the future.



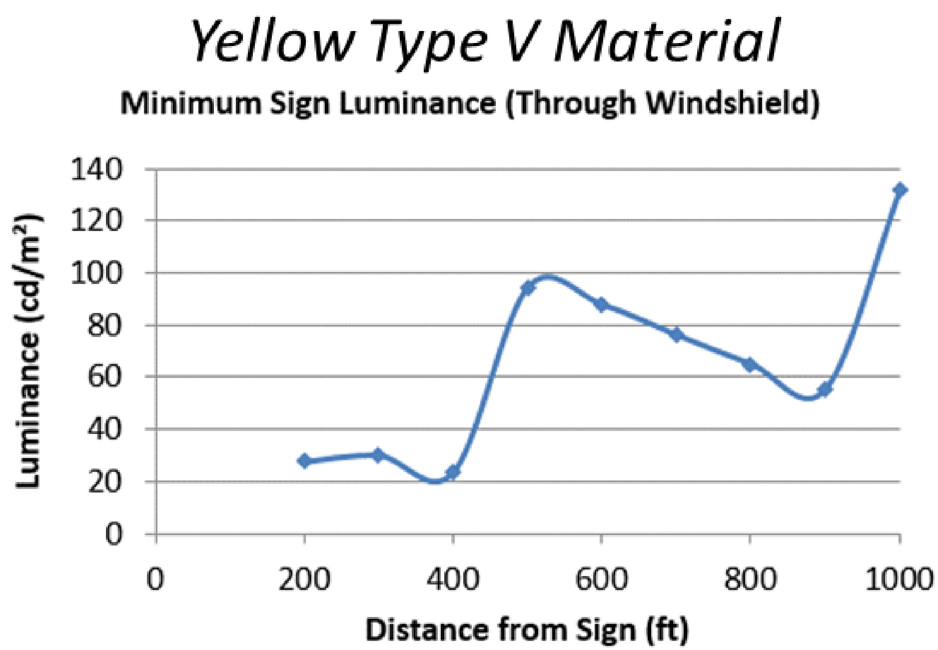


Figure 9. Minimum luminances of yellow ASTM Type I and Type V materials as a passenger vehicle with low-beam headlights approaches.

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) is beneficial to the safety of first responders.

Implications and Preliminary Recommendations

Based on the results of this study, it can be seen that higher intensity lights present more glare, but those higher intensities do not necessarily make lights more visible at night. The lower intensity lights in this study provided practically the same level of visibility as the higher intensity lights, under the nighttime conditions used in the experiment. Thus, when vehicles are stationary and used in nighttime blocking mode, they should be sufficiently visible with reduced intensity lights.

The perceived level of visibility of the lights is related to the color of the lights. Blue and red lights have the greatest perceived saturation and were judged as brighter than white and yellow lights of the same intensity. The level of discomfort glare also differs between colors; blue and white lights were judged as more glaring, and red and yellow lights were least glaring at the same intensity. This suggests that red lights for stationary blocking operations would be judged as most visible but produce the least amount of glare, compared to the other colors tested in this study.

Lights that meet existing minimum intensity requirements (like those from NFPA) for emergency vehicles may be brighter than needed for nighttime driving conditions, at least when the emergency vehicles were stationary as in the present study. Using lower intensities at night will reduce discomfort glare without reducing their visibility.

None of the results of the study contained evidence of a “moth-to-flame” effect or its opposite. Study participants drove no closer to or farther from the lights regardless of their intensity or color.

Finally, the presence of high-reflectivity chevron markings seemed to make it more difficult for drivers to see responders working around their vehicles at night, even when the responders wear safety vests. This suggests that agencies might consider using only Type I reflective materials for marking the rear of fire apparatus, rather than higher types. Investigations on this topic are currently underway.

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