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Responses to Flashing Warning Lights and Colors of Service Vehicles

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Abstract

Flashing warning lights and vehicle markings of various colors are used on a wide range of emergency and other service vehicles to help inform drivers about the presence of these vehicles and the types of situations that drivers are approaching. Although not applied consistently among all jurisdictions, the colors and performance of these visual elements are often selected to help communicate the type of scenario (such as red flashing lights to indicate an emergency vehicle, or yellow flashing lights to indicate a non-emergency service vehicle). Previous investigations have shown that flashing light colors, vehicle and marking colors, and flashing temporal characteristics (e.g., rapid versus slower flashing) can all affect a driver's perception of whether a vehicle along the road is responding to an emergency situation or not. Building on previous research, a laboratory study was carried out to investigate how drivers perceive scale-model roadway scenarios including different numbers of vehicles varying in their colors, and with flashing lights modulating at different intensity levels and flash frequencies. For each scenario, observers were asked whether as drivers they would proceed with caution past the scene or prepare to slow down or stop. Observers' responses were recorded, and the time taken to provide a response was also recorded as a measure of certainty/uncertainty. Overall, the results show that coordinating the presence and color of flashing lights with the colors of vehicles and their markings are among the primary cues used by drivers to assess whether a roadside incident scene is an emergency situation or not. The results also provide suggestions for using flashing lights when multiple vehicles are present to reinforce consistent judgments among drivers.

Introduction

Vehicle crashes are over-represented among the causes of injury and fatality among front-line service workers [1,2] including emergency responders, highway maintenance workers, utility workers, tow truck operators, and delivery personnel. These workers often need to work adjacent to oncoming traffic and with few barriers separating them from the traffic stream. In addition to reflective safety apparel that helps drivers detect service workers from greater distances [3], their vehicles are often equipped with flashing lights and reflective markings to help them stand out among their surroundings and to inform drivers about the type and nature of a roadway incident scene [4].

A number of studies have focused on the intensity [4, 5, 6] and color [6,7] of flashing lights needed for reliable detection under different ambient conditions (e.g., daytime versus nighttime). Present standards for flashing lights on emergency and service vehicles [8, 9, 10] stipulate minimum intensity values for these lights to ensure that they can be readily seen under bright daytime conditions, but do not have upper limits for intensity when deployed at night. Further, a growing body of research [7,11,12] has demonstrated that lights with greater short-wavelength ("blue") spectral content are judged as producing more discomfort glare than those with greater log-wavelength ("yellow" or "red") spectral content.

The color of vehicles, their markings and their flashing lights can also serve as visual cues to inform drivers about the type of situation they are approaching. For example, red vehicles and red flashing lights are commonly used on fire response vehicles [13] and this color typically conveys a greater sense of emergency or danger than other colors [14]. Despite calls to use lighter colors (e.g., lime-green) for fire response vehicles [15] based on the assumption that greater contrast between an emergency vehicle and its background is beneficial, the traditional association of red colors with emergency situations [14] has resulted in most of these vehicles being red [16]. Other cues that might help convey information about the nature of a roadside incident scene include the modulation frequency of flashing lights; faster flashing is usually associated with an increased sense of urgency or danger [17,18].

Two recent studies [19,20] have been carried out to assess how the coordination of vehicle/marking colors and the colors and operation of flashing lights might result in more consistent perceptions about whether a roadway scene is likely to be judged as an emergency or not. Using red and yellow colors for vehicles, their markings and their flashing lights, it was found that red vehicles and especially red lights were more likely to be associated with an emergency situation than yellow ones. Higher (faster) flashing frequencies were also more likely to be judged as being related to an emergency situation, but the effect of frequency was more modest compared to color.

In both of the aforementioned studies [19,20] the primary outcome was whether or not a roadway scene was perceived as being associated with an emergency, but subjects were not asked how they might respond if they were approaching a particular roadway incident while driving. Nor were subjects asked how certain or uncertain they might be in their responses. To begin to understand how perceptions of vehicle/marking and flashing light colors might affect driver responses, a laboratory study building upon the previous studies [19,20] was carried out. In this study the primary outcome measure was whether a subject would be likely to prepare to slow down or stop (as they might in an emergency situation) or to proceed past a roadside incident. As a secondary outcome, the time to make a response was also measured, with the expectation that more ambiguous visual information (e.g., a red vehicle with yellow flashing lights) might result in greater uncertainty and thus result in longer response times to identify how they would approach the scene as a driver.

Method

The study protocols were reviewed and approved by the Institutional Review Board (IRB) at the Icahn School of Medicine to ensure adequate protection of human subjects. Twenty-five adults (14 female/11 male) with current driver's licenses participated in the study, ranging from 20 to 72 years of age (mean 41, SD 14 years). The study took place in the photometric laboratory of the Light and Health Research Center, a windowless, black-painted room.

After being informed about the nature of the experiment, subjects were seated at the end of an O-scale (1:48) model display of a multi-lane road. Along the right-hand side of the road, each trial consisted of a scene containing several combinations of red or yellow vehicles with retroreflective markings (matching the vehicle color) attached to the rear of the vehicle and flashing red or yellow lights. The specific combinations tested are summarized in Table 1.

TABLE 1 Experimental combinations of vehicle color, flashing light color and flashing light position.

Number of Vehicles	Vehicle Color	Flashing Lights Color	Flashing Lights Position
1	Yellow	None	N/A
1	Yellow	Yellow	Single Vehicle
1	Red	None	N/A
1	Red	Red	Single Vehicle
1	Red	Yellow	Single Vehicle
3	Red	None	N/A
3	Red	Red	All Vehicles
3	Red	Red	Left Vehicle
3	Red	Red	Center Vehicle
3	Red	Red	Right Vehicle

FIGURE 1 a: Scene with single yellow vehicle. b: Scene with three red vehicles.

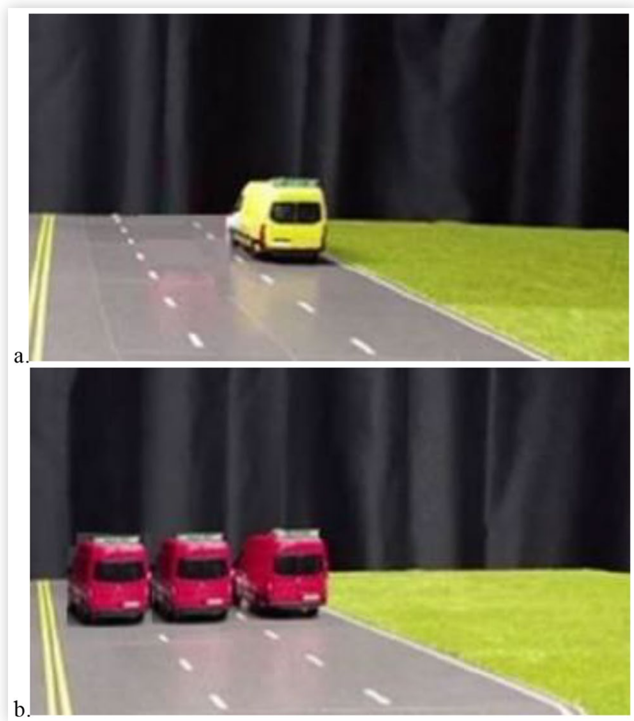


Figure 1a shows a scene with one yellow vehicle present, and Figure 1b shows a scene with three red vehicles present. The instructions to subjects in each trial were to look toward a laptop screen just below the scale model road while the experimenter set up the vehicle/light configuration, and then to look up upon hearing a beep. Subjects were asked to respond, based on how likely they perceived the scene to be an emergency or not, whether they would proceed past the scene with caution, or prepare to slow down or stop. The former response (proceed with caution) was indicated by pressing the up arrow on the laptop computer, and the latter (prepare to slow/stop) by pressing the down arrow. The laptop recorded the response and the response time;

subjects were asked to make their response as quickly as possible. After they responded, the laptop beeped twice to let the experimenter know to set up the next trial, and subjects were asked to look back down at the laptop screen.

The flashing lights were created with dual-color (red/yellow) LEDs and were operated to produce two flashing modes. In the standard mode, the peak intensity of the red or yellow LEDs was adjusted to produce the same illuminance at subjects' eyes as a 2000-cd source would at a simulated distance of 100 m away with a flash frequency of 1 Hz. In enhanced flashing mode, the intensity of the red lights was increased by 50% and the yellow lights decreased by 50%, the flash frequency of the red lights was doubled, and the flash frequency of the yellow lights was halved.

The flashing lights always alternated between 100% and 10% of the peak intensity value to produce "high-low" rather than "on-off" flashing, which was found in previous research [5] to improve visual closure detection.

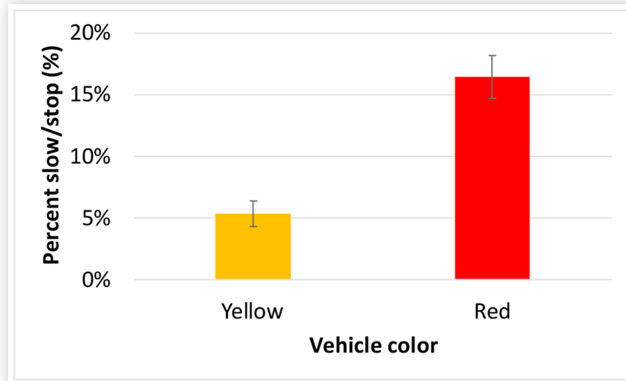
Three blocks of trials, each with the order of vehicle/light configurations presented in random order, were completed by each subject. The first block represented daytime viewing conditions, with the ceiling-mounted room lights producing an illuminance of 500 lux on the road surface near the scale model vehicles. The second represented nighttime conditions with the room lights switched off. A small white LED light source producing an illuminance of 1 lux on the rear surfaces of the scale model vehicles was mounted near the subjects' seating location, serving as a headlight source so that the retroreflective markings on the vehicles were visible. The final block was also carried out in the dark, but with simulated wet pavement. Slightly crinkled plastic film was laid over the road surface so that from the subjects' location, reflections from the flashing lights were present, similar to reflections on wet pavement. Each block of trials took between 20 and 30 minutes for subjects to complete, and they were given a couple minutes for a break between each block. Half the trials with flashing lights used the standard flashing mode and half used the enhanced mode.

Results

Vehicle Color

To assess the impact of vehicle color on subjects' decisions to proceed with caution or to prepare to slow/stop, the conditions with a single vehicle, either yellow or red, and with no lights, were compared. In addition, the ambient condition (day, night or wet night) was an independent factor. The dependent outcome measures were the percentage of times subjects decided to prepare to slow/stop and the response time; the latter was used as a possible measure of certainty/uncertainty in subjects' decisions.

FIGURE 2 Percentage of slow/stop decisions (+/- standard error of the mean) for single yellow and red vehicles with no flashing lights.



Within-subjects analyses of variance (ANOVAs) were carried out on the perception of stop/slow decisions and the response times. There was a statistically significant ($F_{1,24}$=4.94, p=0.04; Figure 2) effect of vehicle color on the percentage of slow/stop decisions. Subjects were more likely to decide to slow/stop when the vehicle was red. For both colors, the slow/stop percentages were low (under 20%), likely because flashing lights were not present in either condition. There were no other statistically significant main effects or interactions on either the slow/stop percentages or the response times.

Vehicle Color and Flashing Light Color

To evaluate the impacts of the combination of vehicle color and the color of the flashing lights, the conditions consisting of a single yellow vehicle with yellow lights, a single red vehicle with red lights, and a single red vehicle with yellow lights were compared. The ambient condition (day, night, wet night) and the flash mode (standard, enhanced) were also investigated using within-subjects ANOVAs on the slow/stop percentages and on the response times.

There was a statistically significant ($F_{2,48}$=10.5, p<0.001; see Figure 3) effect of the vehicle/lights color combinations on the slow/stop percentages. The combination of a red vehicle with red lights had the highest slow/stop percentage and the combination of a yellow vehicle with yellow lights had the lowest. The combination of a red vehicle with yellow lights had an intermediate slow/stop percentage.

There was also a statistically significant main effect ($F_{2,48}$=11.5, p<0.001; Figure 4) of the ambient condition on the response times. The longest response times occurred under the simulated day ambient condition and the shortest occurred under the simulated wet night condition.

There were no other statistically significant main effects or interactions on either the slow/stop percentages or the response times.

FIGURE 3 Percentage of slow/stop decisions (+/- standard error of the mean) for a yellow vehicle with yellow lights, a red vehicle with red lights, and a red vehicle with yellow lights. Paired comparisons using Tukey's correction revealed statistically significant ($p<0.05$) differences between the red/red condition and each of the other two conditions.

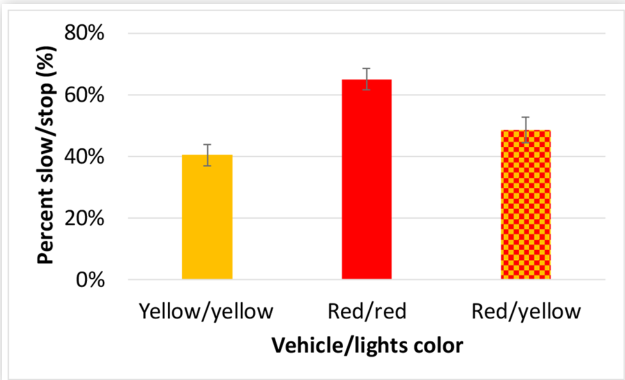
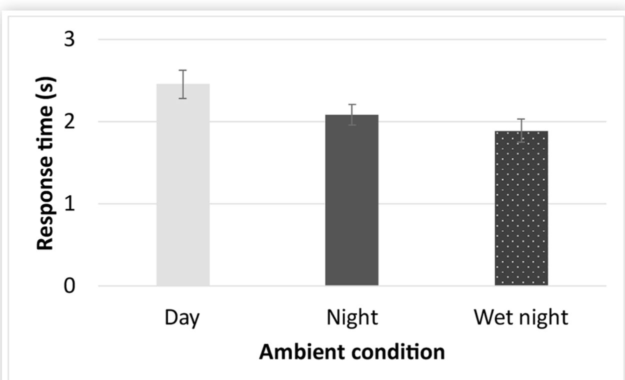


FIGURE 4 Mean response times (+/- standard error of the mean) under simulated day, night and wet night ambient conditions. Paired comparisons using Tukey's correction revealed statistically significant ($p<0.05$) differences between the day condition and each of the other two ambient conditions.

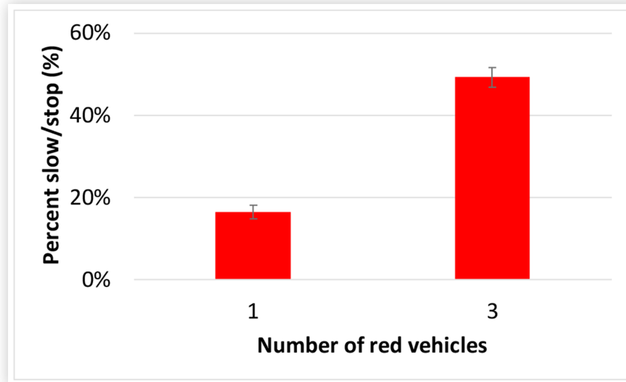


Number of Vehicles

To investigate the impact of the number of vehicles on the likelihood and speed of a decision to prepare to slow/stop, the conditions with either one or three red vehicles, all without flashing lights, were compared. The ambient condition also served as an independent factor in this analysis. A within-subjects ANOVA was carried out, and there was a statistically significant ($F_{1,24}=21.5$, $p<0.001$; Figure 5) effect of the number of vehicles on the slow/stop percentage, with a higher percentage when more vehicles were present.

No other statistically significant main effects or interactions were found on the slow/stop percentages or the response times.

FIGURE 5 Percentage of slow/stop decisions (+/- standard error of the mean) for one versus three red vehicles without flashing lights.



Multiple Vehicles: Number with Flashing Lights

To identify the impact of the number of vehicles among multiple vehicles in a scene that have flashing lights activated, the conditions with three red vehicles where either zero, one or all three of the vehicles had flashing lights were compared. Additional independent factors in this analysis were the ambient condition (day, night, wet night) and the flashing mode (standard, enhanced).

A within-subjects ANOVA was carried out, and there were statistically significant main effects of the number of lights ($F_{2,48}=28.6$, $p<0.001$; Figure 6) and the flashing mode ($F_{1,24}=4.5$, $p=0.04$) on the slow/stop percentage, with a statistically significant interaction ($F_{2,48}=5.84$, $p=0.005$; Figure 7) between the ambient condition and the flash mode. In Figure 6 it can be seen that the slow/stop percentage increased as a function of the number of vehicles (out of three) with flashing lights.

Figure 7 shows that the slow/stop percentage was higher for the enhanced flashing mode (2 Hz, brighter

FIGURE 6 Percentage of slow/stop decisions (+/- standard error of the mean) for three red vehicles when zero, one or three of the vehicles had red flashing lights. Paired comparisons using Tukey's correction revealed statistically significant ($p<0.05$) differences among all of the conditions.

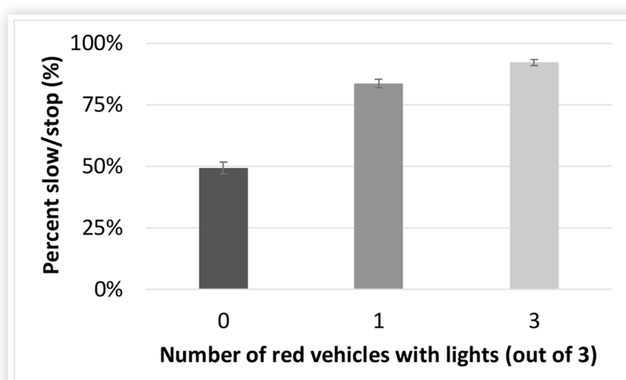


FIGURE 7 Percentage of slow/stop decisions (+/- standard error of the mean) for three red vehicles under each combination of ambient condition and flashing mode. Paired comparisons using Tukey's correction revealed a statistically significant (p<0.05) difference between the day and night wet ambient conditions.

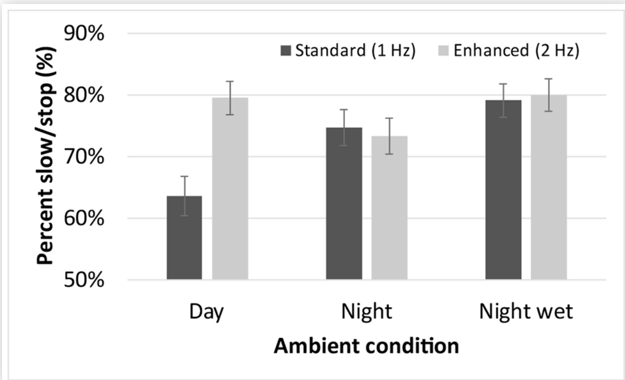
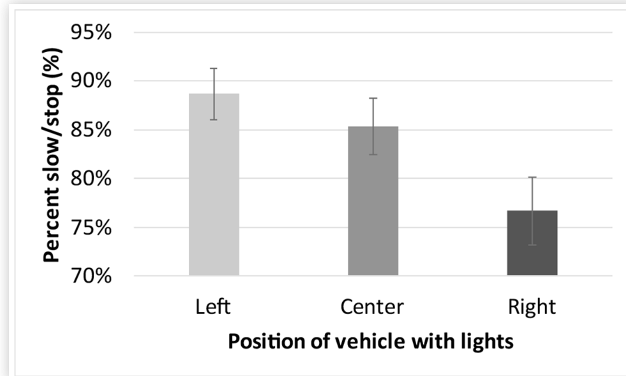


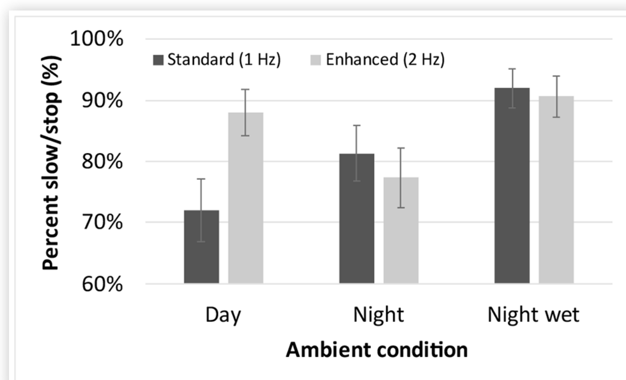
FIGURE 8 Percentage of slow/stop decisions (+/- standard error of the mean) for each position of flashing lights (as viewed by the subjects), when only one of three red vehicles had flashing lights. Paired comparisons using Tukey's correction revealed a statistically significant (p<0.05) difference between the left and right positions.



lights) than for the standard flashing mode only during the day ambient condition. During the night and wet night conditions, the flashing mode made little difference on the slow/stop percentage.

A within-subjects ANOVA was carried out on the response times, and there were significant effects of the number of lights ($F_{2,48}$=7.98, p=0.001) and of the ambient condition ($F_{2,48}$=5.37, p=0.008), with a statistically significant interaction between these two factors ($F_{4,96}$=2.79, p=0.03). Overall response times were longest for the ambient day condition and shortest for the wet night condition (as also seen in Figure 4), and they decreased with an increasing number of vehicles operating their flashing lights. The interaction is evident based on the observation that when all vehicles had flashing lights, response times were short and consistent among all ambient conditions. When fewer vehicles had flashing lights, response times were longest for the daytime ambient condition.

FIGURE 9 Percentage of slow/stop decisions (+/- standard error of the mean) for each combination of ambient condition and flashing mode. Paired comparisons using Tukey's correction revealed statistically significant (p<0.05) differences between the night wet condition and each of the other two ambient conditions.



Multiple Vehicles: Position of Flashing Lights

In order to evaluate whether the position of a vehicle with flashing lights among other vehicles influenced the judgments of subjects to decide to slow/stop, the conditions in which three red vehicles were included but where one of the vehicles had red flashing lights were compared. The ambient condition (day, night, wet night) and the flashing mode (standard, enhanced) were additional independent factors in this analysis.

A within-subjects ANOVA revealed statistically significant effects of the ambient condition ($F_{2,48}$=3.52, p=0.04) and of the position of the flashing lights ($F_{2,48}$=5.70, p=0.006; Figure 8) on the slow/stop percentage, which was highest when the flashing lights were located on the vehicle farthest to the left (and closest to passing traffic). There was a significant interaction between the ambient condition and the flashing mode ($F_{2,48}$=3.41, p=0.04; Figure 9), such that enhanced (brighter and faster) flashing resulted in a greater slow/stop percentage only for the daytime ambient condition.

A within-subjects ANOVA on the response times revealed a statistically significant ($F_{2,48}$=5.57, p=0.007) main effect of the ambient condition, with no other significant main effects or interactions. The response times were shortest for the wet night condition and longest for the day condition, consistent with the trend illustrated in Figure 4.

Discussion

Our previous studies [19,20] showed that the primary visual factors impacting the likelihood of a roadway incident scene being identified as an emergency were, in decreasing order of importance, the color of flashing lights, the color of a vehicle and its markings, and the flashing mode (standard or enhanced) of the lights.

In the present study, subjects were not asked directly whether they perceived each scene they viewed as an emergency or non-emergency situation. Rather, they were asked how they would behave as a driver (by preparing to slow or stop, or by proceeding ahead) in response to each scene. We expected that participants would be more likely to prepare to slow down or stop when they perceived the scene to be an emergency situation. The present results show that red flashing lights on red vehicles were more likely to elicit a slow/stop response than yellow lights on yellow vehicles, which is consistent with previous findings that red lights on red vehicles were judged as emergency situations.

When conditions differed only in the color of the flashing lights (i.e., a red vehicle with red lights versus a red vehicle with yellow lights), the difference in slow/stop percentages between the conditions was 16% (65% versus 49%). When conditions differed only in the color of the vehicle and its markings (i.e., a yellow vehicle with yellow lights versus a red vehicle with yellow lights), the difference in slow/stop percentages was smaller (41% versus 49%). Thus, the present results are consistent with earlier findings [20] about the relative influence of the color of flashing lights and vehicle/marking color.

The flashing mode had little impact on subjects' responses in the present study with one exception. The enhanced mode (with brighter and faster flashing of red lights) resulted in a larger percentage of slow/stop responses than the standard flashing mode only during the ambient day conditions, not during the night or wet night conditions. This finding underscores the importance of having high intensity levels for flashing lights during the daytime as required by existing standards [8, 9, 10]. During the nighttime, however, even flashing lights with a reduced intensity are likely to be judged as highly visible [7] because their contrast against the dark ambient environment is high even at a reduced intensity level, and excessively bright lights can contribute to disability glare at night [3].

It was expected that inconsistent vehicle/marking and flashing light colors would lead to greater uncertainty, resulting in longer times for subjects to formulate their responses. Instead, however, the average response times for each condition were negatively [and statistically significantly ($p<0.05$)] correlated with one another. The more likely a subject was to slow or stop in response to a particular condition, the shorter the response time tended to be.

This study has yielded a new finding, in addition to showing that the presence of more vehicles at a roadway incident scene (Figure 5) and the use of flashing lights on more vehicles (Figure 6) increases the likelihood that drivers will prepare to slow or stop. We also found that using flashing lights on one vehicle (out of three) resulted in a similar response as deploying them on all vehicles within a scene, if the lights were mounted on the vehicle located closest to approaching traffic (Figure 8); such a practice could help reduce disability and discomfort glare, especially at night [3,6,7]. Of course, this and other findings from the present study should be validated under realistic, full-scale driving conditions before implementation. Indeed, such field validation is presently underway.

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Definitions/Abbreviations

ANOVA - Analysis of variance
cd - candela
Hz - hertz
IRB - Institutional Review Board
LED - Light-emitting diode
SD - Standard deviation

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