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INFORMATION AND RESEARCH PROVIDED TO
THE SENATE COMMITTEE ON TRANSPORTATION
APRIL 24, 2003
AB444
NEVADA DEPARTMENT OF PUBLIC SAFETY
HIGHWAY PATROL DIVISION

Visual Conspicuity of Emergency Vehicle Lighting Systems and Markings to Avoid Rear-End Stopped Crashes

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The Nevada Department of Public Safety opposes the provisions of AB444 as stated in section 1. The Department supports the provisions of section 1.5 through 25. The Department does not recommend the use of blue light on highway maintenance vehicles. Blue is a color commonly recognized as associated with emergency vehicles. It is beneficial to members of the public that vehicles with blue lights can be trusted to be authentic emergency vehicles. An additional and compelling reason to oppose blue lights on maintenance vehicles is the data amassed that indicates that blue is not a particularly effective color as a warning devise. Visibility and safety for maintenance vehicles can be more effectively improved through a combination of reflective vehicle markings, the combining of multiple light sources and flash rates, as well as the use of colors such as green-yellow combination and amber. The lighter colors have greater visibility to the human eye than do red or blue.

Prologue

The Crown Victoria Police Interceptor (CVPI) has become the dominant police vehicle in the United States because of its features and its overall performance and safety record. Today, over 80 percent of the police vehicles in North America are CVPIs.

In the past several months, media coverage has focused on high-speed, rear-collision accidents involving police. These involved speeds of as much as 70 to 100 mph and resulted in fires. Some involved semi-tractor/trailers. Even though this type of accident is extremely rare and unusual, these high-speed crashes have evoked concern among some police customers.

As a result of this problem, the Arizona Department of Public Safety and the Florida Highway Patrol partnered with the Ford Motor Company and the National Highway Traffic Safety Administration to identify solutions and enhance the safety of police personnel who may be involved in high speed rear-end collisions. In addition to the design characteristics, the partnership also studied the effects of vehicle lighting and conspicuity. While the information in this study is specifically related to emergency vehicles, the information is also relevant to any other vehicles exposed to the risk of high speed rear-end collisions on our highways. Further information on the results of the study group can be found at www.cvpi.com. The following information was obtained from the Arizona DPS and from other published sources which are referenced.

Introduction

Visual conspicuity refers to the ability of a lighting system or markings to enhance detection by attracting visual attention. Ideally, a vehicle's lighting system or markings will also influence an approaching driver's perception of an object's identity, distance, and motion (or lack of motion) in such a way as to promote safe driving. In this section, the factors of lighting systems and vehicle markings that influence conspicuity (i.e., detection) and perception will be summarized.

The intent of this discussion is to identify lighting configurations and markings that are likely to make stopped emergency vehicles more conspicuous to oncoming drivers and thereby reduce rear-end crashes into stopped emergency vehicles. The lighting that best accomplishes such goals may be different from the kind of lighting that will enhance perception of vehicles in motion. The latter is not discussed here.

It is also important to clarify what message or information the lighting systems and markings should convey. Information regarding, say, the identity of a vehicle as a police vehicle as opposed to a fire department vehicle is not considered. Instead, the following information items are considered the "message" a lighting system and markings need to convey to reduce or avoid rear-end crashes into stopped emergency vehicles. Specifically, the emergency vehicle's lighting should convey the message(s):

- I am present
- I am stopped (a true state) or moving toward you (an illusion that might promote safety)
- Slow down and stay away from me.

General Principles

The following points summarize some key human factors research results regarding conspicuity of emergency vehicles (Code 3, Inc., 2002):

- Objects are likely to pop out and be conspicuous if they are large, very bright relative to their background, if they move or flash, if they suddenly appear, or if they are familiar to us.
- Within reasonable bounds, response time improves with increasing flash rate, flash duration, and brighter lights.
- In order to maintain the same signal range (i.e., range of conspicuity), the intensity of a flashing light will need to be increased over that of a steady light.
- It is the intensity at an observer's eye, produced by a light, that largely determines if the light will be seen.
- The human eye is more sensitive to a light source the closer that source is to the observer's line of sight. This means that the further a signal is from the line of sight, the brighter it will need to be to gain attention.

- Compared to threshold illuminance (where the observer can barely detect the light), increases of factors of 100 to 1000 are not excessive to attract the attention of an observer not searching for the light.
- White light is effective in gaining attention but fails to identify the vehicle. Green is also effective but is a "go" or "safe" color in our society. Yellow, at threshold levels, is often mistaken for a white flash. Red can be easily lost among tail lamps.

In the following sections, different aspects of lighting systems and markings will be examined. Nuances and qualifications to the general principles outlined above will be discussed in the context of a particular factor.

Lighting Factors that influence Conspicuity

Three key factors that affect the visual conspicuity of a vehicle lighting system are a) light output, b) light color, and c) light flash rate or pattern (Smith, 1991). Each of these will be discussed in turn.

Light Output. The light output of a light source can influence conspicuity, though in complex ways. If a light source is too dim, a driver may not notice it until it is too late. Beyond a certain brightness, detection remains constant so that increasing the light output doesn't improve detection. In fact, at very high output levels, disability glare would set in and degrade safety. All of these effects depend upon the prevailing illumination, other light sources in the visual field, the driver's light adaptation, etc.

All else being equal, one would think that the light source with the greatest intensity ought to be the most visible. For flashing lights, however, this is not true. For flash durations of up to 100 milliseconds ($1/10^{th}$ of a second), the law of visual perception called Bloch's Law, states that perceived brightness (B) of a light source is the product of light intensity (I) times duration (D), or $B=I \times D$ (Schiffman, 1976). Because of Bloch's Law, a light source like a xenon tube that has a much higher light output rating than, say, an incandescent bulb, could appear less bright because of a much shorter flash time. This explains the findings of the Society of Automotive Engineers reported by Smith (1991) that halogen lights were perceived as bright as strobe lights because even thought the halogen lights were $1/20^{th}$ the peak intensity, they were on 100 times longer than the strobe light's 250 microseconds.

Thus, the total amount of light present with flashing lights depends on product of intensity and duration, not candlepower ratings alone. Our recommendation is to compare alternative lighting systems for their perceived brightness or 'flash energy' as determined by Bloch's Law rather than rely on candlepower ratings alone .

Light Color:

The sensitivity of human vision peaks in the yellow-green portion of the spectrum. It is established that white is the most visible color for warning lights, followed by green, amber and red (Allen, Strickland). White is effective in gaining attention but fails to identify the vehicle; it is therefore rarely used alone. Green is also visually effective but has similarly failed to gain widespread use because green is a "go," or "safe," color in our society. Yellow and red are colors that signify "danger," and this has led to their popularity as warning and caution identifiers. Yellow, at threshold levels, is often mistaken for a white flash (Vos). Red, too, has been criticized for being weakly visible (Allen), easily lost in tail lamps (Lamm), and psychologically associated with rage and passion (Solomon).

Light color is also a powerful determiner of visual conspicuity. A key factor related to light color is called transmittance, the amount of light that will pass through a colored filter or lens. A white filter allows the most light to pass through from a halogen light source. Other colors filter the light source more. For example, amber filters will allow 60% of a halogen light to pass. Red filters will pass about 25% of the light to pass. Blue filters will allow only about 15% of the halogen light to shine through.

Human sensation complicates matters somewhat. At night, sensitivity to blue is greater than sensitivity for red while in daylight sensitivity for red is greater than sensitivity for blue. Smith (1991) reports that with flashing lights, twice the amount of blue light energy is needed in daylight to be perceived as bright as the brightness of a red light. At night, though, the situation is reversed. In night viewing conditions, only about one-third the intensity of a blue light is needed to match the perceived brightness of a red light. So, the sensitivity of the human eye to lighting of different colors depends, at least in part, on the ambient light levels in which those lights are being viewed.

Blue Advancing-Red Receding Illusions: Another aspect of color is that some colors appear to advance nearer than others. Luckiesh (1922/1965) points out that, in general, colors whose dominant hues are shorter wave-lengths (e.g., blue or violet) appear retiring or receding while those whose dominant hues are longer wave-lengths (e.g., red) appear advancing. This perceptual illusion is sometimes referred to as blue advancing-red receding.

Research conducted by Berkhout (1979) identified color-based perceptual illusions at night that could have safety implications in driving. In his tests, Berkhout's test participants took 7-second looks at eight (8) different configurations and color combinations of rotating-beam emergency vehicle lighting at night under a variety of conditions. Berkhout's experiment was conducted with observers looking through the windshield of a vehicle parked in the driving lane of an unused gravel road crossing a small river between two bluffs. The vehicle with the lighting on it traveled back and forth on this road at a distance of between 300 meters and 450 meters ahead of the parked observer vehicle. There was no lateral movement of the stimulus vehicle and no other light sources in observer's central 60-degree of field of view other than the stimulus vehicle. The lighting systems were moved toward or away from a stationary observer at rates of 0 (i.e., lighting was at a standstill), 5, or 10 meters/sec at ranges of between 300 and 450 meters. The observers were given 7 second glimpses of the lighting. The lighting systems evaluated were:

- Federal Signal Co. #184: single dome red, center roof mount, 4 sealed beams, 90^0 separation , 1.75 flashes per second
- Federal Signal Co. #184: single dome blue, center roof mount, , 4 sealed beams, 90^0 separation , 1.75 flashes per second
- Federal Signal Co. #11: Twin beacon red, 2 sealed beams in each dome, 90^0 separation , 1.17 meters between lamp centers, 0.87 flashes per second (flashes alternate from side to side at 0.87 flashes per second each, 1.75 flashes per second overall)

- Federal Signal Co. #11: Twin beacon blue, 2 sealed beams in each dome, 90^0 separation, 1.17 meters between lamp centers, 0.87 flashes per second (flashes alternate from side to side at , at 0.87 flashes per second each, 1.75 flashes per second overall)
- Federal Signal Co. #12: TwinSonic blue, 2 sealed beams in each housing, 180^0 separation, 1.12 meters separation between lamp centers, 0.87 flashes per second (front view), 3.50 flashes per second overall
- Federal Signal Co. #12: TwinSonic red, , 2 sealed beams in each housing, 180^0 separation, , 1.12 meters separation between lamp centers, 0.87 flashes per second (front view), 3.50 flashes per second overall
- Federal Signal Co. #12: TwinsSonic red right/blue left, front view, , 1.12 meters separation between lamp centers, 0.87 flashes per second (front view), 0.87 flashes per second overall
- Federal Signal Co. #12: TwinsSonic red right/blue left, rear view, , 1.12 meters separation between lamp centers, 0.87 flashes per second (rear view), 087 flashes per second overall

Berkhout's results for perception of motion were interesting and complex. Table 1 presents the judgments for those trials where the lighting system-equipped vehicle was actually stationary or parked. The first point to note is that when the lights were stationary, percentages of responses correctly indicating the lighting was not moving were all under 50%. That is, observers reported the lights were moving in more than half of the trials. The TwinBeacon (alternating side-by-side) red lighting produced the worst illusions of a stopped vehicle moving away or receding from the observer with 55% of all responses making this mistake. For vehicles parked on the shoulder of a road and displaying this light, Berkhout suggests that there would be an increased risk of rear-end collision. This provides some evidence for a red-receding illusion.

When the lighting vehicle was parked, the single dome blue and TwinSonic blue lighting systems also produced 30% and 27% erroneous responses of the 'moving away or receding' variety, respectively. On the other hand, the TwinSonic blue lighting, single dome blue, and three blue lights together creating the strongest illusion of an objectively stationary lighting system moving toward or advancing on the observer with 31% , 26%, ad 26% of responses in error respectively. The table shows almost the same percentages of "toward" and "away" judgments for many lighting configurations, which might be interpreted as confusion and chance guessing. Overall, the results do not show as strong a set of evidence for a "blue advancing" phenomenon. Both 'red receding' and 'blue advancing' phenomena are subject to substantial individual differences. Direction of motion perception is quite poor in the conditions of this study, regardless of lighting systems and direction of motion. There is some cause of concern that red lighting under certain night time conditions would be perceived as a vehicle in motion away from the observer, but this is not uniform nor are blue lights immune from such misperceptions.

Table 1. Percent Responses (N=78) For Stationary Lighting Systems (Source: Berkhout, 1979).

	Percent of Responses		
Light System	**Moving Towards**	**Still (Stopped)**	**Moving Away**
Single Dome (Red)	17	47	36
TwinSonic (Red)	16	46	38
Single Dome (Blue)	26	44	30
TwinSonic (B+R; rear)	20	44	36

TwinSonic (Blue)	31	42	27
TwinSonic(B+R; front)	24	36	40
Twin Beacon (Blue)	20	36	44
Twin Beacon (Red)	9	36	55
3 Blue Lights Together	26	40	34
3 Red Lights Together	14	43	43

Note: Still (i.e., Stopped) responses are correct. Light systems are listed in order of percent correct.

Taken together, these studies have several implications. First, red-only alternating side-by-side lighting is a poor choice for night-time warnings of an emergency vehicle stopped on the roadway or berm. Red-receding illusory motion for a parked vehicle is of particular concern for safety. Second, blue-only lighting will be more conspicuous (due to human visual sensitivity at night) than red lighting at night, though the reverse holds for daylight conditions. Third, blue lighting sometimes leads to an impression of a stopped vehicle advancing toward the stationary observer, but can also be associated with an illusion of receding. Thus, blue is also not a good cue for motion (or lack thereof.). Combining the two lights into a lighting system has some advantages. Bicolor (red and blue) lighting has been successful in reducing rear-end collisions with stationary vehicles (Pudinski, 1974). However, the perceived intensity differences of bicolor lighting have made it difficult for observers to perceive them as equidistant from the observer. Headlight glare has also washed out the blue lighting more than the red and this too led to a perception of the lights being located at different distances. In total, to help prevent rear-end collisions with stopped emergency vehicles under night conditions and to accommodate visual sensitivity under day light and night conditions, bi-color lighting is recommended. But it should not be expected that this lighting by itself will provide good cues to motion.

Some mention of the 'meaning' of different colors is in order. In American culture, red means 'danger' or 'caution' and, in the driving context, 'stop', 'stopping' or 'prepare to stop' according to a survey of motorists by the Texas Department of Transportation (Ullman and Lewis, 1998?). Smith (1991) points out that, depending on jurisdiction, blue may indicate 'emergency vehicle', while amber typically indicates 'yield or prepare to yield'. He suggests that amber lights be sequenced to generate an arrow to direct traffic in a specific direction. Wells (1999) points out that red beacons might be confused with tail lights.

The conspicuity of a lighting system will depend, at least in part, on the color contrast between the lighting and its surround or background. A setting sun with deep reds will tend to make red lighting less noticeable. Bright sunlight and strobe lights have similar color temperatures, suggesting that strobe lighting might blend with the daylight and therefore appear dim in bright daylight. Also, the color effects reported by Berkhout (1979) may not hold for lighting with less saturation or purity and might be more pronounced with lighting of greater saturation or purity.

Flash Rates. Motion is an especially effective stimulus in the visual periphery. Central vision is of a small area (1 to 2 degrees of visual angle), very high-resolution, and (normally) full color vision. Peripheral vision is of progressively lower resolution or detail , with color vision dropping from full color in central vision to sensitivity for yellow and blue out to 40 to 50 degrees from a central fixation point, and finally to black-and-white vision beyond about 60 degrees in the periphery. The rods that make up the receptors in the visual periphery are many times more sensitive to blue light than to red light, regardless of the color perception The loss of color vision and detail in peripheral vision is made up for by greater sensitivity to movement, including flashing or blinking. This suggests that for maximum impact, high-intensity flashing lights will capture attention even if the light source is off-axis from the driver's line of sight.

One concern that has been voiced about flashing lights is that they may induce nausea or epilepsy in some observers; this term is called 'photic driving' (Schiffman, 1976). The phenomenon is real enough and is used as a routine laboratory procedure to induce epilepsy in certain individuals, generally in the 6 to 40 Hz range, faster than typical emergency vehicle devices. De Lorenzo and Eilers (1991) , a pair of physicians, report that there are no data to support a seizure risk with strobe light in emergency vehicle applications.

Smith (1991) points out that there are several advantages to rotating lights as opposed to flashing lights. If the light is rotated rather than turned on and off, this achieves the attention-getting effect of flashing but also provides continuous light output in all directions. This allows other drivers from all directions to see the stopped vehicle. The continuous light output also reflects off of the ground and other objects to increase conspicuity. Solomon (1999) considers a slowly rotating beacon a common sense approach to using warning lights. Solomon generally advocates that emergency vehicles be equipped with fewer lights that flash less rapidly (no flash rate recommendation provided) and less brightly, and that convey a minimum number of messages.

ICE Ergonomics (2002) recently provided some guidance on flash rates based on both laboratory and field work. The primary method used involved ratings, so the data should be interpreted with caution. Ratings or conspicuity and actual detection performance are not necessarily the same thing. The report indicates the following. First, strobe (flash) warning beacons convey greater urgency but rotating beacons were considered less annoying a (day) and minimized effects of disability glare (at night). High flash rates of 4 Hz (240 flashes per minute) are better at conveying urgency (day or night). Low flash rates of 1 Hz (60 flashes per minute) minimize discomfort glare (day or night), disability glare (night), and perceived annoyance (day and night). With more than one beacon, beacons flashed simultaneously were detected significantly more quickly than those that flashed alternately. Multiple beacons were rated as more attention-getting than a single beacon, with 4 beacons rated higher than 1 beacon but less than 8 beacons. The report concludes with a recommendation for road trials.

In summary, the flash rates used in emergency vehicle beacons are generally not in the range of concern for inducing epilepsy. More flashes per minute generally imply higher conspicuity, but this is also associated with higher glare and annoyance. Multiple beacons increase attention-getting but at the cost of annoyance. It is unclear how ratings of conspicuity would relate to actual driver detection and response performance.

Vehicle Color and Markings and Conspicuity

It seems plausible that vehicle color can affect visual conspicuity. Allen (1970) reported insurance studies that demonstrated fewer automobile collisions with white or yellow cars. It is not known whether this is truly an effect of color or instead that color is confounded with other factors that really underlie the crash experience. For example, more aggressive drivers (e.g., younger males) may favor red or black vehicles while more cautious drivers (e.g., parents, older persons) favor white or yellow vehicles. Still, other research on driver vision has reported that cream, yellow, and white objects are most visible on the highway (Hills, 1980; Birren, 1957).

Consistent with the previously noted findings, Solomon (1990) has advocated for the use of lime-yellow color to make emergency vehicles more conspicuous. He bases his recommendations on a study he conducted comparing the number of collisions that occurred with fire departments with red vehicles as compared with fire departments with lime-yellow vehicles across nine fire departments. The results of this study showed that the lime-yellow vehicles had a collision rate less than half that of the red vehicles. More recently, Solomon and King (1999) have pointed out that peripheral or off-center vision is most often responsible for early detection and that lime-yellow is seen significantly faster (earlier) than red in a peripheral view. Solomon's recommendations have been taken up by many fire departments, though less so by police departments.

Color variations are also intended to enhance conspicuity. National Highway Traffic Safety Administration (NHTSA, 1985) specifications for ambulances dictate that the ambulance be painted white with a horizontal orange stripe and blue lettering . In urban environments, this color selection may be less conspicuous than, say, the lime-yellow color scheme.

Rubin and Hewitt (1981) recommended a harlequin pattern for emergency (police) vehicles to enhance their conspicuity. In Europe, two-color chevron patterns applied to the back of emergency vehicles are intended to reduce the incidence or rear-end collisions. A wide variety of color combinations have been used, though lime-yellow and orange appear to be a popular combination in the UK.. The main problem with any multi-color markings is that instead of enhancing conspicuity, they may in fact reduce it. Some patterns may effectively serve as camouflage by breaking up the outline of the vehicle and making it appear less like a vehicle. Recently, Langham and Rillie (2002) have recommended uniform color rather than a parti-color or harlequin pattern that might disrupt the percept of the vehicle as a whole. Research is needed to determine the effectiveness of chevrons, harlequin patterns, and other treatments.

On the other hand, retro reflective markings that demarcate the outline of the vehicle should, in principle, enhance conspicuity (Langham and Rillie, 2002, Green, 1977, Solomon, 1999). Retro reflective markings have been quite effective in enhancing truck conspicuity and reducing the incidence of collisions with trucks at intersections and elsewhere. Edge markings or demarcation appear to be the most appropriate or important effect to be achieved.

Recommendations on vehicle color and markings might be summarized as follows. Based on the available research, white, crème, yellow, or lime – yellow vehicles might be more conspicuous than other colors in vehicles (red, orange, blue, black). Rear-end chevron patterns may serve as useful conspicuity enhancements for emergency vehicles but the actual safety benefits are unknown. Similarly, checkerboard or harlequin markings on emergency vehicle bodies are also intended to enhance conspicuity but may in fact break up the percept of the vehicle and make it less identifiable. Unfortunately, no definitive studies have been found that compare crash rates for these markings and other vehicle options, controlling for exposure factors and or nuisance variables. Careful research is needed to determine whether putative benefits are truly due to the color and markings rather than to other factors. Furthermore, research is needed to determine if markings intended to enhance conspicuity do not, ironically, serve to camouflage the vehicle instead. The backgrounds against which emergency vehicles operate is also a critical concern. A crème color vehicle may be quite conspicuous against dark pavement, yet blend into a desert background.

Luminaire Types: Code 3 (2002) indicates that there is no basis to prefer one type of lighting over another. Smith (1991), on the other hand, points out that strobe lighting can be less effectively bright than halogen lamps, that halogen color temperature is more compatible with colored lenses, and that strobe lighting's color temperature can blend in with daylight, reducing conspicuity. Beyond this, strobe lighting can create a stop-action effect that creates ambiguity regarding a vehicle's motion or lack of motion, among other illusions . LEDs offer great versatility, long life, high light output, and low maintenance, but they tend to be highly directional. This latter feature should be of no concern for vehicles approaching a stopped emergency vehicle from a distant, straight approach or for rotating beacons. On the other hand, LEDs may be less conspicuous when viewed at an angle.

Highway Flares and Conspicuity

Solomon (1999, pp. 75-79) points out that highway flares, while not part of an emergency vehicle, are often used along side it with the intention of enhancing conspicuity. However, flares may ignite flammable materials nearby, may generate so much smoke that the flare obscures rather than renders more conspicuous, and provide a flickering light source on the road that distracts the approaching driver from the emergency vehicle itself. Together these factors may actually contribute to emergency vehicle camoflouge rather than to conspicuity. He acknowledges a lack of scientific data on such factors and cautions against inaccurate assumptions behind flare use (and other conspicuity enhancements).

Retroreflective or High Visibility Vests

A pedestrian by the side of the road is generally noteworthy. It is also unlikely that a moving vehicle would be adjacent to a standing pedestrian, thus making the stationary state of the vehicle more cognitively noticeable. On the face of it, then, treatments that increase the conspicuity of a police officer or other pedestrian on the side of the road beside a stopped emergency vehicle ought to be of general benefit. High visibility clothing in the UK, for instance, is not simply retroreflective. It aims to give a high level of conspicuity in normal day light and limited light/bad weather as well as having highly reflective elements which work when wet (a lot of reflective clothing doesn't apparently!). Its specification is covered by a European Standard (EN471) which includes differing specification classes.

From the operational standpoint, the circumstances are not so straightforward. Wells (2002, personal communication) points out that officers often do use reflective and hi-visibility vests now, but only on longer incidents such as crashes or traffic direction. In Florida, state police are currently moving to a vest that meets the new ANSI standard, but it may not be possible to meet level 3 (highest level of visibility) because it would require pants as well as a vest/coat. One difficulty is that officers can't cover the uniform belt and hinder access to equipment. Also, some departments will advise not to use at night at least for traffic stops to reduce the risk of being seen and possibly shot at least upon first approach. This compromise between conspicuity and others types of threats must be discussed and assessed in the costs and benefits of each of alternative.

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