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Toward performance specifications for flashing warning beacons

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ABSTRACT

Yellow flashing warning beacons help protect front line service workers, including those in transportation, utility and construction sectors. To safeguard these workers, beacons should be readily detected and should provide veridical information about their relative movement. Two psychophysical laboratory experiments were conducted to provide empirical foundations for two aspects of warning beacon performance, detection and judgments of relative movement. In the first experiment reaction times were measured to the onset of flashing warning beacons varying in peak intensity while observers viewed different scene conditions. Observers also judged the visibility of nearby low-contrast targets in the presence of the flashing warning beacons. Asymptotic response times to the onset of beacons occurred when their peak intensity was at least 750 cd during daytime. Visibility of low contrast targets during nighttime, when glare is most critical, did not decrease substantially when the peak intensity was below 2000 cd. In the second experiment response times were measured to warning beacons of different flash-sequence patterns as they approached the observer. Judgments of gap closure were improved, relative to fully-on/fully-off flashing, with flash sequences where the minimum beacon intensity was at least 10% of the peak intensity and with two synchronized flashing beacons rather than one. With regard to performance specifications, the minimum value for the peak intensity of warning beacons should be 750 cd, with a maximum value of 2000 cd for detection. Fully-on/fully-off flash sequences should be changed to fully-on/partial-off to enhance judgments of gap closure on moving vehicles. Moreover, two flashing warning beacons, rather than one, should be mounted on service vehicles to improve gap closure judgments.

1. Introduction

More than 18 million U.S. workers are in the construction, transportation, warehousing and utilities sectors, comprising about 13% of the U.S. work force. These front line service workers rely on yellow flashing warning beacons mounted on their vehicles for protection against inadvertent collisions with driver-operated moving vehicles. Despite the widespread use of flashing yellow warning beacons, service workers are involved in a disproportionately large percentage, 36%, of workplace fatalities (NIOSH, 2014). Cook, Quigley, and Clift (2000) estimated for the United Kingdom that approximately 61,000 service vehicles with flashing warning beacons were involved in crashes, resulting in 65 fatalities and 5000 injuries per year. Adjusting for the U.S. population (U.S. Census, 2009), some 316,000 vehicles equipped with warning beacons would be expected to

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be involved in crashes with about 340 fatalities and 26,000 injuries annually. Cook et al. (2000) argued that the poor design and performance of warning beacons contribute to 20% of these casualties. Recent efforts in the U.S. to reduce service worker fatalities include enactments of "move over" laws in some states (National Safety Commission, 2015) for vehicles with yellow flashing warning beacons. None of these efforts, however, have addressed the design and performance of the warning beacons themselves.

This paper represents a systematic research effort to improve the design and performance of flashing yellow warning beacons so that (a) they can be reliably detected by approaching drivers in urban and rural contexts during both day and night and (b) they support a driver's judgment of gap closure (reductions in the distance between a driver's vehicle and a preceding vehicle) so that collisions can be more reliably avoided. Performance specifications are offered for flashing yellow warning beacons based upon the research.

2. Background

Warning beacon performance is specified in several standards published by the Society of Automotive Engineers (SAE). For example, Standard J595, "Flashing Warning Lamps for Authorized Emergency, Maintenance and Service Vehicles" (SAE, 1990) stipulates a flash frequency of 1–2 flashes per second (Hz) and a peak luminous intensity (when the beacon is on) of at least 600 cd for yellow warning beacons. Standard J845, "Optical Warning Devices for Authorized Emergency, Maintenance and Service Vehicles" (SAE, 1997) permits the flash frequency to be between 1 and 4 Hz, and specifies intensity by minimum flash energy values (in candela seconds), with yellow beacons needing lower values (10 cd s) for identification only and higher values (90 cd s) for emergency situations. Emergency situations are not defined by this standard. Standard J1318, "Gaseous Discharge Warning Lamp for Authorized Emergency, Maintenance and Service Vehicles" (SAE, 1998) requires the same flash frequencies and similar minimum flash energy values as in the J845 standard. The underlying technical bases for these specifications are not provided in the standards, but the peak luminous intensity of 600 cd specified by SAE J595 (SAE, 1990) is consistent with data from Howard and Finch (1960) and with the conclusions of Hargroves (1971) and Bullough et al. (2000) regarding the intensity requirements for detecting the onset of yellow warning lights under daytime viewing conditions.

Warning beacons should be bright enough to be seen both during daytime and nighttime, but not so bright that they contribute to glare to drivers approaching them. An upper limit for luminous intensity, and thus illuminance at the cornea, is especially important at night where they might cause disability glare to approaching drivers. Disability glare is primarily affected by the illuminance at the cornea from a glare source and the angular distance between the glare source and the line of sight (Fry, 1954), both of which are fully specified by the luminous intensity distribution of the light source. The SAE standards cited above (1990, 1997, 1998) do not have, however, separate requirements for daytime or nighttime conditions. The required photometric values are presumably offered as minima for daytime conditions when dim lights would be especially difficult to detect.

Flannagan, Blower, and Devonshire (2008) reported that response times to the onset of yellow flashing warning lights decreased as their peak luminous intensity increased from about 1000 to 2000 cd. This could suggest that peak intensities higher than 600 cd might be necessary for initial detection in certain viewing conditions, but Howard and Finch (1960) reported that the principal viewing angles for flashing warning lights were no more than 5° off axis. Similarly, Mourant and Rockwell (1970) found driver gaze locations to rarely be more than 5° from the roadway ahead, and Brooks, Tyrrell, and Frank (2005) reported that drivers' lane-keeping performance and ability to detect pedestrians was not substantially impaired unless the field of view was reduced to less than 5°. In comparison, the viewing fixation located used by Flannagan et al. (2008) was 45° off axis from the line of sight. This suggests that 1000–2000 cd may be unnecessarily high because warning beacons relevant to the driver (i.e., on or near the roadway) would be likely to be within 5° of the driver's line of sight.

The SAE standard, J1690, "Flashers" (SAE, 1996) specifies the performance of control mechanisms used to modulate the warning beacon intensity. These specifications are made in terms of current on-time, during which the circuit including the warning light is closed, current flows through the light source, and the light appears on. Outside of the current on-time, the circuit is open and the warning light emits no intensity. Current on-off flashing is the *de facto* default flash mode for warning beacons, but, again, the foundation for these recommendations is not available. In fact, warning beacons that go fully on and fully off may not be best for judging relative speed. Croft (1971) noted that visual tracking associated with catching a small object was difficult under stroboscopic (full-on and full-off) illumination. More relevant to judging relative speed while driving, Bullough, Rea, Pysar, Nakhla, and Amsler (2001) found the time to detect reductions in speed of a lead vehicle while driving were significantly longer and less accurate for snow plow warning lights that flashed full-on and full-off, than for ones that did not go full-off. This is consistent with evidence from Barnes and Asselman (1992) who found that visual tracking eye movements under non-steady illumination were jerkier, often exhibiting reduced accuracy than under steady light conditions. The spatial extent of visual information can also influence judgments of gap closure, particularly at night. Hoffmann and Mortimer (1996) found that an angular velocity of 0.003 rad/s (0.17 degrees/s) was needed before observers could reliably judge that they were approaching an object like a preceding vehicle. This threshold would be obtained sooner when the object has a larger size, suggesting that an array of two (or more) warning beacons would be superior to a single beacon for gap closure judgments. This inference is supported by a recent study of (non-flashing) motorcycle headlight con-