LUMINOUS INTENSITY REQUIREMENTS FOR SERVICE VEHICLE WARNING BEACONS (TRB Paper 15-1117)

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Word count: 3150 words + 8 figures = 5150 words

ABSTRACT

Flashing yellow warning beacons are used on a wide variety of service vehicles including highway construction vehicles, dump trucks, delivery vehicles, snow plows, and tow trucks. These lights serve as an important line of defense for several million U.S. workers in the transportation, construction and utilities sectors, who are over-represented in terms of workplace fatalities. In order to understand visual responses to warning beacons varying in their luminous intensity characteristics, flashing yellow warning beacons were presented under laboratory conditions simulating daytime and nighttime roadway scenes. Response times to the onset of flashing and subjective ratings of beacon visibility and of the visibility of low-contrast objects in the scenes were measured. The results provide a preliminary basis for the development of quantitative specifications of warning beacon luminous intensity characteristics that ensure high levels of visibility under both daytime and nighttime conditions, while minimizing glare, especially at night.

INTRODUCTION

Many workers in the U.S. utilize yellow flashing warning beacons for safety. More than 18 million U.S. workers are in the construction, transportation, warehousing and utilities sectors (NIOSH, 2014), comprising about 13% of the U.S. work force. In contrast, these workers are involved in 36% of workplace fatalities. Efforts to reduce these fatalities include rigorous lighting and traffic control practices (MUTCD, 2009) for locations such as roadway work zones, and enactment of "move over" laws (National Safety Commission, 2012) requiring drivers to change lanes or slow down when approaching emergency vehicles and in some states, service and maintenance vehicles with yellow flashing warning beacons. Cook et al. (2000) estimated for the United Kingdom that among the estimated 61,000 service vehicles with warning beacons, crashes involving them result in 65 fatalities and 5000 injuries each year. Adjusting for the U.S. population (U.S. Census, 2009) there would be an estimated 316,000 warning beacons in the U.S. and about 340 fatalities and 26,000 injuries annually involving vehicles with beacons. Cook et al. (2000) estimated that the design and performance of warning beacons contribute to 20% of these casualties.

Warning beacon performance is specified in several standards published by the Society of Automotive Engineers (SAE). 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 beacons. Standard J845, "Optical Warning Devices for Authorized Emergency, Maintenance and Service Vehicles" (SAE, 1997) includes the same flash frequency but 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. Standard J1318, "Gaseous Discharge Warning Lamp for Authorized Emergency, Maintenance and Service Vehicles" (SAE, 1998) permits flash frequencies between 1 and 4 Hz, with 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 600 cd value (SAE, 199) is consistent with data from Howard and Finch (1960).

With regard to luminous intensity characteristics, warning beacons should be bright enough to be seen both during daytime and nighttime viewing conditions, but not so bright that they contribute to glare to drivers approaching them, especially at night. The SAE (1990, 1997, 1998) standards described above do not have separate requirements for daytime or nighttime conditions and the photometric values they stipulate are presumably minima for daytime conditions, which would be the most challenging for visual detection. Gibbons et al. (2008) recommended higher intensities for yellow warning lights on service vehicles, but those recommendations were made in terms of the sum of intensities for all lights facing a particular direction, whereas SAE requirements are for a single warning beacon. Since a single beacon represents a worst-case scenario for detection (one or more beacons could be blocked by obstructions) the focus of the present paper is on intensity requirements for individual warning beacons, balancing the need to detect them with their potential negative impacts through glare.

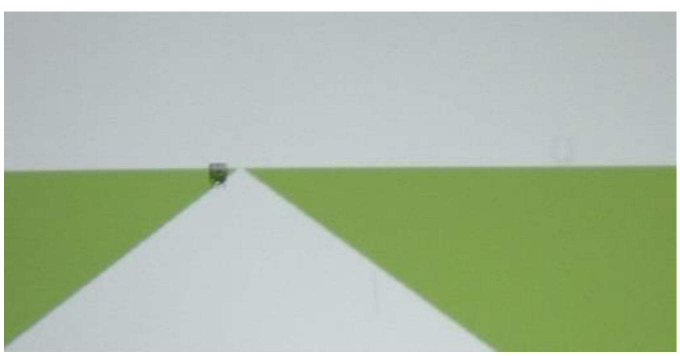


FIGURE 1 Portion of a projected scene showing the LED to the left of the roadway simulating a service vehicle.

EXPERIMENTAL METHOD

A series of three laboratory human factors experiments was conducted to investigate the influence of warning beacon intensity, ambient light level, visual clutter, and location in the field of view on the ability of individuals to detect the onset of a flashing warning beacon, and on the visibility of other objects in the field of view. In all three experiments, a yellow LED (peak wavelength 590 nm, half-bandwidth 18 nm) meeting SAE yellow color specifications (SAE, 1995) was mounted to a white-painted plywood screen located 3 m in front of the subjects' seating position. When the LED was flashed (at a frequency of 1 Hz), the LED had the appearance of a truck with a yellow warning beacon. Simulated roadway scenes subtending 20^{o} horizontally were projected onto the screen, positioned to make the LED look like a truck parked along the side of the road (Figure 1). The LED was controlled by a custom software application that switched it on and off and adjusted its intensity by supplying current through a calibrated power supply. Also included within the projected roadway scenes were low-contrast Landolt ring targets (contrast 0.1) located so that when it was fixated by the subjects, the warning beacon was either immediately adjacent to (on-axis), or 5^{o} to the left (off-axis) of the beacon.

For the daytime scenes, the background roadway luminance was 300 cd/m², corresponding to the luminance of pavement (reflectance 0.1) under 10,000 lux of illumination from daylight. For the nighttime scenes the background luminance was 1 cd/m², representative of the roadway luminance under headlight illumination (Olson et al., 1999). For the conditions including visual clutter, simulated flashing white and yellow lights and signs were randomly located throughout the projected scenes; these flashed with random frequencies between 0.9 and 1.1 Hz. Figure 2 shows examples of the types of background scenes used in each experiment. Simple, abstract scenes were used in the first two experiments, and more realistic scenes based on photographs were used in the third experiment.

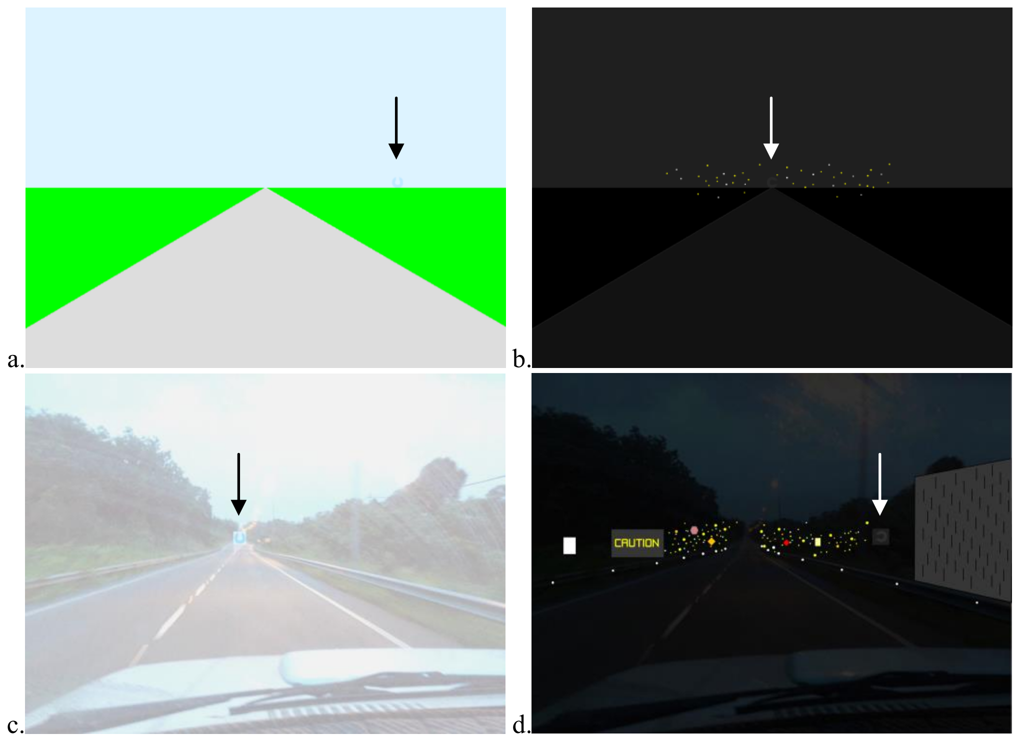


FIGURE 2 Example background scenes used in the experiments. Arrows indicate the locations of low-contrast Landolt ring targets, either on- or off-axis from the warning beacon location. a: Simple daytime scene without visual clutter. b: Simple nighttime scene with clutter. c: Realistic scene without visual clutter. d: Realistic scene with visual clutter.

In each experiment, participants were asked to view the low-contrast Landolt ring target in the scene and respond to the onset of the flashing warning beacon, which appeared at random intervals during each trial, as soon as it was detected by pressing a button on a keypad. In addition, participants were also asked to rate the visibility of the low-contrast target (while the beacon was flashing) on a scale of 1 to 10, where a rating of 10 corresponded to its visibility without the beacon flashing.

EXPERIMENT 1: SIMPLE SCENES WITHOUT VISUAL CLUTTER

In the first experiment, simple projected scenes were used as shown in Figure 2a. The warning beacon, when presented, was flashed at 1 Hz with a 50% duty cycle, having a maximum intensity scaled to mimic a luminous intensity of 80, 180 or 530 cd for a simulated viewing distance of 100 m. The order of daytime and nighttime scenes and trials with on-axis or off-axis beacon locations was randomized for each subject to counter potential learning or practice effects, and subjects adapted to the background luminance for 5 minutes before starting each block of trials. Six participants (two females) aged 31 to 67 years (mean 49, s.d. 16) participated in this experiment.

Results: Experiment 1
The reaction time data from Experiment 1 are shown in Figure 3. A within-subjects analysis of variance (ANOVA) revealed statistically significant ($p<0.05$) main effects of the maximum intensity and the beacon location (on- or off-axis). There were also statistically significant ($p<0.05$) two-way interactions between the ambient light level and the maximum intensity, and between the ambient light level and the beacon location. As seen in Figure 3, response times for on-axis beacons were asymptotic across the range of maximum intensities for both daytime and nighttime conditions, but for beacons viewed off-axis, the reaction times in daytime conditions were highly dependent upon the maximum intensity and continued to improve as the intensity increased; only when the maximum intensity was 530 cd were the daytime off-axis reaction times similar to those for daytime on-axis conditions.

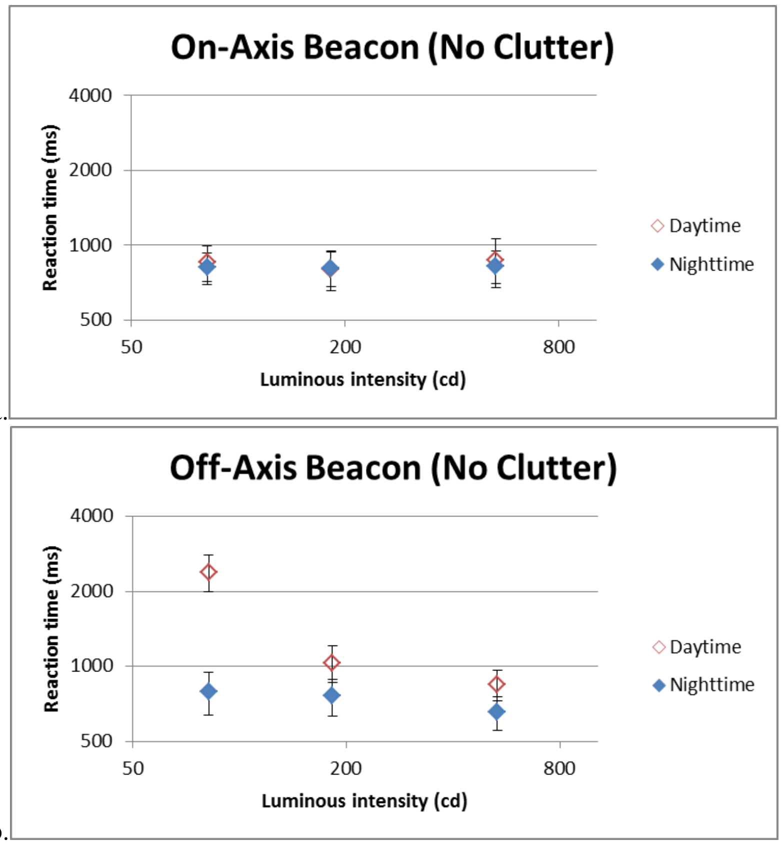


FIGURE 3 Reaction times (±s.e.m.) to the onset of the warning beacons in Experiment 1, as a function of the maximum beacon intensity. a: On-axis beacon location; b: off-axis beacon location.

Figure 4 shows the mean ratings of target visibility from Experiment 1, also collapsed across the different minimum intensity values. A within-subjects ANOVA revealed statistically significant two-way interactions between the maximum beacon intensity and both the ambient light level and the beacon location. As seen in Figure 4, rating values were close to 10 for all conditions, but there is a slight separation between the daytime and nighttime ratings for the on-axis beacon at the highest maximum intensity, suggesting that the maximum intensity of 530 cd elicited a slight reduction in target visibility at night when presented near the line of sight. For all other conditions, glare from the warning beacons had little, if any, impact on subjective judgments of target visibility.

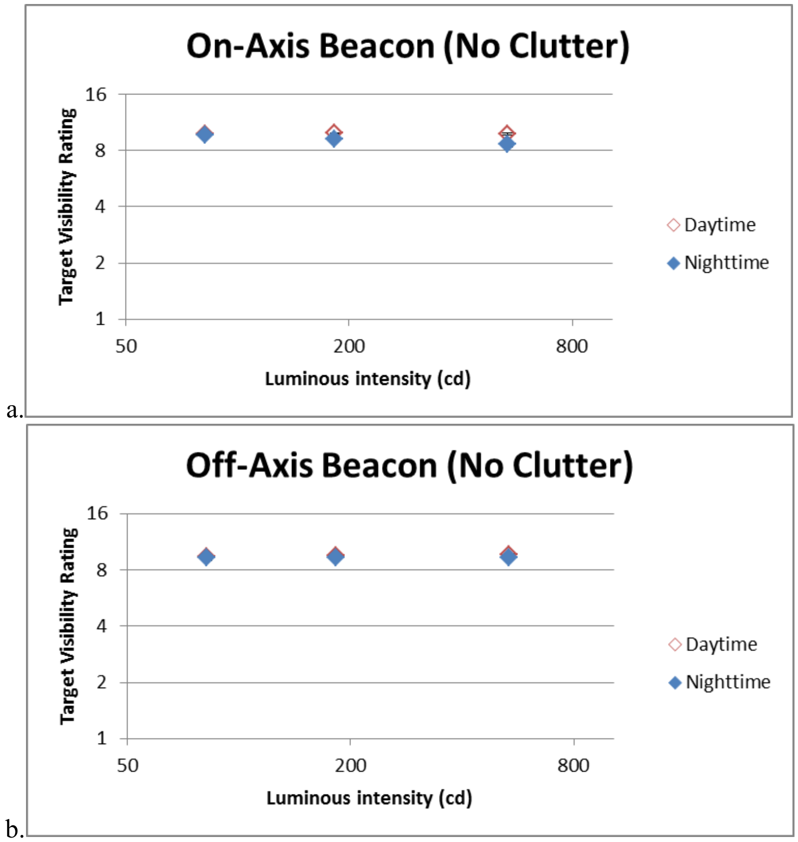


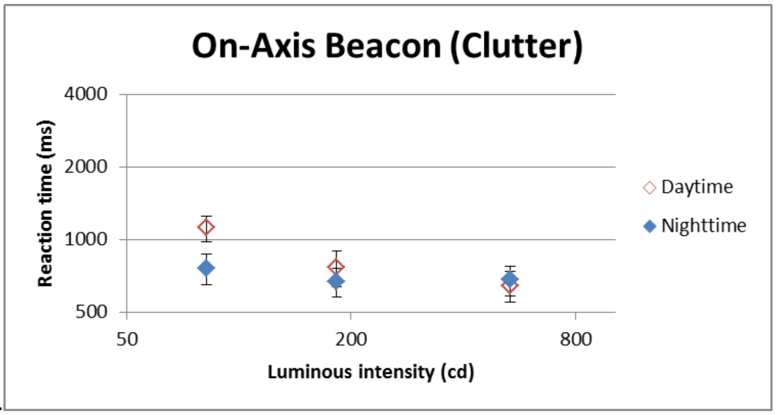
FIGURE 4 Target visibility ratings (±s.e.m.) for the warning beacons in Experiment 1, as a function of the maximum beacon intensity. a: On-axis beacon location; b: off-axis beacon location.

EXPERIMENT 2: SIMPLE SCENES WITH VISUAL CLUTTER

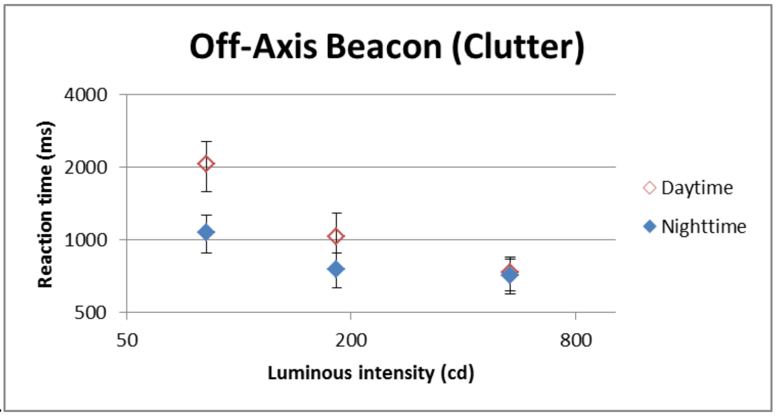
Five subjects (two females) aged 31 to 65 years (mean 49, s.d. 13) participated in Experiment 2. The same conditions as in Experiment 1 were used, except only one minimum beacon intensity was used (0%) so that the beacon always appeared to flash on and off at 1 Hz with a 50% duty cycle, and a moderate amount of visual clutter was present in the simple roadway scenes such as that illustrated in Figure 2b. Randomization of condition order and adaptation to the background luminance occurred as in Experiment 1.

The reaction time data from Experiment 2 are shown in Figure 5. Because different subjects participated in each experiment, direct comparisons between data from different experiments cannot be made. For the data from Experiment 2, a within-subjects ANOVA revealed a statistically significant ($p<0.05$) main effect of the maximum beacon intensity, and a statistically significant ($p<0.05$) interaction between the beacon intensity and the ambient light level. Unlike the data from Experiment 1 (without visual clutter) in Figure 2, the lower maximum intensities (80 and 180 cd) resulted in longer reaction times that the highest intensity (530 cd), but this latter intensity seemed to result in asymptotically short reaction times for all conditions tested.

The mean target visibility ratings for each condition in Experiment 2 are shown in Figure 6. A within-subjects ANOVA revealed statistically significant two-way interactions between the maximum beacon intensity and both the ambient light level and the beacon location. As in Experiment 1, the impacts of warning beacon intensity were relatively small, but were manifested by small rating differences between daytime and nighttime viewing conditions at the highest maximum beacon intensity (530 cd). Of interest, this difference seemed to occur for both on- and off-axis presentation of the warning beacon, possibly suggesting that glare can be exacerbated by the presence of visual clutter, since in Experiment 1 (without visual clutter), the off-axis beacon did not appear to impact target visibility under the nighttime viewing conditions.



a.



b.

FIGURE 5 Reaction times (±s.e.m.) to the onset of the warning beacons in Experiment 2, as a function of the maximum beacon intensity. a: On-axis beacon location; b: off-axis beacon location.

EXPERIMENT 3: REALISTIC SCENES WITH AND WITHOUT VISUAL CLUTTER

In the third experiment, more realistic scenes were used, and visual clutter was higher in density as illustrated in Figures 2c and 2d. In addition, the number and range of maximum beacon intensities was extended to 80, 190, 850 and 3100 cd, with the same frequency (1 Hz), duty cycle (50%) and minimum intensity (0%) as in the previous experiment. Six subjects (one female) aged 31 to 67 years (mean 50, s.d. 14) participated in Experiment 3. The order of conditions presented to subjects was randomized as in prior experiments.

The reaction time data from this experiment are shown in Figure 7. A within-subjects ANOVA revealed statistically significant ($p<0.05$) main effects of the maximum beacon intensity, the background light level, the position of the beacon, and the presence of visual clutter. Statistically significant ($p<0.05$) two-way interactions were also found between the maximum beacon intensity and each of the ambient light level, beacon location and presence of visual clutter; and between the beacon location and both ambient light level and presence of clutter. On-axis reaction times were largely asymptotic within the range of intensities used, but not off-axis reaction times. At the lowest maximum intensity for off-axis viewing (80 cd), both the ambient light level and the presence of visual clutter impacted reaction times.

a.

b.

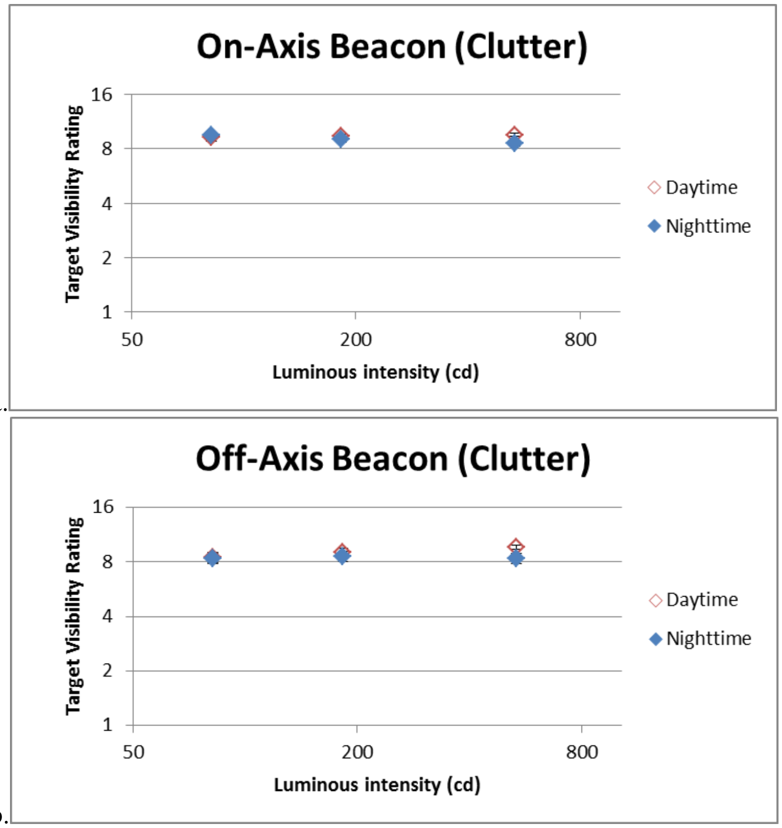


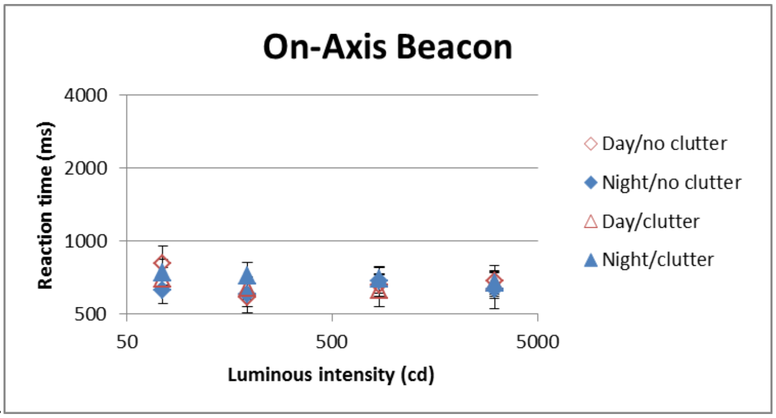
FIGURE 6 Target visibility ratings (±s.e.m.) for the warning beacons in Experiment 2, as a function of the maximum beacon intensity. a: On-axis beacon location; b: off-axis beacon location.

For the target visibility ratings shown in Figure 8, a within-subjects ANOVA revealed statistically significant ($p<0.05$) main effects of the maximum beacon intensity and of the ambient light level. The ANOVA also identified statistically significant ($p<0.05$) two-way interactions between the maximum intensity and both the ambient light level and the beacon location. Inspection of Figure 8 suggests that for the highest maximum beacon intensities (850 and 3100 cd), the on-axis beacon produced modest but persistent reductions in rated target visibility for the nighttime conditions relative to daytime; the same type of difference, with a smaller magnitude, was only found for the highest maximum intensity when the beacon was located off-axis.

DISCUSSION AND CONCLUSIONS

The results from the series of experiments summarized in this paper are consistent with the notion that it is possible to develop photometric performance specifications for flashing warning beacons that strike a balance between sufficient intensity to ensure rapid detection, while ensuring that warning beacons will not negatively impact the visibility of drivers as they approach vehicles equipped with them at night. The data from the experiments also indicate that higher maximum luminous intensities are needed during the daytime to achieve asymptotic reaction times than are needed under nighttime conditions. While the absolute values of the asymptotic reaction times differ among the experiments, this is caused by differences among the subject populations in each study and not by the differences in lighting conditions.

The results also show the clear differences between performance-based responses like reaction times and subjective visibility responses (Rea, 1989). Reaction times to luminous stimuli tend to follow non-linear functions of intensity whereby large reaction time differences are found with small changes in intensity for the lowest intensities, and negligible differences are found at higher intensities (Rea and Ouellette, 1991; Bullough et al., 2000). Subjective ratings tend to be related linearly to changes in apparent contrast, such as those created by the veiling luminance from warning beacons under nighttime viewing conditions.

a.


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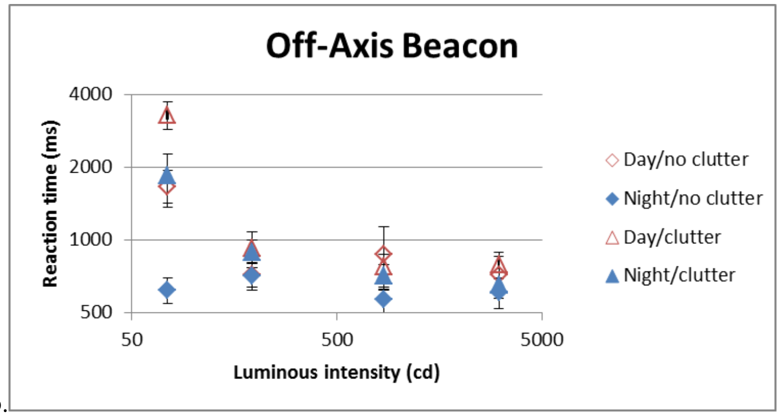


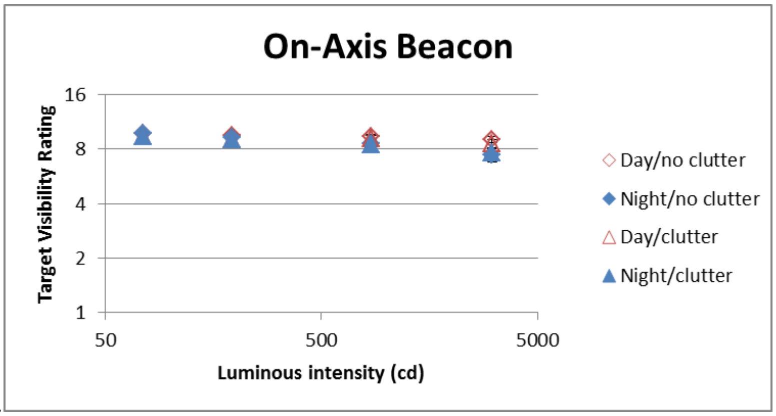
FIGURE 7 Reaction times (±s.e.m.) to the onset of the warning beacons in Experiment 3, as a function of the maximum beacon intensity. a: On-axis beacon location; b: off-axis beacon location.

With regard to performance specifications for warning beacons, the present experimental data suggest that a maximum beacon intensity of 180 cd would produce the shortest reaction times at night, but higher intensities (530 cd or higher) could be problematic because of the potential for glare at night because the nighttime target visibility ratings began to decrease relative to daytime conditions when the warning beacon produced these higher intensities. During daytime conditions, a maximum intensity of at least 530 cd produced asymptotic reaction times without glare (at least up to a maximum intensity of 3100 cd). This is consistent with the SAE (1990) standard requiring at least 600 cd as the maximum intensity for warning beacons and with data published by Howard and Finch (1960), at least for daytime conditions. Allowances for intensity reductions under nighttime viewing conditions not presently in the SAE standard could help prevent glare.

Caveats and Next Steps

The focus of the present research is on the luminous intensity requirements for flashing lights under different daytime and nighttime viewing conditions. Undoubtedly the ambient light levels used in these laboratory studies do not represent the entire range of light levels that could be experienced outdoors; indeed, outdoor field trials are anticipated to validate and, if necessary, extend the preliminary conclusions described above.

Areas for future research will include the number of warning beacons deployed on a single vehicle. Configurations that subtend a greater visual angle than that of a single warning beacon might assist in identifying if and when a preceding service vehicle's speed differs from that of an observer's vehicle. In addition, subsequent research will investigate different flashing patterns in addition to those used in the present study. Patterns that maintain some visible luminous intensity may also assist in identifying differences in speed (Bullough et al., 2001).



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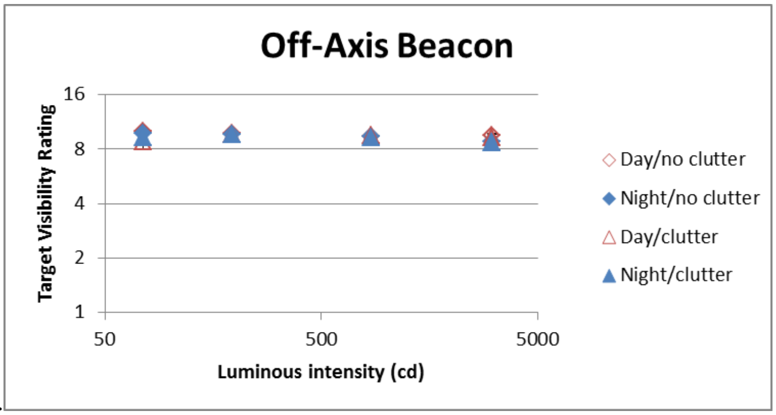

b.

FIGURE 8 Target visibility ratings (±s.e.m.) for the warning beacons in Experiment 3, as a function of the maximum beacon intensity. a: On-axis beacon location; b: off-axis beacon location.

ACKNOWLEDGMENTS
The studies described in this paper were sponsored by the National Institute of Occupational Safety and Health (Grant 1R01OH010165-01A1 to M. S. Rea). Nicholas Skinner developed the experimental apparatus and assisted with running the experiments. Helpful input was also provided by Philip Garvey, Eric Donnell and Martin Pietrucha from the Pennsylvania State University Larson Transportation Institute.

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