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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.

### Keywords

lighting; reaction time; gap closure; closure detection; disability glare

## 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

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use of flashing yellow warning beacons, service workers are involved in a disproportionately large percentage, 36%, of workplace fatalities (NIOSH, 2014). Cook et al. (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 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 et al. (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 et al. (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 to 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 et al. (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 configurations (Cavallo et al., 2015) in which the motion of headlight arrays subtending larger visual angles was judged more accurately than a single motorcycle headlight.

Two laboratory experiments were conducted to assess the luminous intensities needed by flashing yellow warning lights to provide reliable detection under a wide range of visual conditions without creating excessive disability glare. In the first experiment the peak luminous intensity characteristics of beacons were studied under simulated daytime and nighttime conditions in both “cluttered” and “uncluttered” contexts, respectively simulating urban and rural environments. The second experiment was conducted to validate and to extend the results from Bullough et al. (2001), identifying gap closure, or the change in relative speed of warning beacons approaching an observer, when the beacons are operated (a) full-on/full-off, (b) steady-on, or (c) full-on/10%-on.

## 3. METHOD

### 3.1. Visibility Experiment

The visibility experiment used a similar method as a previous pilot study (Bullough and Rea, 2015) that used a much smaller subject sample size. Twenty-six subjects, divided evenly by sex, and divided into two age groups (15 younger: <30 years, 11 older: >50 years), responded to the onset of warning beacons placed in simulated roadway scenes (see Figure 1). Both daytime (measured background luminance of the screen display of 300 cd/m²) and nighttime (measured background luminance 1 cd/m²) conditions were used in combination with visual clutter (simulating an urban scene with the presence of 120 randomly located lights along the left and right edges of the roadway, mostly within a horizontal angle of 10° and flashing at rates between 0.9 and 1.1 Hz) and without visual clutter (simulating a rural scene, without the randomly flashing lights). The higher background luminance corresponds to that of a roadway surface for the maximum daylight achieved on a cloudy day (Reinhart and Herkel, 2000) and the lower luminance corresponds to that of the roadway produced by vehicle headlights at night (Olson et al., 1990). The simulated roadway scenes (subtending 20° horizontally) were projected with a digital projector (Compaq, iPAQ MP3800) onto a white wall surface located 3 m ahead of the subjects’ seating position. Subjects fixated on a Landolt C ring target (oriented with the gap up in the daytime scene and with the gap to the left in the nighttime scene) incorporated into the projected scene and located adjacent to the roadway (Figure 1) or 5° to the right of the roadway edge (not shown). The Landolt ring was of low-contrast (C=0.2) where the contrast is defined as follows:

$$C = \left| L_t - L_b \right| / L_b \quad \text{(Equation 1)}$$

In Equation 1, $L_t$ is the luminance of the ring target and $L_b$ is the luminance of the immediate background.

The flashing warning beacon was created using a yellow light emitting diode (LED) source meeting SAE (1995) yellow color specifications (chromaticity: x=0.604, y=0.395; peak wavelength 590 nm; half-bandwidth 18 nm) and subtending a visual angle of 1 minute of arc, small enough to be perceived as a point source (Bullough and Skinner, 2013). The peak luminous intensity was varied randomly across trials, simulating values of 80, 190, 850 or 3100 cd as viewed from a 100 m viewing distance by producing the same illuminances at subjects’ eyes that full-scale lights with these intensities would produce from 100 m away. A viewing distance of 100 m corresponds to the decision sight distance for a driving speed of 96 km/h (60 mph), approximating the distance at which a driver would need to detect the warning beacon in order to recognize it as a potential hazard and engage in a defensive driving maneuver (Dewar, 2007). When energized, the LED was operated at a 1 Hz flash frequency and at a 50% duty cycle. In a previous study (Bullough and Rea, 2014), response times to the onset of the simulated warning beacon were not influenced by the amount of temporal modulation contrast (e.g., whether the beacon was steady-burning or exhibited full-on/full-off flashing), and depended only on the peak intensity, so a full-on/full-off flashing pattern was used in this experiment. Subjects were instructed to fixate on the low-contrast target and to push a button as soon as they detected the onset of a warning beacon located adjacent to the roadway edge. The warning beacon onset time was varied randomly during each trial to prevent anticipation. If 6 s had elapsed without a response, the trial was considered a “miss.” Trials with reaction times shorter than 200 ms, which is the minimum visual response time for high-contrast targets (He et al., 1997), were considered “false positives.”

After detecting the beacon onset subjects then were instructed to rate the visibility of the warning beacon relative to a reference warning beacon that was operated with a peak luminous intensity of 850 cd. The reference condition was presented to subjects before the session began and defined by the experimenter as having a visibility rating of 10. Subjects were also asked to rate the visibility of the low-contrast Landolt ring that served as the fixation target during each trial relative to its visibility when no warning beacon was present. The Landolt ring was defined by the experimenter as having a rating of 10 for the reference condition. Both rating scales were open-ended, so subjects were free to assign subjective magnitudes higher or lower than 10 to the reference stimulus (i.e., a value of 5 implied a stimulus half as visible as the reference; a value of 20 implied a stimulus twice as visible).

Every subject completed 96 trials that had been divided into 8 randomly ordered blocks of 12 trials each. Every block of trials included 3 repetition trials for each of the four peak luminous intensities. Each block was defined in terms of one of the two ambient lighting conditions (day or night), one of the two visual clutter conditions (urban or rural), and one of the two warning beacon locations relative to the fixation target (adjacent to the road or $5^{o}$ off axis).

### 3.2. Closure Detection Experiment

The same subjects who participated in the visibility experiment also participated in the closure detection experiment, in which they were asked to identify the relative speed of either 1 or 2 synchronized yellow warning beacon lights. Three types of warning beacons were simulated in a video animation program, (a) on continuously (100% steady-burning) (b) full-on/full-off or (c) full-on/10%-on; the flashing lights were both modulated at 1 Hz with a 50% duty cycle (Figure 2). The measured background luminance for the animations was always 1 cd/m² and the maximum measured luminance of the beacons in the animation was 300 cd/m². After a random delay, the animation simulated the warning beacon(s) moving toward an observer at a constant speed of 10 mph from a starting distance of 100 m. (This presentation would also simulate conditions where two vehicles, a lead vehicle and a following vehicle containing the observer, traveling at the same speed began to travel at different rates whereby the lead vehicle were traveling 10 mph slower than the following vehicle.) During a given trial, subjects were instructed to either look directly at the animated warning lights (on-axis), or to fixate on an array of 3 LEDs (one red, one yellow and one green) located 5° to the left of the center of the animation display (off-axis). For the latter conditions, only one LED color was shown at a time but was randomly changed every few seconds when subjects were asked to name the new color verbally. This task was included to ensure that the fixation of the subjects in the off-axis trials was 5° from the initial location of the flashing lights. Subjects were instructed to press a button as soon as they were able to identify that the simulated warning beacon(s) had moved toward them.

Every subject completed a total of 24 trials that had been divided into 2 counterbalanced blocks of 12 trials. Each block was defined by the viewing location (either on axis or 5° off axis). Within each block, every combination of the number of warning lights (1 or 2) and temporal profile (full-on/full-off, full-on/10% on, and on continuously) was presented twice, in randomized order.

# 4. RESULTS

## 4.1. Visibility Experiment

**4.1.1. Reaction times to warning beacon onset—**Figure 3 shows the mean reaction times (RTs) to the onset of the warning beacon, as a function of the peak luminous intensity, under simulated daytime and nighttime conditions and located adjacent to (on-axis) or 5° from (off-axis) the subjects' line of sight.

0.8% of the trials were scored as misses and 0.4% as false positives. Because of the small number of misses and false positives, inferential statistics were not used to analyze these responses. As described by Rea (1986), misses and false positives are less reliable than RTs in characterizing performance at visual tasks, although they both appear to follow the same functional forms as RTs for different stimulus conditions.

A mixed-model (Sheskin, 1997) analysis of variance (ANOVA) using the RTs to the onset of the warning beacon as the dependent variable revealed three significant main effects: peak warning beacon intensity ($F_{3,66}=9.41$, $p<0.001$), with higher intensities associated with shorter RTs; fixation location ($F_{1,22}=7.33$, $p<0.05$), with off-axis viewing producing longer RTs; and sex ($F_{1,22}=6.64$, $p<0.05$), with longer response times for the female subjects. There were five statistically significant, two-way interactions, but no other higher-order interactions reached statistical significance. Figure 3 is an efficient way to illustrate three of the significant two-way interactions, one between ambient light level and peak intensity ($F_{3,66}=6.15$, $p<0.005$), another between fixation location and peak intensity ($F_{3,66}=10.93$, $p<0.001$), and a third between ambient light level and fixation location ($F_{1,22}=12.1$, $p<0.005$). Above a peak intensity of 190 cd all four curves are very similar, with RTs decreasing slightly at the same rate with increasing peak intensity. The two-way interactions were statistically significant because the rate of change below 190 cd differed for the combination of off-axis fixation location during the night and during the day conditions but not for on-axis fixation location during the night and during the day. Thus, the combination of off-axis detection during the simulated daytime had the longest RT at 80 cd, but on-axis detection is much shorter both day and night.

There were two statistically significant two-way interactions involving clutter, one with the ambient light level ($F_{1,22}$=3.34, p<0.05) and the other with fixation location ($F_{1,22}$=13.2, p<0.005). Neither of these significant interactions affect the performance specifications for peak beacon intensity, so they will not be discussed further.

**4.1.2. Rated visibility of warning beacons—**Figure 4 shows the mean visibility ratings for the warning beacons as a function of peak luminous intensity under simulated daytime and nighttime conditions and for on- and off-axis viewing. A mixed-model ANOVA (Sheskin, 1997) using visibility ratings of the warning beacons as the dependent variable showed that rated visibility statistically increased with higher warning beacon intensities ($F_{3,66}$=545, p<0.001), with nighttime viewing conditions ($F_{1,22}$=31.5, p<0.001), for the on-axis fixation location ($F_{1,22}$=20.2, p<0.001) and for uncluttered roadway scenes ($F_{1,22}$=24.5, p<0.001). The visibility rating data did not exhibit asymptotic behavior as exhibited by the RT data; higher peak intensities (up to 3100 cd) elicited higher ratings of warning beacon visibility under all viewing conditions. This finding is consistent with those reported by Rea (1989) and Goodspeed and Rea (1999); different visual channels appear to underlie visual RTs compared to subjective ratings of visibility, and physiological data exist (Kaplan and Shapley, 1986) that confirm the existence of these channels in the primate visual system. The apparent brightness of the beacon is not directly related to its reaction time performance (Rea and Ouellette, 1991), and therefore, to performance specifications for peak beacon intensity; consequently these findings will not be discussed further.

**4.1.3. Rated visibility of targets (glare)—**Figure 5 shows the mean target visibility ratings, plotted as a function the peak luminous intensity of the beacon, for daytime and nighttime conditions and when the beacon was located on- or off-axis from the subjects' line of sight. A mixed-model ANOVA (Sheskin, 1997) showed that visibility ratings of the low-contrast fixation target statistically decreased as the beacon peak intensity increased ($F_{3,66}$=6.12, p<0.005). There were also statistically significant main effects of the warning beacon location ($F_{1,22}$=7.25, p<0.05), with target visibility rated higher for off-axis fixation, and the presence of visual clutter ($F_{1,22}$=6.33, p<0.05), with target visibility rated higher for no clutter (simulated rural conditions). A significant two-way interaction was found between the warning beacon peak intensity and the ambient light level ($F_{3,66}$=8.84, p<0.05), so that the decrease in rated target visibility only occurred under nighttime ambient conditions, and especially for on-axis viewing conditions, when, as found, disability glare should be most problematic (Fry, 1954; Rea, 2000). Significant two-way interactions were also found between peak intensity and age ($F_{3,66}$=2.86, p<0.05), between peak intensity and viewing location ($F_{3,66}$=9.70, p<0.001) and between ambient light level and viewing location ($F_{1,22}$=5.36, p<0.05).

For comparison, the mean target visibility ratings in Figure 5 are plotted in Figure 6 as a function of the apparent luminance contrasts of the Landolt ring targets, taking into account the veiling luminance (Fry, 1954) produced by the warning beacon under each condition. Overall there is a strong, positive linear correlation ($r^2$=0.77, p<0.01) between these sets of values. This correlation suggests that the subjective ratings of target visibility are a reasonable measure of the contrast-reducing effects of disability glare. As described in the previous subsection, it is worth noting that when observers are asked to judge the saliency of visual stimuli, their ratings are often strongly correlated with their luminance contrast against their immediate background (Rea, 1989; Goodspeed and Rea, 1999).

### 4.2. Closure Detection Experiment

Figure 7 shows the main effects found in the closure detection experiment. A mixed-model ANOVA (Sheskin, 1997) using gap closure detection time as the dependent variable revealed reliable main effects of the number of warning beacons ($F_{1,22}=62.1$, $p<0.05$) with two beacons resulting in shorter closure detection times than one; the minimum flashing intensity ($F_{2,44}=11.2$, $p<0.05$), with full-on/full-off flashing resulting in longer closure detection times than the other conditions; and the location of the warning beacons in the field of view ($F_{1,22}=70.4$, $p<0.05$), with an on-axis viewing location resulting in shorter closure detection times than an off-axis location. No two- or three-way interactions were statistically significant.

## 5. DISCUSSION

The overarching goal of this study was to establish preliminary performance specifications for the intensity characteristics of flashing yellow warning beacons based upon the empirical psychophysical data. Two basic considerations were important for developing the performance specifications. First, the specifications should be based upon a “worst-case scenario” under the assumption that the experimental conditions represented the full range of conditions important for the intensity performance specifications. Second, they should be based upon an objective performance criterion applied to the empirical data.

Regarding the first consideration, the experimental design included six independent variables; two variables characterized the experimental subjects, age (20–30 years versus 50–60 years) and sex (male versus female); three variables characterized the visual stimulus conditions, ambient light level (day versus night), context (urban versus rural) and fixation location (on-axis versus off-axis). The sixth independent variable, peak intensity, was the object of the performance specifications. Although there were no three-way or higher statistically significant interactions revealed by the ANOVA, the combination of all six independent variables resulting in the longest mean RTs was that for older, female subjects using the off-axis fixation during the daytime in the urban context (Table 1). Figure 8 shows the mean response times as a function of flashing beacon peak intensity for this combination of independent variables. The data for each combination of independent variables (Table 1), including the worst-case combination illustrated in Figure 8, were fitted with power functions having the form:

$$RT = a + bI^{c} \quad \text{(Equation 2)}$$

In Equation 2, RT is reaction time (in ms), I is peak intensity (in cd) and a, b, and c are free parameters meeting a least-squares criterion.

Regarding the second consideration, all of the fitted RT functions of the form used to fit the data in Table 1 will continue to decrease with higher and higher peak intensities, as seen in Figure 8, but there comes a point of diminishing returns whereby incremental increases in the beacon's peak intensity have smaller and smaller reductions in response times. Moreover, as peak intensity increases, the visibility of other objects in the visual environment can become worse due to disability glare, particularly at night (Rea, 2000). Therefore, an objective method is needed for estimating that point of diminishing returns for the RT data and, importantly, that beacon peak intensity should be lower than that which begins to affect the visibility of other objects in the visual environment through disability glare. Figure 8 includes an estimate of the asymptotic point of diminishing returns for that data set. This estimate is based upon an objective 10-to-1 slope criterion applied to the functional relationship between peak intensity and response time, whereby a 10% change in peak intensity produces a 1% change in reaction time. Table 1 lists the 10-to-1 asymptote peak intensity for every combination of the independent variables (if the asymptote occurred outside the range of peak intensities used in the study, the asymptote is noted as "< 80 cd" or "> 3100 cd"). For the worst-case scenario illustrated in Figure 8, the asymptote peak intensity for RTs was 739 cd.

The same objective analysis was conducted to estimate the point of inflection for disability glare measured through magnitude estimations of target visibility, and fitted to the same functional form in Equation 2, for every combination of the independent variables (excluding peak intensity). Table 1 includes these 10-to-1 asymptote peak intensities for disability glare. As can be seen from this table, the criterion response time beacon intensity is always lower than the criterion disability glare beacon intensity. The worst-case scenario for disability glare using this method was for older female subjects viewing the beacon from an on-axis location at night in an urban context, where the criterion occurred for a beacon peak intensity of 2108 cd, as illustrated in Figure 9. Therefore, 739 cd represents the objectively determined beacon peak intensity for minimum *detection* RT for the worst-case scenario combination of the other independent variables, while simultaneously ensuring that that this beacon intensity does not exceed the objectively determined disability glare beacon intensity of 2108 cd.

It is worth noting that a similar analysis of reaction times for the worst-case nighttime viewing condition results in an asymptote reaction time when the peak beacon intensity is 214 cd (for older male subjects viewing the beacon from an off-axis location in the urban context). This suggests that to maintain asymptotic response times at night, the beacon peak intensity does not need to exceed 214 cd, while for the daytime conditions it needs to be at least 739 cd. However, since the worst case scenario for glare indicates that even under nighttime conditions, the peak intensity could be as high as 2108 cd before the 10-to-1 criterion for disability glare is reached, the present data do not suggest that it is necessary to specify different peak intensities for daytime and nighttime conditions. A different criterion based on discomfort glare (Rea, 2000) rather than disability glare might, however, result in a different conclusion.

Regarding the intensity characteristics of temporal modulation to support judgments of gap closure detection, the results of the second experiment demonstrate that if the minimum intensity of the warning beacon is at least 10% of the peak luminous intensity, closure detection times will be significantly better than if the flash sequence was fully on, then fully off. These findings are consistent with previous literature (Croft, 1971; Barnes and Asselman, 1992; Bullough et al., 2001) suggesting that as long as the light(s) remain visible at all times, visual tracking for closure detection will be better than conditions where the light(s) are switched off completely. Whether even lower minimum intensities than 10% (e.g., 5%, 2% or 1% of the peak luminous intensity) could also elicit closure detection times similar to those from steady-burning lights would need to be addressed in more detail, although a pilot study (Bullough and Rea, 2014) found little difference in closure detection times for minimum intensities between 1% and 33% of the maximum. While the steady burning lights in the second experiment also elicited shorter closure detection times than the full-on/full-off temporal flashing pattern, steady burning lights do not attract attention as much as flashing lights (Crawford, 1962), a highly desirable feature of yellow warning beacons. So despite their equivalent performance in the closure detection experiment, steady lights should not be used for warning beacons because they are not as effective at attracting attention.

The experimental data also suggest that using two warning beacons is superior to a single beacon, which is consistent with data from Hoffmann and Mortimer (1996), who showed that individuals had a constant threshold for the change in angular size of an object such as a roadside hazard. When two lights were present, the change in angular size (in rad/s or degrees/s) would be substantially larger than when a single light was present.

## 6. CONCLUSIONS

The data from the experiments conducted in the present study can be used in the development of preliminary performance specifications for the photometric characteristics of warning beacons to support visual detection while avoiding problems with disability glare, and while providing observers with sufficient visual cues for gap closure detection. Table 2 provides preliminary performance specifications based on the present results of this study, along with the supporting rationale. Values based on the asymptote peak intensities from the analyses in this section of the paper are rounded for simplicity.

The specifications in Table 2 are for “passive” yellow flashing warning beacons, that is, beacons that are not responsive to ambient conditions and cannot provide dynamic information that might be useful to drivers approaching a worksite, a service vehicle or an emergency situation. These specifications differ from those published by the SAE (1990) by including a higher minimum value for the peak intensity and specifying a maximum value of the peak intensity to avoid excessive disability glare. In addition, the requirement of a minimum flash intensity (rather than full-off) can better support judgments of gap closure than the full-on/full-off flashing mode implied in the SAE (1996) standard for flashers. Finally, the proposed specifications in Table 2 recognize the benefit of using more than one warning beacon on a vehicle as a more potent cue for closure detection than a single warning beacon.

By supporting asymptotic visual response times while maintaining closure detection and minimizing disability glare, warning beacons adhering to the performance specifications in Table 2 will provide drivers with the necessary visual information to allow them to quickly and accurately respond to the presence of workers in work locations along the roadway. Having longer times to perform defensive driving maneuvers and reducing the impacts on the visibility of workers and other hazards should provide a safety benefit to front line service workers and reduce the likelihood of crashes involving these workers.

The context of the present study is the detection and response to warning beacons mounted on maintenance or construction vehicles. Yellow flashing lights are also used with hazardous roadway situations, as, for example, with barricade lights mounted to traffic drums or other channelization devices in work zones. These lights follow different standards, such as those published by the Institute of Transportation Engineers (ITE, 2001). The preliminary performance specification data in Table 2 could apply to barricade lights as well as warning beacons, insofar as these lights need to be readily detected and they need to support judgments of gap closure. It should be noted that barricade lights also serve a delineation function such as outlining the extent of a desired lane change maneuver; Table 2 does not address this type of informational function. It has been suggested, for example, that the luminous intensities required of road studs for helping drivers maintain lane position (Villa et al., 2015) are substantially lower than 750 cd specified in Table 2 for detection.

Of course, the research findings in the present study have some limitations that could result in refined specifications in the future. Although the maximum value of the peak intensity (2000 cd in Table 2) was selected to minimize disability glare at night, drivers exposed to intensities of 750 cd or higher might experience visual discomfort at night, and for this reason, a lower nighttime intensity (as low as 215 cd based on the nighttime asymptote intensity) might be warranted. Also, as mentioned previously, the ideal intensities for driver guidance through a work area were not studied, so the proposed performance specifications are strictly limited to the detection of warning beacons. The present studies also simulated clear, dry roadway conditions, and the presence of rain or fog (Bullough and Rea, 2016) might warrant different nighttime intensities than those recommended in Table 2 (e.g., because of scattered light in the atmosphere). Further, the proposed upper limit might not be ideal for, say, sunny days where the ground is covered with snow. Future research will extend that presented here for “passive” yellow warning beacons by examining various ways that warning beacons might respond to ambient conditions (e.g., rain at night) and, in addition, might provide dynamic information to drivers to facilitate traffic flow while minimizing danger to front line service workers. Nonetheless, the findings of the present research provide some important data and an objective rationale for improving the design and performance of flashing yellow warning beacons.

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**Figure 1.**

Daytime roadway scene used in the visibility experiment with the fixation target located near the center of the display.

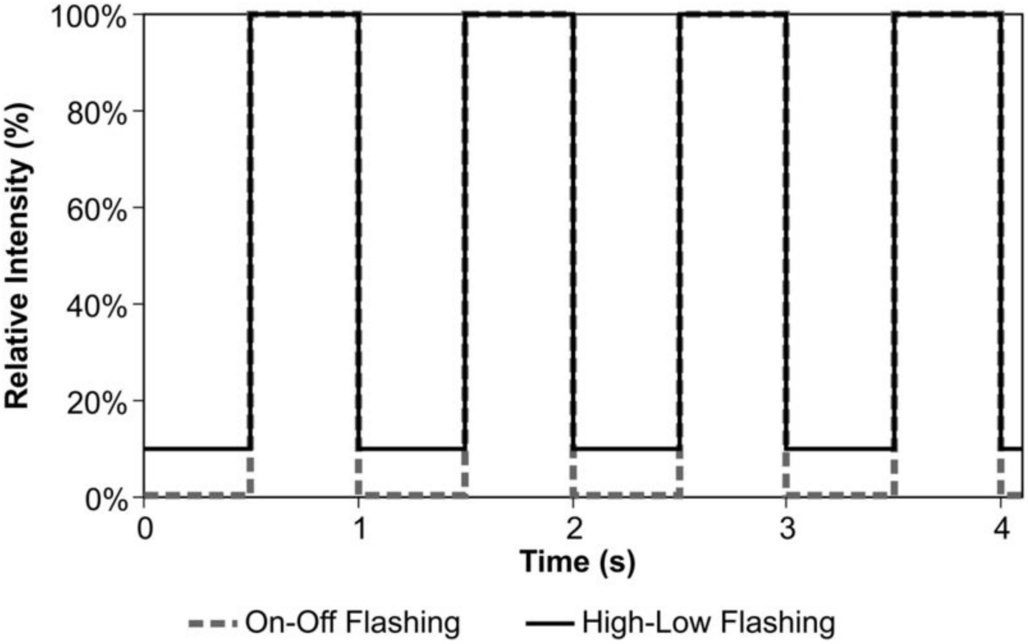

**Figure 2.**

Temporal intensity profiles for the full-on/full-off and the full-on/10%-on flashing conditions, both modulated at 1 Hz at 50% duty cycle, in the closure detection experiment. A steady-burning, continuously on condition was also used. The maximum luminance of the simulated beacons was always 300 cd/m², and the background luminance was always 1 cd/m².

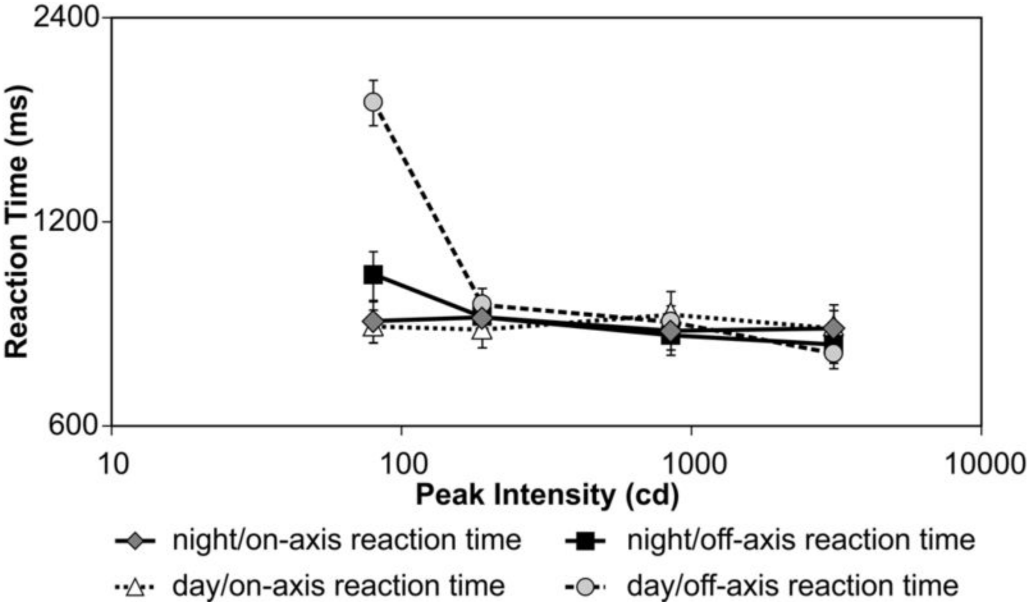

**Figure 3.**

Mean reaction times (RTs) to the onset of warning beacons as a function of peak intensity, for simulated day and night conditions and when viewed on and off axis.

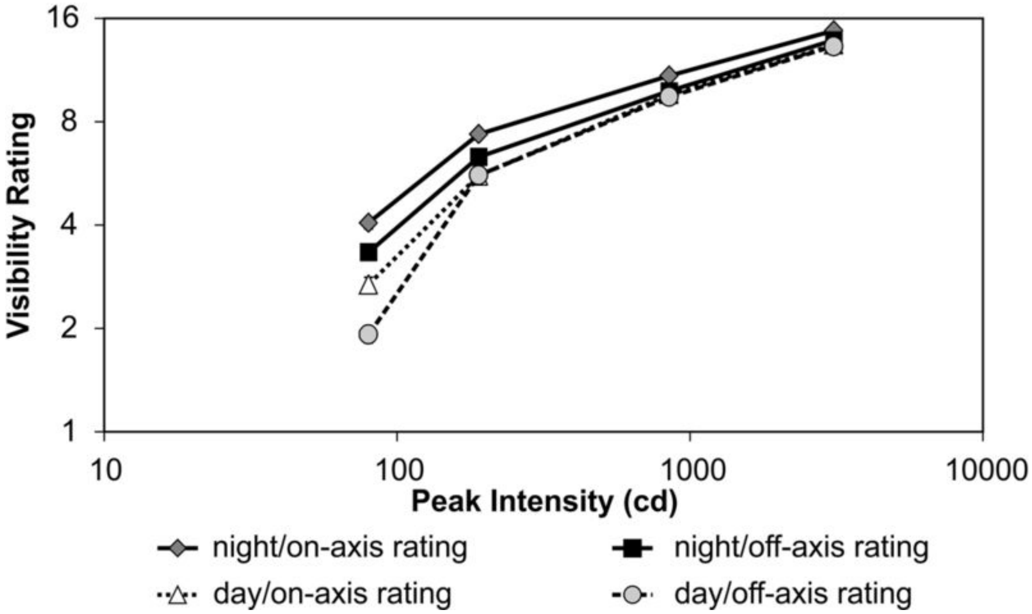

**Figure 4.**

Mean visibility ratings (±s.e.m.) as a function of peak intensity, for day and night conditions and when viewed on and off axis.

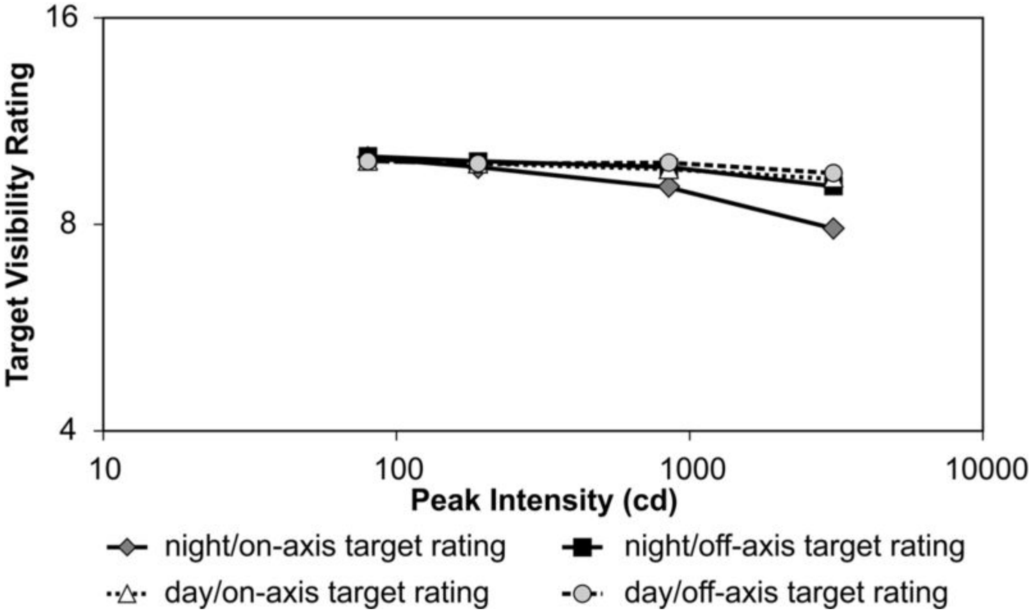

**Figure 5.**

Target visibility ratings as a function of the peak intensity of the warning beacon, for day and night conditions and when viewed on and off axis.

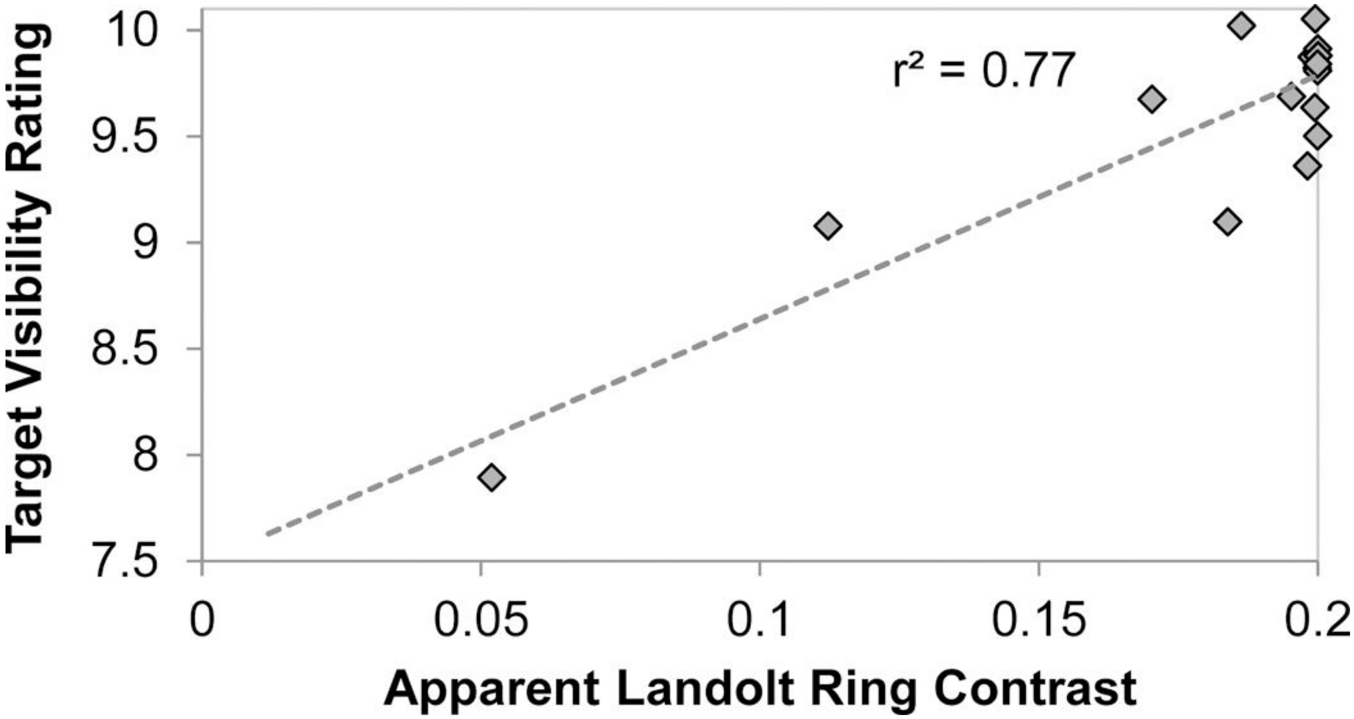

**Figure 6.**
Mean target visibility ratings for the Landolt ring targets as a function of their apparent luminance contrast (including veiling luminance effects), for each experimental condition.

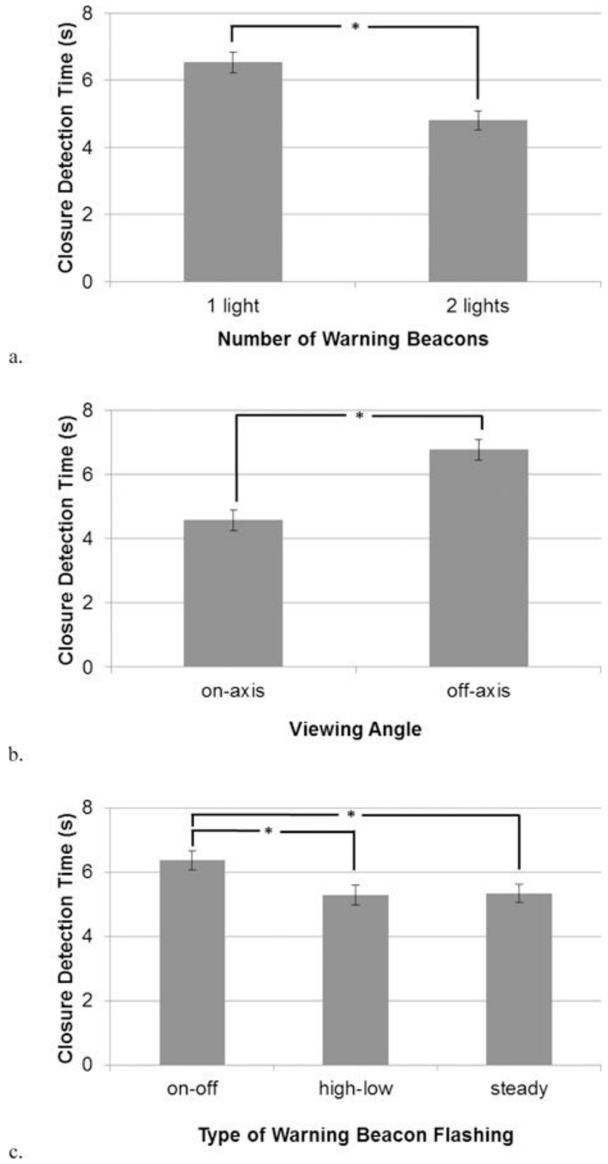

**Figure 7.**

Mean closure detection times for a gap closure speed of 10 mph, as a function of the number of warning beacons (a), the viewing angle (b), and the type of flashing (c). Statistically significant ($p<0.05$) differences are indicated by asterisks.

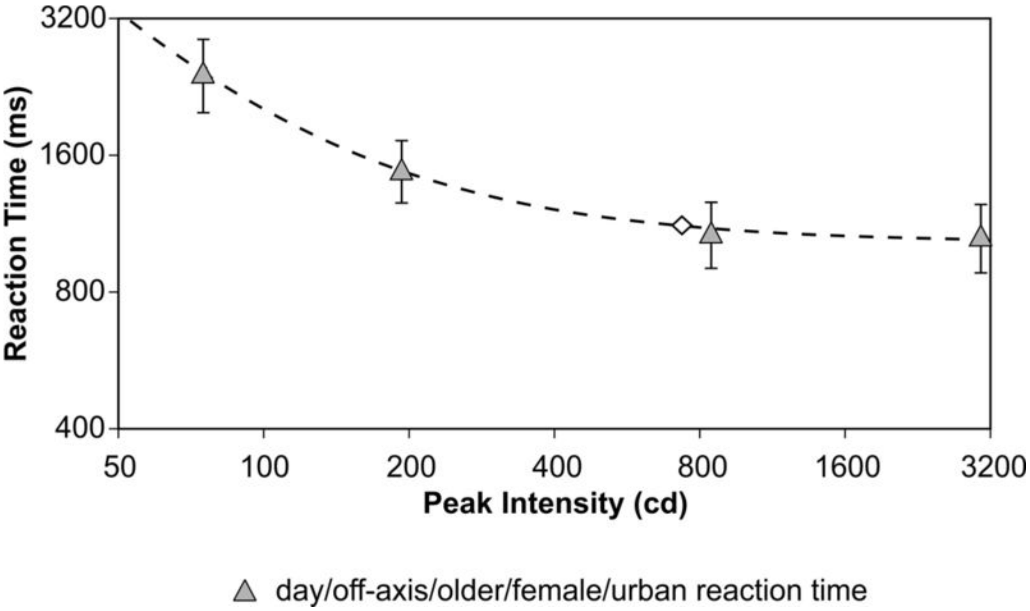

**Figure 8.**

Mean RT values (±s.e.m.) for each peak intensity (triangles) for the older, female subjects viewing the beacon under daytime urban conditions from an off-axis location. Also shown (dashed line) is the best-fitting power function of the form shown in Equation 2. The open diamond represents the 10-to-1 slope criterion described in the text.

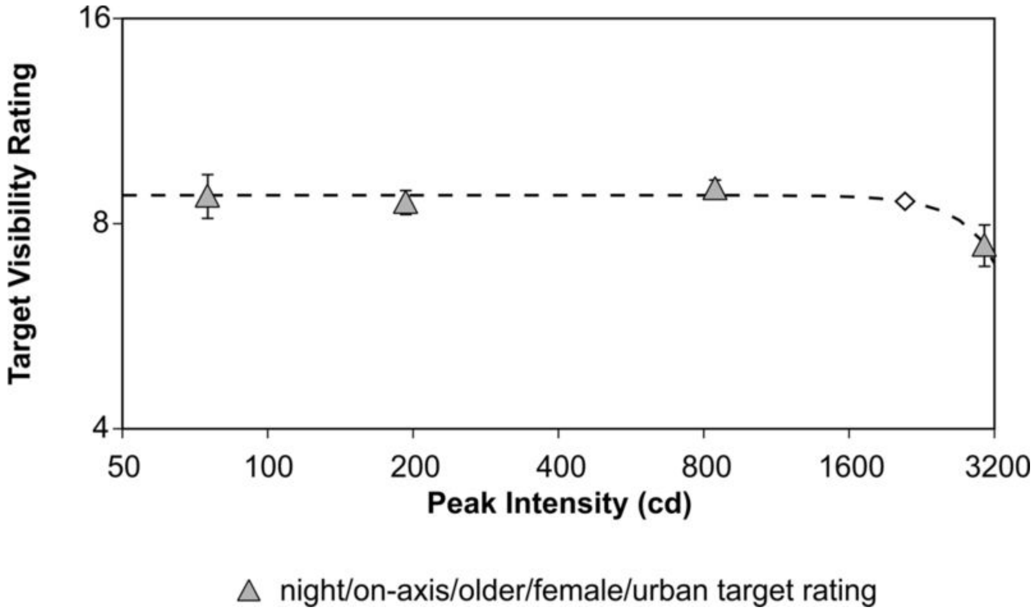

**Figure 9.**

Mean target visibility ratings (±s.e.m.) for each peak intensity (triangles) for the older, female subjects viewing the beacon under nighttime urban conditions from an on-axis location. Also shown (dashed line) is the best-fitting power function of the form shown in Equation 2. The open diamond represents the 10-to-1 slope criterion described in the text.

## Table 1.

Mean and asymptote peak intensities for reaction times (RTs) and target visibility ratings for each combination of five independent variables. Asymptote peak intensities are based on power-function fitted curves to the data as a function of peak intensity, for the 10-to-1 slope criterion described in the text. Shaded cells represent the worst-case combination resulting in the longest mean RT or the lowest mean target visibility rating.

| Independent Variables | | | | | Dependent Variables | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Response Time | | Disability Glare | |
| Ambient | Fixation Location | Clutter | Age | Sex | Average RT (ms) | Asymptote (cd) | Average Target Visibility | Asymptote (cd) |
| Night | On-Axis | Rural | Younger | Female | 608 | < 80 | 9.90 | > 3100 |
| | | | | Male | 612 | 83 | 9.25 | > 3100 |
| | | | Older | Female | 1486 | < 80 | 8.99 | 2805 |
| | | | | Male | 779 | < 80 | 9.11 | 2550 |
| | | Urban | Younger | Female | 660 | < 80 | 9.39 | > 3100 |
| | | | | Male | 541 | < 80 | 9.27 | 3086 |
| | | | Older | Female | 1330 | < 80 | 8.46 | 2108 |
| | | | | Male | 845 | < 80 | 8.96 | > 3100 |
| | Off-Axis | Rural | Younger | Female | 618 | < 80 | 10.99 | > 3100 |
| | | | | Male | 496 | < 80 | 9.60 | 2678 |
| | | | Older | Female | 1326 | < 80 | 9.68 | > 3100 |
| | | | | Male | 818 | < 80 | 9.48 | 2945 |
| | | Urban | Younger | Female | 621 | < 80 | 9.93 | > 3100 |
| | | | | Male | 676 | < 80 | 9.61 | > 3100 |
| | | | Older | Female | 1403 | 161 | 9.07 | > 3100 |
| | | | | Male | 1069 | 214 | 9.20 | 2627 |
| Day | On-Axis | Rural | Younger | Female | 858 | < 80 | 10.15 | > 3100 |
| | | | | Male | 747 | < 80 | 9.79 | > 3100 |
| | | | Older | Female | 1316 | < 80 | 9.56 | > 3100 |
| | | | | Male | 831 | < 80 | 9.86 | > 3100 |
| | | Urban | Younger | Female | 695 | 110 | 9.85 | > 3100 |
| | | | | Male | 610 | < 80 | 9.29 | 2480 |
| | | | Older | Female | 1179 | < 80 | 9.35 | > 3100 |
| | | | | Male | 657 | < 80 | 9.64 | 2503 |
| | Off-Axis | Rural | Younger | Female | 1027 | 417 | 9.90 | > 3100 |
| | | | | Male | 791 | 161 | 9.49 | > 3100 |
| | | | Older | Female | 1456 | 235 | 9.64 | > 3100 |
| | | | | Male | 1133 | 214 | 10.14 | > 3100 |
| | | Urban | Younger | Female | 946 | 195 | 9.89 | 2435 |
| | | | | Male | 824 | 259 | 9.82 | 2728 |
| | | | Older | Female | 1568 | 739 | 9.03 | > 3100 |

| **Independent Variables** | | | | | **Dependent Variables** | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | **Response Time** | | **Disability Glare** | |
| **Ambient** | **Fixation Location** | **Clutter** | **Age** | **Sex** | **Average RT (ms)** | **Asymptote (cd)** | **Average Target Visibility** | **Asymptote (cd)** |
| | | | | Male | 1011 | 672 | 10.06 | > 3100 |

**Table 2.**

Preliminary performance specifications for passive yellow warning beacons to support visual detection and hazard recognition and to support judgments of closure detection.

| Characteristic | Recommended Value | Rationale |
|---|---|---|
| Peak intensity (day or night) | • 750 cd minimum | • Produce asymptotic response time during day and night conditions |
| | • 2000 cd maximum | • Avoid reducing visibility of low-contrast hazards (pedestrians or other workers) at night |
| Flashing minimum intensity (day or night) | • 10% of peak intensity | • Provides conspicuity of flashing light while supporting closure detection |
| Number of warning beacons | • Two | • Supports improved closure detection over a single beacon |