EVALUATION OF LIGHT-EMITTING DIODE WARNING BEACONS FOR MAINTENANCE VEHICLES (11-0490)

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ABSTRACT
Rotating warning beacons containing filament light sources have long been used on highway maintenance vehicles to indicate the presence of the vehicle to other drivers. Flashing warning beacons containing light-emitting diodes (LEDs) are beginning to be used in place of rotating warning beacons, in part because they use considerably less power. To help ensure that LED warning beacons will provide a comparable warning signal to drivers approaching vehicles outfitted with them, their photometric and temporal characteristics were measured and compared to human response time data. In addition, several LED warning beacons were compared to a conventional incandescent rotating warning beacon in terms of the distance at which observers could detect that a vehicle had moved closer to the observer. Pairs of LED warning beacons provided equivalent closure detection distances to a pair of conventional rotating beacons. While single LED warning light configurations were not tested, the pairs of LED beacons tested reliably outperformed a single conventional beacon configuration in terms of both energy use and closure detection distance. Overall, the results suggest that LED warning beacons provide comparable visual information to other drivers, while using substantially less power than conventional rotating beacons.
INTRODUCTION
Highway maintenance vehicles are often parked at the start of highway construction or maintenance zones in order to provide a warning signal to drivers that they should exercise increased caution as they approach. Typically these vehicles are equipped with a pair of rotating warning beacons containing filament sources, that project rotating beams of high-intensity light around the vehicle. Such warning beacons typically use on the order of 50 W or 60 W, and to avoid problems with discharging the vehicle's battery (thus making it difficult or impossible to start the vehicle after a period of up to 8 hours), the maintenance vehicle is often left running during this time. The result is a substantial expense in terms of fuel, and a contribution of greenhouse gases to the environment.

Previous research (1) has shown that flashing, rotating or strobing lights are less effective than steady-burning lights for detecting when a vehicle equipped with these lights is approaching a driver or when a driver is approaching such a vehicle. This is because visual tasks such as tracking are more difficult under intermittent viewing conditions (2,3). Nonetheless, conspicuity of flashing or rotating lights is quite high because of their dynamic nature, and dynamic lights are used for this purpose (4). They also can be configured to provide short visual detection times (5). Generally, maintenance vehicles will often have tail position lights or other marker lights on while warning beacons are used, which will provide a steady-burning visual cue as well as a dynamic, attention-getting signal, to assist in detecting and making judgments of relative speed and position.

Advances in light-emitting diode (LED) technologies have made flashing warning beacons feasible for use in place of conventional rotating warning beacons (6,7). Unlike the conventional warning beacons, LED warning beacons flash rather than rotate. For example, a typical flash pattern used in New York State for LED warning beacons is two short, successive flashes (of 0.1 to 0.3 s in duration) per second. The flash briefly illuminates the entire angular region around the vehicle. Averaged across time, LED warning beacons can be expected to use on the order of 6 W to 15 W, substantially lower than the power used by conventional incandescent warning beacons, which could allow a truck to be turned off rather than idle for 8 hours, and still be able to be started.

From a visual effectiveness perspective, the LED warning beacons evaluated in this study have one potential advantage and one potential disadvantage compared to conventional rotating warning beacons. The advantage is that when they are illuminated, the LED warning beacons produce a 360º beam of light around the vehicle. Conventional incandescent warning beacons produce a beam of light in a narrow angular region at any given time, which is rotated to create the flashing effect as the beam sweeps past the observer very rapidly. An LED warning beacon (depending on its configuration) might be emitting light, visible from all directions, for 20% or more of its flash cycle (some units have greater than 50% duty cycle). A rotating beacon, in comparison, will sweep its beam past an observer for less than 5% of its flash cycle.

The disadvantage is that in the time between flashes, the LED warning beacons are not producing light, whereas the conventional warning beacons are always on, at least in some direction. The significance of this difference is that observers may be able to view reflections of the beam from objects in the visual field when the beam is not sweeping past them.

In the present paper, evaluation is described of several commercially available LED warning beacons and one type of conventional rotating warning beacon, in order to assess whether LED warning beacons provide similar visual information to a driver approaching them as conventional warning beacons. Strobe type warning beacons were not included in the study. The evaluation consisted of photometric, temporal measurements of the luminous intensity profiles from each warning beacon, with comparisons to literature on visual response times, and a human factors study conducted in the field to assess the relative ability of observers to identify when a vehicle equipped with different types of warning beacons had moved closer to them. All of the warning beacons used in the study were lent by the New York State Department of Transportation (NYSDOT).

PHOTOMETRIC AND TEMPORAL MEASUREMENTS

Methods
Each warning beacon’s flash pattern temporal characteristics were measured in the photometric laboratory at Rensselaer’s Lighting Research Center (LRC) using an oscilloscope and photomultiplier tube (PMT). A PMT was chosen due to its fast response time. The PMT was connected with a solid-state amplifier to the oscilloscope as illustrated in Figure 1. Each warning beacon was energized using a laboratory power supply set to 12.8 V. The oscilloscope was adjusted and set to capture a full flash cycle. Determination of pulse timing and duration was made using the cursors of the oscilloscope. The waveform was digitized so that it could be plotted using a mathematical computation software package (Matlab).

Regarding the photometric measurement data, each warning beacon was measured a second time to determine the average (per cycle) intensity of the beacons’ output. This was done using essentially the same
equipment as before. However, for these measurements a calibrated illuminance detector and amplifier were used (see Figure 2). These devices were not used for the temporal measurements because they do not have the speed to resolve a rapidly changing signal; this was not a problem for measuring the average intensity, because they will integrate over the measurement time. As before, each warning beacon was energized using a laboratory power supply set to 12.8 V. The oscilloscope was again adjusted and set to capture a full flash cycle. The waveform was digitized and saved to file. The saved file was then analyzed using mathematical software to determine the average intensity over one flash cycle.

**FIGURE 1** Block diagram of the temporal testing apparatus.

**FIGURE 2** Block diagram of the intensity measurement apparatus.

**Results and Analyses**

In the present paper, the conventional incandescent rotating warning beacon is denoted A, and the three LED warning beacons, each from a different manufacturer, are denoted B, C and D. Figure 3 shows the relative luminous intensity profiles measured from beacons A through D. Table 1 summarizes the characteristics of the temporal and intensity patterns produced by each beacon light.

**TABLE 1** Temporal, Photometric and Electrical Characteristics of Each Warning Beacon

<table>
<thead>
<tr>
<th>Unit</th>
<th>Frequency (Hz)</th>
<th>Flashes per cycle</th>
<th>Pulse duration (sec)</th>
<th>Average intensity (cd)</th>
<th>Average power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.5</td>
<td>1</td>
<td>0.036</td>
<td>392</td>
<td>64</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>2</td>
<td>0.25</td>
<td>191</td>
<td>6</td>
</tr>
<tr>
<td>C</td>
<td>1.25</td>
<td>2</td>
<td>0.125</td>
<td>91</td>
<td>7</td>
</tr>
<tr>
<td>D</td>
<td>0.98</td>
<td>3</td>
<td>0.245, 0.191, 0.163</td>
<td>209</td>
<td>16</td>
</tr>
</tbody>
</table>

The solid appearance of the waveform for the LED warning beacon labeled B in Figure 3b is caused by pulse-width modulation of this unit, which very rapidly changes the output of the LEDs in the device from off to on. Visually, the effect was like seeing a single flash with approximately half the peak intensity exhibited by the very rapid modulations. In comparison, LED warning beacons C and D exhibit some fluctuations during the on time, but to much lower extent, and the peak intensity is largely constant during the duration of each flash. Each flash has a slightly higher intensity at the start than at the end, an effect likely caused by thermal build-up in the LED sources (6). LED warning beacon D produced three flashes per cycle. The manufacturer's instructions for programming this particular module were consulted in an attempt to reprogram it to produce two flashes per cycle. The attempt was unsuccessful, and this beacon was not used in the subsequent field experiment.

The average intensities (per cycle) of the LED warning beacons were lower than for the conventional warning beacon. Despite this, all four warning beacons were observed to be clearly visible from 300 m under daytime viewing conditions, as required by NYSDOT's standard specifications. In addition, Bullough (5) reported response times for amber signal lights having different temporal (onset time) characteristics, under daytime viewing conditions. It was found that response times consisted of a constant nonvisual component, associated with decision
making and performing a physical response to a signal light (such as pressing a button or brake pedal), and a visual component that is dependent upon receiving a required amount of light-energy (in terms of candela-seconds [cd·s]). For amber signal lights, the required amount of light-energy is 9 cd·s. Figure 4 illustrates the constant light-energy response characteristics of signal light detection.

![Figure 4](image_url)

**FIGURE 4** Constant light-energy response characteristics of signal light detection.

If the waveform for the conventional warning beacon (A) is assumed to be triangular in shape, and the waveforms for the LED beacons are assumed to be rectangular in shape, then the waveforms for the light pulses produced by warning beacons A through D would be expected to produce a light-energy quantity of 9 cd·s in 5, 24, 31 and 26 ms, respectively. Although the visual response time component is shorter for the conventional warning beacon (A), it should be noted that the nonvisual response time component for the response of releasing a switch, which is already being held down in an experiment where subjects are expecting to see the onset of an amber signal, is on the order of 370 ms (5). Cole and Brown (8) measured foot pedal response times under similar experimental conditions and these were even longer, by 150 to 200 ms, so a difference of less than 30 ms for the total reaction time is relatively small. Since a vehicle traveling 90 km/h will travel only about 0.6 m in 30 ms, the practical difference in response times among any of the measured warning beacons is probably negligible.

In addition, all of the LED warning beacons (even D, if it had been programmed to produce two rather than three flashes per cycle) have shorter "dark" times (between visible flashes or trains of successive flashes) than the conventional rotating warning beacon A. There is an interval of about 0.6 s between flashes for warning beacon A, whereas for LED warning beacon B, there is about 0.4 s between pairs of flashes, and for LED warning beacons C and D there is about 0.5 s between pairs of flashes (for warning beacon D, the third flash was ignored in making this estimate). This shorter "dark time" for the LED warning beacons also offsets the longer visual response time components estimated above.

![Figure 3](image_url)

**FIGURE 3** Relative luminous intensity profiles from a) the conventional rotating warning beacon, b) LED warning beacon B, c) LED warning beacon C, and d) LED warning beacon D.
FIELD EXPERIMENT

Methods
In the field experiment, subjects sat in a parked car (in groups of three, two in the front seat and one in the back) along a long, flat, straight portion of an unused public roadway in the Town of East Greenbush, NY. The warning beacons were mounted to a rack in the bed of a pickup truck in such a manner that they could be switched and replaced easily (Figure 5). Power for the warning beacons was provided by a regulated laboratory power supply (set to 12.8 volts). A total of four lighting configurations were tested:

- A single rotating warning beacon (A) mounted in the center of the truck
- A pair of rotating warning beacons (A) mounted on the driver and passenger side of the truck
- A pair of LED warning beacons (B) mounted on the driver and passenger side of the truck
- A pair of LED warning beacons (C) mounted on the driver and passenger side of the truck

Figure 6 shows several views of the truck with a single and a pair of warning beacons attached. As described previously, the LED warning beacon D, which produced three successive flashes per cycle, was not used in the field experiment. Since the intensity of the individual flashes for this unit were between those of LED warning beacons B and C, the expected performance of this unit would be expected to be between those warning beacons as well.
The truck's initial starting location was 120 m directly ahead of the parked car (Figure 7). No other lights (e.g., headlights, tail lights, marker lights) were in use on the truck during the experiment. When subjects in the parked car were ready, an experimenter near the parked car signaled to another experimenter in the truck to begin to drive slowly (~1 m/s) toward the parked car after a random delay between 20 and 60 s. Subjects in the car held switches that they were instructed to press quietly, without speaking, when they could detect that the truck had moved from its initial location.

The switches were connected to a laptop computer that was also connected to an infrared laser range finder pointed toward the truck in the road; the laser was located next to the parked car. The laptop computer recorded the distance between the car and the truck when each of the three subjects' buttons was pressed. At this point, the experimenter near the car notified the subjects that the trial was completed. The truck was returned to its initial starting point, the lighting configuration was switched, and each group of subjects responded in the same manner to all four lighting conditions.

Four groups of three subjects (12 subjects in total, seven males and five females, mean age 35 yr, ranging from 22 to 63 yr) completed the experiment, and the order of lighting conditions was randomized and counterbalanced among all four groups so that they were experienced by each group in a different order. When used in pairs, the warning beacons were not synchronized to each other.

Results
Figure 8 illustrates the mean closure detection distances for each lighting configuration. All of the distances are close to 100 m, meaning on average the truck traveled about 20 m before it was noticed that it had moved. However, the distances for the single rotating warning beacon (A) were statistically significantly shorter (p<0.05), according to a repeated-measures analysis of variance (9), than for the other configurations, which consisted of pairs of warning beacons (A, B and C). None of the pairs of warning beacons yielded statistically significant (p>0.05) differences from each other, according to two-tailed Student's t-tests with Bonferroni correction (9). The single warning beacon A resulted in statistically significantly (p<0.05) shorter detection distances than the warning beacon A pair and the warning beacon C pair, according to two-tailed Student's t-tests with Bonferroni correction (9).
FIGURE 8 Mean closure detection distances for each lighting configuration (longer detection distances represent earlier detection of movement). Error bars indicate the standard deviations for all subjects under each condition.

DISCUSSION
The photometric and temporal measurements of each of the warning beacons evaluated in this study suggest that although the time-averaged luminous intensity of the LED warning beacons measured in this study were lower than that of the conventional warning beacon that was measured, the practical consequences of this finding were negligible, because all of the warning beacons measured would result in similar response times resulting in differences in stopping distances of less than 0.6 m among all of them.

The results from the field study suggest that drivers' ability to detect closure on a truck equipped with LED beacon lights will not be affected as long as the beacons are used in pairs, as they are normally used on maintenance vehicles (at least in New York State) when compared to conventional incandescent rotating beacons. Using a single warning beacon did result in slightly but statistically significantly shorter detection distances, suggesting that the extra visual information provided by a pair of warning beacons is beneficial, and confirming the utility of current practices. While single LED warning light configurations were not tested, the pairs of LED beacons tested reliably outperformed a single conventional beacon configuration in terms of both energy use and closure detection distance. As stated previously, the warning beacons used in the field study were not synchronized, so the potential effect of synchronized flashing patterns was not assessed. This was done because NYSDOT does not normally synchronize beacons installed on vehicles, as of the time of the experiment. It may be worthwhile to note that some manufacturers have made provisions for the synchronization of their warning beacons.

Table 1 includes the results of electrical measurements for each warning beacon; they are consistent with the manufacturers' published specifications for these units regarding electrical power use, and confirm that all of the LED warning beacons will use substantially less energy than the conventional rotating warning beacon. Based on prices from several suppliers of warning beacons obtained online in 2010, it is estimated that a conventional beacon would cost about US$100 and an LED beacon around US$200. A dump truck is estimated to use at least 0.8 gal/hr of fuel when idling (10). If the use of LED beacons permits the truck's engine to be switched off during work operations, the resulting fuel savings corresponds to US$2.40/hr, suggesting that the incremental cost could be recovered after just over 40 hr. Use of these beacons would therefore appear to be a useful cost-saving and environmentally friendly measure, with little practical impact on the visual information produced by these units.

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REFERENCES