FINAL REPORT

EVALUATION OF LIGHT-EMITTING DIODE BEACON LIGHT FIXTURES

by

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16. Abstract

Rotating beacons containing filament light sources have long been used on highway maintenance trucks to indicate the presence of the truck to other drivers. Because of advances in light-emitting diode (LED) technologies, flashing lights containing LEDs are beginning to be used in place of conventional rotating beacons. These devices use considerably less power, an important consideration for an equipment-laden maintenance truck. To ensure that LED beacon lights 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 beacon light fixtures were compared to conventional rotating beacons in terms of the distance at which observers could detect that a vehicle had moved closer to the observer (the longer this distance, the better performance is). LED beacon lights provided equivalent closure detection distances as conventional rotating beacons, as long as they were used in pairs as per common practice. Closure detection distances when only one beacon light was present were statistically significantly shorter. Overall, the results suggest that using LED beacon light fixtures provides comparable visual information to other drivers, while using substantially less power.

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ABSTRACT

Rotating beacons containing filament light sources have long been used on highway maintenance trucks to indicate the presence of the truck to other drivers. Because of advances in light-emitting diode (LED) technologies, flashing lights containing LEDs are beginning to be used in place of conventional rotating beacons. These devices use considerably less power, an important consideration for an equipment-laden maintenance truck. To ensure that LED beacon lights 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 beacon light fixtures were compared to conventional rotating beacons in terms of the distance at which observers could detect that a vehicle had moved closer to the observer (the longer this distance, the better performance is). LED beacon lights provided equivalent closure detection distances as conventional rotating beacons, as long as they were used in pairs as per common practice. Closure detection distances when only one beacon light was present were statistically significantly shorter. Overall, the results suggest that using LED beacon light fixtures provides comparable visual information to other drivers, while using substantially less power.

1. 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 beacon light fixtures containing filament sources, that project rotating beams of high-intensity light around the vehicle. Such light fixtures 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.

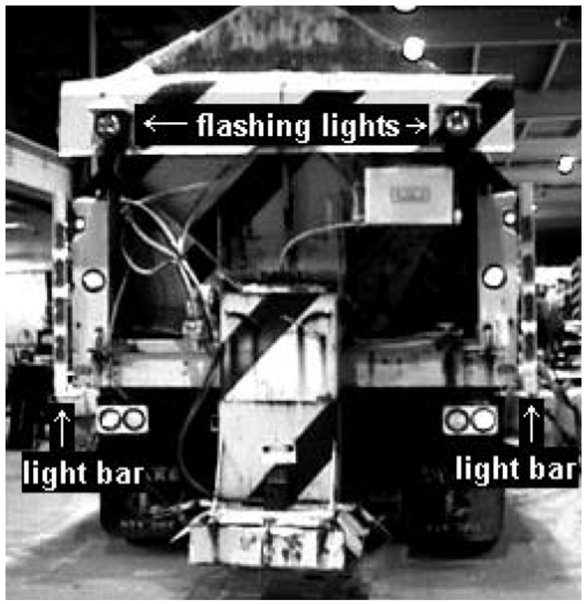

Figure 1. *Rear lighting configurations (flashing lights and steady-burning light bars) evaluated by Bullough et al. (2001) on snow plow vehicles.*

Previous research (Bullough et al., 2001) 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 (see Figure 1). This is because visual tasks such as tracking are more difficult under intermittent viewing conditions (Croft, 1971; Prablanc et al., 1986). Nonetheless, conspicuity of flashing or rotating lights is quite high because of their dynamic nature, and dynamic lights are used for this purpose (Bullough et al., 2002). They also can be configured to provide short visual detection times (Bullough, 2005). Generally, maintenance vehicles will often have tail position lights or other marker lights on while beacon lights 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 beacon lights feasible for use in place of conventional rotating beacons (Bullough, 2003; Gibbons et al., 2009). Unlike the conventional beacon lights, LED beacons flash rather than rotate. A typical flash pattern used in New York State for LED beacons is two short, successive flashes (of 0.1 to 0.3 sec in duration) per second. The flash briefly illuminates the entire angular region around the vehicle. Averaged across time, LED beacons might use on the order of 6 W to 15 W, substantially lower than the power used by conventional beacons, which would 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 beacons have one potential advantage and one potential disadvantage compared to conventional rotating beacons. The advantage is that when they are illuminated, the LED beacons illuminate in every direction (the entire 360º angle) around the vehicle, whereas the conventional beacons only illuminate a narrow angular region at any given time. The disadvantage is that sometimes, the LED beacons are off and produce no light at all, whereas the conventional beacons are always on, at least in some direction.

At the request of the New York State Department of Transportation (NYSDOT), the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute evaluated several commercially available LED beacon lights and one type of conventional rotating beacon to assess whether LED beacons provide similar visual information to a driver approaching them as conventional beacons. The evaluation consisted of photometric, temporal measurements of the luminous intensity profiles from each 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 beacons had moved closer to them. All beacon light fixtures were provided by NYSDOT.

2. PHOTOMETRIC AND TEMPORAL MEASUREMENTS

Methods

Each of the beacon's flash pattern temporal characteristics were measured in the LRC photometric laboratory. An oscilloscope and photomultiplier tube (PMT) were used to perform this task. A PMT was chosen due to its fast response time. The PMT was connected with a solid-state amplifier to the oscilloscope (Figure 2).

The light source 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 Matlab (a mathematical computation software package).

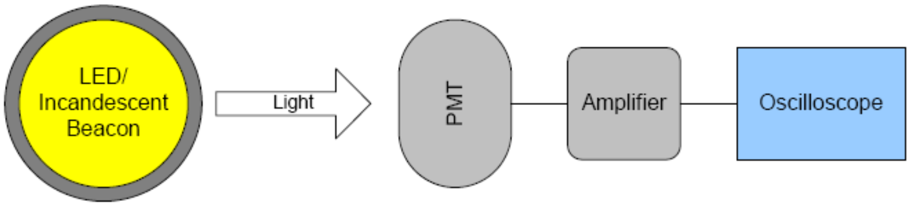

Figure 2. *Block diagram of the temporal testing apparatus.*

Regarding the photometric measurement data, each 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 3). These devices were not used for the temporal measurements because they do not have the speed to resolve a rapidly changing signal; this however was not a problem for measuring the average intensity because they will integrate over the measurement time.

As before, the light source 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 Matlab software to determine the average intensity over one flash cycle.

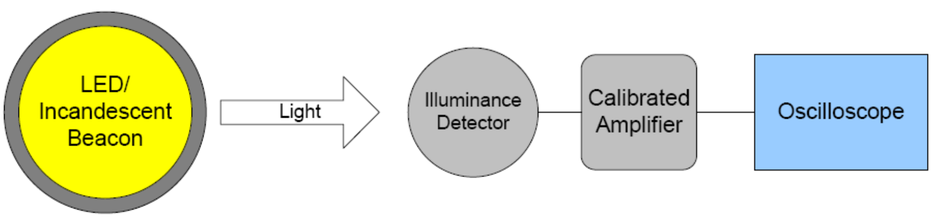

Figure 3. *Block diagram of the intensity measurement apparatus.*

Results and Analyses

Throughout the present report, the conventional rotating beacon is denoted by the letter A, and the three LED beacons, each from a different manufacturer, are denoted B, C and D. Figures 4a through 4d show the relative luminous intensity profiles measured from beacons A through D, respectively. Table 1 summarizes the characteristics of the temporal and intensity patterns produced by each beacon light.

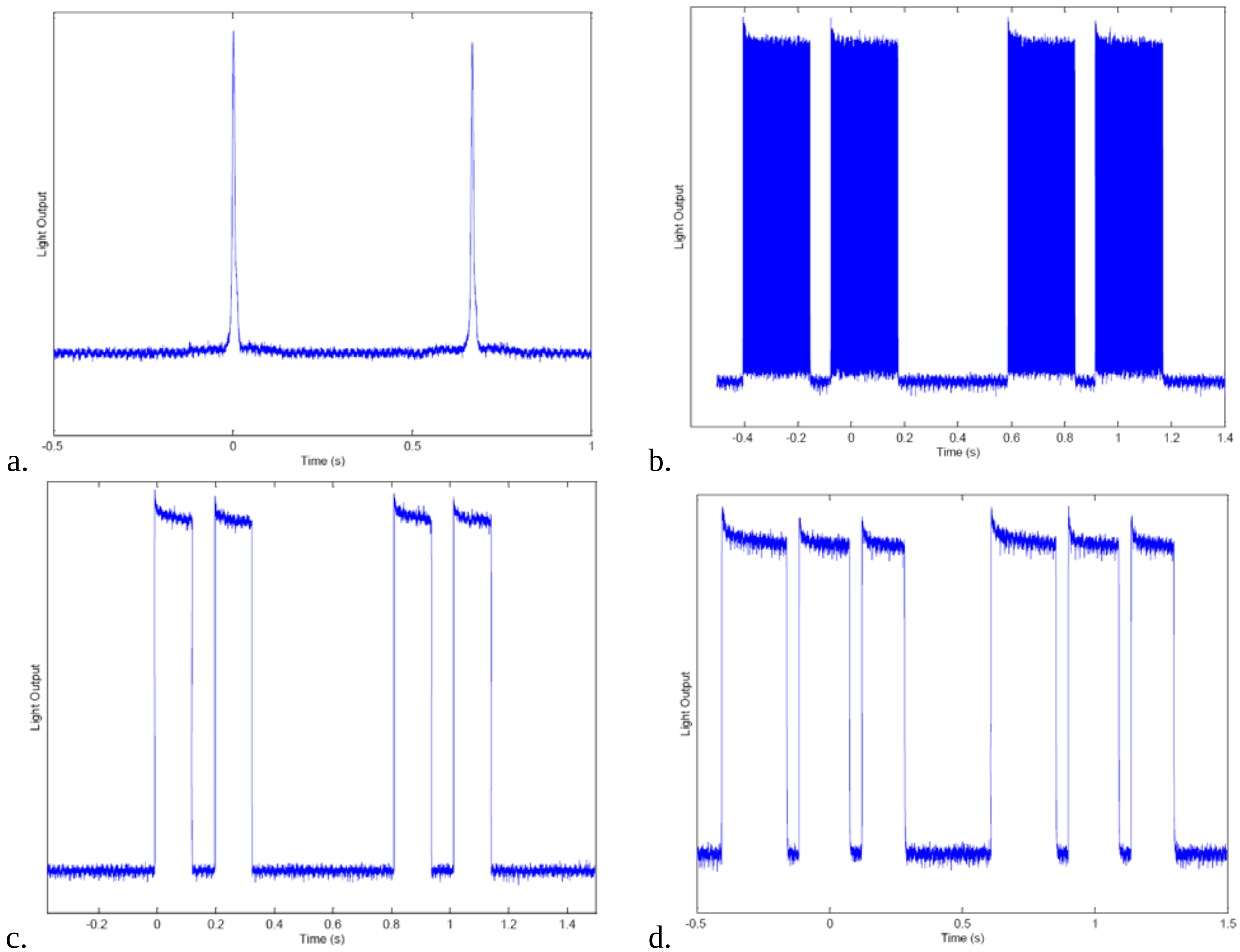

Figure 4. *Relative luminous intensity profiles from a) the conventional rotating beacon, b) LED beacon B, c) LED beacon C, and d) LED beacon D.* *<u>Note: All waveforms are plotted on relative vertical axes.</u>*

Table 1. *Temporal, photometric and electrical characteristics of the beacon light fixtures.*

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

The solid appearance of the waveform for LED beacon B in Figure 4b 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 short modulations. In comparison, LED 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 [Bullough, 2003].) LED beacon D produced three flashes per cycle. The manufacturer's instructions for programming this particular module were consulted in an attempt to re-program it to produce two flashes per cycle. The attempt was unsuccessful, and this beacon was not used in the subsequent field experiment.

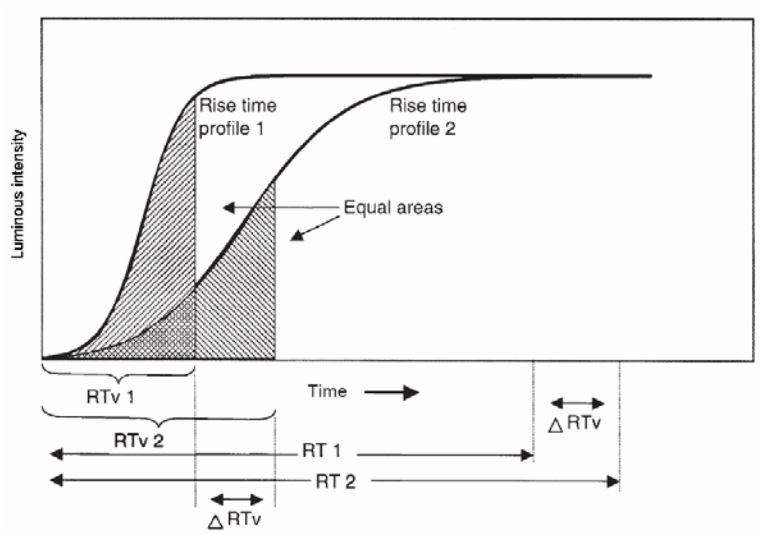

Figure 5. *Illustration of the constant light-energy response for the detection of signal lights with different onset characteristics. Response times are a combination of visual and nonvisual components.*

The average intensities (per cycle) of the LED beacon lights were lower than for the conventional beacon light. Despite this, all four beacons were observed to be clearly visible from 300 m under daytime viewing conditions, as required by NYSDOT's standard specifications. In addition, Bullough (2005) 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 5 illustrates the constant light-energy response characteristics of signal light detection.

If the waveform for the conventional 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 beacons A through D would be expected to produce a light-energy quantity of 9 cd·s in 5, 24, 31 and 26 milliseconds [ms], respectively. Although the visual response time component is shorter for the conventional light 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 (Bullough, 2005). Cole and Brown (1966) 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 55 mph will travel only about 2 ft in 30 ms, the practical difference in response times among any of the measured beacons is negligible.

In addition, all of the LED beacons (even beacon D, if it were 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 beacon A. There is about 0.6 sec between flashes for beacon A, whereas for LED beacon B, there is about 0.4 sec between pairs of flashes, and for LED beacons C and D there is about 0.5 sec between pairs of flashes (for beacon D, the third flash was ignored in making this estimate). This shorter "dark time" for the LED beacons also offsets the longer visual response time components estimated above.

3. 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 Temple Lane in the Town of East Greenbush, NY (permission to use this road was obtained in advance from the town supervisor and chief of police). The beacon lights 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 6). Four lighting configurations were tested:

Figure 6. *View of the beacon light mounting assembly.*

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

Figure 7 shows several views of the truck with the single and double beacon lights attached.

a. b.

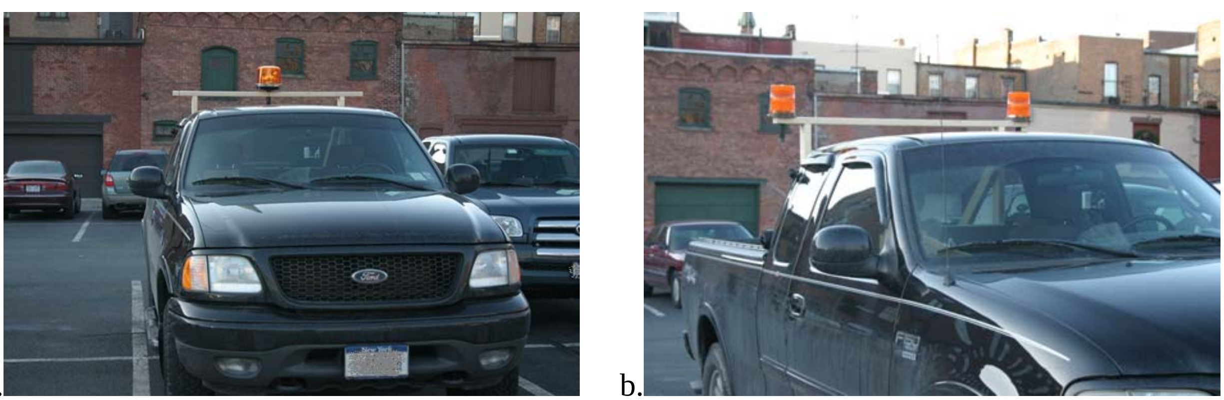

Figure 7. *a) View of truck with single rotating beacon. b) View of truck with pair of beacons.*

As described in the previous chapter, the LED beacon denoted 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 beacons B and C, the expected performance of this unit would be expected to be between those beacons as well.

The truck's initial starting location was 120 m directly ahead of the parked car (Figure 8). 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 (~2 mph) toward the parked car (after a random delay between 20 and 60 sec). 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.

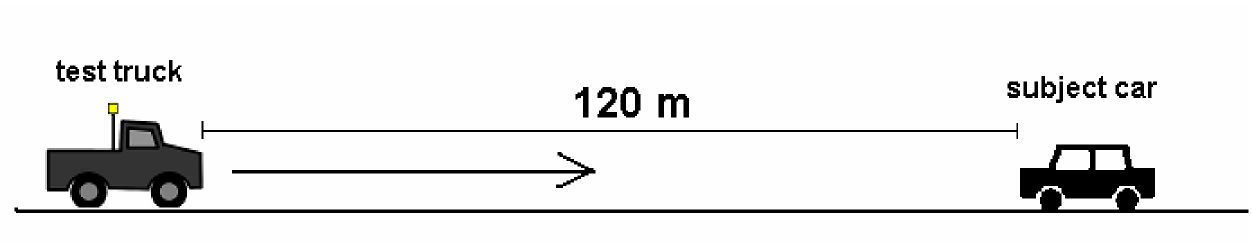

Figure 8. *Experimental layout. The truck started 120 m from the subject car and drove slowly toward it for each experimental trial.*

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 (12 subjects in total, seven males and five females, mean age 35 years, ranging from 22 to 63 years) 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 beacon light fixtures were not synchronized to each other.

Results

Figure 9 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 beacon (A) were statistically significantly shorter ($p<0.05$, using a repeated-measures analysis of variance [ANOVA; Sheskin, 1997]) than for the other configurations, which consisted of pairs of beacons (A, B and C). None of the pairs of beacons yielded statistically significant differences from each other ($p>0.05$, using two-tailed Student's t-tests with Bonferroni correction [Sheskin, 1997]). The single beacon A configuration resulted in statistically significantly shorter ($p<0.05$, using two-tailed Student's t-tests with Bonferroni correction [Sheskin, 1997]) detection distances than the beacon A pair and the beacon C pair.

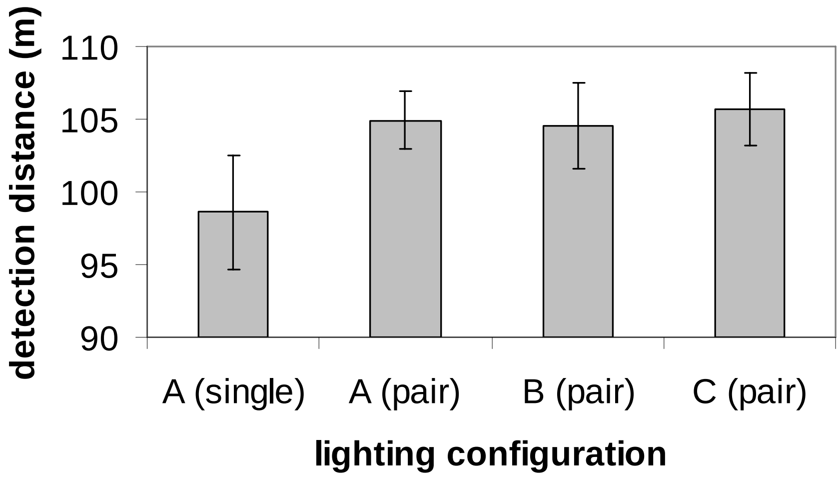

Figure 9. *Mean closure detection distances for each lighting configuration. Error bars indicate the standard deviations for all subjects under each condition.*

4. DISCUSSION AND CONCLUSIONS

The photometric and temporal measurements of each of the beacons evaluated in this study suggest that although the time-averaged luminous intensity of the LED beacon lights measured in this study were lower than for the conventional beacon light that was measured, the practical consequences of this finding was negligible, because all of the beacons measured would result in similar response times resulting in differences in stopping distances of less than 2 ft among all of them.

The results from the field study suggest that as long as LED beacon lights are used in pairs, as they are normally used on NYSDOT maintenance vehicles, drivers' ability to detect when they have gotten closer to a truck using them will not be affected. Using a single beacon light did result in slightly, but statistically significantly, shorter detection distances, suggesting that the extra visual information provided by a pair of beacon lights is beneficial, and confirming the utility of current practices. As stated previously, the beacon light fixtures were not synchronized, so the potential effect of synchronized flashing patterns was not assessed.

Table 1 includes the results of electrical measurements for each beacon; they are consistent with the manufacturers' published specifications for these units regarding electrical power use, and confirm that all of the LED beacon lights will use substantially less energy than the conventional rotating beacon. 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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