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LED Lighting for Snow Plows and Related Maintenance and Construction Vehicles

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16. Abstract (Limit: 200 words)

The goal of this project was to understand the effectiveness of light emitting diode (LED) based lights for replacement of the standard strobes on Mn/DOT snow plows and to develop a set of specifications for LED based snow plow strobe lights. Intensity measurements were performed along with field testing in order to understand the correlation between optical power output of the lights and the conspicuity of the lights under typical viewing conditions. A robust correlation between intensity and conspicuity was not established, but we were able to make a qualitative connection between intensity and conspicuity for the LED based lights under the conditions tested.

The results suggest that LED based lights are comparable in conspicuity to the standard strobe lights currently used on Mn/DOT plows, under specific conditions. We found that when viewed from a direction corresponding to that typical of a vehicle approaching from the rear; the LED based lights were equally conspicuous as the standard strobe. However, when viewed from other angles the standard strobe outperforms the LED lights in field tests. A specification was not completed, but recommendations were made for possible improvements to LED based lights to improve field test results.

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LED Lighting for Snow Plows and Related Maintenance and Construction Vehicles

Final Report

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The authors thank Sherburne County for allowing us to mount test equipment on various road signs throughout the county for the visibility studies.

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EXECUTIVE SUMMARY

Strobe or rotating beacon type emergency lighting is a requirement on all Minnesota Department of Transportation (Mn/DOT) maintenance and construction vehicles. There is an effort to replace the standard warning lighting with light-emitting diode (LED) based lights in order to reduce cost of replacement and maintenance. LEDs are well known for their long life and low current requirements resulting in their use in a variety of applications including emergency vehicle lighting. However, concerns of LED based systems include limited angularity, visibility under certain environmental conditions such as bright sunlight, and dimming capabilities during low light conditions. Because of the unique features of LED lighting, it has not been able to meet requirements for emergency lighting on maintenance and construction vehicles.

Although there appears to be little quantitative information in the research literature regarding the use of light emitting diodes (LED) for use as strobes on snow plows, LEDs are being used on many maintenance vehicles throughout the country.[1-4] The benefits of LED technology include lower energy, higher reliability, and reduced maintenance costs. There are many applications of LED technology for general lighting replacement, but there appears to be little information regarding the comparison of LED based snowplow strobes with some of the more traditional technologies.

The scope of this project is to review the strobe type lighting currently used on Mn/DOT snow plows and LED replacements for that lighting. Included in the study is laboratory and field testing of the different light types in order to correlate objective and subjective test results. Lab testing included detailed optical measurements of angularity, brightness, and color for the standard and LED strobes. Field tests included visibility testing of different lights under typical driving conditions.

The results of this study are generally mixed. First, it is clear from the data that the low power benefit of LED lights can be realized under specific conditions. For similar visibility conditions the LED lights performed as well, or in some cases better, than the standard strobe used by Mn/DOT. Viewed directly from the rear, side, or front of the plow vehicle, it appears that LED based strobes can be made to be equally conspicuous while reducing the costs associated with high power, maintenance, and reliability issues.

However, the above benefits are limited by the problems associated with angularity of the LED lights. The LED lights were shown to be equally conspicuous as the standard strobe at well defined angles only. The reduced conspicuity at off angles is a direct result of the angular intensity variation of the LED devices due to the lenses used to increase the intensity at the front, back, and side of the plow vehicle. Decisions must be made regarding the requirements of visibility at off angles in order to determine if LED lights can be made to meet the needs of Mn/DOT. If the expectation is that conspicuity comparable to the standard strobe is needed at all angles, LED lights must be designed to meet those needs. However, if conspicuity at limited angles is acceptable, then LED fixtures are already on the market that meets those needs.

CHAPTER 1

1.1 Introduction

In general there is a strong interest in replacing standard lighting systems with light emitting diode (LED) based systems for a variety of reasons. The most commonly stated benefits include, but are not limited to, increased reliability, improved efficiency, and reduced maintenance costs. In particular, there is interest in replacing standard warning lights on a variety of maintenance, construction, and emergency vehicles with light emitting diode (LED) based systems because of the same perceived benefits. In the relatively harsh environments of many of the above applications, the robust nature of solid state lighting provides a clear advantage in regard to reliability and maintenance. In addition, increased efficiency results in less demand on the vehicle electrical systems leading to less maintenance. The following paragraphs discuss the basics of LED based lighting as it relates to the more traditional lighting in order to prepare the reader to better understand the measured characteristics.

1.2 Background on Lighting Terminology

The types of lighting that are used on maintenance and construction vehicles can be broadly categorized into three groups – gas-discharge strobes, rotating beacon, and LED strobes. Each lighting scheme has strengths and weaknesses depending on the application.

Optical characteristics of the different light types discussed in this report can be measured and specified in a variety of different ways and may lead to confusion. Comparing the results of the measurements and how they relate to the road testing of the different lights requires fairly detailed knowledge of how the light is generated, directed, and focused in order to understand how the benefits of each light type is realized. In this study measurements of radiant flux were used in an attempt to establish a connection between the luminous flux incident on an observer and the perceived brightness of a distant snowplow strobe. This section is intended to clear up any confusion regarding the different units of measure used in this project.

The most straightforward measure of the light output of a source is the radiometric measurement called radiant flux – measured in watts (W). Radiant flux is the direct measurement of the total light generated by a light source and is directly related to the electrical power required to generate the light. In the simplest form, radiant flux is given by the product of electrical power consumed and the efficiency of the source at converting the electrical power into light. Although radiant flux is an accurate direct measure of the optical power generated by a source, it is misleading when discussing the perceived brightness of light sources such as snow plow strobes. The intensity of a light source is dependent on the characteristics of the system used to detect the light, in this case the human eye. An incandescent lamp is used as an example. Figure 1.1 gives the radiant flux characteristic of an incandescent lamp (curve #1) along with the response of the human eye (curve #2) to different wavelengths of light. Since the human eye cannot detect ultraviolet (<~300nm) or infrared wavelengths (>~800nm), the radiant flux ‘observed’ by an individual is less than the total radiant flux emitted by the incandescent source. Radiant flux measurements must be corrected by the response of the human eye (photopic response) in order to estimate the brightness perceived by the observer. The experimental data collected on the lights in this study were measured using an optical power meter with a photopic filter in the optical path.

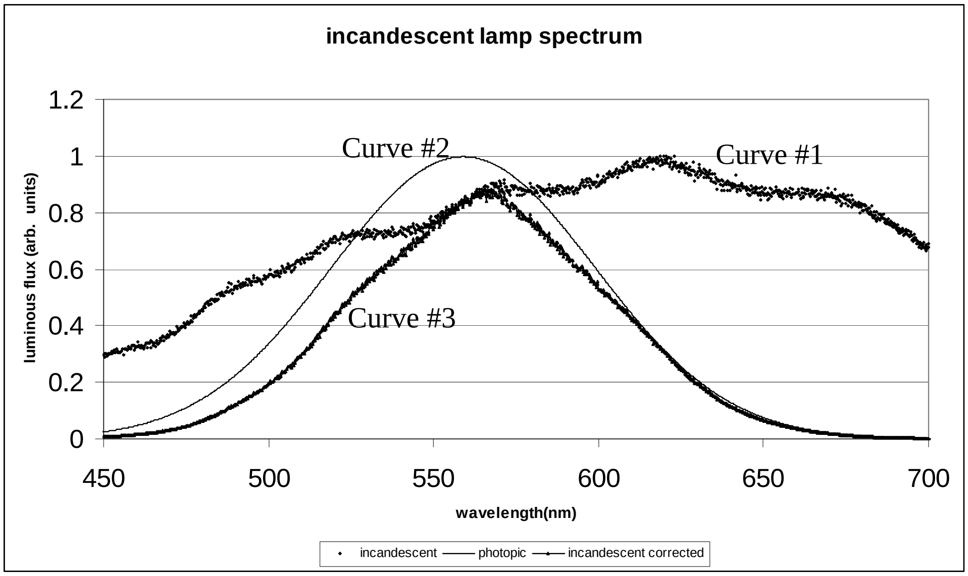


Figure 1. 1. Incandescent lamp spectral characteristics and eye response

The perceived brightness of a light source viewed by a human observer is dependent on the response of the human eye. When the radiant flux values are adjusted by the magnitude of the human eye response at that wavelength, the result is luminous flux in units of lumens. Light sources used for general illumination are usually specified in units of lumens giving a measure of the total visible light useful for illumination. The luminous flux of the incandescent source is found by the product of the radiant flux and the photopic response at each wavelength and is shown as curve 3 in figure 1.1.

Finally, luminous intensity can be thought of as a measure of the luminous flux of a light source confined to a particular angle. Luminous intensity is given in candela which has units of lumens/solid angle. Imagine two equivalent light sources as shown in figure 1.2. The top light source has a lens that focuses the light into a beam pattern that is less narrow than the bottom beam. In the upper image the amount of light incident on an object is a small percentage of the total light emitted from the source, whereas in the bottom figure, most (a higher percentage) of the light is incident on the object. Since the luminous flux of the two sources is equivalent, the object in the bottom figure will receive more light and the observer will perceive a brighter source even though both sources are emitting the same amount of visible power. Since the light is confined to a smaller angle, the luminous flux (lm) per unit angle will be higher for the bottom figure and the resulting luminous intensity (cd) will be higher. The point is that by tightly focusing the light output of an optical source, one can significantly increase the perceived brightness of the source over small angles without increasing the power consumed by the light source. High intensity LED-based strobes rely on this focusing technique in order to achieve high brightness for particular directions while maintaining low electrical power. Luminous intensity (in candela) is often used to specify the 'brightness' of focused and directed lights such as vehicle warning lights where general illumination is not of interest.

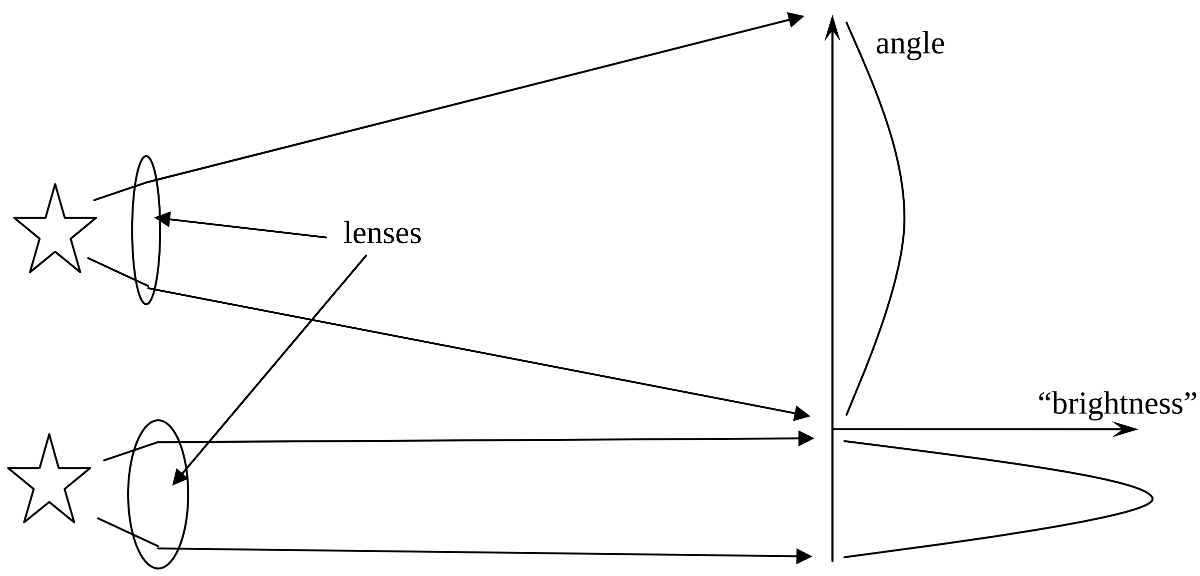


Figure 1. 2. Conceptual sketch demonstrating intensity variation caused by focusing

1.3 Strobe Types

There are a variety of different lighting technologies for application in strobe type warning lights. Following is a brief description of two of the three main technologies giving a basic discussion of the technology with benefits and drawbacks of each. The discussion is focused on the HID and LED technologies since in Mn/DOT snow plowing operations the interest is focused on those technologies. Lights tested in this study were supplied by Whelen Engineering (Whelen) [5], Public Safety Equipment (PSE) [6], and Federal Signal (Federal) [7]. Detailed information of the lights tested in this study can be found in the Appendix.

The standard plow lighting currently used on Mn/DOT snow plows is a HID strobe made by Whelen Engineering and is hereafter referred to as the standard strobe. The standard strobe tested is shown in figure 1.3. The standard strobe uses a flash lamp similar to the xenon-based flash lamps that are used in photography equipment.

The standard strobe operates on the principle of discharge in a gas mixture. Electrodes at the ends of the lamps are energized to a high voltage and an arc forms in the gas. The result is a short but very bright emission of visible light. The spectral output of the flash lamp is centered near the human eye response, but extends past it at both high and low wavelengths. Broad coverage of the photopic curve results in a white color variation. The amber lens/filter shown in the figure is used to filter the white light produced by the flash lamp and results in the characteristic yellow light generated by the standard strobe.

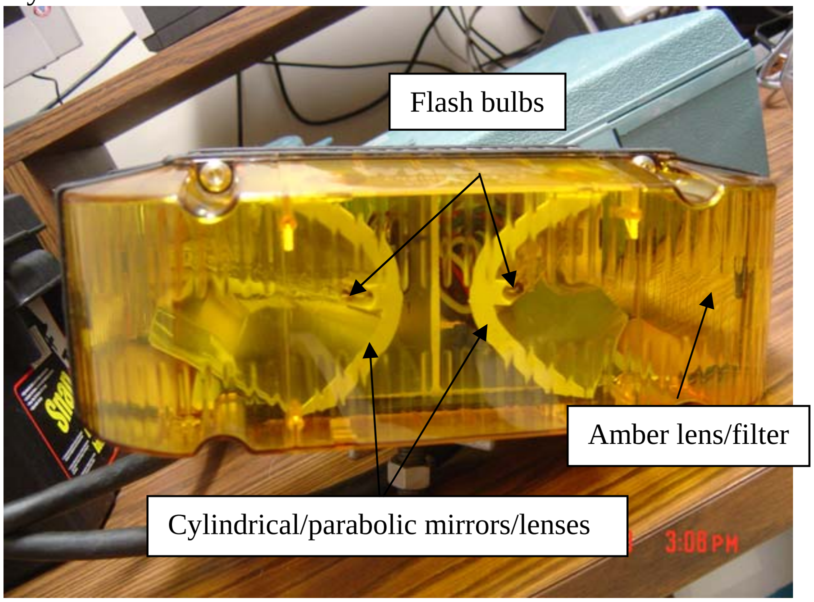


Figure 1. 3. HID Standard strobe tested in this study

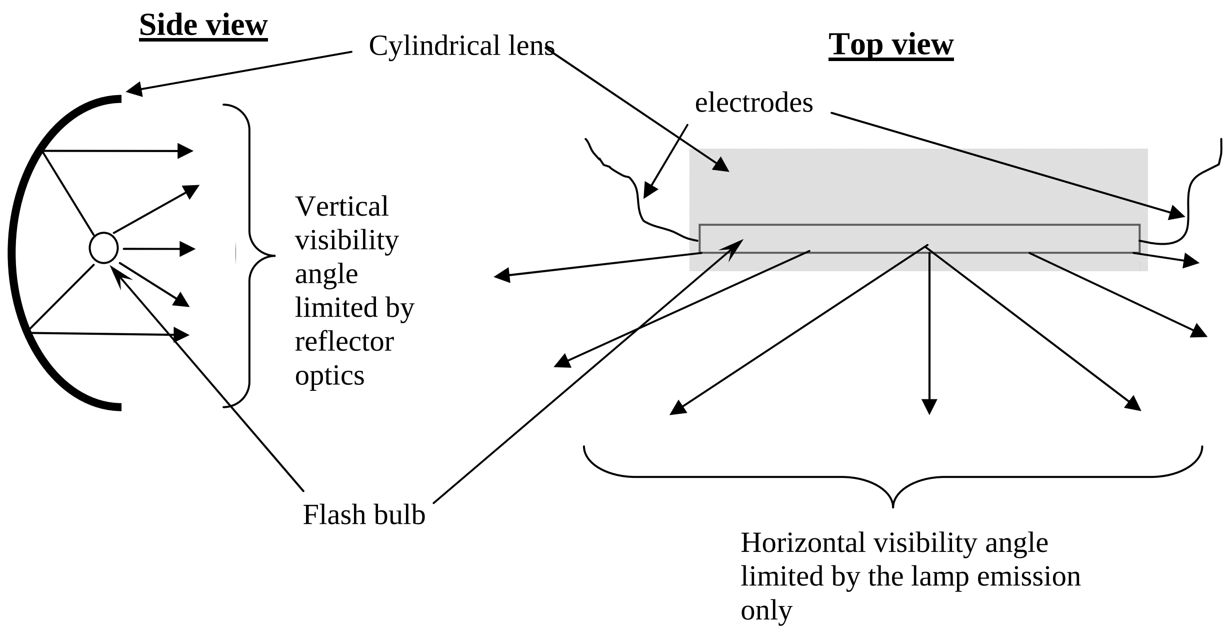


Figure 1. 4. Sketch highlighting the physical and optical structure of a single light assembly for the standard strobe

A sketch of the system is shown in figure 1.4 highlighting the important components to demonstrate the directional characteristics of the strobe. Physically, the strobe is configured with a tube shaped lamp near the focal point of a cylindrical/parabolic mirror/lens. The lens limits the amount of light that is given off in the vertical direction, but does not limit the light in the horizontal direction. The cylindrical lens shown in the figure reduces the beam divergence in the vertical direction resulting in a higher luminous intensity in the direction of the observer. Horizontally the light emitted from the flash bulb leaves the lamp housing covering nearly 270^o when the flash lamps are placed at 90^o angles as shown in figure 1.5. The result is high visibility of the lamp at nearly all angles around the plow vehicle.

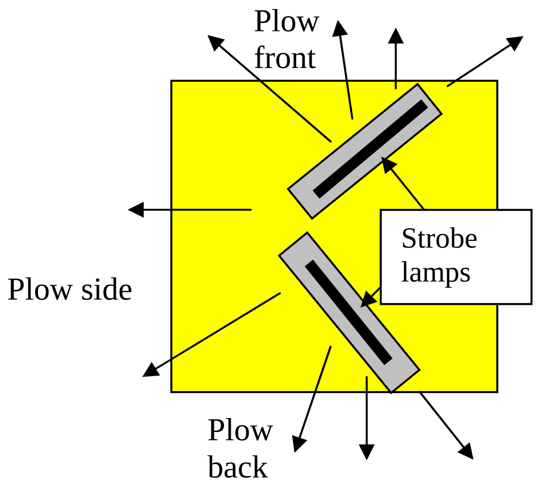


Figure 1. 5. Top view sketch representative of the standard strobe used in this study

An LED strobe made by Public Safety Equipment (PSE) and tested in this study is shown in Figure 1.6. The light from each array is generally directed towards the front, back, or side of the plow vehicle. The picture shows one side of the strobe with 12 individual LED lamps assembled in to a 2x6 array. The complete strobe is based on arrays of LED lamps directed towards different angles as sketched in figure 1.7. All of the LED strobes considered in this study have the same basic configuration of LED arrays facing in three directions.

Figure 1. 6. Photo of one of the LED strobes from PSE used in this study

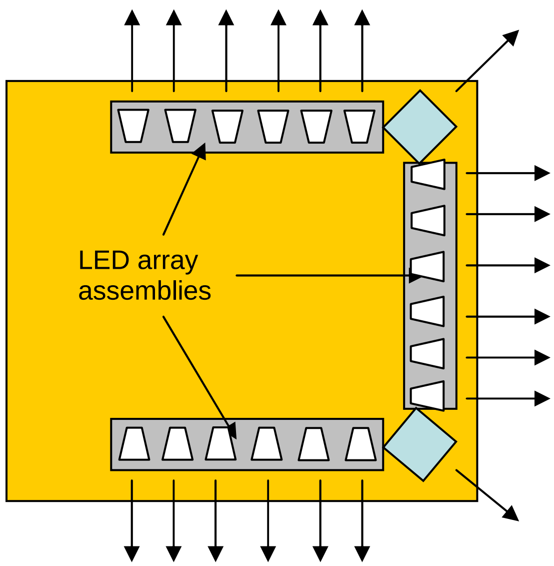


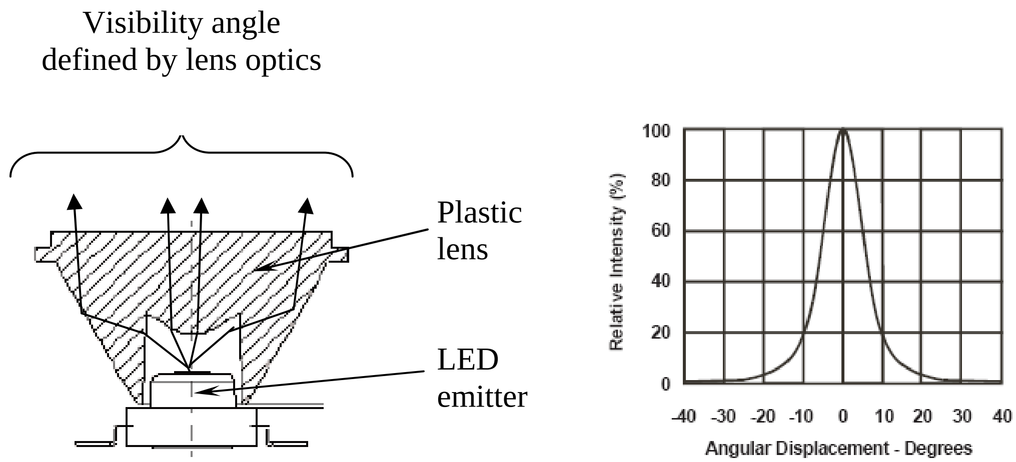
Figure 1. 7. Top view sketch representative of the LED lights tested in this study

Each individual LED lamp consists of an LED emitter and a lens assembly similar to that shown in Figure 1.8. Figure 1.8(a) shows a typical LED emitter used in the LED strobes. The LED emitter shown is a Luxeon LED manufactured by Lumileds [8] and is typical of what one might find in an LED strobe. The light output from the emitter shown would generally be directed in a relatively large angle (~>100deg) without the use of collimating optics. Lenses like those shown in Figure 1.8(b) or similar reflecting lenses are used in the LED strobes to focus the light generated by the emitters.

(a) (b)

Figure 1. 8. Image of a typical (a) LED emitter and (b) lens used in the LED strobes [8]

Figure 1.9 (a) shows one possible sketch of how an LED lamp is assembled. The lens is attached at the emitting surface of the LED so as to redirect as much of the light as possible in the direction of interest. Each strobe manufacturer uses a proprietary lens structure, but the end result is similar. Partial collimation directs more of the light into a smaller angle increasing the luminous intensity at the observer and making the lamp appear brighter. The curve in Figure 1.9(b) is representative of the angular displacement of the light for the emitter/lens assembly shown.



(a) (b)

Figure 1. 9. Sketch of (a) a typical LED emitter assembly and (b) the corresponding angular intensity profile [8]

Note that the light intensity drops significantly at a viewing angle of greater than ±10 degrees resulting in very low intensity at angles away from the beam center. This is the origin of the angularity concerns associated with LED based strobes. One should note that alternate lenses could be used to produce a wide variety of angular displacements to produce better coverage around the plow vehicle. However, given the limited luminous flux generated by LED devices, increasing the angular displacement would result in significantly reduced luminous intensity and hence lower perceived brightness Additional LED emitters would be needed to increase the intensity. LED lamps and lenses can be purchased off-the-shelf with a variety of angular displacement characteristics [9].

LEDs are designed to produce a very narrow color range based on the materials used in the emitting region of the device. The LEDs used for snow plow strobes are designed to produce amber light around 590nm in the visible region. A typical spectral response from an amber LED is shown in Figure 1.10.

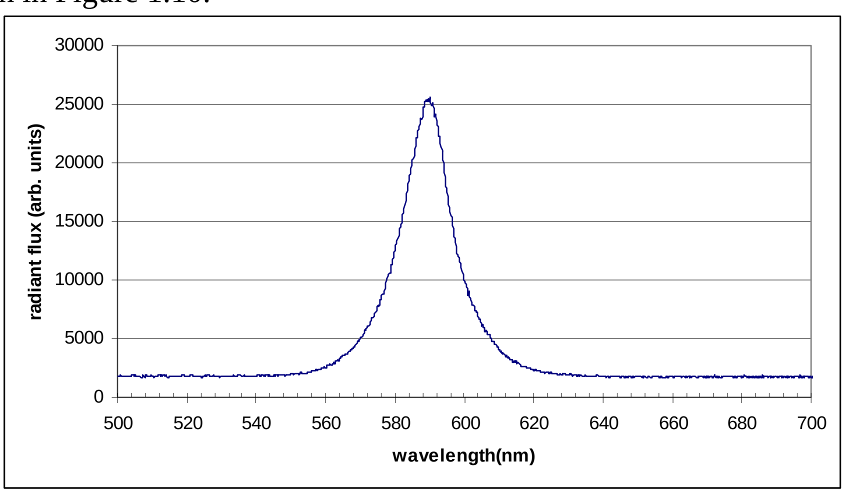


Figure 1. 10. Spectral characteristics of typical amber LED materials (InGaAlP)

Note that the light generated is centered near 590 nm and covers only a very small band of wavelengths near the center wavelength. This characteristic is much different than most other light sources which have an emission spectrum spread out across the visible spectrum as with the incandescent spectrum shown above. The narrow LED spectrum is in part responsible for the efficiency increase achieved using LED strobes in place of the standard strobes. Essentially, all of the light generated by the LED is emitted in the visible region.

The above discussions should make it clear that the color, lens structure, and light generation methods contribute to the results in this study. More details of the above effects will be addressed throughout the remainder of this report. Detailed measurements of a variety of characteristics are presented to help demonstrate some of the trade-offs between HID and LED based strobes.

1.4 Benefits of LED Lighting

LEDs are ideally suited for emergency lighting applications for a variety of reasons, but have a few drawbacks that make the decision to use them more than trivial. The main benefits of LED based technologies for plow lighting are efficiency, reliability, and to some extent directionality. The main drawbacks of LED based technologies are mostly up front cost and total light output or luminous flux.

Table 1.1 gives luminous characteristics for three different light sources. Luminous efficacy is defined as luminous flux/electrical power in units of lumens/watt and is the measure of visible light generated for a given amount of electrical power input to a source. Luminous efficiency is defined as the percent of light generated by a source that can be seen by the human eye. The types of lamps listed are representative of those used in emergency strobe lights and the parameters listed explain well the different efficiency characteristics of each type. Incandescent lamps like those used in rotating beacon lights are at a clear efficiency disadvantage. Both efficacy and efficiency are less than that for the other technologies. In comparing xenon arc lamp and LEDs, the choice is more difficult. First, the luminous efficacy is comparable between the two technologies implying that from an efficiency standpoint the trade-off is minimal. However, since the LEDs can be made to emit at narrow wavelengths, the luminous efficiency is greatly enhanced. In other words, the efficiency of the source is reduced for the arc lamp because it emits light of uniform white color and must be filtered to produce the amber color. The other trade-off between LED and arc lamp is the total light output or total luminous flux. Currently, high power amber LEDs can be driven to produce only less than 100 lumens of light for a single device. In contrast, an arc lamp can be made to produce orders of magnitude more light from a single source. The result is that in order to produce equivalent light output, many LED devices must be assembled into a single source. This explains the different physical structures of the warning lights tested in this study.

Table 1. 1. Optical characteristics of common light sources [10]

Technology	Overall luminous efficacy (lm/W)	Typical luminous flux (lm)	Luminous efficiency
incandescent	15-20	500-2500	2-3.5%
Typical high power white LED	60 to 90	100-200	10-20%
Amber LED	40-50	40-50	50%
xenon arc lamp	30–50	kilo lumens	5-8%

CHAPTER 2

MEASUREMENT PROCEDURES/METHODS

2.1 Optical Power Measurements

Optical intensity measurements were performed using an apparatus made in-house that allowed for semi-automatic measurements of optical intensity at typical observation distances and over different viewing angles. The measurement configuration is shown in figure 2.1. A motorized control system was built that allowed for automatic rotation of the strobe lights during measurement. A stepper motor was used to rotate the strobes and control rotation angle during the measurement. A simple microcontroller circuit was used for control of the rotation apparatus. The optical system consists of a silicon photo detector and a photopic filter attached to small rifle scope. The photopic filter was used to emulate the spectral response of the human eye during daylight viewing conditions.

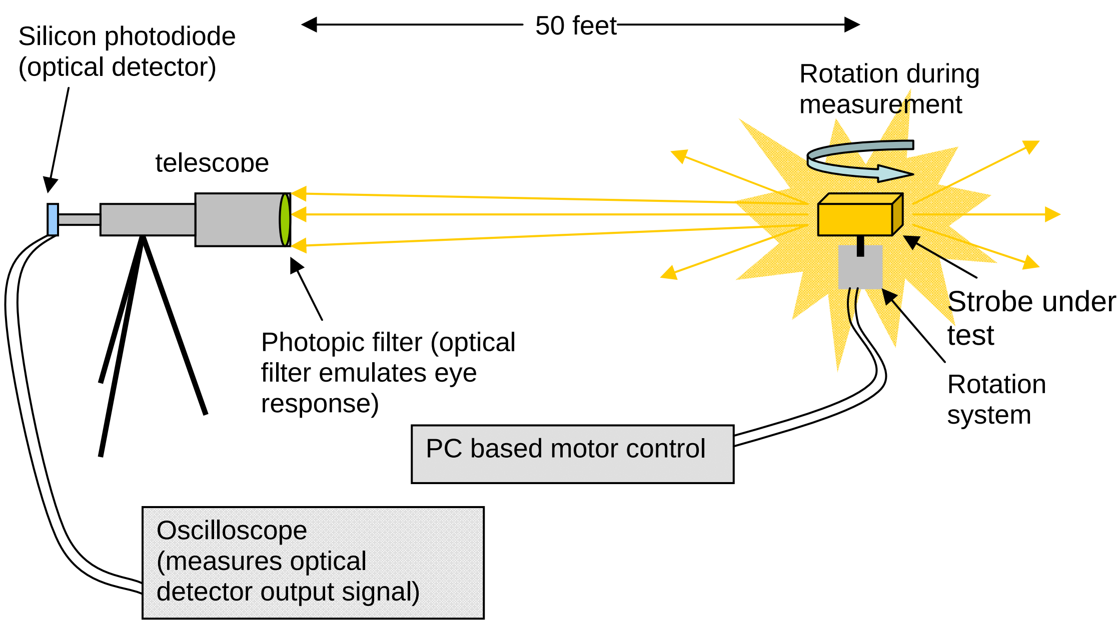


Figure 2. 1. Optical power measurement system sketch

The output of the photo-detector was amplified with a simple electronic amplifier so that the response to be more easily measured on an oscilloscope. The response of the circuit was calibrated so as not to saturate the detector/amplifier combination during measurement and was tested to verify the time response was much faster than any of the critical characteristics of the strobes being tested. Time response data was also collected to help understand the effect of pulse width/spacing on perceived brightness. Measurements were made at a tilt angle of 0^o and over rotation angles of 0^o to 360^o. The distance between the strobe and measurement apparatus was set large enough (20-30 feet) so that the strobe under test would appear to the detector as a single light source, but small enough so significant light levels reached the detector. The absolute accuracy of the rotation angle is about +/- 5 ^{o} and the resolution is approximately 1 ^{o} based on analysis of the data.

Figure 3.2 defines the reference angles for the measurements taken for all measurement techniques. The angle defined as 0^{o} corresponds to the side of the strobe normally facing the cab of the truck. The 90^{o} angle corresponds to the side of the strobe normally facing the rear of the truck – the point of observation for a vehicle approaching the truck from the rear. The 180 ^{o} and 270 ^{o} angles correspond to the faces of the strobe normally observed from the side and front of the truck, respectively.

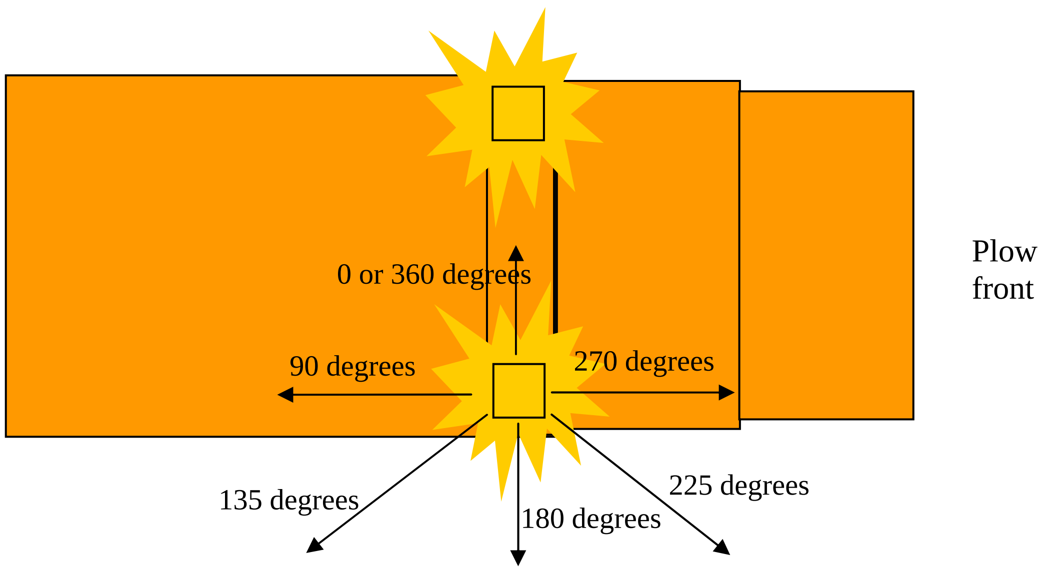


Figure 2. 2. Angles of reference for data collected

2.2 Visibility Testing

Several attempts were made to collect data on the conspicuity or observability of the different strobes. Correlation of the analytical data with conspicuity results is needed in order to allow Mn/DOT to use more consistent and less subjective measurement techniques when evaluating strobes from different vendors. The data discussed below shows that purely analytical results can be misleading when judging relative brightness of the different strobes. Therefore, correlation of the analytical results to observation data taken under normal driving conditions is required. Two methods were attempted to collect observation data under driving conditions: track testing and distance of minimum observability. Following are descriptions of the two test methods.

2.2.1 Track Testing

Tests were run on 7 March 2007 at the Minnesota Highway Safety and Research Center. These tests were run as an evaluation of the planned comparison between LED and conventional lights for snowplows. The track at the safety center was dry, and the plows were used to bring snow from the sides onto the pavement. Testing was done on the westbound side of the track going around a left-turn then right-turn section with partial shading from trees on the right. Selection was made to have the drivers heading into a setting sun with snow being driven by the plow. The combination of snow and sun was selected to create the maximum possible masking of the plow lights. Test drivers left 10 seconds after the plow and would approach as the plow entered the evaluation area. Plow drivers coasted to a lower speed when approaching the observation area forcing the driver to judge the approaching speed after both vehicles were in the snow.

The observer rode in the passenger seat of the vehicle and noted the following distance when the drive first lifted off the throttle approaching the plow, and the following distance when it stabilized. Drivers all used their own vehicles. Speeds during the test were taken from the vehicle speedometer. Each driver made two passes, one after each plow. Distances were observed using cones spaced every 25 feet along the side of the track.

2.2.2 Road Tests

Given the lack of meaningful results from the track testing we attempted to gather useful data with another method. The alternate method consisted of placing stationary plow lights on the sides of a road under diminished visibility conditions and measuring the distance when the two strobes are first observed by an approaching motorist. We made several attempts at distance of observability (DOO) testing during the Winter/Spring 2007 and Winter/Spring 2008 seasons. The test facilities, observers, and conditions varied between the attempts.

This testing was established to determine the minimum distance at which an observer could identify strobes under differing weather and driving conditions. Tests were done on days with conditions ranging from light fog to snow-fog to heavy snow conditions and morning to late afternoon sun. Motorists were asked to drive on a road in the direction of two strobes set up on the side of the road. At the point where the driver first noticed the strobe, the distance was recorded.

A schematic of one test facility used for the road tests is shown in figure 2.3. Strobes were set up at the intersection of county 65 and county 8. The distance between the start of the drive and the strobes was set so that under the given weather conditions the strobes were not immediately visible. Cones were set on the side of the road at 0.1 mile increments and the driver was asked to record the number of the cone at the point where he/she first observed the strobe. The drivers were collected to start the test at a cross road approximately 1.5 miles from the placement of the strobe lights.

Motorists were asked to drive in a normal manner for the given conditions toward the intersection where the strobes were located. The distance that the driver first noticed the strobe is recorded and the process is repeated for another strobe. Eight drivers and two strobes were tested under heavy snow conditions and three drivers and two strobes were tested under fog conditions. All drivers were university students ranging from 18 to 30 years in age. Approximately one minute wait was allowed between drivers so that slowing, braking, etc. of the previous driver would not influence the results of the following driver. All drivers completed the test for one of the strobes, the strobe was changed and then all drivers completed the test for the next strobe. The standard strobe and the PSE LED strobe were tested and all testing was completed in approximately 20 minutes. Discussion of the results of the driving test is given in the test results section.

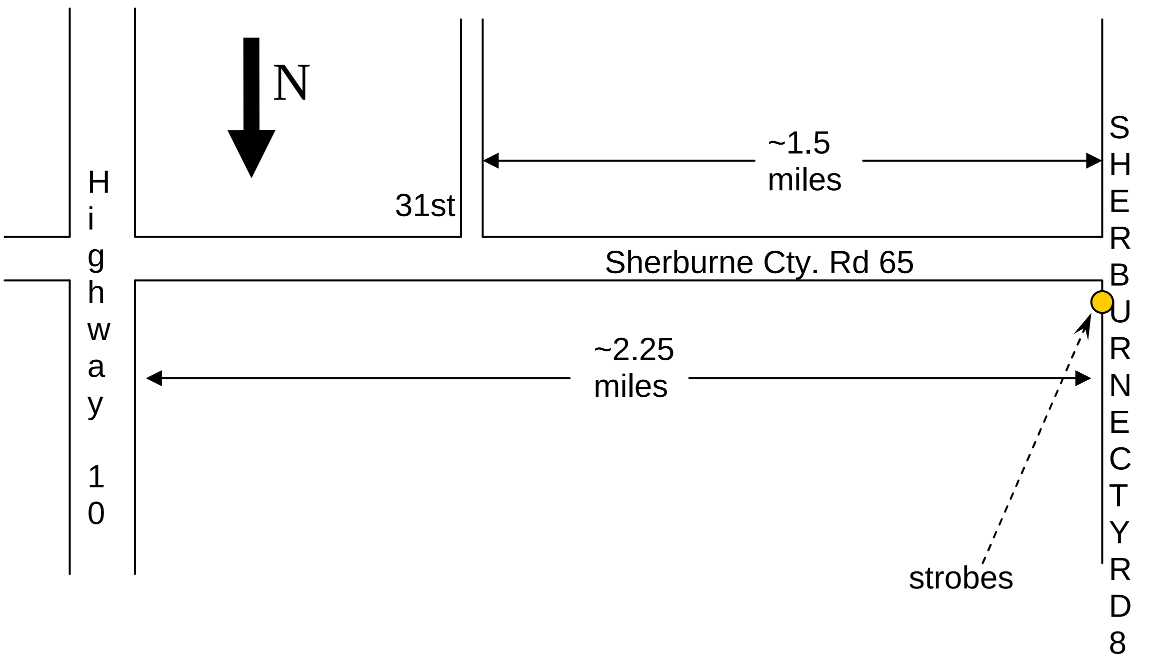


Figure 2. 3. Facility for minimum observability testing during spring 2007

Figure 2.4 describes an alternate set of test facilities used during the evaluation. The locations consisted of flat, straight sections of road with two strobes placed 12-14 feet off the ground on each side of the road. The strobes were fastened to extensions and then attached to road sign posts. The placement of the strobes on either side of the road allowed for direct comparison of the units against each other. The spacing of the devices was large enough so that the lights could be clearly distinguished at distances of about 1 mile under clear conditions. Since the angular orientation of the lights has a strong effect on the measured light intensity, the orientation of the lights during the road tests was critical. Care was taken to ensure that the correct face of all of the lights was directed toward the approaching test vehicle.

Volunteer drivers, along with passengers, were asked to drive along Sherburne Cty. 8 or 32 toward the strobes positioned on the roadside. The drivers were instructed that as the vehicle approached the strobes one or both of the lights, at some point, would appear through the snow cloud. At the point the first light was observed, the volunteer was asked to reset the odometer on the test vehicle. At the point the second light was observed the volunteer was asked to make a mental note of the odometer reading.

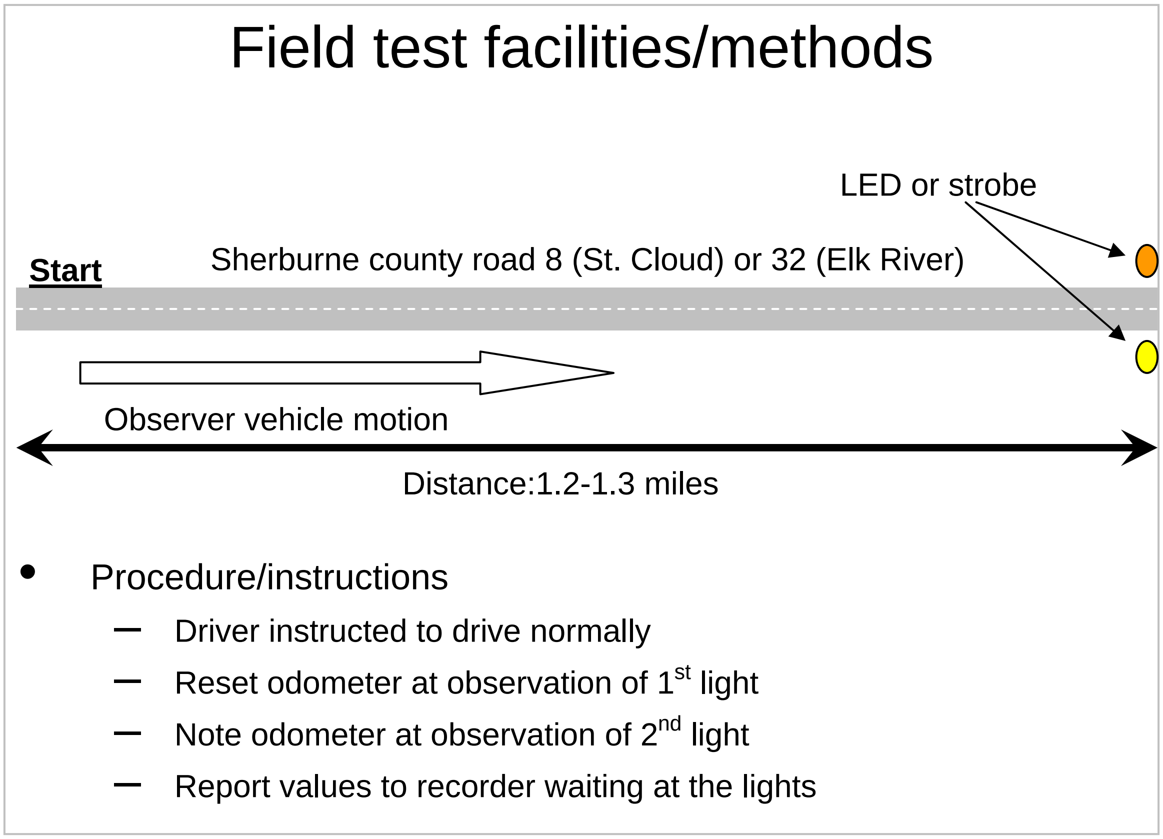


Figure 2. 4. Alternate road test facility and method used in spring 2008

The motorist was then instructed to proceed toward the location of the lights and report the final and intermediate odometer readings to a volunteer. The final odometer reading was used for the distance of observability (DOO) of the 'brighter' of the two lights and the difference between the final reading and the intermediate reading was used for the DOO of the 'dim' light. The DOO values were recorded and compared for three LED strobes and the standard strobe.

2.3 Pulsed Minimally Distinct Border Method

Although the above optical power measurements give valuable data regarding the variation of the optical output of the different strobes, the results appear to be inconsistent with observed brightness comparisons by participants in field tests. As expected the human eye perceives brightness levels of the strobes differently than a photo detector depending on a variety of conditions, including color and time. One method developed in an attempt to make better perceived brightness comparisons is a variation on the Minimally Distinct Border (MDB) method used to determine the color response of the human eye [1]. In this method the perceived brightness of a colored light source is compared to a reference light source by adjusting the brightness of two adjacent images generated by the two lights. The brightness of one of the lights is varied until the border between the adjacent image components is minimally distinct. Figure 2.5 shows a sketch of the images under varied intensity conditions. Each of the five images shown in the figure consists of two rectangular sides. The right side of each image is set to a reference brightness level and the left side of the image is varied in brightness until the border between the two regions is minimally distinct as shown in the center image of figure 2.5.

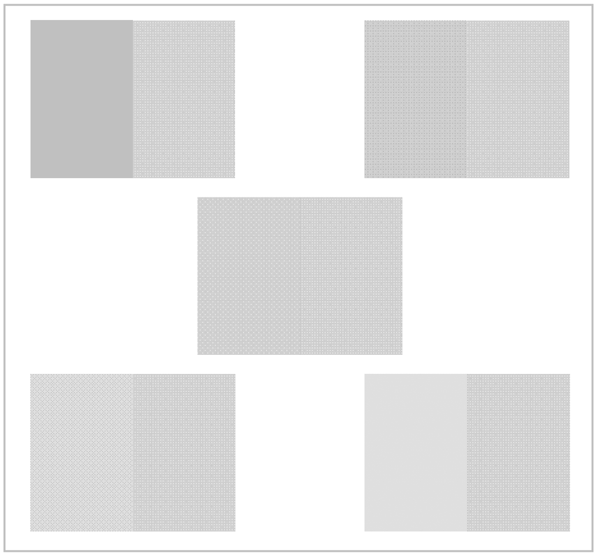


Figure 2. 5. Minimally distinct border method visualization

One of the issues with making perceived brightness measurements of strobes is that each strobe has a unique timing characteristic. That is, each strobe flashes in a unique way so that comparison in brightness between strobes is difficult. To resolve the timing variation issue we developed a MDB system for use with strobed light sources. Figure2.6 shows a sketch of the system we used to make the strobed MDB measurements. The system consists of a dark room with an optical shield to generate the border between the image components, an in-house built reference strobe against which to compare the supplied strobes, neutral density filters to vary the reference intensity, and a system to generate the pulse sequence for the reference strobe so it is pulsed the same rate as the device under test (DUT). The reference strobe was built to be brighter than any of the supplied strobes so that the intensity could be reduced to the DUT level by placing intensity reducing (neutral density) filters in the optical path between the reference and the image screen.

The test is performed by placing an observer inside the dark room facing the image screen with eyes closed. The DUT, pulse generator, and reference strobe are powered on so that the image is projected onto the image screen. The pulse generator measures the pulses from the DUT and generates the pulse needed to flash the reference strobe at the same rate/time. The filter is changed to reduce the reference intensity while observer is asked to watch the image screen to identify the point where the border is minimally distinct between the sides. The percent transmission for the filter is recorded as a measure of the brightness difference between the reference and DUT. The test is repeated for multiple observers and DUTs. The end result is a comparison of intensity of the different supplied strobes to that of the reference. The brightness of the supplied strobes can then be compared to each other by way of the reference.

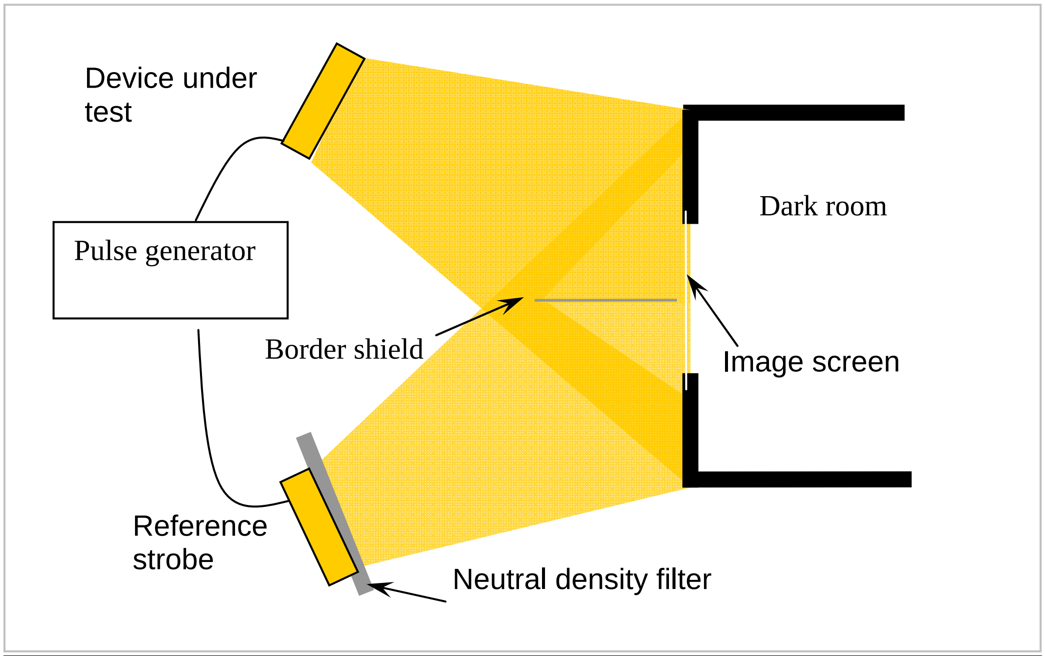


Figure 2. 6. Strobed minimally distinct border (MDB) method test facility

2.4 Spectral/Color Characterization

Measurements were taken of the visible light spectrum to compare color differences between the standard strobe and the LED based strobes. The measurements were taken using a CCD based spectrometer (from Edmund Optics) under dark room conditions. Raw data was taken using the spectrometer and was then corrected for the human eye response by normalizing with the standard photopic response curve. Photopic correction is required in order to be able to directly compare the relative brightness of each of the strobes at different wavelengths.

2.5 Electrical Power Measurement

Since one of the driving forces behind the move to LED lighting is an improvement in power efficiency, electrical power data is of interest. Electrical power measurements were performed for all of the provided lamps. The measurements were done by simply measuring the DC voltage supplied to the strobes along with the pulsed current drawn by each light. The voltage was monitored using a bench top multimeter and the current was measured using a current probe connected to an oscilloscope. The current probe/oscilloscope system allowed for the measurement of instantaneous current and power in order to determine peak values for those parameters during a single strobe cycle.

CHAPTER 3

MEASUREMENT RESULTS AND DISCUSSION

3.1 Optical Intensity Results

Plots of intensity v.s. rotation angle for each of the strobes measured are given in Figure 3.1.

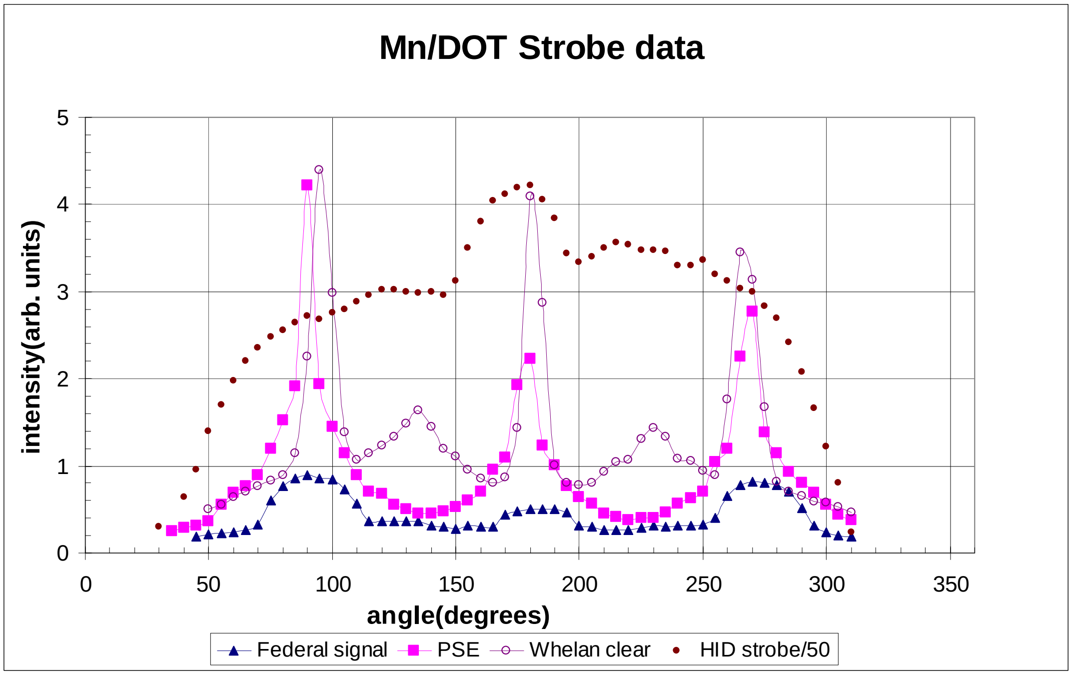


Figure 3. 1. Optical power measurement data – intensity v.s. rotation angle

Four key observations in the intensity v.s. rotation angle data are noted. First, there is a significant variation in the intensity for the three LED strobes when observed at different angles. The intensity decreases dramatically when the LED strobes are viewed at angles of 135 degrees and 225 degrees corresponding to viewing the truck at positions midway between the side and back or side and front of the vehicle. This variation is consistent with expectations of the light output from a fairly well focused LED lamp. The high intensity levels required for snowplows, emergency, and maintenance vehicles necessitates the use of 'collimating' optics in order to achieve the high brightness needed. It should be noted that the standard strobe does not have the same angularity characteristics as the LED lights. Although there is some variation in intensity for the standard strobe, the variation is not as large and the light output produced by the standard strobe is much more uniform for all directions around the plow. The Whelen LED strobe has secondary peaks at 135^{o} and 225^{o} rotation angles. The Whelen LED strobes have an additional set of LEDs at the 135^{o} and 225^{o} angles contributing to the higher values for those strobes at the intermediate angles.

Second, the intensity of the standard strobe is approximately 50 times higher than the most intense LED strobes. The graph shows the data for the standard strobe with magnitude reduced by a factor of 50 plotted along with the LED data. A peak for the standard strobe occurs at 180 ^{o} which is consistent with a brightness peak on the side of the truck; however the intensity does not drop below 60% of the maximum for any of the typical viewing angles. At the peak the standard strobe is 50 times more intense than the brightest LED strobe and is at least 30 times more intense than the brightest LED strobe at any of the standard viewing angles. A note of caution should be made at this point because of the dramatic difference in the intensity measurements between the LEDs and standard strobe. This data was collected with a high speed photo detector so that time response effects could be minimized. The human visual system is much more complicated and timing effects may play a large part in the perceived brightness of the strobes under different conditions.

Third, there is a significant difference in the light output produced by the different LED strobes. The Whelen strobes with or without colored lens materials performed equally well and were measured to be the brightest of the LED strobes, regardless of angle. The PSE strobes produced intensity levels only slightly lower than that of the Whelen strobes. Both manufacturers use the same number and general type of LED in the main faces of their strobes. The Federal Signal LED strobe performs poorly in comparison to the other LED strobes in the optical intensity measurements. The light output from the Federal LED strobe is approximately 20% of the light output from the Whelen LED strobes. The causes for this are unclear, but one obvious difference is that the Federal strobe has less LEDs on the 'bright' faces. In addition, the lenses on the Federal strobe produce a broader beam as seen in the data. The lenses reduce the peak intensity by spreading the light out over a larger area reducing the optical intensity measured at the detector.

Finally, the data shows a slight downward drift in intensity from the zero to 360 ^{o} rotation angle for the LED strobes and a slight upward drift for the standard strobe. We believe that this can be explained by heating of the lamps during the measurement. Temperature measurements were completed on several of the lights and a discussion is given later in this chapter. Allowing for a standard warm-up time for each lamp prior to measurement allows for a correction of this effect.

Timing data for each of the strobes measured is given in figure 3.2 to help understand the effect of pulse width and strobe sequence on perceived brightness. The time response of the strobes as supplied is significantly different between manufacturer and technology as can be seen in figure 3.2. A single pulse for the standard strobe (figure 3.2a) is anywhere from 20 to 100 times shorter than the pulses for any of the LED based strobes. The standard strobe produces a series of 4 pulses approximately 1-2 milliseconds in length separated by off times of ~80 milliseconds. In contrast the PSE LED strobe (figure 3.2d) produces a series of three pulses approximately 180 milliseconds separated by off times of 20 milliseconds. The Whelen LED strobe (figure 3.2c) produces a series of three short 40 millisecond pulses separated by 40 milliseconds of off time and followed by a long pulse of approximately 180 milliseconds. Finally, the Federal system (figure 3.2b) uses a very unique series of pulses that produces a longer overall cycle than the Whelen and PSE sequences.

The timing and pulse sequences of the different lights contribute two significant effects when comparing LED to strobe and LEDs to each other. First, the time that the light spends in the on state compared to the off state (duty cycle) during a complete cycle has a significant impact on the energy efficiency of the LED based strobes. The duty cycles for the different lights are listed in table 3.1.

Table 3. 1. Summary of strobe duty cycles

Light fixture	Duty cycle (%)
Whelen LED	35
PSE 257 LED	58
Federal LED	25
Standard Strobe	~0.7

When the LED lamps are on they draw significant amounts of current while when off the currents are virtually zero. Therefore, the average power consumption should be directly related to the duty cycle of the lights of the same technologies. Data showing power consumption is presented later in this report.

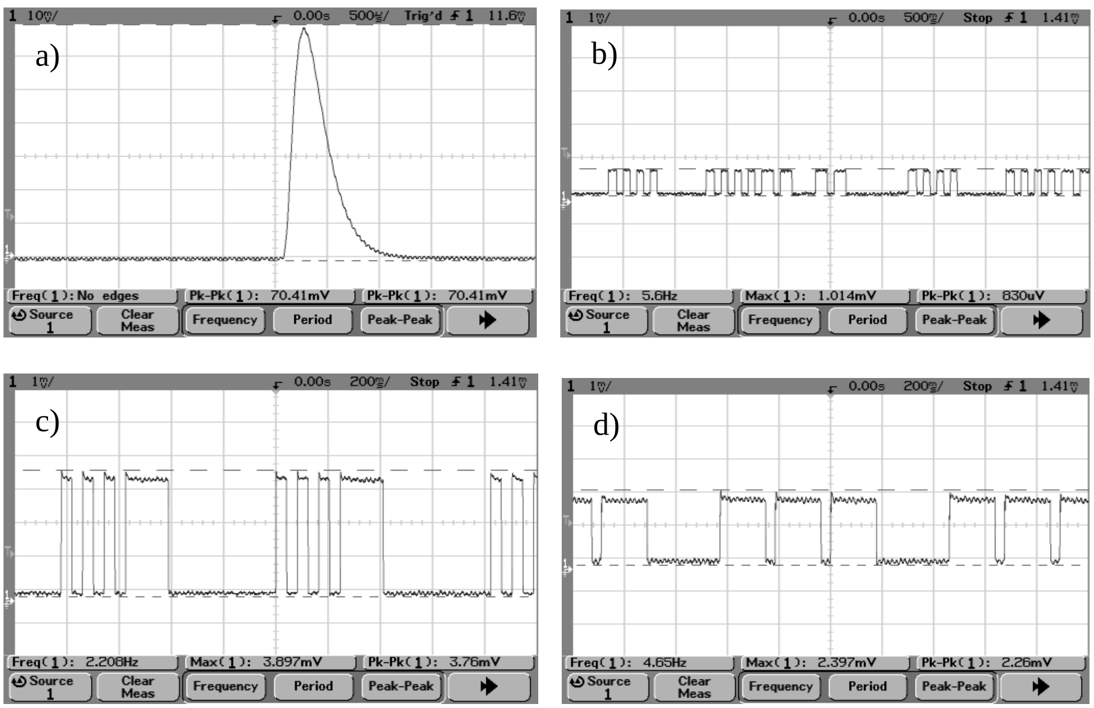


Figure 3. 2. Time response of the supplied strobes: a) standard strobe, b) Federal Signal, c) Whelen, and d) PSE

Timing of the pulses is also important when evaluating the visibility of the lights. The most interesting observation regarding the timing sequences comes when comparing the standard strobe with any of the LED strobes. Figure 3.3 shows a comparison of the pulses between the standard strobe and the PSE LED strobe.

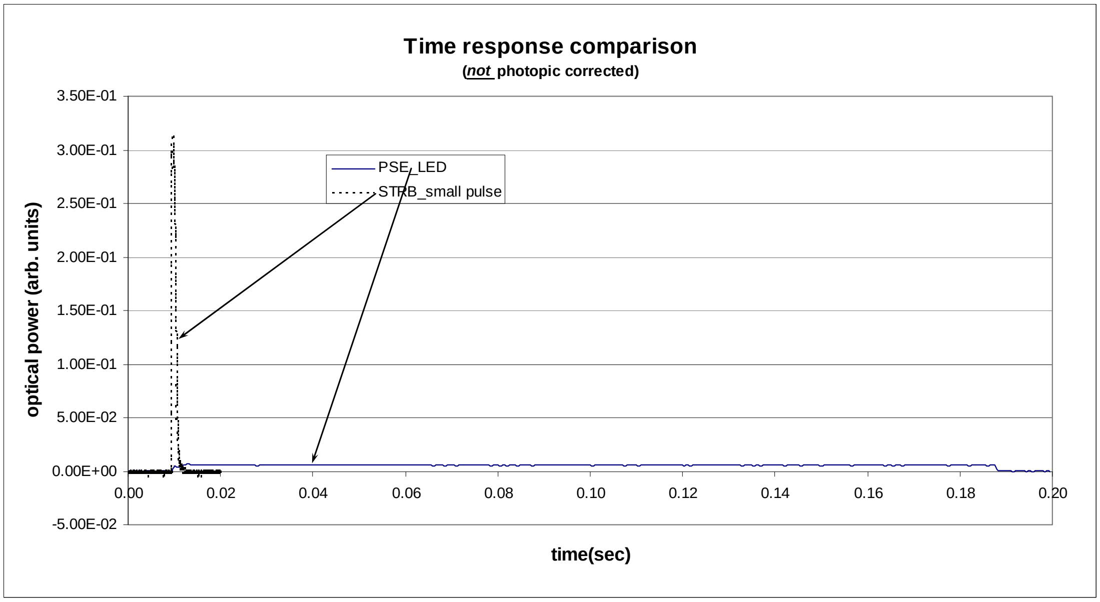


Figure 3. 3. Comparison of time response for LED and standard strobe

The intensity measurements show that the standard strobe is approximately 50 times more intense than the PSE LED strobe. In contrast, the PSE LED duty cycle is approximately 100 times longer than that of the standard strobe. Using a time-intensity product, the PSE LED strobe produces anywhere from 2 to 3 times as much light output during the on time. The Whelen LED measured to have peak intensities comparable to the PSE LED with a significantly smaller duty cycle. The total light output by the PSE LED is higher over time, but the two lights are comparable in visibility tests. This seems to suggest that at some critical duty cycle the human vision system ceases to perceive increased brightness and instead simply perceives that the light is on longer. An interesting note is that the Whelen standard strobe measures about 50 times more intense than the Whelen LED at peak, but has a duty cycle that is about 50 times smaller. The time-intensity products are nearly equal implying equal total light output by both Whelen lights during any given cycle. It seems possible that the lights were designed with that in mind and that the time-intensity products were set equal in order to maintain similar visibility characteristics.

Given the limited temporal response of the human eye, it seems reasonable to expect that an observer might perceive the LED lights to appear brighter than the standard strobe under certain conditions even though the instantaneous power output of the standard strobe is 50 times larger. Indeed, observations by students resulted in the standard strobe, the PSE LED, and the Whelen LED having similar perceived brightness, under equal conditions. However, the physiology of the human eye and its effects on visibility are subjects better left to individuals better versed in that area. The effect of timing on perceived brightness is a complex issue that should be explored more carefully as it relates to snow plow lights. It appears that the longer on-time of the LED based strobes compensates for the low instantaneous intensity to produce a perceived brightness comparable to the standard strobe under certain limited visibility conditions.

Similar intensity measurements were taken as a function of *tilt* angle for the LED lights. Figure 3.4 shows a plot of intensity v.s. tilt angle for the Whelen LED with tilt angle varying from -45^{o}

to +45°. The narrow peak with a half width of ~10° centered on 0° is typical of that measured for all of the LED lights and highlights another concern regarding the LED technology. As with the horizontal rotation, the angularity issues are significant for different tilt angles. Fortunately, traffic approaching from the rear of the plow vehicle generally will observe the lights at nearly 0° or at the peak intensity. However, the data show that it is critical that the LED based lights are mounted properly so that maximum intensity can be observed by traffic approaching from the rear of the vehicle.

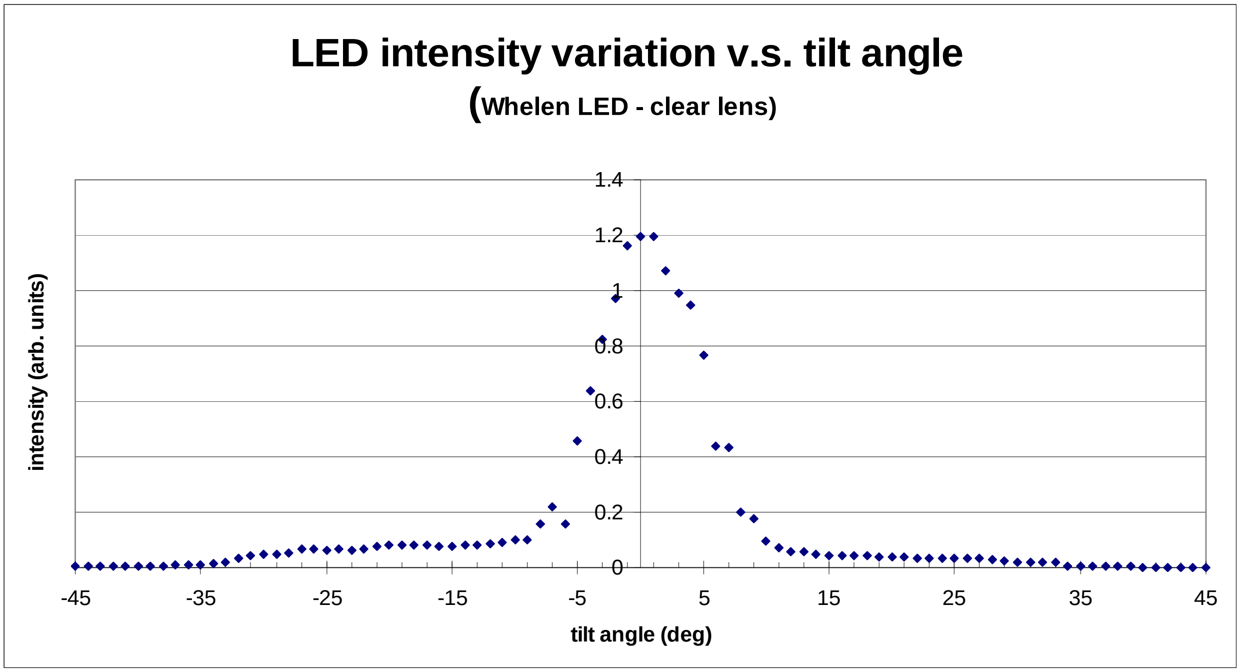


Figure 3. 4. Effect of tilt on optical intensity for Whelen LED – typical for all LEDs

3.2 Visibility Test Results

Unfortunately, the mild 2006-2007 winter season resulted in a very limited number of days when road and track testing could be accomplished resulting in a very limited data set. The study was extended through an additional season in order to produce more useful data. Following is a summary of the road/track testing that was accomplished during the 2006-2007 and 2007-2008 winter seasons.

3.2.1 Track Testing

There were a few problems encountered during the tests. The test method showed promise, but was greatly compromised by the amount of time since the latest snowfall. The lack of snow until very late in the season made it impossible to verify the test methods earlier. The constraint is that the plows are not available until at least a day after any significant snowfall. Less than ideal test conditions diminish the meaning of the results and the track test method was abandoned.

3.2.2 Road Testing (Distance of Observability - DOO)

Limited visibility testing was completed during the winter/spring 2007 season. Figure 3.5 summarizes the results for the testing under the snow and fog conditions. Tests were performed on the standard strobe and the PSE LED strobe and under fog and snow conditions.
The y-axis gives the distance at which the driver observed a given strobe and weather conditions are given on the x-axis of the plot. The results are quite conflicting. Under snow conditions, the PSE LED lamp tested to be visible at a greater distance (~0.6 miles) than the standard strobe (~0.5 miles), while under fog conditions the standard strobe (~1.3 miles) tested to be significantly more visible than the LED strobe (~0.8 miles).

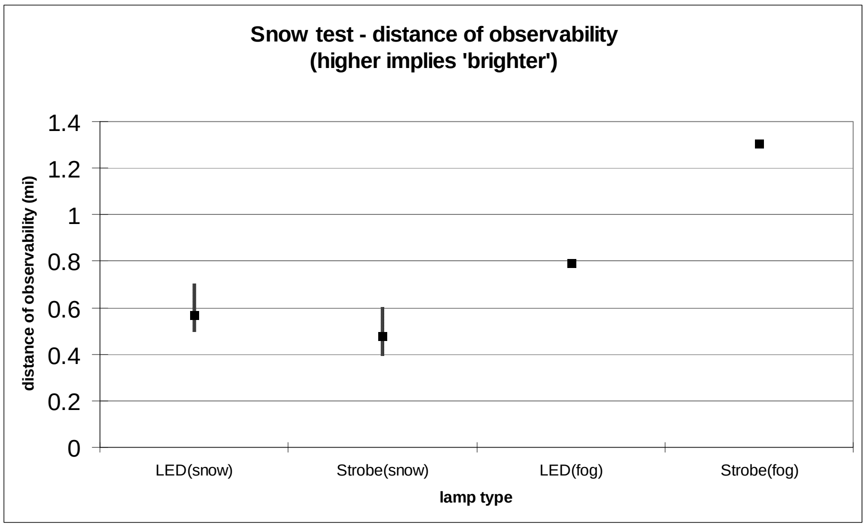


Figure 3. 5. Winter/Spring 2007 visibility results

Although the data set is limited we believe that the conflicting results can be explained, in part, by the difference in color between the two strobes. The ambient light conditions during the snow test were noted to be brighter resulting in almost “white-out” conditions. The weather conditions produced a visual environment around the strobe that was very white. As discussed in the color section above, the standard strobe produces a more white color spectrum. The result is a reduced color contrast between the standard strobe and the white snow in comparison to the amber LED strobe. It is our opinion that the amber LED strobe was more observable simply because its color differed more from the environment than did the color of the standard strobe. Alternately, the fog conditions produced a visual environment around the strobes that was darker than the white snow conditions. The fog was relatively less dense than the snow during the tests and more of the dark background was visible. With the darker conditions during the fog test the intense yellow light of the standard strobe was more noticeable because of the greater light-dark contrast in comparison to the LED strobe.

These limited results suggest that different lighting configurations may be useful depending on the ambient conditions. Considering typical use of a snow plow, the enhanced color contrast of the LED strobe lends itself well to bright snow conditions, while the standard strobe may be better suited for conditions where the ambient lighting is reduced such as dawn and dusk. More detailed measurements under more varied conditions should help to better understand the effects of ambient lighting on the observability of warning lights.

Additional road testing was completed in the spring of 2008 resulting in much more detailed results. The testing was completed during two different snow events in March 2008 using a variety of test subjects. The weather conditions varied from mild snow and road spray to heavy snowfall. Throughout the study, observers ranged from a single trained observer to as many as eight untrained observers. All drivers were between 18 and 45 years of age with a strong weighting toward the low end of the age range.

Figure 3.6 shows raw data for one of the tests completed. This particular test was performed comparing the standard strobe with the Whelen LED. The test was performed with the side of the plow light that would normally correspond to the rear of the plow vehicle directed at the observer. The horizontal axis corresponds to the number of times a motorist was asked to complete the test. Visibility conditions varied significantly from pass to pass since the DOO varied from a low of 0.4mi to a maximum of 0.7mi. Even with the large variation in conditions it is clear that the DOO for the standard strobe and the Whelen LED are comparable. In general, the Whelen LED strobe was measured to be slightly more noticeable for all observers. Participants noted that the more amber color of the LED light was more easily observed against the white snow background. The results suggest that under typical reduced visibility conditions the standard strobe currently used on Mn/DOT plows is no more or less visible than LED based lights can be.

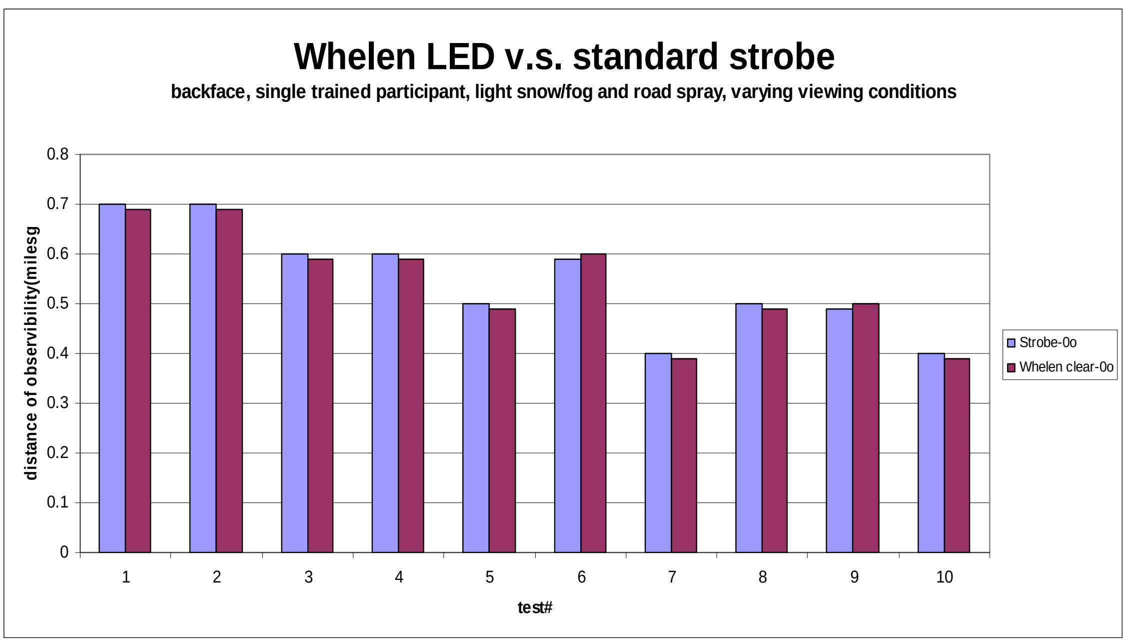


Figure 3. 6. Distance of observability data comparing visibility for the standard strobe and Whelen LED

After the Whelen LED strobe was determined to have approximately equal visibility as the standard strobe at the 0^o angle, it was used as the reference strobe for testing of the other LED based strobes. Figure 3.7 summarizes the results of all testing at the angle corresponding to the back of the plow vehicle. The field test results suggest that there is no significant difference in the visibility of the Whelen LED, the PSE LED, and the standard strobe at the angle tested, while the Federal LED measured significantly less visible. Given that the standard strobe measured to have at least an order of magnitude higher intensity in the lab it is surprising that it tested approximately equal to the Whelen and PSE LED lights. In contrast, the Federal LED tested significantly lower in intensity than the other LED lights which agrees with the field test results. We believe that the combination of pulse width and color have a significant effect on the conspicuity of the different lights. However, a detailed study of timing and color effects was not undertaken as it was outside the scope of this study.

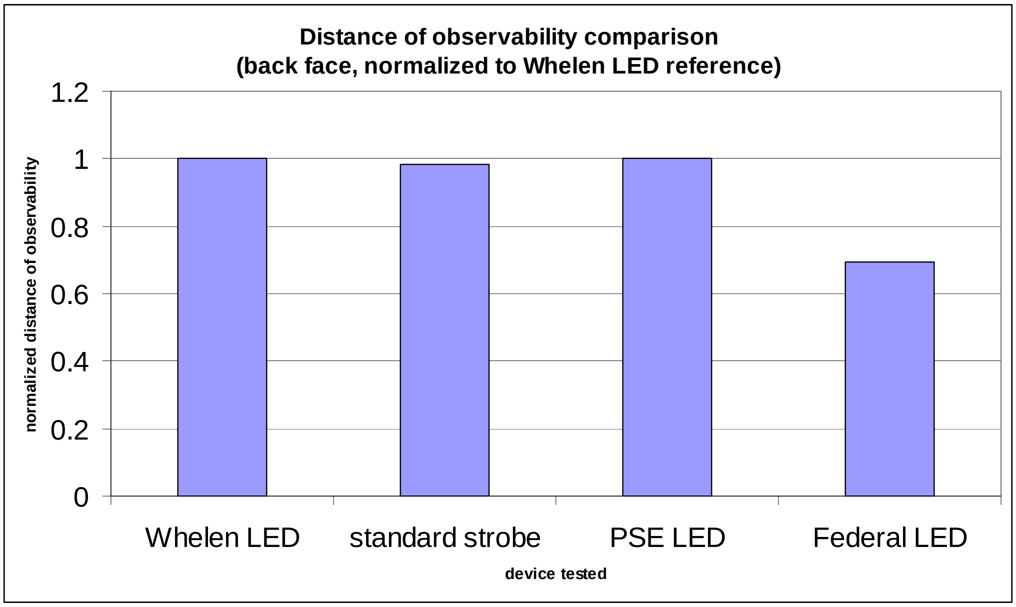


Figure 3. 7. Summary of distance of observability data comparing visibility for all strobes referenced to the Whelen LED

Additional field tests were completed at different rotation angles in order to understand the effects on visibility of the lower intensity levels measured in the lab at those angles. The results are summarized in figure 3.8. At the 135^{o} rotation angle, the measured intensity was reduced by about a factor of three for the Whelen LED and about eight for the PSE LED. Not surprisingly, the field test results agree qualitatively with the lower intensity at the off angle. The results suggest that although two of the LED lights are nearly equal in visibility to the standard strobe from the rear of the plow vehicle, the visibility to a vehicle approaching from an off angle is reduced for the LED lights. This result is likely the origin of comments regarding “dead spots” in the brightness as an observer walks around the plow vehicle.

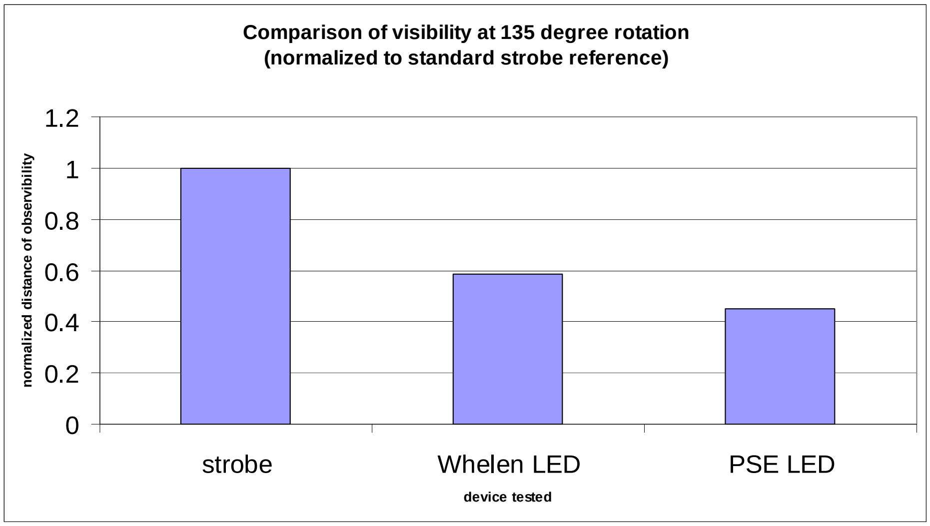


Figure 3. 8. Summary of DOO data comparing off axis visibility for all strobes referenced to the Whelen LED. (angle=135o)

Field tests were also completed at a rotation angle of approximately 112.5^{o} in an attempt to capture results at the minimum measured intensity for the Whelen LED and possibly correlate DOO to intensity. The results were similar in that the visibility was reduced, but inaccuracies in the measurement of the rotation angle made it difficult to directly correlate DOO to intensity. These results suggest that visibility of the plow is reduced for all of the LED lights at any angle other than directly at the back, front, or side of the plow vehicle.

Finally, field tests were done under conditions where the lights were coated with ice and snow. Figure 3.9 are photographs of two of the lights after approximately 30 minutes of heavy snow conditions. A coating of ice/snow can be seen clearly on both light fixtures; however, the LED light on the right has a heavier coating that is likely the result of less heat produced during operation.

Figure 3. 9. Photographs of standard strobe and Whelen LED after heavy snow conditions

Figure 3.10 shows visibility data for the standard strobe and the Whelen LED lights during the snow event that caused the ice/snow coating shown above. The data clearly show a reduction in DOO for the LED in comparison to the standard strobe. Although the ice/snow coating will likely affect the DOO results for both lights, it is reasonable to assume that the LED will be more affected by similar conditions, for two reasons. First, the LED will be more likely to develop a thicker coating assuming thermal effects are involved. Second, the scattering effect produced by the ice coating is likely to have a more significant effect on the intensity of light emitted in a particular direction for the LED than for the standard strobe. The light emitted from the standard strobe is already distributed uniformly around the plow vehicle in comparison to the LED lights. Any scattering of the light would only tend to distribute the light more uniformly and would have minimal effect on angular variations in intensity. In contrast, scattering of the focused light of the LED will redirect the light in all directions reducing the intensity at the angles of interest. The result is a less visible light.

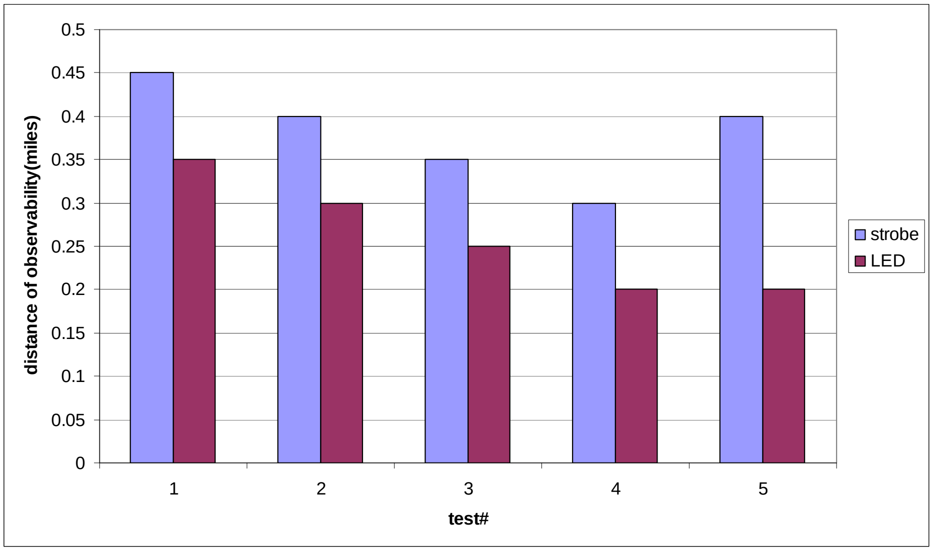


Figure 3. 10. Distance of observability data for ice/snow coated standard and Whelen LED strobes

3.3 Subjective Brightness Testing

Figure 3.11 shows data for the strobed Minimally Distinct Border Method (MDB) measurements. The value indicated in the y-axis corresponds to the brightness of the DUT normalized to the reference strobe.

Three of the supplied strobes were measured using this method: PSE LED, Federal LED, and Whelen LED. The results are consistent with the optical power measurements discussed earlier. The PSE and Whelen LED strobe were determined to have comparable perceived brightness while the Federal LED strobe was determined to have perceived brightness significantly less than the PSE and Whelen strobes. The PSE strobe is perceived to be slightly brighter than the Whelen strobe with the MDB method, but the difference is likely not significant. The Federal strobe is perceived to be about ½ as bright as the PSE and Whelen even though the intensity measurements determined the Federal strobe to produce about 1/5 the luminous intensity at peak angles.

The MDB data highlights a difficulty in using purely analytical measurements to compare the quality of different strobe technologies. The correlation between the eye response and the analytical measurements is not fully understood.

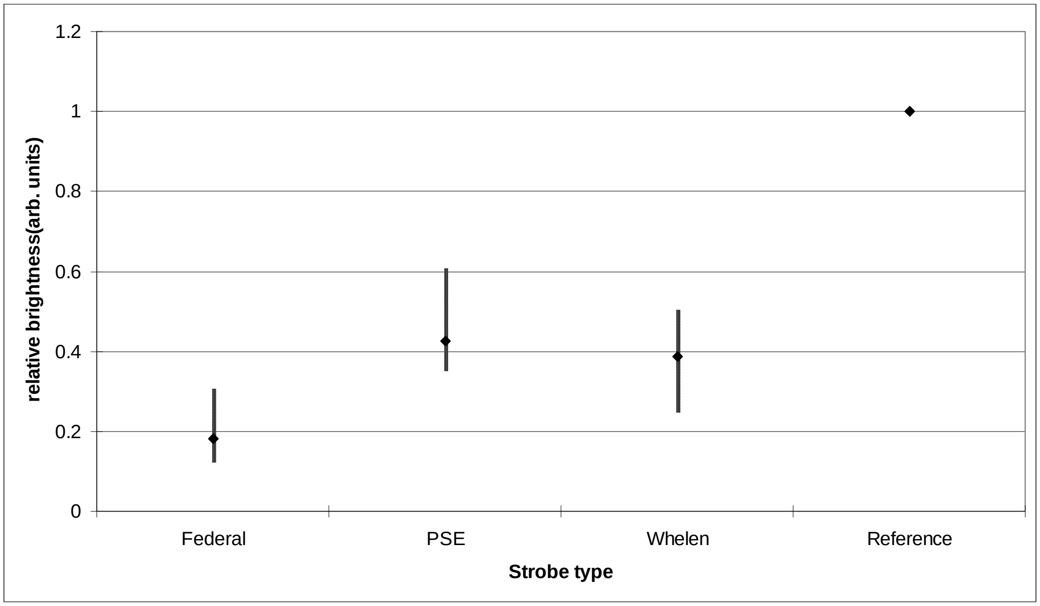


Figure 3. 11. Perceived brightness comparison – MDB method

3.4 Electrical Power

Table 3.2 gives current, voltage, and power data for several of the lights tested. The benefit of the LED technology is clear looking at any of the given parameters. Instantaneous power and average power are lower for all of the LED fixtures in comparison to the standard strobe. In addition, peak power and current are also lower for the LED lights. Probably the most interesting result presented in the table is the wide variation in the average power for the LED based lights. The Whelen LED, which was generally the most visible of all of the LED lights, had a significantly lower average power number. The PSE 257 LED was nearly equal in visibility to the Whelen LED in field tests but uses significantly more power. The reasons for this result are not completely clear; however a few differences can be noted. First, the peak currents drawn by the Whelen LED and Federal LED are nearly ½ the currents of the PSE LED lights. Power is directly related to current and the reduced current clearly contributes to the lower average power numbers. It is unclear why there is a large current difference. Both manufacturers use similar LED devices in their respective lights and the lens structure is not significantly different. It is possible that the PSE LED lights have earlier generation LED emitters compared to the Whelen lights. LED technology is advancing rapidly and emitter efficiency numbers improve on a regular basis. Earlier generation LED emitters are expected to be lower in cost when available, but also have lower luminous flux resulting in lower intensities.

The smaller duty cycle of the Whelen LED appears to have a significant effect on the average power values. The duty cycle is directly related to average power since the LED lights are only consuming significant power when the emitters are on. The duty cycle for the Whelen LED is 60% of the PSE LED corresponding to a direct reduction in the Whelen LED average power by the same percentage.

Table 3. 2. Electrical characteristics of the strobes tested

Fixture description	Peak current (Amps)	Peak power (Watts)	Energy/cycle (Joules)	Average power (Watts)	Duty cycle (%)	Cycle time (sec)
Standard strobe	11.3	137.3	49.6	58.2	>0.7	0.82
Whelen LED	3.1	38.1	10.8	13.1	35	0.82
PSE 257 LED	5.9	73.0	37.4	41.9	58	0.89
Federal LED	3.8	46.0	46.0	15.9	25	2.90

The power data presented favors the Whelen LED light over the other manufacturers. However, it should be noted that the application of the LED technology by all of the manufacturers is similar and that given the proper specifications each manufacturer could likely meet the needs of Mn/DOT.

3.5 Color Measurements

Figure 3.12 shows the color spectrum taken for the standard strobe and the PSE LED strobe with the data corrected for the standard photopic response of the human eye. Since the other LED based strobes use the same technology, the spectral output of those strobes is nearly identical to the PSE strobe. The x-axis gives the wavelength of light while the y-axis gives relative intensity for the two strobes at each wavelength.

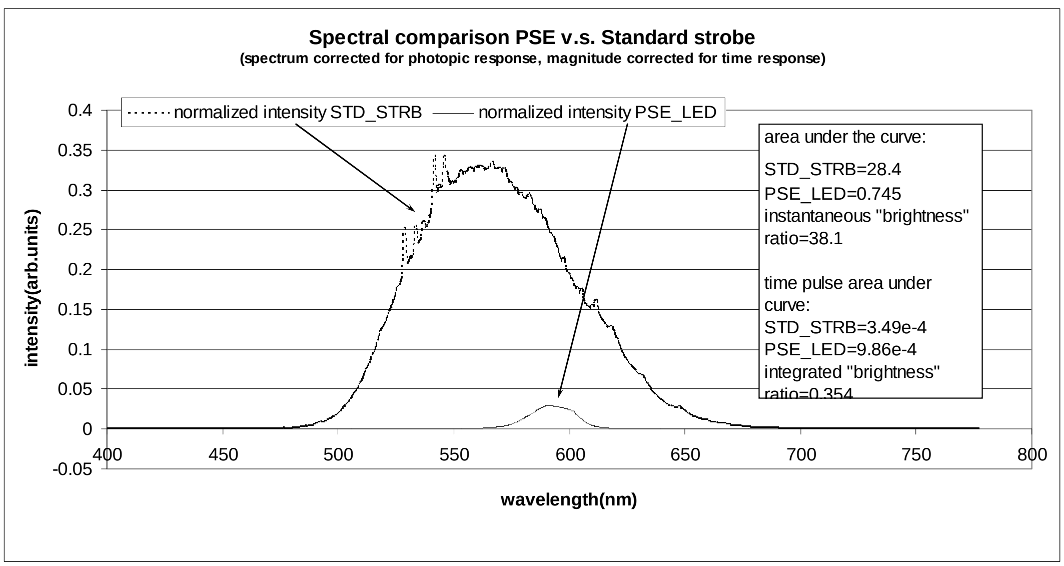


Figure 3. 12. Color spectrum – LED v.s. standard strobe

Two points can be made regarding the optical spectrum results. First, the higher relative intensity of the standard strobe is easily observed in the plot. The total instantaneous intensity can be compared using the spectral curve by comparing the area under the curve for the two strobes. As shown in the figure, the area under the standard strobe curve is approximately 40 times larger than the area under the PSE LED curve. This is consistent with the 50:1 intensity ratio determined by optical power measurements. Second, the spectral content of the standard strobe covers a much larger portion of the eye response resulting in a more 'white' looking color to the observer. The LED based strobes emit fairly monochromatic light near 590 nm (+/- 10 nm) in wavelength producing a more pure amber color.

The color difference may explain some of the results of the DOO testing. Motorists participating in the road testing stated several times that the amber color of the LED strobe was more noticeable during heavy snow conditions. The different color spectra may help explain the perception differences between the standard and LED based strobes.

3.6 Temperature Effects

Finally, intensity measurements were performed with time in order to quantify the drift in the light output caused by heating effects in the lights. Figure 3.13 shows a plot of peak intensity v.s. time for the Whelen LED and the standard strobe over several minutes. There are clear temperature effects for both the LED and standard strobe with the LED intensity decreasing and the strobe intensity increasing with time. Only the Whelen LED is shown in the plot, but all of the LED lights showed similar intensity deceases with time. The 30% decrease in emitted light is reasonable for LED devices and is a normal thermal effect. In contrast the standard strobe intensity increased with time by about 25%. Over time the intensity ratio of the standard strobe v.s. the Whelen LED doubles due to the temperature drift shown. Temperature variation is another effect that should be taken into account when evaluating and specifying different lights, especially LED lights, for all applications.

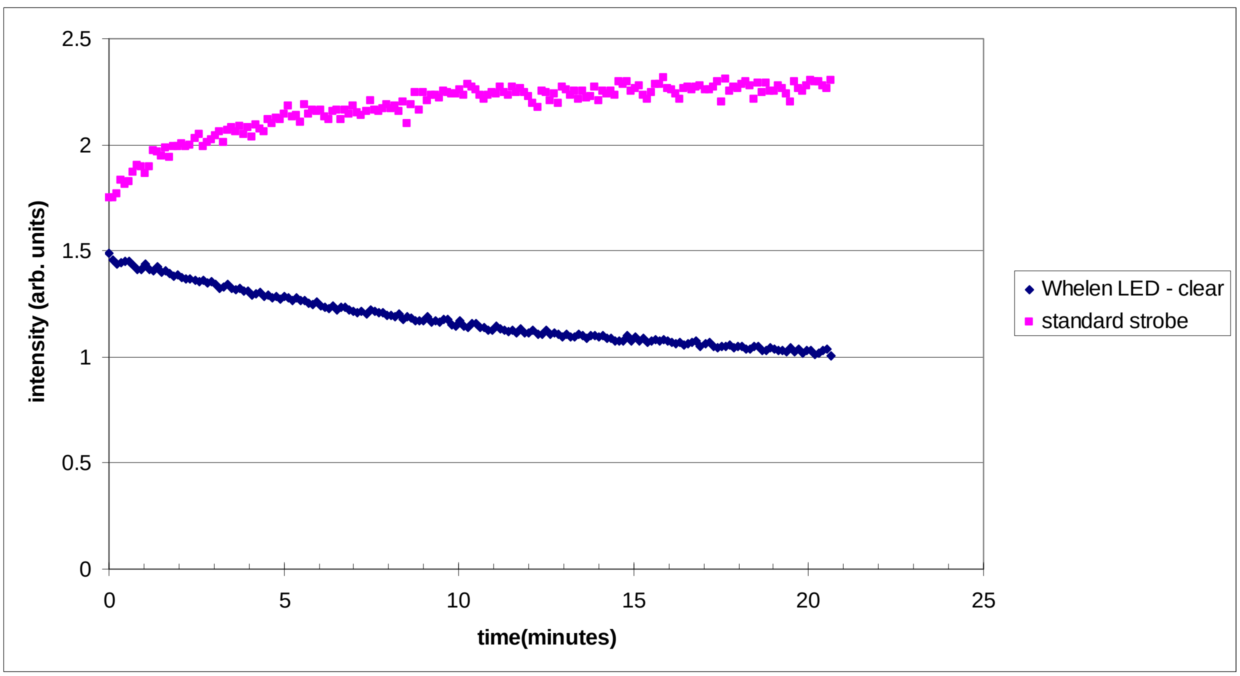


Figure 3. 13. Time/temperature drift of the luminous intensity of the LED and standard strobes

3.7 Discussion

The analysis of the field test data suggests that the LED based lights can be configured to be equally visible under conditions limited by snow and fog. The LED lights as they are currently configured have comparable visibility to the standard strobe for the vehicle front, back, and side observation points, but are less visible for off angles. The question is whether Mn/DOT considers the visibilities at off angles to be critical. If so, the LED lights, as they are currently configured, are not capable of producing the desired results.

However, an obvious modification would give LED lighting similar visibility at all angles. Of course the modification would come at an increased cost and power. Using the Whelen LED intensity v.s. angle characteristics we generated an intensity v.s. angle distribution that would give more uniform intensity levels at the off angles thereby increasing the distance of observability at those angles. A more uniform intensity distribution could be generated by using approximately three times as many LED emitters distributed over the angles of interest leading to better visibilities at those angles. Figure 3.14 shows a conceptual sketch of one possible LED configuration. Currently there are 12-emitter LED modules directed at the 90^o, 180^o, and 270^o orientations. If similar LED modules were rotated vertically, oriented at 22.5^o increments, and the LED lens modified to give a wider distribution angle, the measured intensity would be as high as the peak intensities currently available and uniform over all angles toward the rear and side of the vehicle. As shown, the intensity in the front of the plow would be the same as current LED lights.

Keep in mind that this is only one possible configuration and that LED modules such as those used in the current lights allow for significant flexibility in the configuration. In addition, added costs could be partially mitigated by the use of a single strobe in the center of the vehicle as has been proposed by others for added safety [11].

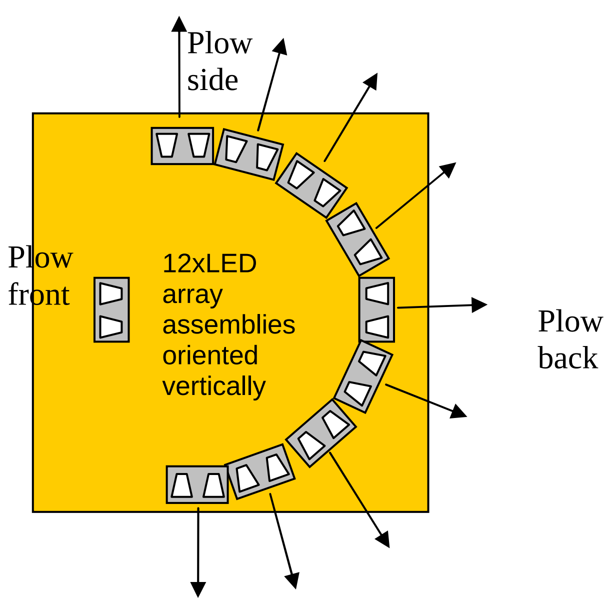


Figure 3. 14. One possible light configuration for improved LED strobe visibility

CHAPTER 4

4.1 Summary and Conclusions

A variety of different test methods were employed to better understand the differences between standard gas discharge based strobe lighting and LED based strobe lighting for snow plows. The results presented in this report highlight some of the differences and in part demonstrate the benefits of selecting one particular technology over another. Parameters of most interest are visibility during snow/fog conditions and energy efficiency. The LED technology was demonstrated to be equally visible to the standard strobe lights under the conditions tested if the angles of observation are well defined. However, it was shown that the visibility of LED based lighting is reduced at many angles around the plow vehicle due to the strong variation in intensity v.s. angle for the LED devices. This is the origin of LED angularity concerns expressed by many at Mn/DOT. As expected, the LED lights were measured to be significantly more energy efficient than the standard strobe supporting one of the main benefits of LED lighting.

The results of this study tend to raise more questions regarding the requirements of the strobe systems on Mn/DOT snow plows. It should be noted that the strobe lights tested were manufactured in the 2006-2007 time frame and improvements in technology should be considered when reading these conclusions. Since the LED based lights were shown to be equally visible under certain conditions, a question arises regarding what conditions are acceptable. If the reduced visibility at off angles is acceptable from a safety perspective, then some of the currently available LED lights may be acceptable. However, if the reduced off-angle visibility is unacceptable then the standard strobe visibility far exceeds what can be achieved with LED lights.

If additional costs are acceptable, it is possible to produce LED lights with visibilities comparable to the standard strobe at all angles around the vehicle. The flexibility provided by LEDs allows for a wide variety of lamp configurations that may prove better at increasing snow plow conspicuity.

4.2 Recommendations

Since it is expected that LED based technologies will continue to become more prevalent in a variety of Mn/DOT applications, a more detailed understanding of the fundamentals of LED technology is needed. The parameters of LED based lighting - intensity, angle, color, timing, and power - can be controlled very well. How that control can be used to the benefit of Mn/DOT should be better understood. Snowplow lights are an excellent example.

Intensity v.s. visibility should be better correlated for the conditions of interest. If correlations can be established, specification of lighting requirements will be more straightforward. Visibility requirements for distance and angle need to be better established so that intensity information can be used to satisfy those requirements and LED lenses can be specified to meet the angularity constraints. Visibility v.s. flash rate/type needs to be correlated so that the LED flashers can be configured for maximum visibility and low power. Finally, visibility v.s. color for different conditions needs to be better understood in order to optimize visibility for the conditions of interest. Without better understanding of the basic visibility requirements, it is very difficult to deliver detailed specifications of LED strobe lighting that can be used by the manufacturers to design lights.

If the visibility requirements for snow plows can be defined such that the rear, side, and front of the plow are critical and off angles are not, this study shows that under the conditions tested, current LED based plow lights are equally visible and could be used to replace standard strobe lights. If a more even angular distribution of light is required, LED based lights as they are currently configured should not be used. However, the results of this study suggest that LED lights could be developed to meet those requirements and development of those lights should be pursued.

REFERENCES

[1] J.D. Bullough, M. S. Rea, R. M. Pysar, H. K. Nakhla and D. E. Amsler. "Rear lighting configurations for winter maintenance vehicles" *Proceedings of the Illuminating Engineering Society of North America Annual Conference*, Ottawa, ON, August 5-8. New York, NY

[2] "Snowplow Rear Lighting Research Project", Alberta Infrastructure and Transportation, October 2005 (cited June 2008), www.infratrans.gov.ab.ca/INFTRA_Content/docType241/Production/RR0501.pdf

[3] Wisconsin Department of Transportation (Internet), *LED Warning Lights for DOT Vehicles*, December 2003 (cited June 2008), www.dot.state.wi.us/library/research/docs/tsrs/tsrleddotvehicleswithsupplement.pdf

[4] Iowa State University, Center for Transportation Research and Education (Internet), *Synthesis of Best Practice for Increasing Protection and Visibility of Highway Maintenance Vehicles*, August 2003 (cited June 2008) www.ctre.iastate.edu/pubs/midcon2003/kamyabvisibility.pdf

[5] Whelen Engineering Company Inc. (Internet), Company website (cited June 2008), http://www.whelen.com/index.php

[6] Code3 Public Safety Equipment (Internet), Company website (cited June 2008), http://www.code3pse.com/

[7]Federal Signal Corporation (Internet), Company website (cited June 2008), http://www.federalsignal.com/

[8] Philips Lumileds Lighting Company (Internet), *Luxeon Collimator Technical Datasheet DS26, June 2006* (cited June 2008**),** http://www.lumileds.com/pdfs/DS26.PDF

[9] Future Electronics (Internet), Company website (cited June 2008), http://www.futureelectronics.com/home.asp

[10] Wikipedia (internet), *Luminous Efficacy*, June 2008 (cited June 2008), http://en.wikipedia.org/wiki/Luminous_efficacy

[11] A. Yonas and L. Zimmerman, *Improving the Ability of Drivers to Avoid Collisions with Snowplows in Fog and Snow*, (Minnesota Department of Transportation, St. Paul, MN, July 2006)

APPENDIX A

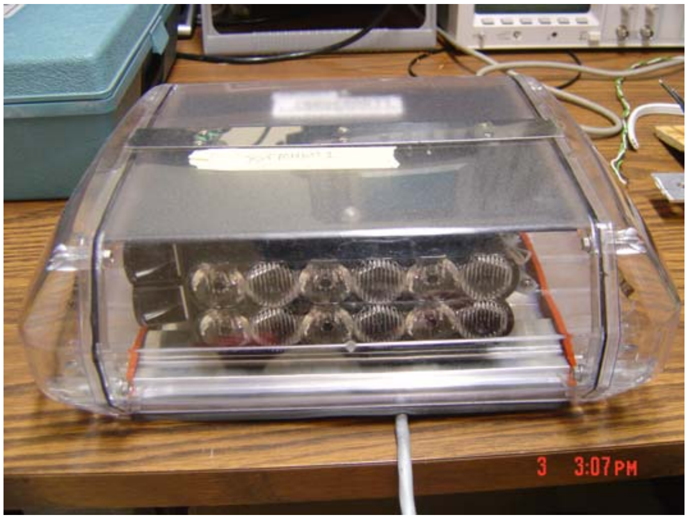
SUMMARY OF STROBES TESTED

The following describes the strobes measured in this study. The information given is incomplete, but gives as much information as was available at the time of this writing. The numbers listed were taken from the lights themselves and we believe correspond to part numbers and/or serial numbers of the strobes

1) Standard strobe: Whelen Micro-edge strobe
P/N: 01-0684367-ADA
Mfg. Date: 9-06

2) Whelen LED: Whelen Micro-Edge 3LT 400 L.E.D.
P/N: 01-0684247 ( ) 3B
Mfg. Date: N/A

3) PSE LED: Code3 Public Safety Equipment XS8000
LL00235256
and/or
LL00235257



4) Federal LED: Federal Signal Escape
Date Code: 06164