STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION
TECHNICAL REPORT DOCUMENTATION PAGE
TR0003 (REV 10/98)

1. REPORT NUMBER
CA17-2887

2. GOVERNMENT ASSOCIATION NUMBER

3. RECIPIENT'S CATALOG NUMBER

4. TITLE AND SUBTITLE
Solar Lighting Evaluation for Highway Applications – An Evaluation of a Solar Lighting Trailer

5. REPORT DATE
April 14, 2017

6. PERFORMING ORGANIZATION CODE
AHMCT Research Center, UC Davis

7. AUTHOR
Bahram Ravani, Ph.D., Wil White, P.E., Kristopher Wehage, M. Hadi Tabatabaee

8. PERFORMING ORGANIZATION REPORT NO.
UCD-ARR-16-12-31-01

9. PERFORMING ORGANIZATION NAME AND ADDRESS
AHMCT Research Center
University of California – Davis
Department of Mechanical & Aerospace Engineering
Davis, California 95616-5294

10. WORK UNIT NUMBER

11. CONTRACT OR GRANT NUMBER
65A0573; Task ID: 2887

12. SPONSORING AGENCY AND ADDRESS
California Department of Transportation
P.O. Box 942873, MS #83
Sacramento, CA 94273-0001

13. TYPE OF REPORT AND PERIOD COVERED
Final Report
September 1, 2015 to December 31, 2016

14. SPONSORING AGENCY CODE
Caltrans

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This research study evaluated the applicability of a solar powered LED lighting trailer for highway work zone applications. The research study involved using both laboratory testing and field evaluations of a solar powered based trailer with LED light tower systems. The results show that the solar powered LED lighting trailer tested does provide sufficient illumination for work in general areas and around equipment as specified in the California Manual for Uniform Traffic Control Devices (MUTCD). It has an important advantage over diesel powered lighting trailers in that it does not produce any greenhouse gases or noise. Its overall illumination, or lighting output, however, is approximately three to four times less than that of the diesel powered lighting trailers evaluated, which are equipped with metal halide lights; but its illumination is slightly over one and a half times more than that of the balloon lights tested. The solar lighting trailer also has lower maintenance requirements during its life cycle as compared to diesel powered lighting trailers.

The solar lighting trailer tested also has a higher initial cost but its life cycle cost over a 10-year period is only 88% to 93% of the cost of a diesel based lighting trailer. The solar panels increase the footprint of the solar lighting trailer as compared to a diesel powered lighting trailer, and makes it more susceptible to damage due to the solar panels. However, simple design modifications are evaluated and discussed that can overcome these shortcomings. In addition, design concepts for distributing solar powered LED lights on a maintenance vehicle are developed and simulated, which can expand the applicability of using solar powered LED lighting systems in highway maintenance operations.

17. KEY WORDS
Solar Lighting Trailer, Highway Work Zone Lighting, Carbon Emission, Lighting Standards; LED lighting

18. DISTRIBUTION STATEMENT
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. SECURITY CLASSIFICATION *(of this report)*
Unclassified

20. NUMBER OF PAGES
78

21. COST OF REPORT CHARGED

DISCLAIMER

The research reported herein was performed by the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aerospace Engineering at the University of California – Davis, for the Division of Research, Innovation and System Information (DRISI) at the California Department of Transportation. AHMCT and DRISI work collaboratively to complete valuable research for the California Department of Transportation.

Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Solar Lighting Evaluation for Highway Applications – An Evaluation of a Solar Lighting Trailer

Bahram Ravani, PhD: Principal Investigator, Wil White, P.E., Kristopher Wehage, M. Hadi Tabatabaee

Report Number: TBD
AHMCT Research Report: UCD-ARR-16-12-31-01
Final Report of Contract: TBD

4-14-2017

California Department of Transportation

Division of Research, Innovation and System Information

ABSTRACT

This research study evaluated the applicability of a solar powered LED lighting trailer for highway work zone applications. The research study involved using both laboratory testing and field evaluations of a solar powered trailer based LED light tower system. The results show that the solar powered LED lighting trailer tested does provide sufficient illumination for work in general areas and around equipment as specified in the California Manual for Uniform Traffic Control Devices (MUTCD). It has an important advantage over diesel powered lighting trailers in that it does not produce any greenhouse gases or noise. Its overall illumination, or lighting output, however, is approximately three to four times less than that of the diesel powered lighting trailers evaluated, which are equipped with metal halide lights; but its illumination is slightly over one and a half times more than that of the balloon lights tested. The solar lighting trailer also has lower maintenance requirements during its life cycle compared to diesel powered lighting trailers.

The solar lighting trailer tested also has a higher initial cost but its life cycle cost over a 10-year period is only 88% to 93% of the cost of a diesel based lighting trailer. The solar panels increase the footprint of the solar lighting trailer as compared to a diesel powered lighting trailer, and make it more susceptible to damage due to the solar panels. Simple design modifications are evaluated and discussed, however, that can overcome such shortcomings. In addition, design concepts for distributing solar powered LED lights on a maintenance vehicle are developed and simulated, which can expand the applicability of using solar powered LED lighting systems in highway maintenance operations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Definition
3D	3 Dimensional
AC	Alternative Current
AGM	Absorbent Glass Mat
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Ah	Amp hour
ANSI	American National Standards Institute
ATIRC	Advanced Transportation Infrastructure Research Center
CAMUTCD	California Manual for Uniform Traffic Control Devices
CAL-OSHA	California Occupational Safety and Health
Caltrans	California Department of Transportation
CGI	CIE Glare Index
CEN	Comite European de Normalisation
CIE	Commission Internationale de l'Eclairage
CSO	Construction Safety Orders
DC	Direct Current
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
EU	European
fc	foot-candle
ft.	feet
fL	footLambert
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America
kWh	kilo Watt hours
LED	Light Emitting Diode
MUTCD	Manual for Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
NREL	National Renewable Energy Laboratory
PV	Photo Voltaic
PV 2016	Present Value 2016
STV	Small Target Visibility
TAG	Technical Advisory Group
VL	Veiling Luminance
YOE	Year of Expenditure

ACKNOWLEDGMENTS

The authors thank the California Department of Transportation (Caltrans) for the support of this research, in particular Bradley Mizuno, Fouad M. Ziaullah, and Justin Unck with the Division of Research, Innovation and System Information.

EXECUTIVE SUMMARY

Motivation

This research study performed experimental and field evaluations of the use of a solar powered LED lighting for application in highway work zones. The main objectives of the performed work were to determine whether or not solar lighting can be as effective as existing lighting methods for tasks in highway work zones, and what are the cost and emission benefits of such systems. In California, most highway construction tasks, and some highway maintenance tasks, are performed during the night time since night operations provide certain advantages. These advantages include reduced traffic congestion that can help in decreasing air pollution due to fewer idling vehicles, more comfort for the work crew due to lower temperatures during summer months and possibly longer work shifts. The use of a proper lighting system is therefore important not only for worker and traveler safety but also in terms of cost and environmental impact.

Approach

The approach used for this research study consisted of three steps:

- Laboratory Testing
- Field Evaluations
- Analysis and Computer Simulations

Computer simulation was used to evaluate some new design concepts for solar LED lighting that can potentially be applicable in more highway applications. The research study did not include any hardware development, but computer simulation allowed for the evaluation of lighting performance of two new design concepts developed without the need for any hardware prototyping.

Results and Conclusions

The results of this research study indicate that a solar powered LED lighting trailer can be an alternative to existing lighting for many highway applications and can be used as part of a fleet of lighting systems. Solar powered LED lights, in terms their illumination levels and lighting footprint, can provide illumination levels that can satisfy the requirements of the California MUTCD for many highway work zone applications. This level of illumination is specified for general work activity and work around equipment in highway applications. The LED lights can also provide a footprint that can have a half circle diameter of 20 foot or better depending on the number of LED lights used and their configurations on a tower.

Solar powered LED lights on a trailer mounted tower have several advantages over metal halide lights and balloon lights which are both powered with diesel generators. These include:

- Solar powered LED lights are environmentally friendlier, resulting in Carbon emission reduction. This research study has determined an annual CO_2 emission reduction of up to approximately 4.1 tons per lighting system used. This calculation assumes that a highway work zone lighting system has a usage of approximately 618 hours on an annual basis, and that the combustion of diesel fuel results in the output of 13.12 lb. of CO_2 per hour.

- Solar powered LED lights result in noise reduction at a worksite since the diesel generators used for existing lighting systems are noisy.

- Solar LED lights operate at much lower temperatures as compared to metal halide lights on diesel lighting trailers, and therefore lighting directions can easily be readjusted at the work site since fixtures are not at high temperatures; furthermore, any existing vibrations at the work site will not adversely impact the lifespan of the lights.

- Several LED light fixture configurations on a trailer mounted tower system (tested in this research) were identified that can produce similar or better lighting illumination and footprints in work areas on the side of the light as compared to balloon lights and metal halide light towers.

- The solar powered LED lighting trailers have lower maintenance requirements as compared to diesel powered lighting trailers.

Solar powered LED lights on a trailer mounted tower system also have a few disadvantages over diesel powered lighting trailers. These disadvantages include:

- The initial unit cost of a solar powered LED lighting trailer is higher than that of a diesel powered lighting trailer. The life cycle cost over a ten-year period, however, is lower for the solar powered lighting trailer considering maintenance, fuel and other costs (a ratio of 88% to 93% of the cost of the diesel unit for a usage of ten years).

- Solar powered LED lighting trailers are typically larger for the same illumination level as compared to diesel powered trailers due to the size of the solar panels. This shortcoming can be potentially overcome if the charging station including the solar panels could be separated from the trailer.

- Solar powered LED lighting trailers cannot be used in areas where there is limited sun or solar power for charging their batteries.

- The overall lighting output of the solar powered lighting trailer is a few times lower than that of a diesel powered lighting trailer with metal halide lights; but the solar powered lighting trailer does provide enough illumination and footprint to be consistent with the requirements of the California MUTCD for work in general areas and around equipment in highway work zones.

- In-the-field handling of solar lighting trailers is more difficult as compared to diesel lighting trailers due to the existence of their solar panels that can be easily damaged and will require a larger footprint as compared to standard diesel trailers. A design modification separating the battery charging station from the trailer or the lighting system can overcome this limitation.

Filed evaluations of a solar LED lighting trailer performed in this research study indicate, in general, that trailer mounted lighting systems have limited applicability in highway work zone applications when there are confined spaces. This is also true for diesel powered lighting trailers. This research study has developed two new design concepts through the use of computer simulation to show how solar powered LED lighting can be integrated onto maintenance vehicles in a tower as well as in a distributed configuration, thus significantly enhancing the applicability of this kind of lighting system for highway work zones and capturing its important environmental benefits while eliminating its limitation in terms of using a trailer based system.

In terms of evaluating the availability of solar power, this research determined that, in the winter and spring time in the Sacramento area, the total solar energy availability hours approximately range from a low of 13.3 hours/week in December to a maximum of 35.1 hours/week in June. Evaluating the charge and discharge cycles of the solar panels and mapping them into the solar energy availability in Sacramento area, it is likely that that a crew would need to use grid power to charge the batteries during the winter months.

The following conclusions are made in regards to the two new design concepts:

- When six solar powered LED lights are installed on a vehicle integrated tower configuration similar to a vehicle integrated with balloon lights, an acceptable lighting distribution both in terms of illumination levels and footprint can be obtained on the light tower side of the maintenance vehicle for general activities and work around equipment.

- If at least six LED lights are mounted in a distributed configuration alongside a maintenance truck, then the lighting footprint and illumination levels can even be improved on the same side for general activity areas as well as work around equipment.

Recommendations

The following recommendations are made from the results and the experience gained from this research task:

- If reduction of greenhouse gasses is a goal, then the use of solar lighting trailers over diesel powered lighting trailers is recommended for consideration for highway maintenance applications when applicable.

    - In areas where there are long periods of sunlight in a year, then use of solar powered LED lighting is recommended, under the same considerations, when applicable. In such areas there will be an approximate CO_2 reduction of 4.1 tons per unit of equipment used on an annual basis.

- When noise reduction at a work site is a goal then use of solar lighting trailers is recommended over diesel powered lighting trailers.

- Solar powered lighting trailers that separate the solar panels from the lighting trailer and position them in a separate charging station eliminate in-the-field handling issues of solar powered lighting trailers and can enhance their utility. This kind of solar panel configuration is recommended when there are concerns related to potential damage to the panels at a work site.

- LED solar powered lighting designs that are integrated into the maintenance vehicles are recommended for consideration over the use of trailer based systems for applications in work zones with confined spaces which limit the use of a trailer based system.

- Distributing LED lights alongside a maintenance truck can improve the lighting distribution footprint on the same side as compared to the tower configuration. This kind of LED lighting distribution on a maintenance vehicle is recommended for consideration to enhance night time work zone operations.

- In its present (tested) configuration, the use of a solar powered LED lighting trailer is recommended for consideration for stationary work when there is enough room for the utilization of a trailer and enough sun during daylight hours for charging the batteries. Examples of such operations are:

    - Operations which remain in a single, relatively small area for a long enough time such that a trailered light source may be utilized. The operation is performed by workers using relatively stationary equipment so the operation could also be successfully lit with a solar LED lighting trailer with properly configured lighting when there is enough room for the trailer at the work site. The repair of concrete slabs is example of such an operation. Alternatively, if equipment mounted lighting is used, then a secondary support vehicle with solar LED lighting trailer could also be utilized to provide additional illumination.

    - Situations where operations are spread out and equipment is moving in and out of an immediate point of operation that is distributed across a relatively wide area. An example of this would be the repair of slopes where loaders, dump trucks, and graders move in and out of the area with workers also on foot. In this type of operation, a wide area must be lit and no piece of equipment is stationary. A secondary vehicle with lighting would not be of great advantage over a solar lighting trailer. In this case, a solar LED lighting trailer with properly configured lighting could be used.

    - Operations that occur with various combinations of equipment and workers operating in a relatively small area but enough room to utilize a trailer based system. An example is sign replacement where a solar LED lighting trailer with appropriately configured lighting could be used.

CHAPTER 1: INTRODUCTION

This research study dealt with evaluating whether or not solar lighting can effectively replace existing lighting methods for tasks in highway work zones during dark hours. This report summarizes the results of a 15-month study consisting of a review of the literature, laboratory testing, field evaluations, and computer simulations. The following research questions were considered in this study:

1. Can solar lighting be an alternative to existing methods of lighting used in highway maintenance and construction in highway work zones?

2. How do the solar lighting systems compare technically to existing lighting systems used in highway work zones in terms of performance?

3. What are the cost benefits of using solar lighting in highway work zones?

4. What type of modifications would be necessary to make the commercially available solar lighting systems more appropriate for Caltrans' use in highway work zones?

This research study built upon and expanded the previous work of the AHMCT research center in evaluating the effectiveness of using hydrogen based fuel cell type lighting systems in highway work zones [4].

In California, most highway construction tasks and some highway maintenance tasks are performed during the night time since night operations provide certain advantages. These include reduced traffic congestion that can help in decreasing air pollution due to fewer idling vehicles, more comfort for the work crew due to lower temperatures during summer months, and possibly longer work shifts. Some studies [1-2] have indicated that performing these operations at night time would result in reduced user costs. There is, however, important drawbacks due to reduced visibility for the work crew, glare, decreased driver awareness of road conditions due to fatigue and/or intoxication, and potentially increased construction costs [3]. In California, the economic and environmental benefits of a decrease in congestion and delays have resulted in an increased use of night time work for highway construction and repairs.

The present methods of lighting highway work zones at night involves the use of lighting systems powered by diesel generators that contribute to air pollution, vibrations, and noise in the work environment. Lighting systems using alternative, clean energy systems are therefore more desirable if they can provide the same performance in providing visibility at a highway work zone at reasonable operational costs. Recently, AHMCT evaluated the use of lighting systems powered by hydrogen fuel [4] and found them to be effective as an alternative source for temporary lighting in work zones. The use of hydrogen lighting systems is not presently practical, however, due to their cost (together with the cost of the fuel) and lack of availability of facilities for refueling them. It was envisioned that a solar lighting system could be a potential competitor since there is easy access to sun light in many areas in California, especially during the summer months. Furthermore, use of such lighting systems not only increases Caltrans' use of alternative energy but also provides environmental benefits.

The objective of this research study was to evaluate the use of solar lighting trailers as a method of temporary lighting for highway work zones. The scope of work involved the evaluation of lighting illumination, its comparison with lighting standards, and a cost benefit analysis of the use of such alternative lighting technology. It involved technical evaluations, laboratory as well as field testing, and computer simulations.

CHAPTER 2:
RESEARCH APPROACH

The research approach utilized started with a literature and technology review to develop an understanding of state of the art lightning systems and some of the relevant terminologies in evaluating and accessing them. In addition, the existing standards in use of lighting for various tasks were evaluated, and those that can be relevant to highway work zones were identified.

The research approach then involved using a three-tier methodology:

- Laboratory Testing
- Field Evaluation
- Analysis and Computer Simulation

The third level of the methodology was utilized after the first two levels to see what lighting options not captured by the solar LED lighting trailer tested could be most useful for highway applications. The laboratory testing was performed at AHMCT's Advanced Transportation Infrastructure Research Center (ATIRC) facilities. The field evaluations were intended to evaluate the in-the-field experience of using the system and develop data or an understanding of the actual usability of the system in real work zones.

The research approach consisted of eight tasks starting with forming a Technical Advisory Group (TAG) that guided the research, followed by a survey of the relevant literature, renting a solar lighting unit for testing, and so forth. The eight tasks are listed below:

1. Form the Technical Advisory Group (TAG)
2. Literature Survey and Evaluation of Existing Solar LED Lighting Systems for Highway Work Zone Applications.
3. Procurement, through a rental, of a Solar LED Lighting Trailer for Testing and Evaluation.
4. Experimental Laboratory Testing of the System.
5. Identification of a Work Zone Site for Field Testing.
6. Scheduling and Performing Field Testing.
7. Analysis of the Results and Computer Simulations.
8. Documentation and Presentation of Research Results to Caltrans.

CHAPTER 3: LITERATURE REVIEW, TERMINOLOGY, AND LIGHTING REQUIREMENTS

There are several existing temporary lighting systems used in highway work zones. These include the light tower (see Figure 1) which is the most common type used [5]. Diesel generators are used as a power source for these lights.

Figure 1. The Light Tower.

Another kind of light used are the so-called Nite Lites shown in Figure 2. This kind of lighting is either used in a stationary manner or mounted onto a vehicle or a trailer [6]. This lighting system is also an electric light, which needs a diesel generator.

Figure 2. The Nite Light.

A relatively newer type of lighting is balloon lighting, which uses an inflatable cloth balloon surrounding light bulbs (Figure 3). These can either be mounted on vehicles or left stationary on the roadway, and are praised for their light uniformity and low glare [7-8]. There is also temporary mast lighting that can be considered in some special situations, but these are not deployable lighting systems, making them inappropriate for highway work zones.

Figure 3. Balloon Lighting at a Highway Work Zone.

The important issue, however, is that all these lighting systems use fossil fuel based generators to generate the electricity needed to power them. The only exception, other than solar lighting, are the fuel cell lighting systems which use hydrogen as fuel.

An alternative approach is to consider solar powered LED lighting systems. Such systems use alternative energy in the form of rechargeable batteries powered by solar energy, and therefore are not dependent on the use of fossil fuels. Solar LED lighting systems are becoming commercially available, but have not been tested for their use and effectiveness in highway work zone construction and/or maintenance sites. For instance, Colorado based Wanco, Inc. manufactures a trailer based solar powered LED lighting system as shown in Figure 4. The Wanco solar LED lighting trailer was the system procured on a rental agreement and was tested as a typical solar powered LED lighting system in this research study.

Figure 4. Wanco Solar LED Lighting Trailer.

In recent years, LED lighting systems have found increasing applications in roadway and street lighting. In 1997, Evans [9] highlighted that the dependability, low power requirements, cost effectiveness, and visibility in sunlight are the four main advantages of LED technologies as compared to incandescent light sources. LED lights typically have mean times to burnout 100s of times higher than incandescent light sources with power requirements 1/9th that of incandescent lighting.

In 2009, Wu and coworkers [10] studied the economic feasibility of using 100W solar powered LED lighting installations for a 2 lane 10 km highway. They found that although the initial cost was 22% higher for conventional LED lighting and 45% higher for solar-powered LED lighting compared to mercury lamps, the lights were found to be economically feasible, with a payback time of 2.2 and 3.3 years required, respectively, to offset the excess investment. Wu et al. also noted that LED lighting systems generate better directed light, with 85% of the light generated by the lamp reaching the roadway surface (without requiring complex reflector systems), versus only 40-50% light output from the lamp reaching the road surface from conventional sodium or mercury installations. In their study, Wu et al. also found that LED lights realize a 35-65% reduction in energy consumption compared to sodium or mercury lamps and have a longer service lifetime.

In 2011, Rodrigues and coworkers [11] evaluated LED luminaires as a replacement for high pressure sodium lamps. Their work focused on evaluating relative perception with varying spectral distributions in the scotopic operating state. Rodrigues et al. [11] suggested that the chromaticity of LED luminaires yields better perception in low light conditions than high pressure sodium lamps. Additionally, Rodrigues et al. [11] found that LED light sources were economically viable because payback occurs before the end of the lifespan of the LED luminaires.

Design of temporary night time highway illumination for highway construction and maintenance poses a number of challenges for a lighting engineer. On the one hand, the work zone must be illuminated in such a way that a worker can readily perform construction and maintenance tasks with minimal visual discomfort. On the other hand, the roadway, workers, and construction environment must be sufficiently illuminated so that drivers can easily identify and rapidly respond to the construction environment, while avoiding a level of glare that can affect their driving behavior. These requirements can sometimes be at odds with one another (Bremond [28]).

In contrast to lighting design applications where visual appearance is important, lighting for road construction is usually designed from a functional point of view. In comparing different lighting options, quantitative metrics can be employed. Most of these metrics for lighting design are related to the concept of visual performance, which has its roots in psychophysical science (Rea and Ouellette [12]). In visual performance assessments, experimental data are collected from a population of human test subjects for a given visual task and a mean psychophysical curve is computed from their responses. A performance threshold is typically set as a measure of the percent probability of success of the task, which may consist of identifying a visual target in varying lighting configurations or background settings (Richard [13]). In night time highway applications, visual performance is related to the brightness and uniformity of light as perceived by both a driver approaching a work zone and a construction or maintenance worker within the work zone.

Although visual performance is the most important metric for safety and comfort in night time highway construction and maintenance applications, the cost of operation is another important metric that cannot be neglected. In analyzing the cost of lighting installations, both the initial up-front cost of equipment and operating costs must be considered. Related to the operational cost is a lighting system's efficacy, i.e., the ratio of a luminaire's light output to power consumption.

Other effects that can be measured quantitatively include effects of light pollution, i.e. light projected into the surrounding environment (Falchi et al. [14]), and environmental effects, such as noise level and air pollution from diesel generators. Excess noise levels may make it difficult for construction crews to communicate or cause long term hearing damage (Neitzel et al. [15]). Although light pollution and excess noise levels may have an adverse effect on workers and wildlife in the surrounding area (see, for example, Gaston et al. [16] and Turk [17]), the impact of air pollution from diesel generators used in temporary lighting can have far greater environmental impacts. It is important, therefore, to minimize these factors when designing a lighting system for temporary applications in highway work zones.

Although most functional attributes of lighting systems can be measured quantitatively, qualitative aspects, such as ease of transportation and deployment, must also be considered.

Before discussing the lighting requirements for highway applications, some of the useful terminology used in lighting design and the metrics that can be most applicable for highway work zone lighting systems are discussed in the remainder of this section.

Illuminance: Illuminance is the amount of light directly striking a surface – the incident light. Illuminance does not provide an indication of how bright a surface will appear; rather it is a measure of the intensity of light that reaches a surface. It should be noted that light intensity by itself is independent from distance but illuminance is not. Illuminance is inversely dependent on square of the distance to the surface and directly related to light intensity.

Candela: Candela is defined as the luminous intensity in a given direction of a source that emits monochromatic radiation of a frequency of 540 x 1012 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian (equal to the angle at the center of a sphere subtended by a part of the surface equal in area to the square of the radius).

Luminance: Luminance is the intensity of light reflected from a surface. Luminance is a measure of human perception of brightness or how bright we perceive the light that is reflected from a surface. The brightness of light or luminance is measured by footLamberts (fL) (lumen in SI units). One foot-lambert equals $1/\pi$ candela per square foot.

Foot-Candle: Foot-Candle is a unit of illuminance and is equivalent to the illumination produced by a source of one candle at a distance of one foot. The SI unit for illuminance is lux, which is lumen per square meter.

Veiling Luminance (VL): Veiling luminance is defined as luminance superimposed on the retinal image which reduces contrast and the apparent brightness of objects in the visual field.

It is this veiling effect produced by bright sources or areas in the visual field that results in reduced visual performance and visibility. Veiling luminance is related to glare.

Glare: Two types of glare exist. The first type of glare is known as disability glare or absolute glare and is caused by an extremely bright light source, such as the sun or a high luminance light source. High absolute glare causes damage or discomfort to photoreceptors because the luminance is too great to process without damage. Disability glare can be analyzed by an absolute level of luminance in scene; contrast is not important. The second type of glare is known as discomfort glare or relative glare. Discomfort glare is caused by luminance values to which the human eye can adapt. Although discomfort glare may not impair vision, it may cause ocular discomfort, eye fatigue, increased blinking, or tearing. In night time highway construction and maintenance applications discomfort glare typically plays an important role (see, for example, Schreuder [18]), but disability glare may also play a role in temporary lighting design considerations, particularly if a high intensity light source is aimed directly at oncoming traffic.

Illuminance Uniformity: Illuminance uniformity is defined as the ratio of the maximum-to-average or maximum-to-minimum illuminance in a given region. Lighting configurations with low uniformity ratios exhibit uniform illumination. A high uniformity ratio indicates that illuminance fluctuates greatly in the region of analysis. Uniformity of illuminance (typically of the roadway) within a highway work zone environment or of luminance as perceived by a driver of a vehicle approaching the highway work zone or a worker within the work zone are important concepts in the design of a night time work zone lighting system.

Luminance Uniformity: Luminance uniformity, also called contrast ratio, is the ratio of maximum-to-average or maximum-to-minimum luminance within an observer's field of view.

Veiling Luminance Ratio: Veiling Luminance Ratio (VLR) is a method for quantifying perceived glare in night time highway applications. It is defined as the ratio of luminance of the roadway to the luminance in the driver's field of view. Larger ratios indicate a higher level of perceived glare. While this metric is commonly used in roadway lighting system designs, one of the drawbacks to this metric is that it takes into account only the illumination of the roadway and not the illumination of other targets in the driver's field of view that may be important, such as signage or workers in a construction zone.

Small Target Visibility (STV): STV is a method of illumination design that determines the visibility level of an array of targets on the roadway considering the luminance of the targets: luminance of the immediate background, adaptation level of the adjacent surroundings, and disability glare. STV is the weighted average of the visibility level of these targets. The disability glare is defined in terms of veiling luminance and is included in STV calculation methodology. The disability glare or veiling luminance ratio is measured as the ratio of the veiling luminance (directly from the light sources) to the average pavement luminance. The STV as used in highway applications (Adrian

[19]) computes the detection threshold for a small 7.9 inch (20 cm) target located on the roadway based on the threshold luminance contrast of the Human Visual System (HVS). Lecocq [20] points out that one of the weak points of the STV model is that the planar 7.9 inch (20 cm) target does not take into account the shape and visual properties of real objects such as construction and maintenance workers or equipment. Lecocq [20] proposes using a spherical target instead of a planar one and carrying out the analysis for a range target reflectance values. Additionally, he proposes using a 50 year old population in the calculations, rather than having the calculation based on the average age of the population. Lecocq [20] also indicated that the analysis should be performed for a range of distances (correlated to a range of traveling speeds) rather than for a fixed value. Schreuder [18] recommends that the analysis be performed as a function of stopping distance for a given traveling speed, typically in the range of 197 to 525 feet (60 to 160 meters). Raynham [21] remarked on additional shortcomings of the STV model. Colored contrast is not taken into account in the detection task. Despite the drawbacks of the basic STV model, it is still widely used in practice.

Lighting Requirements for Permanent Roadway Lighting Fixtures

The Illuminating Engineering Society of North America (IESNA) [22] and the American National Standards Institute (ANSI) [23] provide standards for fixed roadway lighting fixtures. The standards pertaining to freeways and highways are relevant to night time construction and maintenance tasks. The IESNA divides freeways into two categories:

- Freeway A: “Roadways with greater visual complexity and high traffic volumes. Usually this type of freeway will be found in major metropolitan areas in or near the central core and will operate through some of the evening hours of darkness at or near design capacity.”

- Freeway B: “All other divided roadways with full control of access.”

IESNA roadway lighting fixture illuminance guidelines for varying road types and pavement classifications are shown in Table 1. Class B freeways have identical Uniformity Ratio and Veiling Luminance Ratio recommendations as Class A freeways, but lower overall illumination recommendations. Additionally, the IESNA provides guidelines for luminance and STV, as shown in Table 4.

Table 1: Lighting Fixture Illuminance Standards from [30], p.8.

Road and Pedestrian Conflict Area		Average Luminance	Uniformity Ratio	Uniformity Ratio	Veiling Luminance Ratio
Road	Pedestrian Conflict Area	L_{avg} (cd/m^2)	L_{avg}/L_{min} (Maximum Allowed)	L_{max}/L_{min} (Maximum Allowed)	L_{Vmax}/L_{avg} (Maximum Allowed)
Freeway Class A		0.6	3.5	6.0	0.3
Freeway Class B		0.4	3.5	6.0	0.3
Expressway	High	1.0	3.0	5.0	0.3
	Medium	0.8	3.0	5.0	0.3
	Low	0.6	3.5	6.0	0.3
Major	High	1.2	3.0	5.0	0.3
	Medium	0.9	3.0	5.0	0.3
	Low	0.6	3.5	6.0	0.3
Collector	High	0.8	3.0	5.0	0.4
	Medium	0.6	3.5	6.0	0.4
	Low	0.4	4.0	8.0	0.4
Local	High	0.6	6.0	10.0	0.4
	Medium	0.5	6.0	10.0	0.4
	Low	0.3	6.0	10.0	0.4

Table 2: Lighting Fixture Luminance and STV Standards from [30], p. 9.

Road and Pedestrian Conflict Area		STV Criteria	Luminance Criteria		
Road	Pedestrian Conflict Area	Weighting Average VL	L_{avg} cd/m^2 Median <7.3 m	L_{avg} * cd/m^2 Median $\geq$7.3 m	Uniformity Ratio L_{max}/L_{min} (Maximum Allowed)
Freeway "A"		3.2	0.5	0.4	6.0
Freeway "B"		2.6	0.4	0.3	6.0
Expressway		3.8	0.5	0.4	6.0
Major	High	4.9	1.0	0.8	6.0
	Medium	4.0	0.8	0.7	6.0
	Low	3.2	0.6	0.6	6.0
Collector	High	3.8	0.6	0.5	6.0
	Medium	3.2	0.5	0.4	6.0
	Low	2.7	0.4	0.4	6.0
Local	High	2.7	0.5	0.4	10.0
	Medium	2.2	0.4	0.3	10.0
	Low	1.6	0.3	0.3	10.0

Table based on a 60 year old driver with normal vision, an 18 cm x 18 cm (7.1 in. x 7.1 in.) 50 percent reflective target, and a 0.2 second fixation time.

Lighting Requirements for Temporary Work Zones

There are currently rather limited stated requirements for temporary night time lighting for construction and maintenance work sites. California Occupational Safety and Health (Cal-OSHA) provides illuminance recommendations in its Construction Safety Orders (CSO) 1523 [24]. CSO 1523 states that: “construction areas, ramps, corridors, offices shops, and storage areas, etc., shall be lighted to not less than the minimum illumination intensities given in Table 3.”

Table 3. Minimum Illumination Intensities in Foot-Candles.

Foot-Candles	Area of Operations
3	General low activity construction area
5	Outdoor active construction areas: concrete placement, excavation and waste areas, access ways, active storage areas, loading platforms, refueling, and field maintenance areas.
5	Indoors: warehouses, corridors, hallways, stairways, and exit ways.
10	General construction plant and shops (e.g., batch plants, screening plants, mechanical and electrical equipment rooms, carpenter shops, rigging lofts and active storerooms, barracks or living quarters, locker or dressing rooms, mess halls and indoor toilets and workrooms).
10	Night time highway construction work.
30	First-aid stations, infirmaries, and offices.

Similarly, chapter 8 of Caltrans’ maintenance manual states that “sufficient lighting should be provided at the worksites.” Desired illumination levels vary depending on the nature of the task involved. The California Manual for Uniform Traffic Control Devices (CAMUTCD) specifies 10 Foot-Candles as the minimum average horizontal luminance for general activities (the Federal MUTCD specifies 5 Foot-Candles for general activities). Both the California and Federal MUTCD specify 10 Foot-Candles as the minimum average horizontal luminance for activities around equipment. Tasks requiring high levels of precision and extreme care can require an average horizontal luminance of 20 Foot-Candles. The California maintenance manual indicates that “flagger stations must be illuminated during hours of darkness with a minimum 20 foot-diameter foot print so the flagger is clearly visible to approaching traffic.

At work sites, the maintenance manual states that “light plants, flood lights, or work lights shall be mounted and directed in a manner to allow employees to work safely and to prevent glare to approaching traffic.” Additionally, “[f]lood lights shall not produce a disability glare condition for approaching traffic” and the “adequacy of the floodlight placement and elimination of potential glare should be determined by driving through and observing the flood light area from each direction on all approaching roadways after the initial floodlight set up, at night, and periodically.” A more quantitative method of evaluating the potential glare for a light source for approaching traffic in highways is given in California Vehicle Code (CVC) section 21466.5 [25]. This section states that “the brightness reading of an objectionable light source can be measured with a 1 ½ degree photoelectric brightness meter placed at the driver’s point of view. The maximum measured brightness of the light source within 10 degrees from the driver's normal line of sight shall not be more than 1,000 times the minimum measured brightness in the driver's field of view, except when the minimum measured brightness in the field of view is 10 foot-lamberts or less, the measured brightness of the light source in foot-lambert shall not exceed 500 plus 100 times the angle, in degrees, between the driver's line of sight and the light source."

The National Cooperative Highway Research Program (NCHRP) provides task specific illuminance recommendations that range between 5 to 20 Foot-Candles (54 to 108 lux) [26]. Table 4 provides illuminance levels for varying tasks and the distances that illumination should be maintained from the task area. Additionally, Table 5 provides guidelines to mitigate glare.

Table 4. NCHRP Recommended Illuminance Levels [26], p. 2-26.

Description of Construction and Maintenance Task	Average Maintained Illumination	
	Category	Target Level lux (fc)
Excavation – Regular, Lateral Ditch, Channel	I	54 (5)
Embankment, Fill and Compaction	I	54 (5)
Barrier wall, Traffic Separators	II	108 (10)
Milling, Removal of Pavement	II	108 (10)
Asphalt Paving and Resurfacing	II	108 (10)
Concrete Pavement	II	108 (10)
Asphalt Pavement Rolling	I	54 (5)
Subgrade, Stabilization, and Construction	I	54 (5)
Base Course Grading and Shaping	II	108 (10)
Surface Treatment	II	108 (10)
Base Course Rolling	I	54 (5)
Waterproofing and Sealing	II	108 (10)
Sidewalk Construction	II	108 (10)
Sweeping and Cleaning	I	54 (5)
Guard Rails and Fencing	II	108 (10)
Striping and Pavement Marking	II	108 (10)
Landscaping, Sod and Seeding	I	54 (5)
Highway Signs	II	108 (10)
Traffic Signals	III	216 (20)
Highway Lighting Systems	III	216 (20)
Bridge Decks	II	108 (10)
Drainage Structures and Drainage Piping	II	108 (10)
Other Concrete Structures	II	108 (10)
Maintenance of Embankments	I	54 (5)
Reworking Shoulders	I	54 (5)
Repair of Concrete Pavement	II	108 (10)
Crack Filling	III	216 (210)
Pot Hole Filling	II	108 (10)
Repair of Guardrails and Fencing	II	108 (10)

Recommended Illumination Areas for Typical Highway Construction Equipment	
Provide target illumination over task working area. This is the effective working width of the machine by approximately 5 meters.	
Minimum distance from machine to	
Slow Moving Equipment: Paver Milling Machine	5 meters
Fast Moving Equipment: Backhoe Loader Wheel Loader Scraper Roller Motor Grader	20 meters
Other Equipment: Maximum uniformity ratio of 10:1 in the work area. Minimum of average maintained illumination of 54 lx (5 fc) for all work areas.	

Table 5. NCHRP Glare Control Check List [26], p. 2-26.

Beam Spread	Select vertical and horizontal beam spreads to minimize light spillage. Consider using cutoff luminaires.
Mounting Height	Coordinate minimum mounting height with source lumens (see Figure A-2).
Location	Luminaire beam axis crosses normal lines of sight between 45° and 90°.
Aiming	Angle between main beam axis and nadir less than 60° (see Figure 5). Intensity at angles greater than 72° from the vertical less than 20,000 candela.
Supplemental Hardware	Visors Louvers Shields Screens Barriers

EN-12462-2 is the European standard for lighting requirements of outdoor workplaces [27]. The European standard provides recommendations for luminance, uniformity, and glare (as computed by the CIE (Commission Internationale de l'Eclairage) Glare Index (CGI)) for various outdoor tasks. Although specific standards for construction sites are not provided, the recommendations for building and industrial sites, shown in Table 6 and Table 7, can be relevant.

Table 6. European Standard for Lighting of Outdoor Work Places (Building Sites) [36].

Ref. no.	Type of area, task or activity	$\bar{E}_m$ lx	U_o –	GR_L –	R_a –	Remarks
5.3.1	Clearance, excavation and loading	20	0,25	55	20	
5.3.2	Construction areas, drain pipes mounting, transport, auxiliary and storage tasks	50	0,40	50	20	
5.3.3	Framework element mounting, light reinforcement work, wooden mould and framework mounting, electric piping and cabling	100	0,40	45	40	
5.3.4	Element jointing, demanding electrical, machine and pipe mountings	200	0,50	45	40	

Table 7. European Standard for Lighting of Outdoor Work Places (Industrial Sites) [27].

Ref. no.	Type of area, task or activity	$\bar{E}_m$ lx	U_o –	GR_L –	R_a –	Remarks
5.7.1	Short term handling of large units and raw materials, loading and unloading of solid bulk goods	20	0,25	55	20	
5.7.2	Continuous handling of large units and raw materials, loading and unloading of freight, lifting and descending location for cranes, open loading platforms	50	0,40	50	20	
5.7.3	Reading of addresses, covered loading platforms, use of tools, ordinary reinforcement and casting tasks in concrete plants	100	0,50	45	20	
5.7.4	Demanding electrical, machine and piping installations, inspection	200	0,50	45	60	Use local lighting

Comparison of Construction and General Work Zone Lighting Standards

The National Cooperative Highway Research Program describes work zone related tasks as falling under three categories:

(I) “General illumination in work zone for tasks requiring low accuracy work involving slow vehicles or large objects”;

(II) “Tasks around construction equipment and for tasks involving construction equipment (i.e. resurfacing)”; and

(III) “Tasks requiring high visual acuity such as crack filling, critical connections, maintenance of moving machinery, etc.”

For ease of comparison, relevant statements regarding recommendations or requirements for work zone construction activities have been extracted from the NCHRP recommendations, the CAMUTCD, the California Code of Regulations (Title 8, Division 1, Chapter 4, Subchapter 4, Article 3, Section 1523), the Caltrans Maintenance Manual, the Federal MUTCD, and the European Norm 12464-2 for the Lighting of Outdoor Workspaces, and are organized by their corresponding NCHRP category.

<u>Minimum Illumination</u>

A comparative summary of minimum illumination requirements is provided in Table 8. The CAMUTCD, which is derived from the Federal MUTCD, provides illumination requirements for highway construction in California. The CAMUTCD, like the Federal MUTCD, only indicates that the noted lighting levels ‘can be adequate’ which is interpreted to be a recommendation. The CAMUTCD also specifically references the requirements California Code of Regulations which require a minimum of 10 Foot-Candles for night time highway construction work. This appears to be a conflicting requirement. Besides referring to the California Code of Regulations, an additional difference between the CAMUTCD and Federal MUTCD is that 10 Foot-Candles are a recommended minimum for all night time highway construction work, whereas the Federal MUTCD includes a recommendation of 5 Foot-Candles for general activities not around equipment. Both provide the additional recommendation that 20 Foot-Candles be provided for tasks requiring high levels of precision and extreme care.

Table 8. Summary of Minimum Illumination Requirements.

Table of Illumination Recommendations / Requirements						
Source	**NCHRP Designation**					
	I		**II**		**III**	
	Description / Relevant Classifications	**Illumination Requirements**	**Description / Relevant Classifications**	**Illumination Requirements**	**Description / Relevant Classifications**	**Illumination Requirements**
NCHRP	General illumination in workzone. Tasks requiring low accuracy involving slow vehicles or large objects	5 fc (54 lx) *recommended*	Around construction equipment and for tasks involving construction equipment (i.e. resurfacing)	10 fc (108 lx) *recommended*	Tasks requiring high visual acuity such as crack filling, critical connections, maintenance of moving machinery, etc.	20 fc (216 lx) *recommended*
CAMUTCD (Section 6D-6G)	Refer to CA Code of Regulations (Section 1523)	*required*	General activities and activities around construction equipment.	10 fc (108 lx) *recommended*	Tasks requiring high levels of precision and extreme care	20 fc (216 lx) *recommended*
			Refer to CA Code of Regulations (Section 1523)	*required*		
CA Code of Regulations (Title 8, Division 1, Chapter 4, Subchapter 4, Article 3, Section 1523 – Illumination)	General construction area lighting low activity	3 fc (32.4 lx) *required*	General construction plant and shops (e.g. batch plants, screening plants, mechanical and electrical equipment rooms, carpenter shops, rigging lofts and active storerooms, barracks or living quarters, locker or dressing rooms, mess halls and indoor toilets and workrooms).	10 fc (108 lx) *required*		
	Outdoor active construction areas, concrete placement, excavation and waste areas, accessways, active storage areas, loading platforms, refueling and field maintenance areas.	5 fc (54 lx) *required*	Nighttime highway construction work	10 fc (108 lx) *required*		
MUTCD (Federal, Section 6D-6G)	General activity	5 fc (54 lx) *recommended*	activites around equipment	10 fc (108 lx) *recommended*	Tasks requiring high levels of precision and extreme care	20 fc (216 lx) *recommended*
European Norm 12464-2 Lighting of work places – Part2: Outdoor work places	General illumination in workzone. Tasks requiring low accuracy involving slow vehicles or large objects.	4.6 fc (50 lx) *recommended*	Framework element mounting, light reinforcement work, wooden mould and framework mounting, electric piping and cabling	9.3 lx (100 lx) *recommended*	Element joining, demanding electrical, machine and pipe mountings	18.6 fc (200 lx) *recommended*
	Continuous handling of large units and raw materials, loading and unloading of freight, lifting and descending location for cranes, open loading platforms	4.6 fc (50 lx) *recommended*	Reading of addresses, covered loading platforms, use of tools, ordinary reinforcement and casting tasks in concrete plants.	9.3 lx (100 lx) *recommended*	Demanding electrical, machine and piping installations, inspection.	18.6 fc (200 lx) *recommended*
Caltrans Maintenance Manual	Sufficient light should be provided at the work site. Light plants, floodlights, or work lights shall be mounted and directed in a manner to allow employees to work safely and to prevent glare to approaching traffic.					
	Refers to CAMUTCD					
Caltrans Flagging Instruction Guidebook	Flagger stations must be illuminated during hours of darkness with a minimum 20foot diameter illumination footprint (at 10 foot candles per CSO 1523) so the flagger is clearly visible to approaching traffic.					

The illumination recommendations from the European Norm 12464-2 are similar but do not specifically address highway work zones. Also noted is that Caltrans operational manuals require that flagger stations must be illuminated by 10 Foot-Candles with a 20-foot diameter illumination foot print.

Glare

The CAMUTCD provides glare requirements in the form of glare mitigation safeguards and a qualitative check to ensure that the lights do not exhibit debilitating glare once set up in a construction zone. The CAMUTCD closely follows the Federal MUTCD in this regard. Note that there are no specific quantitative glare requirements in the CAMUTCD or MUTCD, although the CAMUTCD does recommend (but not require) meeting California Vehicle Code 21466.5, which provides a quantitative metric of debilitating glare for the operator of a motor vehicle approaching a construction zone.

Table 9. Summary of Minimum Glare Requirements.

Glare Recommendations / Requirements						
Source	NCHRP Designation					
	I		II		III	
	Description / Relevant Classifications	Glare Requirements	Description	Glare Requirements	Description	Glare Requirements
CAMUTCD (Section 6D-6G)	Nighttime highway construction work lighting shall be provided within the work zone to illuminate the task(s) in a manner that will minimize glare to work crews and not interfere with the vision of oncoming motorists (e.g. providing screens, mounting lamps below the top edge of the barrier wall, varying the beam angle, etc.)					*N/A*
	Refer to CVC 21466.5					*recommended*
	Floodlighting shall not produce a disabling glare condition for approaching road users, flaggers, or workers. The adequacy of the floodlight placement and elimination of potential glare should be determined by driving through and observing the floodlighted area from each direction on all approaching roadways after the initial floodlight setup, at night, and periodically.					*required*
California Vehicle Code 21466.5	The brightness reading of an objectionable light source shall be measured with a 1 1/2 -degree photoelectric brightness meter placed at the driver's point of view. The maximum measured brightness of the light source within 10 degrees from the driver's normal line of sight shall not be more than 1,000 times the minimum measured brightness in the driver's field of view, except that when the minimum measured brightness in the field of view is 10 foot-lamberts or less, the measured brightness of the light source in foot-lambert shall not exceed 500 plus 100 times the angle, in degrees, between the driver's line of sight and the light source.					*see text*
MUTCD (Federal, Section 6D-6G)	The adequacy of the floodlight placement and elimination of potential glare should be determined by driving through and observing the floodlighted area from each direction on all approaching roadways after the initial floodlight setup, at night, and periodically.					*N/A*
European Norm 12464-2 Lighting of work places – Part2: Outdoor work places	General illumination in workzone. Tasks requiring low accuracy involving slow vehicles or large objects.	45-50 GR_L *required*	Framework element mounting, light reinforcement work, wooden mould and framework mounting, electric piping and cabling	45 GR_L *required*	Element joining, demanding electrical, machine and pipe mountings	45 GR_L *required*
	Continuous handling of large units and raw materials, loading and unloading of freight, lifting and descending location for cranes, open loading platforms	45-50 GR_L *required*	Reading of addresses, covered loading platforms, use of tools, ordinary reinforcement and casting tasks in concrete plants.	45 GR_L *required*	Demanding electrical, machine and piping installations, inspection.	45 GR_L *required*

The European norm 12464-2 provides quantitative limits for glare in outdoor work places based on the Commission Internationale de l'Eclairage (CIE) Glare Rating (from CIE 112-1994). The Comite European de Normalisation (CEN) 12464-2 is primarily intended for permanent outdoor lighting installations and the glare analysis described in the EU standard is comprehensive in that calculations are to be performed at regular gridded locations within the illuminated area, making analysis difficult to carry out experimentally.

CHAPTER 4: EXPERIMENTAL LABORATORY TESTING

In order to perform an experimental evaluation of solar lighting systems, a Wanco solar LED lighting trailer was procured through a lease program for testing. This system was recommended by Caltrans for evaluation as it was proposed in the original proposal. It is a trailer based system which has some similarities to the trailer based non-solar lighting systems used by Caltrans in highway work zone applications (see Figure 1). The Wanco LED solar lighting system used for experimentation is shown in Figure 5. This system uses solar power for a series of eight LED lights which can be reoriented in different directions as shown in Figure 5.

Figure 5. Wanco Solar LED Lighting Trailer.

The LED light output in terms of its illuminance on the surface was evaluated and compared to those of a balloon light and a metal halide light typically used in highway road work. A balloon light and a metal halide lighting trailer were obtained through loan and rental, and used in the experimental evaluation for comparison purposes in terms of their light output as measured by their illuminance on the road surface. The balloon light used in experimentation is depicted in Figure 6 and the metal halide lighting trailer used is shown in Figure 7.

Figure 6. Balloon Light Used in the Experimentation.

Figure 7. Magnum MLT3060 metal Halide lighting trailer used in the Experimentation.

Experiments were carried out at the Advanced Transportation Infrastructure Research Center (ATIRC). All experimental data was collected using a light meter placed on a rectangular grid surrounding the light source. A grid was laid out on the ground with illuminance sensing measurements at the grid points. In addition to providing a means for comparison, the experimental data was used to generate an Illuminating Engineering Society (IES) photometric data file that captures the light that is emitted in every direction for each setup. This data file provides for a better visualization of the results and facilitates the replication of the experiments in a computer simulation environment to investigate the effects of parameters, such as height and angular orientation of individual LEDs, which are not easily tested experiments.

Single Light Experiments

In the first test, a single LED light from the solar lighting trailer was positioned 17.5 feet above the ground to illuminate down vertically, and the illuminance values on the grid points were measured. Since LEDs are directional light sources used in arrays, the information gained from testing a single LED is useful for forming effective LED light arrangements. The measured illuminance values are depicted in the contour plot of Figure 8 and the corresponding IES file image for the results are depicted in Figure 9. In this figure, the illuminance (E) values along the grid are shown. The test results show that even with a single LED light, the illuminance values within a semicircular area with a diameter of approximately 13 are 10 Foot-Candles or better, and on a rectangular grid of approximately 3 by 6.5 feet are 20 Foot-Candles or slightly better, and on a grid of 6.5 by 13 feet are 10 Foot-Candles or better. Considering illumination values alone, the test data indicates that even one LED light does provide enough illumination for general activities as well as activities around equipment as specified by the CAMUTCD which requires an illuminance of 10 Foot-Candles. The footprint of the lighted area, however, is less than 20-foot in diameter which is specified by the CAMUTCD. The LED lights, however, are typically used in multiple units or in array configurations.

Similar test results for a single metal halide light from a Diesel Magnum lighting trailer are depicted in Figures 10 and 11. The single metal halide light was also positioned 17.5 feet above the ground in a configuration that it was vertically pointing down, providing results that can be properly compared to the results from the single LED light experiment.

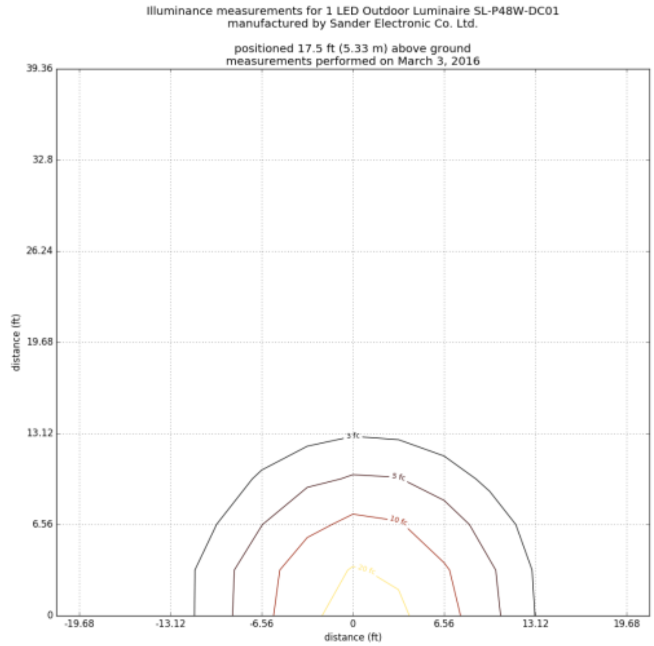

Figure 8. Contour Plots of Test Results for a Single LED with Wanco Trailer.

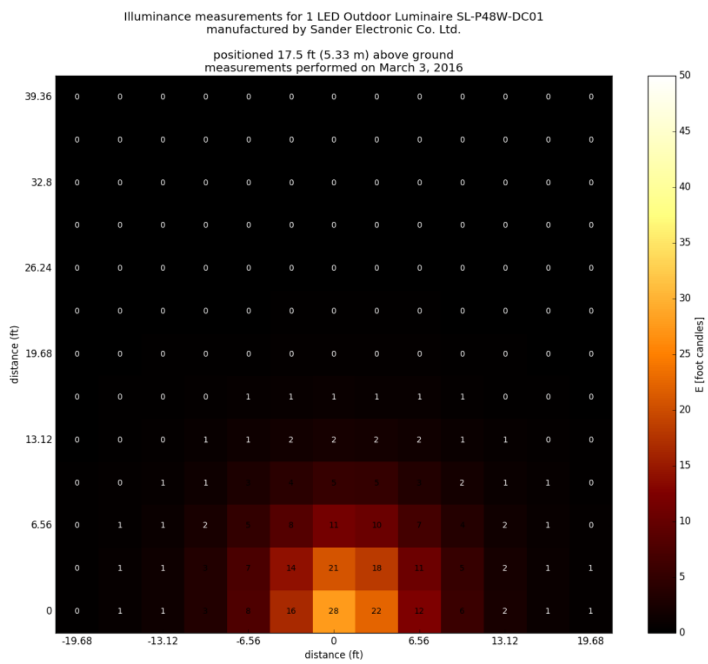

Figure 9. The IES Image of the Results for a Single LED Light.

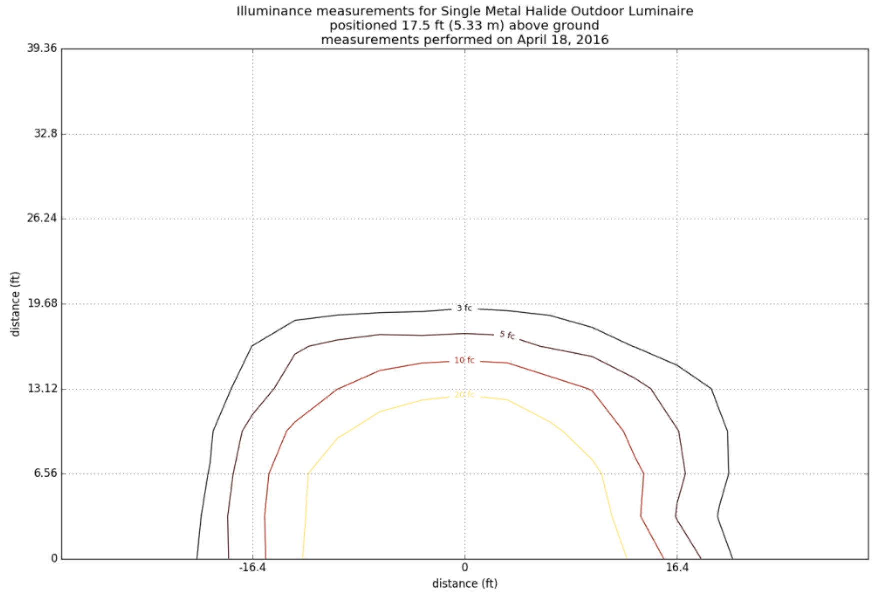

Figure 10. Contour Plots of Test Results for Single Metal Halide Light.

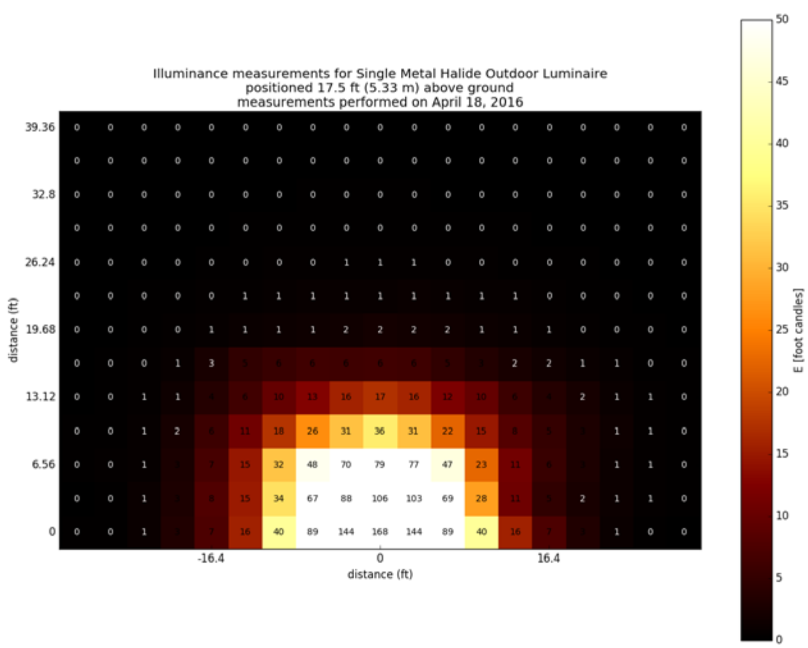

Figure 11. The IES Image of the Results for a Single Metal Halide Light.

The test results for a single metal halide light measured in the same configuration as the single LED light are depicted in Figure 11, indicating that this type of lighting provides much higher illumination levels and lighting over a larger footprint as compared to a single LED light. Evaluating the illumination levels over the same grid sizes as used in the single LED light experiment, the illumination values for a rectangular grid of approximately 3 by 6.5 feet are over 100 Foot-Candles or better, and on a grid of 6.5 by 13 feet are 69 Foot-Candles or better. The average illumination values for the single metal halide light is approximately and slightly over 6 times the average illumination values for a single LED light over the 6.5 by 13 feet rectangular grid size. The footprint for the illumination level of 10 Foot-Candles is a semicircular area with a diameter of approximately 30 feet as compared to 13 feet for the single LED light.

A single balloon light cannot be properly compared to a single LED light. The balloon light has a single metal halide bulb in it and is designed in a configuration to emit light in all directions. In order to obtain a lighting pattern similar to those obtained with the LED and metal halide lights, the experiment was setup such that the illuminance of one half of the area illuminated by the balloon light was measured. The balloon light was tested at a height of 15 feet due to the limitation in the size of the structure in the unit available for testing. The results are depicted in Figures 12 and 13.

The contour plots for the single balloon as tested indicates that, similar to a single LED and a single metal halide light, the balloon light also provides acceptable illuminance values of 10 Foot-Candles or better for general and near equipment activities.

With the exception of the balloon light, the single LED and the single metal halide lights are almost never used as a single fixture in highway applications. Lighting trailers equipped with these two types of lights are typically equipped with several light fixtures. Therefore, the main conclusion of the single light test is that the metal halide lights have a much higher illumination capacity as compared to solar powered LED lights as well as balloon lights. A better comparison of these lighting systems for highway work zone applications were performed next, where the LED lighting trailer with the aggregated lighting fixtures was tested and compared to the other lighting trailers using metal halide and balloon lights.

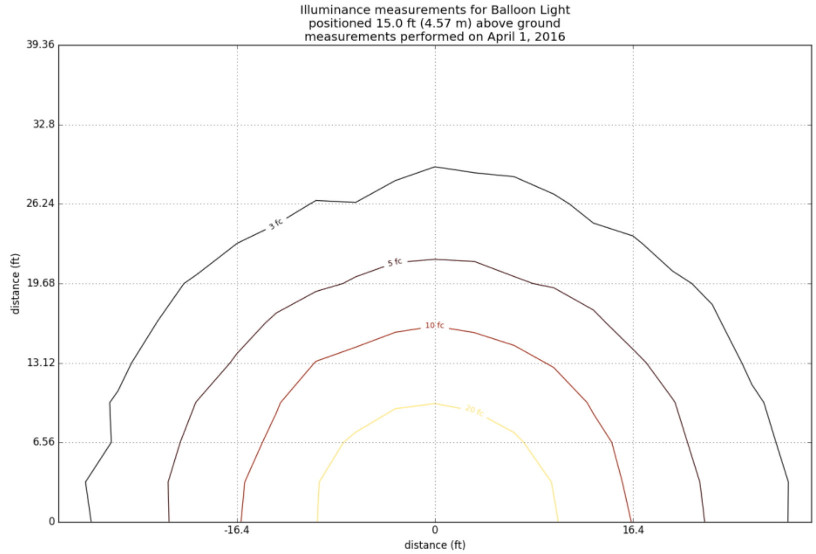

Figure 12. Contour Plots of Test Results for Single Balloon Light.

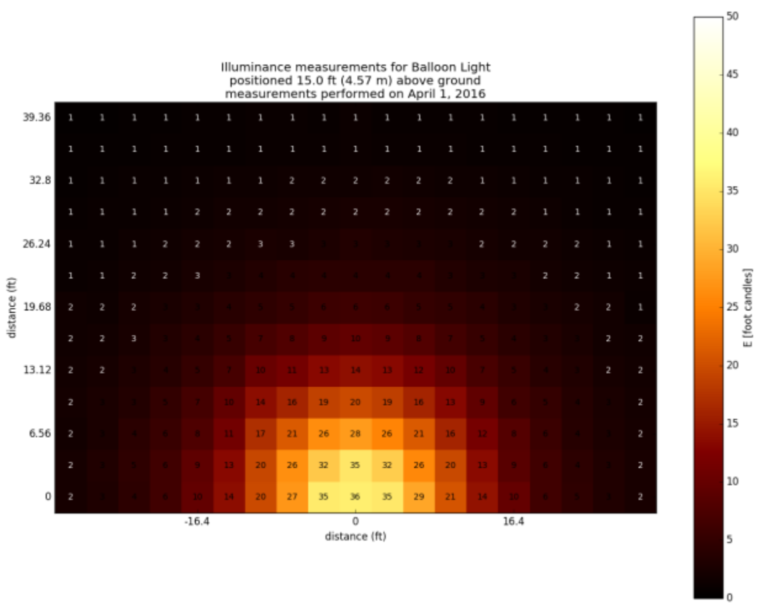

Figure 13. The IES Image of the Results for a Single Balloon Light.

Multiple LED Light Experiments

The next set of tests involved the Wanco solar lighting trailer, but this time all eight LED lights were used in three different configurations. These tests were intended to evaluate the full potential of the LED lighting system in terms of its applicability for use in highway night time work.

Eight LED Lights: Narrow Pattern Light Configuration

In this experiment, the full array of LEDs on the solar lighting trailer was used at same elevation of 17.5 ft. In this narrow pattern configuration, all LEDs had a -45° elevation angel with a 0° azimuth angle. The narrow pattern provides high intensity illumination near the area that the LEDs are pointed at, but due to the directional nature of LED lighting the surrounding areas were not well lit. The resulting contour plot and EIS image of illuminance (E) values on the measurement grid are depicted respectively in Figures 14 and 15

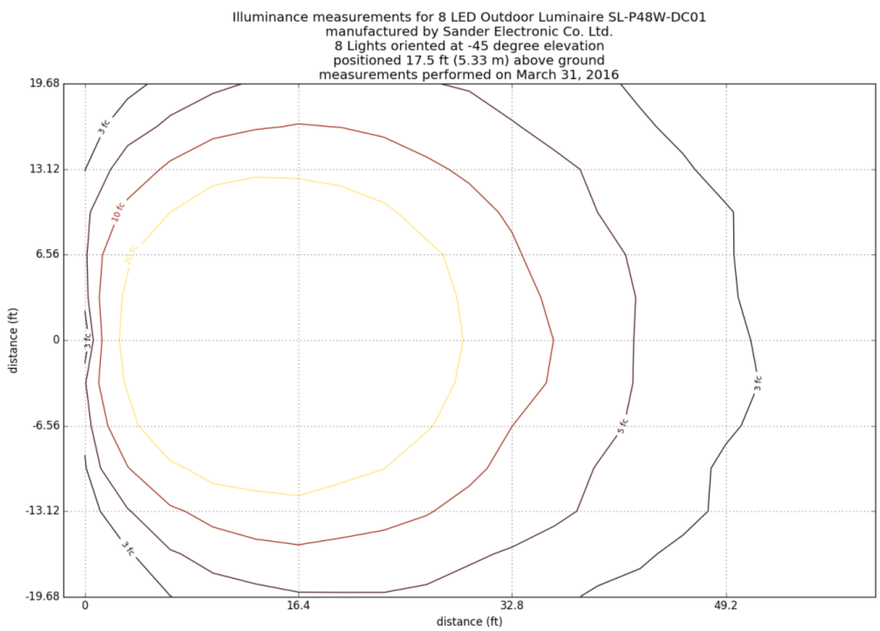

Figure 14. The Contour Plots of Illuminance Values for the Eight LED Lights in the Narrow Pattern Light Configuration.

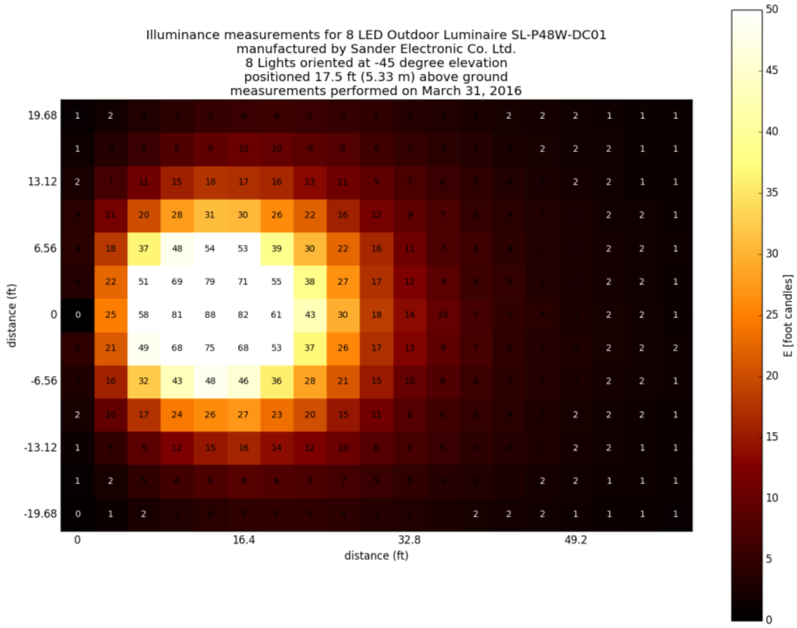

Figure 15. The IES Image of the Eight LED Lights in the Narrow Pattern Light Configuration.

It is clear from the contour plots that the eight LED lights in narrow pattern configuration cover beyond the 20-foot diameter footprint that is needed for some highway work zone tasks and that the illumination levels (as depicted in Figures 14 and 15) for such a footprint are 20 Foot-Candles or better.

Eight LED Lights: Wide Light Pattern Configuration

In this experiment, the LED lights were arranged such that a wide area would be illuminated. The LED array was again at an elevation of 17.5 feet. The angular orientation of each individual LED light in the arrangement is indicated in Table 10.

Table 10. The Angular Orientations of the Eight LED Lights in the Wide Pattern Configuration.

(elevation angle, azimuth angle)			
(-45°, -45°)	(-45°, -22°)	(-45°, 22°)	(-45°, 45°)
(-67.6°, -45°)	(-67.6°, -22°)	(-67.6°, 22°)	(-67.6°, 45°)

The resulting contour plots and EIS images of illuminance (E) values on the measurement grid are depicted in Figures 14 and 15 respectively. This arrangement demonstrates the capability of an LED array at efficiently illuminating a wide area exceeding a 20-foot diameter with illuminance values of 20 Foot-Candles or better.

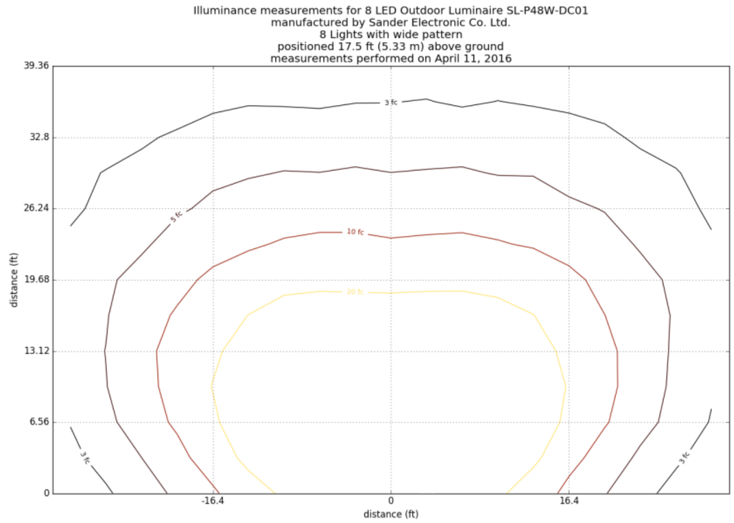

Table 11. The Contour Plots of Illuminance Values for the Eight LED Lights in the Wide Pattern Light Configuration.

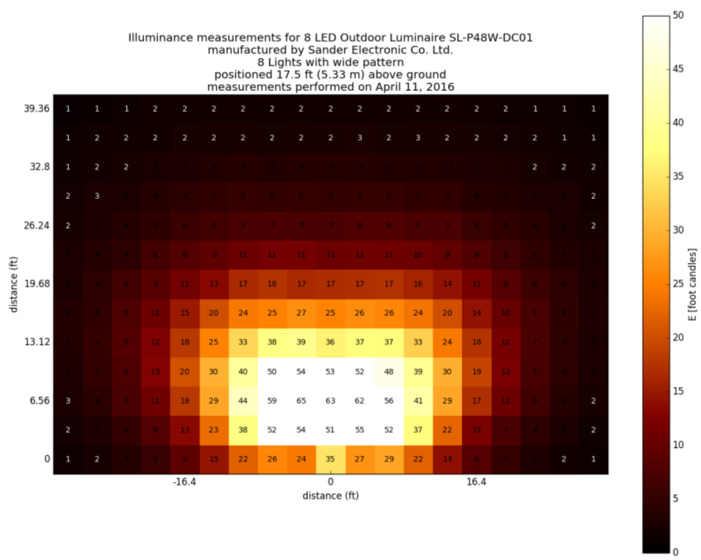

Table 12. The IES Image of the Eight LED Lights in the Wide Pattern Light Configuration.

Eight LED Lights: 360-degree Light Pattern Configuration

In this experiment, the configuration of the eight LED lights selected were such that they would attempt to uniformly illuminate the surroundings in a manner similar to a balloon light. In this experiment only one half of the area illuminated by the lighting arrangement was measured due to symmetry. The same arrangement was used in the balloon light experiment so the results could be easily compared. The LED array was raised to an elevation of 17.5 feet and the individual LED lights in the arrangement had the angular orientation described in Table 13.

Table 13.The Angular Orientations of the Eight LED Lights in the 360 Degrees Pattern Configuration.

(elevation angle, azimuth angle)			
(-45°, -22.5°)	(-45°, -157.5°)	(-45°, 22.5°)	(-45°, 112.5°)
(-45°, -67.5°)	(-45°, -112.5°)	(-45°, 67.5°)	(-45°, 157.5°)

The contour plots and the IES image of the test results for this 360-degree configuration are depicted in Figures 16 and 17.

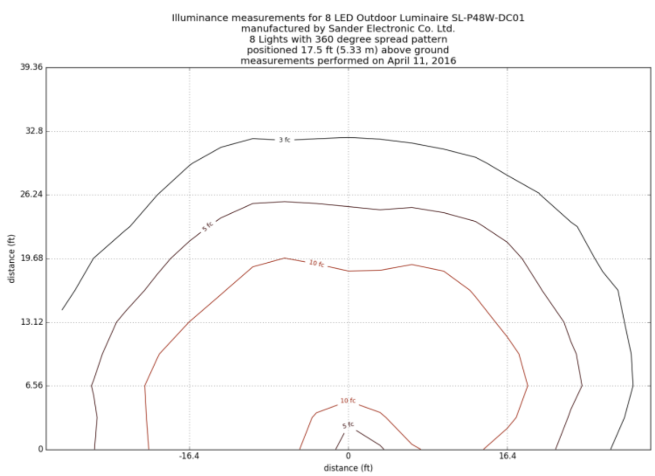

Figure 16. The Contour Plots of Illuminance Values for the Eight LED Lights in the 360 Degrees Light Pattern Configuration.

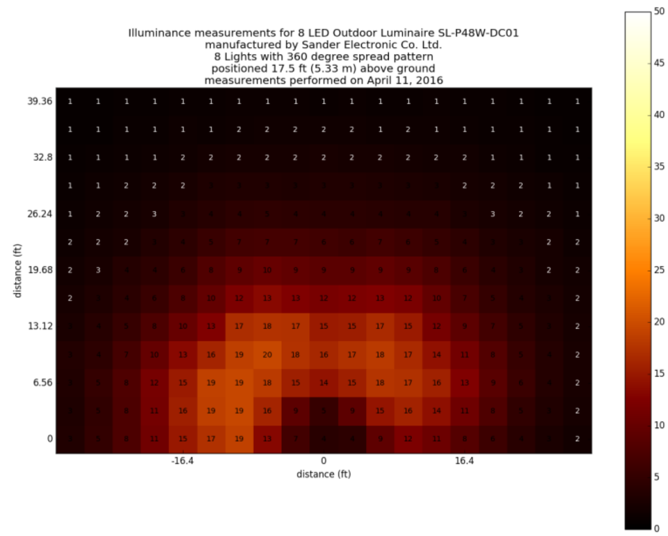

Figure 17. The IES Image of the Eight LED Lights in the 360 Degrees Light Pattern Configuration.

On evaluating the illuminance results for the 360-degree configuration, it is clear that although this configuration provides for a large area of illumination, the level of illuminance is 10 Foot-Candles or better. Therefore this configuration of the eight LED lights is more useful for illuminating larger general activity areas.

Comparative Evaluation of Lighting Illumination of Different Lighting Trailers

The experimental data using different lighting patterns of the light fixtures of the LED solar lighting trailer indicates that this lighting trailer can provide adequate localized lighting for work around equipment as well as limited areas within the general work area.

The total light output rating of a typical diesel trailer with the metal halide lights, such as the one tested, is at least 440,000 lumens (4 of the 1000 W metal halide fixtures). Some manufacturers claim higher, but it is known that the output of the metal halide bulbs drops fairly quickly to as low as 50% of the initial values. One reason this occurs is that a white oxide film will coat the inside of the bulb.

The total light output rating of the Wanco solar trailer tested is 36800 lumens (8 of the 48 W LED fixtures). It is known that LEDs will generate less light as they age. The rate at which they deteriorate is, however, much slower than metal halide lights.

Based on the above light output ratings, the diesel metal halide trailer will generate almost 12 times the light output of the solar LED lighting trailer. These values, however, are theoretical values. Test data conducted at the AHMCT research center in previous research [4] was combined with calculations based on test data on the solar LED lighting system performed in this research task to evaluate a more practical comparison of the light or illumination output of these two lighting systems as well as that of the balloon lighting system.

Each light fixture directs a cone of light onto a relatively small area, therefore, a small grid can be used to capture the majority of emitted light [4]. An approximation of light power from the lighting fixtures used on a lighting trailer can be derived from measurements of illuminance on a grid. Symmetric light fixtures for each of the three kinds of lighting systems were placed at the center of one edge of the grid at AHMCT's ATIRC facility such that the grid captured half the emitted light. The light fixtures were pointed directly at the ground from the tested heights in a range of 15-17.5 ft. Illuminance measurements were taken at each point and the measured values were mirrored along the line of symmetry. By using a grid spaced at 3.3 feet (1 m) apart, the illuminance values were recorded at the grid points. The sum of the illuminance measurements in units of lux approximates the light output in units of lumen. This value is independent of height as long as the majority of the light falls within the grid; but increasing the height does increase the accuracy and resolution of the measurements. The grid pattern used is depicted in Figure 18.

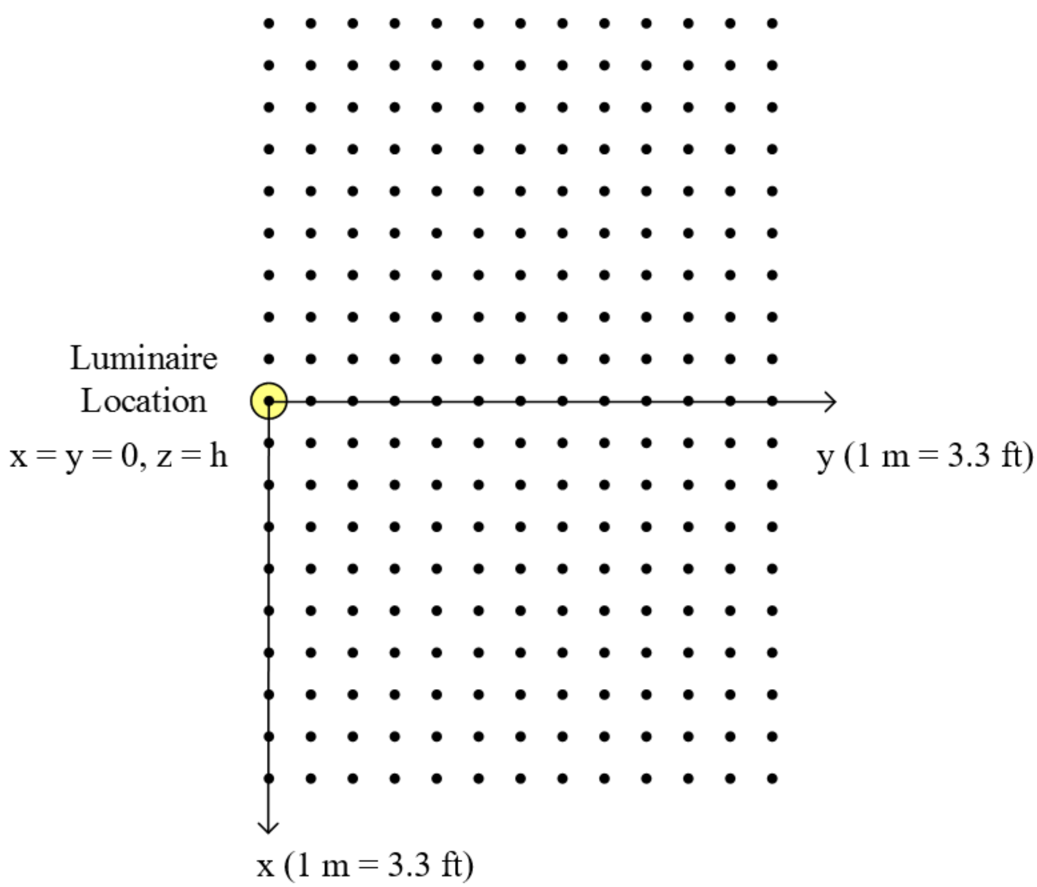

Figure 18. Grid Patterns for the Light Output Measurements.

The results of the light output calculations based on the test data are summarized in Table 14. The light output for the Magnum metal halide lighting trailer as well as the balloon light determined in this research study are consistent with data obtained in other studies [4].

Table 14. Light Output Measurements as Tested and Compared to Ratings.

		Light Ouput (lumen)				
	Metal Halide on Diesel Trailers	**Single Fixture**		**Test/Rating**	**Full Trailer**	
	Rated: 4 Fixtures totaling 440,000 lumen	**Test**	**Rating**	**Ratio**	**Light Set**	Note
a.	Allmand trailer [4]	48770	110000	44%	195080	Calculated for 4 fixtures
b.	Magnum trailer	36544	110000	33%	146176	Calculated for 4 fixtures
	LED on Solar Trailer					
	Rated: 8 Fixtures totaling 36,800 lumen					
c.	Single Fixture Test #1 (5 deg)	5746	4600	125%	45968	Calculated for 8 fixtures
d.	Single Fixture Test #2 (0 deg)	5289	4600	115%	42312	Calculated for 8 fixtures
e.	Test of 8 fixtures Narrow beam 20160407				*34232*	Light not fully captured on test grid
f.	Test of 8 fixtures Wide Area 20160411				*33092*	Light not fully captured on test grid
g.	Test of 8 fixtures 360 deg test 20160511				*31088*	Light not fully captured on test grid
	Balloon Light					
	Rated: 1 bulb @ 110,000 lumen					
h.	Balloon light w/ diffuser	27596	110000	25%		Light not fully captured on test grid
i.	Balloon light w/o diffuser based on sample	40536	110000	37%		Shows a 32% loss due to diffuser

The metal halide lights used in the trailer considered here are 1000 W bulbs with 110,000 lumen ratings specified by the manufacturers. These are indicated in the second column associated with light output in Table 14. The test results, however, indicate that actual light output, as measured in units of lumen, is much lower than the manufacturer’s ratings for the metal halide lights as depicted in the third column associated with light output in Table 14. For the Magnum lighting trailer, for example, the light output measured was only 33% of the manufacturer’s rating. The results in terms of light output for the balloon light were even worse due to its diffuser (white fabric) losses. Similar test results for the LED lights of the solar lighting trailer tested, however, indicated significantly higher light output as measured in units of lumen than the manufacturer’s ratings. These results are indicated in the middle rows of the second column in Table 14. The Wanco solar lighting trailer, therefore, achieves higher performance in lighting output than expected from the LED lights based on their ratings. The lighting efficacy (lumen per Watt of power consumption) of the Wanco lighting trailer tested is calculated to be approximately 109 lumens per Watt while studies of other LED lights [4] have measured only 54 to 67 lumens per Watt.

The lighting output of the diesel metal halide trailer, the balloon light, and the solar lighting trailer tested in units of lumen are listed in the third column of Table 14. The ratio of the light output of the solar LED lighting trailer to the diesel lighting trailers and the balloon light are summarized in Table 15. The data indicates that the ratio of light output from one standard diesel trailer is only 3 to 4 times that of the Wanco solar lighting trailer. Furthermore, the Wanco solar lighting trailer has a lighting output that is more than 1.5 times that of the balloon light. Given that the light illuminance levels drop off at distance squared, it may be possible to recommend less than 3 or 4 LED trailers for every diesel trailer if the objective is to distribute lighting along a roadway work zone.

Table 15. The Ratios of Lighting Outputs of the Trailers Evaluated.

	Comparison of Light Output	
	Ratio of LED Trailer to Allmand Diesel	24%
	Ratio of LED Trailer to Magnum Diesel	31%
	Ratio of LED Trailer to balloon light	167%

The dimensions and some of the other specifications of the Magnum diesel trailer, the Allmand diesel trailer, and the Wanco solar LED lighting trailer are summarized in Table 16. The data in this table indicates that the solar lighting trailer tested has a weight similar to the diesel lighting trailers considered, but higher travel dimensions due to the size of the folded solar panels.

Table 16. Comparative Specifications of Lighting Trailers.

Light Tower Manufacturer and Model	Descriptions	Travel Dimensions L x W (in)	Deployed with Outriggers L x W (in)
Magnum MLT 3060 Diesel	Metal Halide, 4 x 1000 W Rated 440,000 lumen 6 kW output 30 ft. Weight 1820 lb.*	170 x 49	117 x 96
Allmand Night-Lite Pro II Diesel	Metal Halide, 4 x 1250 W Rated 600,000 lumen 8 kW output 25 ft. tower Weight 1980 lb.*	112 x 56	112 x 100
Wanco Medium Solar Light Tower Tested unit	LED, 8 x 48 W @ 24 V Rated 36,800 lumen 20 ft. tower 890 W solar panels 8 4D batteries, 200 Ah at 12V Weight 1900 lb.	181x 92 (Width of folded panels 77 in)	181 x 111

Conclusions and Recommendations

The results from experimental laboratory testing and evaluation of LED lights of the solar lighting trailer as well as a balloon light and a metal halide lighting trailer indicate that the LED lights of the solar lighting trailer tested can be configured to provide illumination at a worksite that would meet the requirements (both in terms of illumination levels and footprint) of the CAMUTCD for general activity areas as well as for areas involving work around equipment. In comparing the overall lighting illumination output for the LED lights of the solar lighting trailer tested with a balloon light and the Magnum diesel metal halide lighting trailer, the results indicate that proper configuration of the eight LED lights on the solar lighting trailer can produce a lighting illumination output more than one and a half times that of the balloon light but one quarter to one third that of the diesel metal halide trailers evaluated.

Using the test data, the following recommendations are made:

- The 360-Degree Light Pattern Configuration of the LED lights on the solar lighting trailer can be used to provide general lighting at a work site. The overall lighting output, however, is approximately one quarter to one third that of the diesel metal halide trailers evaluated. It does provide a lighting output approximately similar to a balloon light with illumination of a minimum of 10 Foot-Candles and a footprint consistent with the requirements of the CAMUTCD, and therefore can be used for lighting general activity areas.

- Both the Narrow and the Wide Light Pattern Configurations of the LED lights on the solar lighting trailer provide lighting illumination of a minimum of 20 Foot-Candles with footprints exceeding a 10-foot diameter and therefore are recommended to be used not only for general activities but also for working around equipment. The Wide Light Pattern Configuration provides a slightly wider footprint than the Narrow Lighting Configuration, but both configurations have higher footprints than the balloon light in terms of an area with an illumination of a minimum of 20 Foot-Candles.

Testing of Solar Power Cycle of the Wanco Solar Lighting Trailer

In evaluating solar lighting for applications in temporary highway work zones, it is not only important to test the lighting output and distribution but also the power cycle of the solar panels. This type of testing was beyond the scope of this research task, but was performed to make the research more complete.

The Wanco solar lighting trailer is configured with solar panels totaling a rated 890 W (2 panels at 250 W and 3 retracting panels at 130 W). The surface area of the panels, including frames, measure 66 feet by 66 feet. It is outfitted with 8 LED light fixtures rated at 48 W each for a total of 384 W. Energy is stored in eight 4-D Absorbent Glass Mat (AGM) batteries rated at 200 Amp hour (Ah) at 12 Volts. The AGM batteries are sealed lead acid batteries which have long service life and are maintenance free. The batteries are wired in pairs resulting in a system voltage of 24 Volts. The trailer is depicted in Figure 18 with the three retracting panels deployed for solar charging and then retracted for transport or use at a worksite. The panels can be tilted up to 45 degrees for a more optimal orientation in the winter when the sun is lower in the sky. Deployment and tilting of the panels can be performed within 30 seconds. For deployment of the lights, approximately another 1 to 2 minutes is required to deploy the outriggers before the mast is raised and then less than 2 minutes to raise the mast.

Measurements of the solar charging cycle were performed to confirm the reported capability of the system. The vendor reported that one day of solar charging will operate the lights for 3-4 hours and that the lights will operate for 50 hours on a full charge.

Test Procedure

The test set up for testing the power cycle of the solar panels is shown in the schematic diagram as shown in Figure 19. In this test set up, a data logger was connected to the charging circuit and recorded the current and voltage while the system was charging and discharging. The physical location of the data logger is depicted in Figure 20. Readings were taken in one minute increments and power was determined by multiplying the voltage and current at each data point. Testing results presented here were performed between July 27 and August 10, 2016. The days that the solar charging was reported were clear and the high temperatures ranged from 86° F to 93° F.

Figure 19. The Solar Light Panels of the Wanco Solar Lighting Trailer.

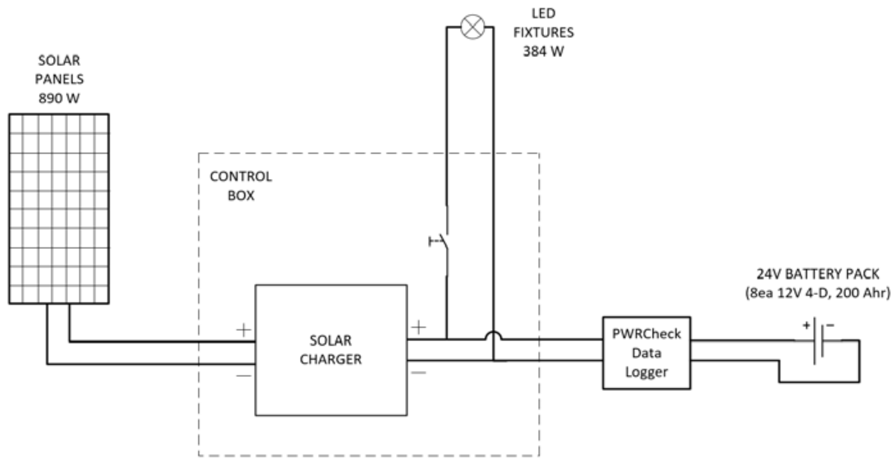

Figure 20. A Schematic of the Testing System Layout.

Figure 21. Physical Location of the Data Logger (PWRcheck) in the Test Set Up.

In order to determine the solar energy stored in a single day, the battery pack was first discharged from an unknown state of charge by operating all lights until they turned off automatically at the system's cutoff voltage. The system was then charged for one day followed by full discharge to the cutoff voltage. The cycle of charging and discharging was repeated. The system cutoff voltage was measured at 23.2 Volts.

Testing of Charge and Discharge Cycles:

The light tower was placed in the sun for a full day of sun exposure. The trailer was located such that no shadows fell on the panel during the course of the day. The panels were pointed to the south and kept at 0 degree of tilt. A total of four complete discharge cycles and six complete charge cycles were logged and the average values in kilo Watt hours (kWh) are shown in Table 14.

Table 17. Average Values of Charge and Discharge Cycles.

	Mean of Energy (kWh)	Standard Deviation (kWh)	Sample Size
Daily Charge	2.41	0.40	6
Daily Discharge	1.99	0.62	4

Conclusions

The data in Table 14 were used to predict the solar charge and energy available for maximum lighting operation during the course of the year. The resulting conclusions are as follows:

- *Daily Charge Input to Battery*: Measured 2.41 kWh
- *Daily Discharge Output from Battery*: Measured 1.99 kWh
- *LED power consumption (Total of 8 LED lights)*: Measured 422 W. This is 109.8% of the rated 384 W

Battery Storage Efficiency is defined as the Daily Discharge Output divided by the Daily Charge Input. This value is calculated to be 82.5%. It should be noted that a value of 75% is commonly used in the industry (http://ecee.colorado.edu/~ecen4517/materials/Battery.pdf). The higher measured value suggests that cycling the batteries at close to their discharge voltage may be more efficient than across the full range. Cycling in this nearly depleted state, however, reduces the life of the battery and is generally not recommended.

The batteries in the Wanco solar lighting trailer are rated at 200 Ah at 12 Volts with a potential energy storage value of 19.2 kWh. These rated values indicate *Maximum Energy Storage Capacity*, which would be equivalent to 46 hours of operation at 422 W. A full discharge cycle from maximum capacity was not measured. Instead the measured Daily Charge value of 2.41 kWh/day is compared to the predicted values for a rooftop solar panel system connected to the grid. The comparison data for the Sacramento area grid is tabulated in Table 15. The Photo Voltaic (PV) Watts Calculator on the National Renewable Energy Laboratory (NREL) website was used as a basis for comparison. The measured value of 2.41 kWh/day is 47% of the mean (5.12 kWh/day) of the values for the July (5.38 kWh/day) and August (4.85 kWh/day) time frames.

Table 18. Solar Power Available for Light Operation in Sacramento.

	NREL PVWatts*		Expected Values per Test Results**			
	Panel DC Ouptut		0 deg Panel Tilt		38.5 deg Panel Tilt	
Month	0 deg Tilt Panel Output (kWh) / day	38.5 deg Tilt Panel Output (kWh) / day	Panel DC Output (kWh) / day	Max Hours of Light Operation per week	Panel DC Output (kWh) / day	Max Hours of Light Operation per week
January	1.44	2.14	0.68	9.3	1.01	**13.8**
February	2.24	3.18	1.06	14.4	1.50	**20.5**
March	3.20	3.92	1.51	20.6	1.85	**25.3**
April	4.33	4.60	2.04	27.9	2.17	**29.7**
May	5.10	4.80	2.40	**32.9**	2.26	31.0
June	5.44	4.79	2.56	**35.1**	2.25	30.8
July	5.38	4.90	2.53	**34.7**	2.31	31.6
August	4.85	4.96	2.29	31.3	2.34	**32.0**
September	3.98	4.79	1.88	25.7	2.26	**30.9**
October	2.81	4.02	1.32	18.1	1.89	**25.9**
November	1.71	2.72	0.80	11.0	1.28	**17.5**
December	1.31	2.07	0.62	8.4	0.98	**13.3**

* Values are for fixed standard crystalline silicon panels rated at 890 W located in Sacramento, CA. Assumed system losses of 14% (default)

** Panel DC Output is 47% of NREL values. Efficiency of Battery storage 82.5%. Light power consumption 422 W.

Per the PV Watts Calculator, a Direct Current (DC) to Alternative Current (AC) inverter would operate at 96% efficiency resulting in a net 4.91 kWh/day to the grid. The measured value is 49% of the net to grid and suggests that the Wanco solar lighting trailer power charger does not implement an ideal power point tracking circuit design which would optimize power to the battery under varying solar and battery conditions.

Given the measured solar charging and efficiency values, the last four columns in Table 15 predict the total solar charge energy available on a weekly basis in Sacramento area during the course of a year. After applying the loss due to battery storage efficiency, this is converted to the maximum number of hours that the LED lights of the Wanco solar lighting trailer would operate on solar energy alone.

Assuming the panels are tilted in the winter months, the total solar energy hours in Sacramento area range from a low of 13.3 hours/week in December to a maximum of 35.1 hours/week in June. Depending on the frequency of use, it is likely that the system could not be used during certain winter months unless the crew would be able to use grid power to charge the batteries during these months.

CHAPTER 5:
FIELD TESTING

In order to field test and evaluate the Wanco solar lighting trailer, maintenance work zones were identified that involved two different maintenance crews at the West Sacramento yard of Caltrans. These two crews were the maintenance and the guard rail crew. Testing was not performed at any construction zones since no arrangements could be made for scheduling a construction zone test during the duration of this research task. Before the actual field test, however, the Wanco solar lighting trailer was taken to the West Sacramento maintenance yard for inspection by a Caltrans crew. The inspection is depicted in Figure 21.

Figure 22. West Sacramento Crew Inspecting the Solar Lighting Trailer on June 9, 2016.

In this inspection two experienced members of the West Sacramento maintenance crew reviewed the various features of the trailer and provided an assessment of its potential use in typical maintenance operations. The consensus was that, in general, any lighting system on a trailer is difficult to use in maintenance operations in confined work spaces that limit the ability to safely place and maneuver a trailer close enough to be able to properly illuminate an area of operation.

Field Testing with West Sacramento Guardrail Crew - June 16, 2016

The West Sacramento guard rail special crew arranged for a field test on June 16. Guardrail replacement was performed on SR 99 south bound near the exit to 12th Avenue. In this operation the crews were repairing two sections of guard rail on the right shoulder about 400 feet before the 12th Ave. exit. The sections were separated by about 150 feet and the working area was about 330 feet long. During the operation, the equipment was moved forward and backward between two locations.

During the operation, the solar lighting trailer was located at the rear of the line of vehicles partially protected by the shadow truck with attenuator as shown in Figure 22. The next trucks in line were: the pounder used to plant the new posts, the rail truck used to remove damaged posts and place the rail, and finally the trash truck in which the damaged post and rail were collected. Figure 23 shows the distribution of vehicles from the front to the rear. In this operation the Wanco solar lighting trailer was used to provide required additional lighting. The crew appreciated the added light from the solar lighting trailer, but they demonstrated how difficult it was to use the trailer due to the confined space of the operation – which would make using any lighting trailer difficult to be properly placed and removed from between the maintenance vehicles and the area of operation.

Figure 23. The Wanco Solar Lighting Trailer Used in Guard Rail Repair Operations.

Figure 24. The Lining of Vehicles in Guard Rail Repair Operations.

In this operation, initial crew activity centered about the removal of damaged guard rail and posts. The majority of effort was centered around this, and it was performed using the rail truck. The rail truck was outfitted with a balloon light, and the crew used a crane to pull the damaged posts out of the ground. Twelve feet sections of new guard rail were assembled on the ground alongside the truck. Once the broken posts were cleared, the rail truck was moved out of the way and the pounder was driven forward and used to place the replacement posts. As depicted in Figure 24, a spot light temporarily connected to a vehicle was used to illuminate the tool end, which used a combination of an auger and a post driver to place the new posts.

Once this phase was completed, the pounder was backed up and then the rail truck returned to its original position to lift the new guardrail section into place which the crew bolted to the posts. Figure 25 shows the beginning of rail installation.

Figure 25. View of the Pounder Truck as it is Auguring a Hole to Place a Post.

Figure 26. A Rail Truck Being Used to Install Rails onto New Posts.

The solar lighting trailer was attached to the rear of the pickup truck used to transport it to the site (Figure 26). The crew did not move the solar lighting trailer during the course of the operation since the maintenance vehicles were moving back and forth and repositioning the solar lighting trailer would add to the duration of the operation. The lack of repositioning the trailer resulted in it not providing adequate lighting for the work being performed. The lighting from the trailer, however, did illuminate the nearby vehicles which increased visibility of the work activity to passing traffic.

Figure 27 shows the area alongside the rail truck illuminated by a balloon light mounted to the truck. The balloon light is powered by a portable generator on the deck of the truck and is lit with a standard single 1000 W metal halide bulb. A simple design for integration of solar powered LED lights are discussed and simulated in a subsequent section of this report that can provide a similar convenient lighting arrangement for this kind of operation. At the work site evaluated, in order to determine the level of light output, illuminance readings were taken at 7 ft. from the edge of the truck. The highest value was 29 Foot-Candles directly across from the light, which dropped to 5 Foot-Candles within 16 feet from it. Figure 27 shows the location where the illuminance measurements were taken overlaid on a photograph of the work site. This figure and the associated measurements show that using a balloon light configuration for much of the assembly work creates less than ideal illuminance.

Figure 27. The Solar Lighting Trailer Attached to a Pick Up Truck.

Figure 28. Locations of Illuminance Measurements Along a Line of Posts at 7ft from the Edge of the Truck.

Field Testing with West Sacramento Maintenance Crew – August 15, 2016

In this field evaluation, the solar lighting trailer was used by the West Sacramento maintenance yard in an operation to trim the oleander located in the median on highway 80 between Davis and the causeway over the Yolo bypass. A boom with cutter head was mounted on the front end of a loader and used to mow back the oleander bushes. The loader was driven against traffic on the shoulder next to the number 1 lane moving at about 3mph. The boom had two floodlights mounted on it. Additional lighting was required and was provided by the solar lighting trailer. The operation with the location of the solar lighting trailer is depicted in Figure 28. As can be seen in Figure 28, the solar lighting trailer being towed by a pickup truck is in the left shoulder near the median and adjacent to the operation.

Figure 29. Solar Lighting Trailer Used in Oleander Trimming Operation.

Conclusions

The solar lighting trailer was assessed with respect to its potential use in typical night time operations for Caltrans. Highway maintenance personnel considered its application within all maintenance operations. They felt, in general, that any trailer mounted lighting system is too inconvenient to place within maintenance operations in confined spaces. Usually space in the closure is very limited in many maintenance operations and it is difficult to place and maneuver a trailer. The maintenance crews typically prefer to have a lighting system like a balloon light on the rail truck. Generally they feel that they can never have enough light. The maintenance crew also felt that the functionality of the solar lighting trailer could be enhanced if it could also serve as a power supply for other tools. Some diesel lighting trailers do provide this additional functionality. Some of the specific positive and negative aspects of the solar lighting trailer identified by the maintenance crew are listed below.

Positive Aspects

- LED light quantity and quality is very good and it would be helpful to have the extra light during operations.
- Operation is silent and emits no fumes.
- Lighting can be pointed in specific directions and light output can be adjusted as necessary.
- LED fixtures are relatively cool to the touch and can be easily handled to adjust light direction.
- LED lights don't need a warmup and cool down time as with metal halide lights which can take 15 minutes or more.
- The unit requires no fueling with diesel or gasoline
- The manual crank mechanism used to raise the light is good for summer time when it is easy to crank and no energy is lost to a lift mechanism

Negative Aspects

- In-the-field handling of solar lighting trailers is more difficult as compared to diesel lighting trailers due to the existence of their solar panels that can be easily damaged and will require a larger footprint as compared to standard diesel trailers.
- Both diesel and solar lighting trailers are too heavy to be easily moved manually and need to be towed. When towed, the light masts on the solar lighting trailer tested was such that, in certain configurations, the light was shining rearward and much of the light was shadowed out due to the size and location of the panels.
- Miscellaneous components of the trailer hardware, such as jacks and tail lights hanging off the corners, can easily be broken off during routine usage. It is suggested that all trailer components be contained within width of the inside edge of fenders and raised as high as possible off the ground.

CHAPTER 6:
LIFE CYCLE COST AND CO2 EMISSION ANALYSIS

The purpose of life cycle cost analysis is to compare the costs of using a traditional diesel generator with four 1000 W metal halide lights and a solar power battery system like the unit on the solar lighting trailer tested. Table 16 lists the basic assumptions used in the life cycle cost analysis. Details of the analysis are provided in Appendix A.

Table 19. Assumptions Used in Life Cycle Cost Analysis.

Quantity	Value
Study Period	10 years
Assumed Usage	618 hours/year
Time Value of Money	5 %
Capital Loan Term	5 years
Cost of Carbon	$11.54/ton ($12.73 per metric ton)
Shop Labor Rate	$90.00
Diesel Fuel Cost	$3.33/gallon

The life cycle cost analysis presented is similar to what was previously performed by the AHMCT research center in the evaluation of a hydrogen fuel cell lighting trailer [4]. This previous evaluation established a unit usage rate of 618 hours based on a survey of used light towers. The cost of CO2 used in this analysis is the value reported in the California Cap-and-Trade Program Summary of Joint Auction Settlement Prices and Results from November 2015 through August 2016. The price of diesel is the average monthly cost reported by the U.S. Energy Information Administration for the period of January 2014 through June 2016.

Additional costs and consumption rates that are used in the analysis are summarized in Table 17. The diesel consumption rate of 0.59 gallon per hour is based on the testing of an actual diesel light tower performed by AHMCT. This value is higher than the more conservative value of about 0.50 gallon per hour typically found in some supplier specifications.

Table 20. Equipment Costs and Consumption Rates.

Quantity	Value
Diesel Tower Cost (Wanco with 4 1000-watt metal halide lamps, 30 ft. tower)	$9,929
Solar Tower Cost (Wanco with 8 48W LED lights, 890W panels, and 8 4-D AGM batteries)	$20,175
Diesel Fuel Rate	0.59 gal/hr.
CO2 Produced	22.38 lb./gallon
Solar Battery Replacement	$4274 after five years

The preventative maintenance schedule for both the solar lighting trailer and diesel powered lighting trailer used in this analysis assumes 30 minutes of labor on a quarterly basis. Considering a maintenance schedule for a typical small diesel engine, maintenance costs for diesel trailers were calculated as detailed in Appendix A. Except for the replacement of the battery pack at the beginning of the sixth year, no additional maintenance cost is assumed for the solar lighting trailer.

The CO2 emission calculation assumes that the combustion of diesel results in the output of 13.12 lb. of CO2 per hour. Considering the 618 hours of operations in a year, the annual CO2 emission is calculated to be 4.1 tons per diesel trailer. Environmental impacts are encapsulated by charging Carbon as a cost to the diesel system at the rate previously discussed. This serves as a simple way to capture some of the environmental aspects without requiring a full life cycle analysis. This cost is proportional to fuel consumption and effectively adds 3.84% to the cost of diesel fuel. It is not a significant factor in the cost analysis.

Using the above data, the expenses for each year over several years for each piece of equipment are calculated and summarized in Tables 18 and 19. The expenses shown in dollar value for the Year of Expenditure (YOE) assume inflation (time value of money) from the baseline year. The table also gives totals in PV 2016 dollars.

Table 21. Expenses for Diesel Powered Lighting Trailer.

Costs - Diesel Tower											
Year	0	1	2	3	4	5	6	7	8	9	Total
Hours Clocked	618	618	618	618	618	618	618	618	618	618	6180
Year Ending Hours	618	1236	1854	2472	3090	3708	4326	4944	5562	6180	N/A
Fuel Cost (YOE)	$ 1,207	$ 1,267	$ 1,331	$ 1,397	$ 1,467	$ 1,540	$ 1,617	$ 1,698	$ 1,783	$ 1,872	$ 15,181
Maintenance (YOE)	$ 350	$ 746	$ 562	$ 823	$ 1,071	$ 549	$ 1,060	$ 605	$ 1,302	$ 1,103	$ 8,170
Debt Service (YOE)	$ 2,293	$ 2,293	$ 2,293	$ 2,293	$ 2,293	$ -	$ -	$ -	$ -	$ -	$ 11,467
CO2 Costs (YOE)	$ 47	$ 49	$ 52	$ 54	$ 57	$ 60	$ 63	$ 66	$ 69	$ 73	$ 589
Total (YOE)	$ 3,897	$ 4,356	$ 4,238	$ 4,568	$ 4,888	$ 2,149	$ 2,740	$ 2,369	$ 3,154	$ 3,048	$ 35,407
Total (PV 2016)	$ 3,897	$ 4,149	$ 3,844	$ 3,946	$ 4,021	$ 1,684	$ 2,045	$ 1,684	$ 2,135	$ 1,965	$ 29,368

Table 22. Expenses for Solar Powered Lighting Trailer.

Costs - Solar Tower											
Year	0	1	2	3	4	5	6	7	8	9	Total
Hours Clocked	618	618	618	618	618	618	618	618	618	618	6180
Year Ending Hours	618	1236	1854	2472	3090	3708	4326	4944	5562	6180	N/A
Fuel Cost (YOE)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Maintenance (YOE)	$ 180	$ 189	$ 198	$ 208	$ 219	$ 5,685	$ 241	$ 253	$ 266	$ 279	$ 7,719
Debt Service (YOE)	$ 4,660	$ 4,660	$ 4,660	$ 4,660	$ 4,660	$ -	$ -	$ -	$ -	$ -	$ 23,300
Total (YOE)	$ 4,840	$ 4,849	$ 4,858	$ 4,868	$ 4,879	$ 5,685	$ 241	$ 253	$ 266	$ 279	$ 31,018
Total (PV 2016)	$ 4,840	$ 4,618	$ 4,407	$ 4,205	$ 4,014	$ 4,454	$ 180	$ 180	$ 180	$ 180	$ 27,258

Based on the above expenses the projected cost in YOE dollars for a diesel powered lighting trailer is $35,407 (PV2016 cost $29,368) while the project cost in YOE dollars for the solar lighting trailer is $31,018 (PV2016 cost $27,258). The ratio of solar powered light to diesel powered light YOE cost is 88% (PV cost ratio is 93%).

Conclusions

Although the initial cost of a solar lighting trailer is approximately twice that of a diesel powered lighting trailer, the fuel and maintenance costs for a diesel unit are significantly higher and the total cost to own and operate a solar powered system is likely to be less than that of a diesel-powered system. Other considerations that could affect cost comparison can be summarized as:

- Cost of electricity required to supplement the solar charging of batteries in the winter.

- Labor costs for the fueling operation. This could be significant if the diesel lighting trailer is used in a remote location.

CHAPTER 7:
DESIGN MODIFICATIONS AND COMPUTER SIMULATIONS

This chapter addresses design modifications of the solar lighting trailer to overcome some of its limitations that were identified in the field evaluations. Field evaluations of the solar lighting trailer indicated that the use of trailer mounted lighting systems have limited applicability in certain highway maintenance work zone operations due to limited space and problems with placing and manually moving the trailer. The solar powered LED lights, however, do not need to be mounted on a tower that is deployed using a trailer system. Furthermore, field evaluations performed in this research task indicated that equipment mounted lighting systems have the highest applicability in many maintenance operations. This research task, therefore, decided to evaluate design modifications or new design concepts of a LED based solar lighting system that could be mounted on a maintenance vehicle. The scope of this research task did not include any equipment and hardware developments. Computer simulation was therefore used to develop and evaluate the new design concepts.

New Design Concepts

Two different design concepts were developed that would replace traditional powered lights with solar LED lights on a maintenance vehicle. The first concept is depicted in Figure 29. This concept replace the balloon lights and generator that are presently integrated onto some maintenance vehicles (Figure 27). To power the solar LED lights, accommodations should be made for the location of the battery packs on the maintenance vehicle without compromising the truck bed for carrying other equipment. In the concepts developed here, two battery packs are designed to fit through trailer hitch type connections on the available openings on the side of the maintenance vehicle as shown in items A of Figure 29. In this fashion, the battery packs can be easily removed and reconnected to a solar charging station at the maintenance yard to be charged or stored when not in use. A light tower with three pairs (a total of six) LED lights is attached to the body of the vehicle as depicted in item B of Figure 29. The separation of the solar panels into a separate charging station could also be easily implemented with the existing trailer system, reducing handling issues in terms of potential damage and footprint requirement of the solar panels at a work site.

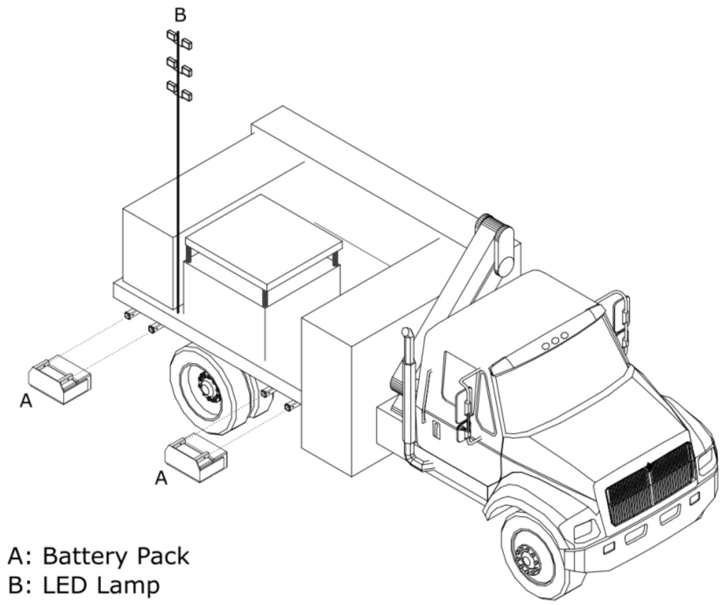

Figure 30. LED Solar Lights Integrated in a Tower Arrangement onto a Maintenance Vehicle.

The second design concept takes advantage of the ability to distribute the LED lights due to their low weight and insensitivity to vibration. This concept is depicted in Figure 30. The LED lights can be installed on one (as shown) or both sides of a maintenance vehicle to be able to handle operations on both sides of the vehicle. The battery pack location and design is the same as the previous concept; the six LED lights however are connected in a distributed fashion along the side of the maintenance vehicle as shown in Figure 30

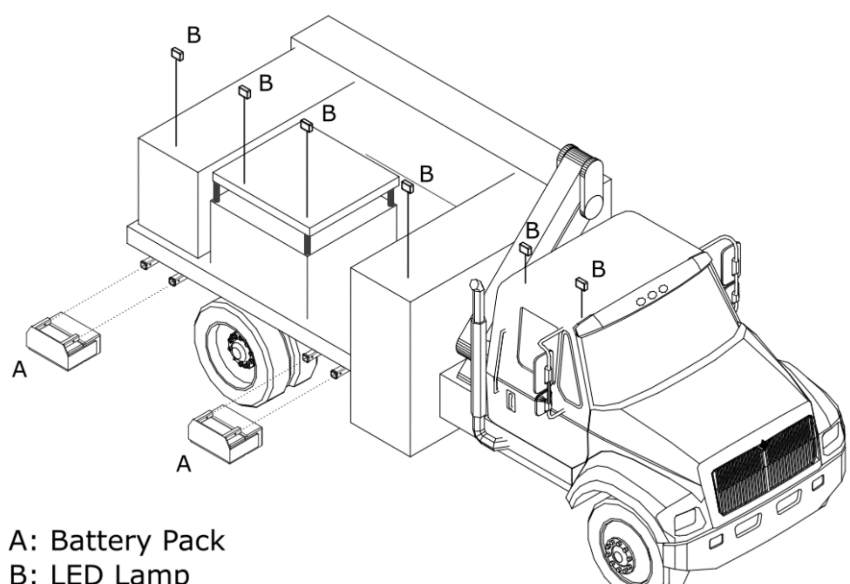

Figure 31. LED Solar Lights Integrated in a Distributed Arrangement into a Maintenance Vehicle.

In order to evaluate the effectiveness of these design concepts in terms of illumination levels and light area footprints, computer simulations were performed. To make sure that the computer models would provide realistic results, first a calibration experiment was conducted. The computer simulation also allowed evaluation of more design concepts in terms of the LED light distribution on a maintenance vehicle. Similar designs with more than six LED lights can also be considered.

Calibration Experiment

A calibration experiment was performed to make sure that the results of the computer simulations would provide a realistic simulation of the actual lighting distribution in illumination levels and footprints. The experiment consisted of performing computer simulations of LED lights in the same configurations as the laboratory experimental evaluations performed and discussed in Chapter 4. A summary of the average differences between the experimental data and the computer simulation results for experiments with LED lights from Chapter 4 is presented in Table 24. The maximum average error observed is just shy of 13% which is viewed as acceptable for proof of concept evaluation of the new design concepts of LED lighting systems for maintenance vehicles.

Table 23. Error Summary for the Calibration Experiments.

Experiment	Average Difference
Single LED	6%
8 LED – Wide Configuration	12.93%
8 LED –Narrow Configuration	11.34%
8 LED – 360 - degree Configuration	9.48%

Computer Simulations of New Design Concepts

The calibration results allowed us to investigate multiple LED lighting design concepts within the accuracy obtained by the calibration using computer simulations. In the simulations presented, an approximate model of a truck used for guardrail post pulling was developed as the maintenance vehicle.

Three Dimensional (3D) models for the computer simulations were created using Blender, an Open Source 3D creation suite. Radiance, an Open Source lighting simulation software copyrighted and distributed by Lawrence Berkeley National Laboratory, was used to run the simulations. The Lighting Visualizer (LiVi) part of the Vi-Suite add-on for Blender was used as the interface between Blender and Radiance.

All of the simulation results presented below use the same coloring scale for the illuminance values to allow for comparison. First, the case of a balloon light tower integrated onto a maintenance vehicle was simulated since this is what is used in some maintenance functions by Caltrans.

Balloon Light Simulation

Simulating a balloon light integrated onto a maintenance vehicle provides for a point of comparison for the two new design concepts using LED solar lights. In this simulation, a balloon light is placed at the approximate location that it would be placed on a maintenance truck. The illuminance values are depicted in Figure 31. The contour plots are depicted in Figure 32. As expected, the balloon light provides near uniform illumination. The area of low light near the base and above the truck is due to the shadow of the truck. The illumination is within 10 Foot-Candles for general activities and work around equipment, and the footprint is barely within a 20-foot diameter on the side and near the area of the installation of the balloon light.

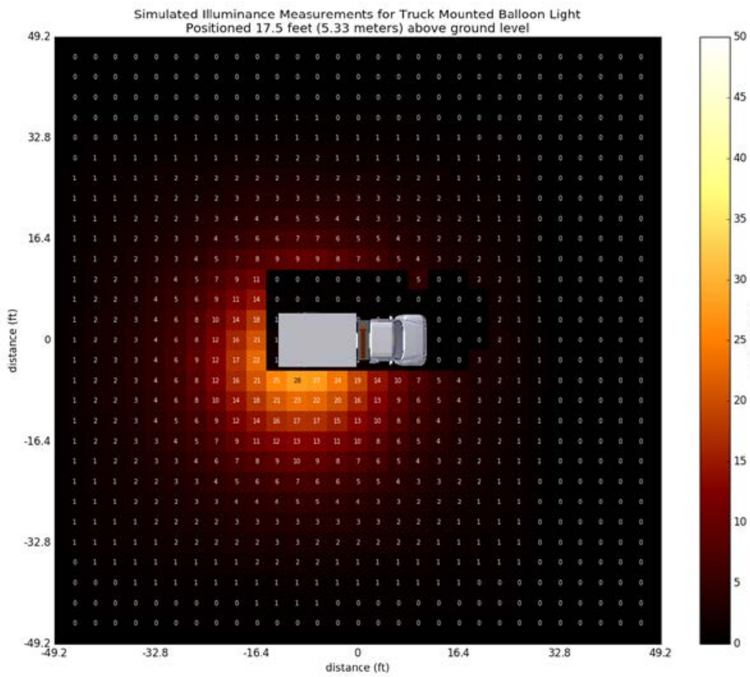

Figure 32. Illumination Results in Simulation of a Vehicle Integrated Balloon Light.

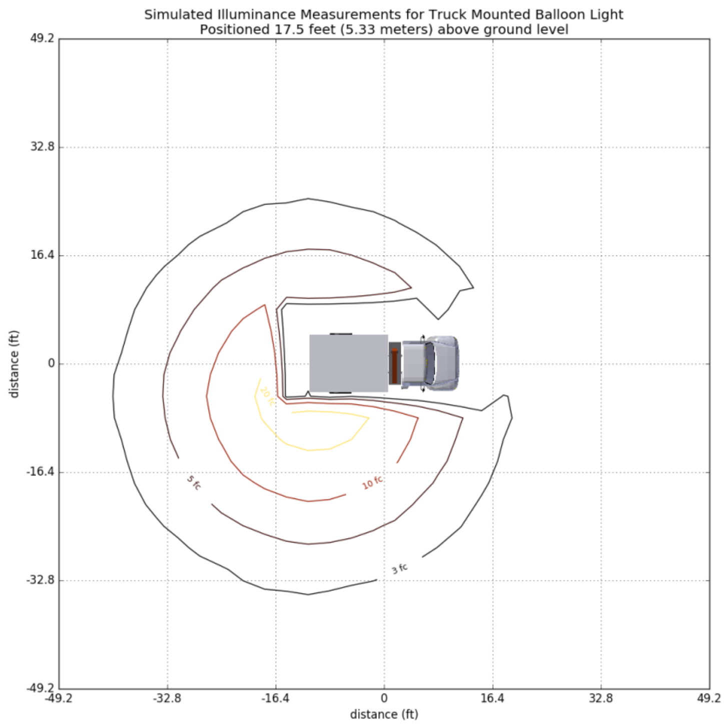

Figure 33. Contour Plots in Simulation Results of a Vehicle Integrated Balloon Light.

Computer Simulation of the First New Design Concept with Six LED Lights in a Tower Configuration

This computer simulation evaluated the first design concept presented earlier in this chapter. The illumination results and the contour plots are depicted in Figures 33 and 34.

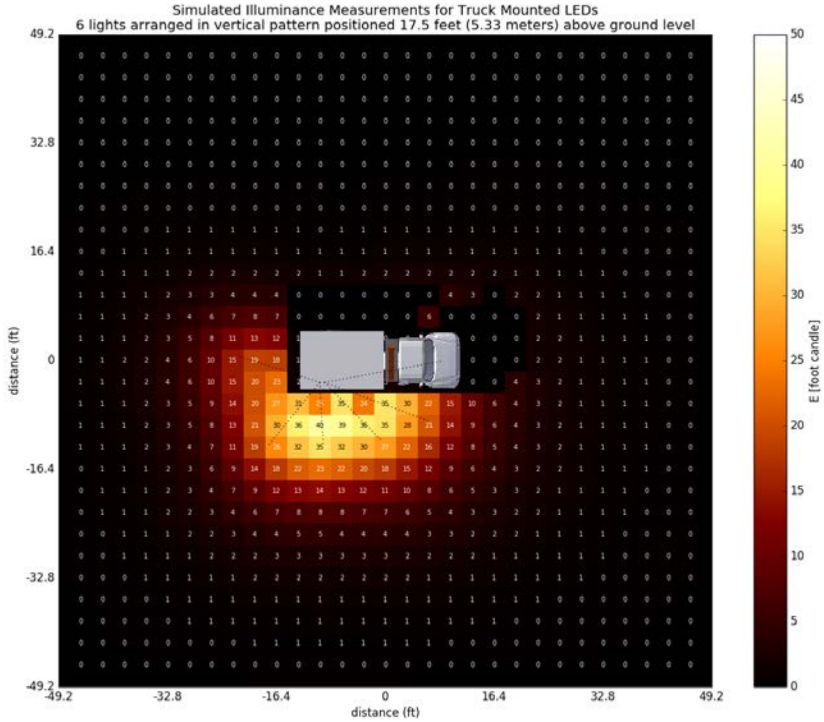

Figure 34. Illumination Results for Simulation of Six LED Lights in a Vehicle Integrated Tower Configuration.

Comparing the contour plots for this LED lighting configuration to the balloon light configuration, it is clear that LED lighting in this configuration provides a better lighting distribution both in terms of illumination levels as well as footprint for the side of the truck where the light tower is attached. The illumination levels and the footprint are good for general activities as well as work around equipment.

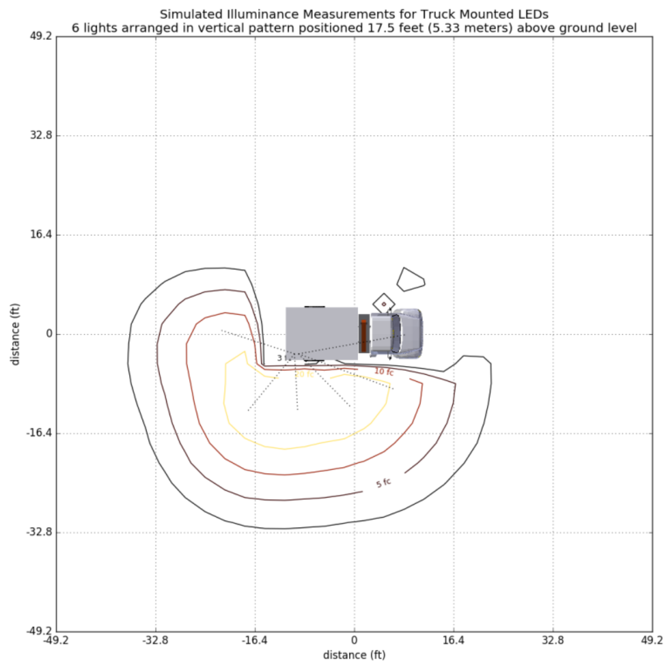

Figure 35. Contour Plots for Simulation of Six LED Lights in a Vehicle Integrated Tower Configuration.

Computer Simulation of the Second New Design Concept with Six LED Lights in a Distributed Configuration

The second design concept with six LED lights distributed on the side of a maintenance truck was also simulated and the results of the illumination levels and the contour plots of the lighting distributions are depicted in Figures 35 and 36 respectively. It is clear from these two figures that in this design of LED light distribution, the footprint of acceptable illumination values behind the maintenance truck is reduced, but the footprint on the lighted side of the truck is increased as compared to the first design concept. The illumination values are again good for general activities as well as work around equipment.

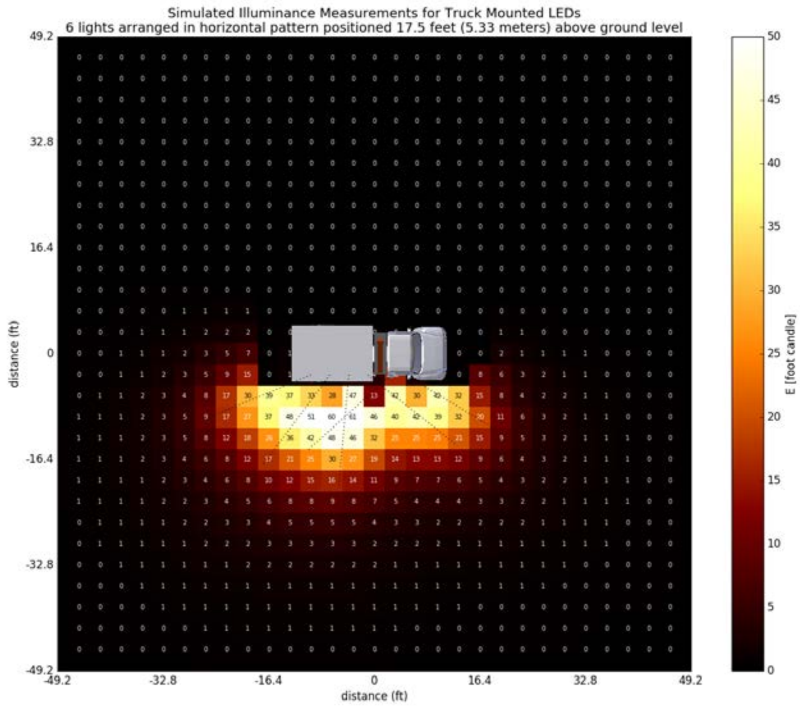

Figure 36. Illumination Results for Simulation of Six LED Lights in a Vehicle Integrated Distributed Configuration.

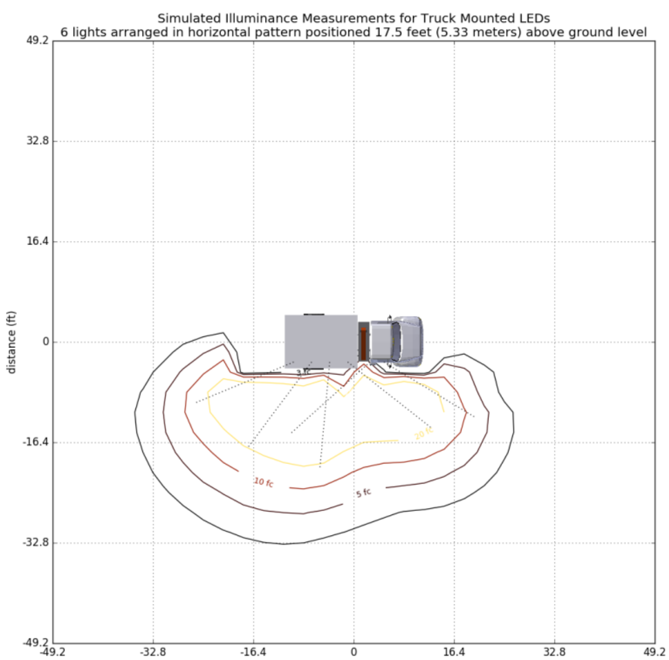

Figure 37. Contour Plots for Simulation of Six LED Lights in a Vehicle Integrated Distributed Configuration.

Conclusions

- When a proper number of solar powered LED lights are installed on a vehicle integrated tower configuration similar to a vehicle integrated balloon light, an acceptable lighting distribution both in terms of illumination levels and footprint can be obtained on the light tower side of the maintenance vehicle for general activities as well as working around equipment.

- If LED lights are mounted in a distributed configuration alongside a maintenance truck, then the lighting footprint and illumination levels are improved on the same side for general activity areas as well as work around equipment.

CHAPTER 8: CONCULUSIONS, RECOMMENDATIONS, AND FUTURE WORK

In testing and evaluating a solar powered LED lighting trailer both in laboratory settings as well as in the field, the following conclusions can be made:

- LED solar lights can produce enough illumination as well as an appropriate footprint (if enough of them are used and configured properly) for highway work sites during dark hours.

- The Narrow and the Wide Light Pattern Configurations of eight LED lights on a solar lighting trailer provide both lighting illumination levels of a minimum of 10 Foot-Candles and a footprint exceeding a 20-foot diameter, and therefore can be used not only for general activities but also for working around equipment.

- The Wide Light Pattern Configuration provides a slightly wider footprint than the Narrow Lighting Configuration, but both configurations have higher footprints than a balloon light in terms of an area with an illumination of a minimum of 10 Foot-Candles.

- A solar powered light system, as compared to a diesel powered light system, for highway applications will result in up to approximately 4.1 tons reduction in CO2 emissions per unit of equipment on an annual basis.

- The solar powered lighting trailer is quiet and does not produce any noise.

- In the Sacramento area, the total solar energy hours approximately range from a low of 13.3 hours/week in December to a maximum of 35.1 hours/week in June. Evaluating the charge and discharge cycles of the solar panels and mapping them into the solar energy availability in Sacramento area, it is likely that that a crew would need to use grid power to charge the batteries during the winter months.

- Although the initial unit cost of a solar lighting trailer (at the time of this research) is approximately twice that of a diesel operated trailer with metal halide lights, the total cost to own and operate a solar powered system is less than that of a diesel-powered system over an operational period of ten years (a ratio of 88% to 93% of the cost of the diesel unit for a usage of ten years).

- The use of solar powered lighting systems in areas with limited sun during certain periods of the year (such as the winter months) would require the use of the power grid for charging its battery packs during such periods.

- In-the-field handling of solar lighting trailers is more difficult as compared to diesel lighting trailers due to their solar panels, which can be easily damaged and will require a larger footprint as compared to standard diesel trailers. Design modifications separating the battery charging station from the trailer or the lighting system can overcome this limitation.

- Using any trailer based lighting system such as the solar lighting trailer has limitations in its application in highway work zones due to limited space in the work zone. Design modifications involving integrating the LED lights of a solar powered lighting system into a maintenance vehicle would overcome this limitation.

- Using solar LED lights in a tower configuration in an integrated fashion on a maintenance truck can provide proper lighting for general activities as well as for work around equipment. This configuration requires separating the solar panels from the batteries into a separate charging station at the maintenance yard with interchangeable batteries between the maintenance truck and the charging station.

Recommendations

The following recommendations are made from the results and the experience gained in this research task:

- If Carbon reduction and emission control is a goal, then use of solar lighting trailers is recommended for consideration over the use of diesel-powered lighting systems for highway maintenance applications when applicable.

    - In areas where there are long periods of sunlight in a year, then use of solar powered LED lighting is recommended, under the same considerations, when applicable. In such areas there will be an approximate CO2 reduction of 4.1 tons per unit of equipment used on an annual basis.

- When noise reduction at a work site is a goal, then the use of solar lighting trailers is recommended for consideration over diesel-powered lighting trailers.

- Solar powered lighting trailers that separate the solar panels from the lighting trailer and position them in a separate charging station eliminate in-the-field handling issues of solar powered lighting trailers and can enhance their utility. This kind of solar panel configuration is recommended when there are concerns related to potential damage to the panels at a work site.

- LED solar powered lighting designs that are integrated onto maintenance vehicles are recommended for consideration over use of trailer based systems for applications in work zones with confined spaces which limit the use of a trailer based system.

- Distributing LED lights along the side of a maintenance truck can improve the lighting distribution both in footprint on the same side as compared to the tower configuration. This kind of LED lighting distribution on a maintenance vehicle is recommended to be considered to enhance night time work zone operations.

- In its present (tested) form, the use of a solar powered LED lighting trailer is recommended for consideration for stationary work when there is enough room for the utilization of a trailer and enough sun during the day for charging the batteries. Examples of such operations are:

    - Operations which remain in a single, relatively small area for a long enough time that such a trailered light source might be utilized. The operation is performed by workers using relatively stationary equipment so the operation could also be successfully lit with a solar LED lighting trailer with properly configured lighting when there is enough room for the trailer at the work site. Repair of concrete slabs is an example of such an operation. Alternatively, if equipment mounted lighting is used, then a secondary support vehicle with a solar LED lighting trailer could be utilized to provide additional illumination.

    - Situations where operations are spread out over a relatively wide area and equipment is moving in and out of the immediate point of operation. An example of this would be the repair of slopes where loaders, dump trucks, and graders move in and out of the area with workers also on foot. In this type of operation, a wide area must be lit and no piece of equipment is stationary. A secondary vehicle with lighting would not be of great advantage over a solar lighting trailer. In this case, a solar LED lighting trailer with properly configured lighting could be used.

    - Operations that occur with various combinations of equipment and workers operating in a relatively small area but enough room to utilize a trailer based system. An example is sign replacement, where a solar LED lighting trailer with appropriately configured lighting can be used.

REFERENCES

1. J. Holguin-Veras et al., (2003), "Toward a Comprehensive Policy of Nighttime Construction Work," Transportation Research Record, no. 1861, pp. 117-124.

2. O. A. Elrahman, (2008), "Night-Time Road Construction Operations Synreport of Practice," New York State Department of Transportation: Transportation Research & Development Bureau.

3. J. W. Hinze and D. Carlisle, (1990), "An Evaluation of the Important Variables in Nighttime Construction," Transportation Northwest (TransNow), Seattle, Final Report TMW90-05.

4. B. C. Creed, S. P. Donohoe, M. H. Jones, L. B. Miller, W. A. White, S. A. Velinsky , (2013), "Evaluation of a Prototype Hydrogen Fuel Cell Powered Lighting trailer", AHMCT Report No. UCD-ARR-13-06-30-01, June 30th, 256 p.

5. Rowko Industries, LLC (2011), Lighttower.net [Online], http://www.lighttower.net/

6. Protection Services Inc. (2009), Traffic Control Sales & Retail, [Online], http://www.protectionservices.com/TrafficControlProducts/Lighting/NiteLite/tabid/182/Default.aspx.

7. Moon-Glo Work Lights, (2012), Moon-Glo, [Online], http://www.moongloworklight.com/.

8. Multiquip Inc., (2012), "GloBug Balloon Systems", [Online], http://www.multiquip.com/multiquip/globug.htm.

9. D. L. Evans, (1997), "High-luminance LEDs replace incandescent lamps in new applications", Photonics West'97, International Society for Optics and Photonics, pp. 142–153.

10. M. S. Wu, H. H. Huang, B. J. Huang, C. W. Tang and C. W. Cheng, (2009), "Economic feasibility of solar-powered led roadway lighting", Renewable energy 34.8, pp. 1934–1938.

11. C. Rodrigues, P. S. Almeida, G. M. Soares, J. M. Jorge, D. P. Pinto and H. A. C. Braga, (2011), "An experimental comparison between different technologies arising for public lighting: LED luminaires replacing high pressure sodium lamps", IEEE International Symposium on Industrial Electronics (ISIE), pp. 141–146.

12. M. S. Rea and M. J. Ouellette. (1991), "Relative visual performance: A basis for application", Lighting Research and Technology, 23.3, pp. 135–144.

13. H. Richard (1946), "Contrast thresholds of the human eye", Journal of the Optical Society of America, 36, p. 11.

14. F. Falchi, P. Cinzano, C. D. Elvidge, D. M. Keith and A. Haim. (2011), “Limiting the impact of light pollution on human health, environment and stellar visibility”, Journal of environmental management, 92.10, pp. 2714–2722.

15. R. Neitzel, N. S. Seixas, J. Camp and M. Yost, (1999), “An assessment of occupational noise exposures in four construction trades”, American Industrial Hygiene Association Journal, 60.6, pp. 807–817.

16. K. J. Gaston, T. W. Davies, J. Bennie and J. Hopkins, (2012), “Review: reducing the ecological consequences of night-time light pollution: options and developments”, Journal of Applied Ecology, 49.6, pp. 1256–1266.

17. A. Turk, (1972), “Ecology, Pollution, Environment”, ERIC.

18. D. A. Schreuder, (1998), “Road lighting for safety”, Thomas Telford.

19. W. Adrian, (1989), “Visibility of targets: Model for calculation”, Lighting Research and Technology 21.4, pp. 181–188.

20. J. Lecocq, (1999),“Calculation of the visibility level of spherical targets in roads”, Lighting Research and Technology 31.4, pp. 171–175.

21. P. Raynham, (2004), “An examination of the fundamentals of road lighting for pedestrians and drivers”, Lighting Research and Technology 36.4, pp. 307–313.

22. Illuminating Engineering Society, (2014), Handbook, Roadway Lighting.

23. ANSI/IESNA. Roadway Lighting RP-8-00, (2000; Reaffirmed 2005), Illuminating Engineering Society of North America.

24. Cal-OSHA, “CSO 1523 Division 1, Chapter 4 of Title 8 Regulations”, 1515 Clay St. Suite 1901, Oakland, CA 94612.

25. California Vehicle Code, (1970), “V C Section 21466.5 Light Impairing Driver’s Vision”, California Department of Motor Vehicles, 2415 1st Ave. Sacramento, CA 95818.

26. R. D. Ellis Jr., S. Amos, and A. Kumar, (2003), “NCHRP Report 498: Illumination Guidelines for Nighttime Highway Work”, Transportation Research Board of the National Academies, Washington, DC.

27. CIE Standard 103/1-1993. International Commission on Illumination, Babenberger strasse 9/9A, A-1010 Vienna, Austria.

28. R. Bremond, (2007), “Quality indexes for road lighting: a review”. Proceedings of the 26th Session of the CIE.

29. Conférence Générale des Poids des Mesures, (1979), “Resolution 3: SI Unit of Luminous Intensity (Candela)”.

30. M. S. Rea, (2000), Lighting Handbook, 9th Edition, Illuminating Engineering Society of North America.

31. S. M. Berman, M. Navvab, M. J. Martin, J. Sheedy and W. Tithof, (2006), “A comparison of traditional and high colour temperature lighting on the near acuity of elementary school children”, Lighting Research and Technology 38.1, pp. 41–49.

32. A. Møgelmose, M. M. Trivedi, and T. B. Moeslund, (2012), “Vision-based traffic sign detection and analysis for intelligent driver assistance systems: Perspectives and survey”, IEEE Transactions on Intelligent Transportation Systems, 13.4, pp. 1484–1497.

33. M. Schiler, (2000), “Toward a definition of glare: can qualitative issues be quantified”, Proceedings of the 2nd ARCC/EAAE conference on architectural research, Paris. Vol. 48, 423e29.

34. J. Suk and M. Schiler, (2012), “Investigation of Evalglare software, daylight glare probability and high dynamic range imaging for daylight glare analysis”, Lighting Research and Technology.

35. A. Jakubiec and C. Reinhart, (2010), “The use of glare metrics in the design of daylit spaces: recommendations for practice”, 9th international Radiance workshop.

36. J. Y. Suk, M. Schiler, and K. Kensek, (2013), “Development of new daylight glare analysis methodology using absolute glare factor and relative glare factor”, Energy and Buildings 64, pp. 113–122.

37. G. A. Fry and M. Alpern, (1954), “Effect of veiling luminance upon the apparent brightness of an object”, American Journal of Optometry.

38. A. Stimson, (1974), “Photometry and radiometry for engineers”, New York, Wiley-Interscience, 460 p.

39. U.S. Department of Energy, Energy Efficiency and Renewable Energy, (2009), “Understanding Photometric Reports for SSL Products”.

40. H. D. Einhorn, (1969), “An analytical expression for the glare position index”, Illuminating Engineering 64.4, p. 228.

41. R. G. Hopkinson, (1972), “Glare from daylighting in buildings”, Applied Ergonomics 3.4 (1972), pp. 206–215.

42. CIE Standard 117-1995, (1995), International Commission on Illumination, Babenberger strasse 9/9A, A-1010 Vienna, Austria.

43. J. Wienold and .J Christoffersen, (2005), "Towards a new daylight glare rating", Lux Europa, Berlin, pp. 157–161.

44. Y. He, M. Rea, A. Bierman and J. Bullough, (1997), "Evaluating light source efficacy under mesopic conditions using reaction times", Journal of the Illuminating Engineering Society 26.1, pp. 125–138.

45. Society of Automotive Engineers, (1995), SAE Ground Vehicle Lighting Standards Manual, Society of Automotive Engineers.

46. European Committee for Standardization, "EN 12464-1", (2007), Avenue Marnix 17 B-1000, Brussels.

47. European Committee for Standardization, "EN 12464-2", (2007), Avenue Marnix 17 B-1000, Brussels.

48. O. Werner, (2009), "Design guidelines for glare-free daylight work environments", Proceedings of the 11th European conference on lighting–Lux Europe.

49. M. D. Egan, (1983), Concepts in architectural lighting, McGraw-Hill Companies.

50. M. S. Rea, J. D. Bullough, and Y. Zhou, (2010), "A method for assessing the visibility benefits of roadway lighting", Lighting Research and Technology.

51. K. El-Rayes and K. Hyari, (2005), "CONLIGHT: Lighting design model for nighttime highway construction", Journal of construction engineering and management.

52. A. Kandil and K. El-Rayes, (2006), "Parallel genetic algorithms for optimizing resource utilization in large-scale construction projects", Journal of Construction Engineering and Management, 132.5, pp. 491–498.

53. K. Nassar, (2008), "Integrating discrete event and lighting simulation for analyzing construction work zones lighting plans". Automation in Construction 17.5, pp. 561–572.

54. G. J. Ward, (1994), "The RADIANCE lighting simulation and rendering system", Proceedings of the 21st annual conference on computer graphics and interactive techniques, ACM, pp. 459–472.

55. T. Roosendaal and S. Selleri, (2004), "The Official Blender 2.3 guide: free 3D creation suite for modeling, animation, and rendering", No Starch Press.

56. R. Southall, (2010), "The Lighting Visualiser (LiVi)".

57. J. Wienold, (2012), "EvalGlare. Version 1.0", Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany.

APPENDIX A:
COST ANALYSIS COMPARING SOLAR AND DIESEL LIGHTING TRAILERS

The cost analysis used in this research task is summarized in Table 25 and Table 26.

Table 24. Cost Analysis Details.

$$FV = PV(1+i)^n$$

$$PV = \frac{C}{(1+i)^n}$$

$$P = L\frac{i(1+i)^n}{(1+i)^n - 1}$$

1 -Study Assumptions				
Study Period	10	[years]		
Assumed Usage	618	[hours/year]		
Time Value of Money	5%			
Capitol Loan Term	5	[years]		
Shop Larbor Rate	$90.0	[per hour]	Why-do-mechanics-cost-so-much/KCRA	
Cost of Carbon (CO2)	$12.73	[per tonne]	$11.54 per ton	CA Cap and Trade 11/2015 thru 8/2016
Diesel Fuel Cost	$0.88	[per l]	$3.31 per gal	

Equipment Specs Solar Tower		
Equipment cost	$ 20,175	Wanco Solar LED Light Tower WLT
		Equipment cost + shipping (excluding taxes)

Service Solar Tower			
Preventative Maint (PM	4	[per year]	
Service Materials Cost	$ -		
PM Cost	$ 45.00	each	Half hour of labor only

Costs - Solar Tower

Year	0	1	2	3	4	5	6	7	8	9	Total
Hours Clocked	618	618	618	618	618	618	618	618	618	618	6180
Year Ending Hours	618	1236	1854	2472	3090	3708	4326	4944	5562	6180	N/A
Fuel Cost (YOE)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Maintenance (YOE)	$ 180	$ 189	$ 198	$ 208	$ 219	$ 5,685	$ 241	$ 253	$ 266	$ 279	$ 7,719
Debt Service (YOE)	$ 4,660	$ 4,660	$ 4,660	$ 4,660	$ 4,660	$ -	$ -	$ -	$ -	$ -	$ 23,300
Total (YOE)	$ 4,840	$ 4,849	$ 4,858	$ 4,868	$ 4,879	$ 5,685	$ 241	$ 253	$ 266	$ 279	$ 31,018
Total (PV 2016)	$ 4,840	$ 4,618	$ 4,407	$ 4,205	$ 4,014	$ 4,454	$ 180	$ 180	$ 180	$ 180	$ 27,258

Equipment Specs Diesel System			
Equipment cost	$ 9,929		Wanco Diesel Light Tower WLT-4MK106K
Fuel Rate	31.44	[g/min]	Per AHMCT fuel consumption testing of Caltrans Allmand trailer May 2011
Fuel Rate	0.0370	[l/min]	0.59 gal/hr
Carbon (CO2)	2.682	[kg/liter]	13.12 lb CO2/hr

Diesel Density	7.1	lb/gallon	**Biodiesel Handling and Use Guide Fourth Edition**
Diesel Density	0.850722	kg/liter	http://www.dieselnet.com/standards/us/nonroad.php#tier4
CO2 output	22.38	lb CO2 per gal of diesel	http://www.eia.gov/tools/faqs/faq.cfm?id=307&t=11

Caterpillar 3011C Maintenance Specs						
Task	Period		Cost Parts	Cost Labor	Total Cost	
Oil & Filter Service	250	[hours]	$ 34.90	$ 45.00	$ 79.90	<-- 4 Quarts 15W40 + filter
Fuel & Air Filter Service	500	[hours]	$ 45.15	$ 45.00	$ 90.15	
Change Coolant	1000	[hours]	$ 9.00	$ 45.00	$ 54.00	<-- Assume 1 gallon
Change Fuel Hoses	1000	[hours]	$ 46.97	$ 180.00	$ 226.97	<-- Assumed 10 feet
Preventative Maint	4	[per year]	$ -	$ 45.00	$ 45.00	

Costs - Diesel Tower

Year	0	1	2	3	4	5	6	7	8	9	Total
Hours Clocked	618	618	618	618	618	618	618	618	618	618	6180
Year Ending Hours	618	1236	1854	2472	3090	3708	4326	4944	5562	6180	N/A
Fuel Cost (YOE)	$ 1,207	$ 1,267	$ 1,331	$ 1,397	$ 1,467	$ 1,540	$ 1,617	$ 1,698	$ 1,783	$ 1,872	$ 15,181
Maintenance (YOE)	$ 350	$ 746	$ 562	$ 823	$ 1,071	$ 549	$ 1,060	$ 605	$ 1,302	$ 1,103	$ 8,170
Debt Service (YOE)	$ 2,293	$ 2,293	$ 2,293	$ 2,293	$ 2,293	$ -	$ -	$ -	$ -	$ -	$ 11,467
CO2 Costs (YOE)	$ 47	$ 49	$ 52	$ 54	$ 57	$ 60	$ 63	$ 66	$ 69	$ 73	$ 589
Total (YOE)	$ 3,897	$ 4,356	$ 4,238	$ 4,568	$ 4,888	$ 2,149	$ 2,740	$ 2,369	$ 3,154	$ 3,048	$ 35,407
Total (PV 2016)	$ 3,897	$ 4,149	$ 3,844	$ 3,946	$ 4,021	$ 1,684	$ 2,045	$ 1,684	$ 2,135	$ 1,965	$ 29,368

CO2 Output	5.95	kg/hr	13.12	lb CO2/hr	3678	kg/yr	8110	lb/yr	4.1 US ton/yr

<-- 250 Hour Services	2	4	7	9	12	14	17	19	22	24
<-- 250 Hour Services I	1	2	3	2	3	2	3	2	3	2
<-- 500 Hour Services	1	2	3	4	6	7	8	9	11	12
<-- 500 Hour Services I	1	1	1	1	2	1	1	1	2	1
<-- 1000 Hour Services	0	1	1	2	3	3	4	4	5	6
<-- 1000 Hour Services	0	1	0	1	1	0	1	0	1	1

Table 25. Consumption Cost Basis.

Coolant (D4985)	$ 9.00	(when purchased in 6 gallon quantity)										
http://www.petroleumservicecompany.com/fca003.html?productid=fca003&channelid=FROOG&utm_source=CSE&utm_medium=GoogleShopping&utm_campaign=SolidCactus												
Oil (15-40)	$4.00											
http://www.oreillyauto.com/site/c/detail/CHV1/4001540/N0434.oap?ck=Search_N0434_-1_3097&pt=N0434&ppt=C0162												
Oil Filter	$18.90											
http://powertech.myshopify.com/products/01focat												
Fuel Filter	$15.75											
http://powertech.myshopify.com/products/08ffcat												
Air Filter	$29.40											
http://powertech.myshopify.com/products/04fa221												
Fuel Hose (1/4" x 10')	$46.97											
http://www.summitracing.com/parts/dac-80083/overview/												
Cost of Replacing AGM Battery at 5 yr interval							Cost of					
8 each of Universal Battery UB-4D AGM							8 batteries	Shipping				
Battery Stuff	https://www.batterystuff.com/batteries/ups-telecom/UB4Dagm-45965.html											
							3555					
Battery Universe	http://www.batteryuniverse.com/sealed-lead-acid/universal-battery/ub-4d-agm/45965-universal-battery-ub-4d-agm-sealed-lead-acid-battery											
							3438	800				
Battery Clerk	http://www.batteryclerk.com/store/p/64052-UPG-12V-200Ah-Sealed-Lead-Acid-AGM-VRLA-Battery-L4.html											
							3717	608				
						$ Average	3570	704	Sum=	4274		
Cost of Diesel												
https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EMD_EPD2D_PTE_SCA_DPG&f=M												
California No 2 Diesel Retail Prices (Dollars per Gallon)												
2014	4.082	4.084	4.092	4.089	4.119	4.101	4.11	4.085	4.054	3.938	3.813	3.542
2015	3.212	3.11	3.182	3.098	3.254	3.192	3.115	2.935	2.85	2.814	2.768	2.644
2016	2.526	2.335	2.387	2.459	2.636	2.782						
	Average 2014 thru June 2016			Conversion								
	3.3136	**$ per gal**		3.785	l per gal	**0.875456**	**$ per liter**					

Trailer Specifications for models used in cost comparison.

Wanco Solar LED Light Tower WLTS-LMA4:

- Eight adjustable high-efficiency light fixtures (48-watt LED lamps)
- 20-foot telescoping tower assembly with 360-degree rotation
- Adjustable-tilt solar panel array
- Eight 4D AGM batteries
- Manual and auto on/off operating modes
- Security battery box, vandal- and theft-resistant
- Black and white powder-coat finish • 2" ball hitch

Wanco Diesel Light Tower WLT-4MK106K –

- Four adjustable high-efficiency light fixtures (1000-watt metal halide lamps)
- 30-foot telescoping tower assembly with 360-degree rotation
- Low-RPM Tier 4i diesel engine with premium four-pole generator • 30-gallon fuel tank

- Compact trailer
- Powder-coat finish
- Gull-wing doors and hinged top panel for engine access
- Combination 2" ball/2½" pintle hitch.

The cost basis for price of Carbon and diesel fuel is calculated based on:

Price of Carbon
https://www.arb.ca.gov/cc/capandtrade/auction/results_summary.pdf
California Cap-and-Trade Program Summary of Joint Auction Settlement Prices and Results Nov 2015 thru August 2016 Price $12.73 per metric tonne

Price of Diesel
https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EMD_EPD2D_PTE_SCA_DPG&f=M
U.S Energy Information Administration Average monthly price of Ultra Low Sulphur Diesel (On-Highway) $3.31 for Jan 2014 thru June 2016