Solid-State Lighting Guide

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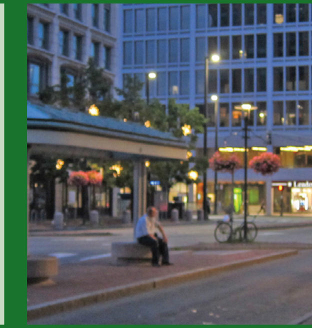


AASHTO

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 RESEARCH OBJECTIVES

The lighting industry has changed dramatically over the past decade. The optical system design of legacy high-intensity discharge (HID) luminaires was restricted to the lamp, refractor, and reflector design, which had limits in the distribution of the light, controls, and adaptability. Roadway luminaires have moved beyond this design methodology to include the vast possibilities presented by solid-state lighting (SSL). At present, in the form of light-emitting diodes (LED), SSL uses lower energy, reduces maintenance, improves color, and can be easily dimmed and controlled.

The SSL roadway luminaire has developed very rapidly, and design standards and methods of applying this new technology have lagged in national recommendations. For example, American Association of State Highway Transportation Officials (AASHTO) target light levels are calculated over a grid limited to the traveled roadway. Any light that lands outside of the calculation grid is not considered, although that surrounding light may provide a safety benefit. With greater and more precise control over the optical distribution, SSL luminaire light levels beyond the calculation grid may be dramatically reduced, and the roadway design will still meet AASHTO criteria, although an element of safety might be missing. Therefore, research is needed to investigate the application of AASHTO criteria to SSL roadway lighting and, if the results dictate, provide guidance for changes or additions to those criteria. Additional research is also needed to explore the benefits and challenges of adaptive lighting controls and provide further guidelines for its use, as well as on the environmental and health effects of SSL roadway lighting.

1.2 OBJECTIVES OF THIS GUIDE

This guide uses the SSL systems research from this project as well as previously done research and offers guidance on implementing SSL technology, specifically as it relates to the current AASHTO *Roadway Lighting Design Guide*. It also identifies areas lacking in research for future consideration.

For further details on the recommendations in this guide, see the NCHRP 940 Final Report—Volume 2.

1.3 DIFFERENCES IN SOLID-STATE TECHNOLOGIES

Until recently, most roadway lighting was HID, specifically high-pressure sodium (HPS). There are many differences between SSL and HID beyond the physical equipment differences: (1) light distribution, (2) lighting output control (dimmability), (3) spectral power distribution (SPD), and (4) efficiency of lighting production suitable for human perception (luminous efficacy). Research comparing SSL to HID for roadway lighting has identified some benefits in terms of energy consumption, luminous efficacy, color rendering, and adaptability.

SSL uses semiconductors such as LEDs as a source of illumination rather than filaments or gas plasmas. In the last decade or so, white SSL has exceeded the efficacy of other lighting, which results in less energy lost in the form of heat. LEDs operate by applying voltage to the leads of a diode, which causes electrons to accelerate. These electrons move through the diode material and recombine with electron holes within the device, which causes a deceleration and in turn releases energy in the form of photons. In broad-spectrum white SSL, the emitted photons create short wavelength light (blue—typically about 450 to 480 nanometers [nm]), which excites a phosphor that emits other colors or spectral content resulting in a white-appearing light. This white-SSL process occurs at a lower temperature than other light sources, allowing for a longer life for the light source compared to gas or filament lights as well as lower costs for dimming and color. LEDs also emit light from a very small area on the diode in a specific direction (as opposed to omnidirectional), which results in more flexibility in terms of optical control.

HID sources and LEDs differ greatly in terms of luminous efficacy, or how well a light source produces visible light as a ratio of luminous flux to power. A metal halide HID lamp ranges from 65 to 116 lumens per watt, which equates to an efficacy of between 9 and 17 percent overall. HPS lamps are slightly better, with a range of 85 to 150 lumens per watt, or an efficacy of 12 percent to 22 percent (Rodrigues et al., 2010) (Stouch, 2016) and are generally regarded to be highly efficient compared to fluorescents, arc lamps, and incandescents resulting in their prevalence in existing roadway lighting. However, modern LED lamps have been found to produce from 37 to as high as 303 lumens per watt, or a range of 0.66 to 43 percent (Cree, 2014) (Stouch, 2016). Luminous efficacy can also be weighted by photopic and scotopic response curves because the eye is more sensitive to certain wavelengths depending on light level (Rodrigues et al., 2010). For example, at very low light levels a source with more blue content may provide greater eye response. Beyond efficacy and lumen output when compared to HID lamps, LEDs have a much better coefficient of utilization, distributing light where it needs to be as result of the small point sources (LED chips) and compact optical system. Most LED optical systems use very effective computer aided design and manufacturing, which adds to their effectiveness.

> The spectral content of a light source has an impact on how well a driver can detect objects. Broader spectral content may result in better visibility.

LEDs can be customized for their intended use. LEDs can be acutely dimmed to specific levels (Dyble et al., 2005) (Fusheng Li, 2009) (Gil-de-Castro et al., 2013) (Jin et al., 2015), be turned on and off rapidly without a need for a warm-up period (Gaston et al., 2012) (Wang and Liu, 2007), be fine-tuned for color output during the manufacturing process to achieve a range of correlated color temperatures (CCTs) (Liu and Luo, 2011), and precise cutoffs can be implemented to increase the control of the light's focus (Timinger and Ries, 2008). In general, LEDs are said to be better in terms of photometric and economic performance compared to HPS light sources. As of 2012, many roadway-lighting-focused organizations such as Illuminating Engineering Society (IES), International Committee on Illumination (CIE), Industrial Lighting Products, the U.S. Department of Energy (DOE), the American National Standards Institute (ANSI), Transportation Association of Canada (TAC), and the National Electrical Manufacturers Association (NEMA) have directed their focus to developing guidelines for LED device performance and predictions. LEDs are said to offer from 50,000 to 100,000 hours of use before substantial degradation due to overheating or prolonged use (Evans, 1997) (Tetra Tech EM Inc., 2010). In terms of life expectancy, LEDs far outperform HID lamps (Josefowicz, 2012).

Prior research, as well as research for this project, show differences in driver detection distances, with 4000 K sources showing some advantages.

The spectral outputs of HID sources and LEDs differ greatly in terms of wavelength content but are often identified by the CCTs measured in Kelvin (K). The CCT values are related in appearance to the absolute temperature of a black body radiator (incandescent). Figure 1 shows the SPDs for HID and LED luminaires of a variety of CCTs. Shown are an HPS luminaires with a 2100 K CCT, 3500 K LED, and 6000 K LED light sources. Note that the CCT of light sources cannot be compared across different technologies; as such, the CCT of the HPS cannot be compared to that of an LED. The critical aspect of the two methods of generating light is that the phosphor-converted LED generally has a broad-spectrum output, and the HPS relies on the energy band conversion of electrons and has significant spectral gaps in the light output. Moreover, the SPD of LEDs can be tailored to achieve specific CCTs. One of the difficulties with the CCT is that it has become (wrongly) a de facto industry standard to describe the light output and spectral content of the LED.

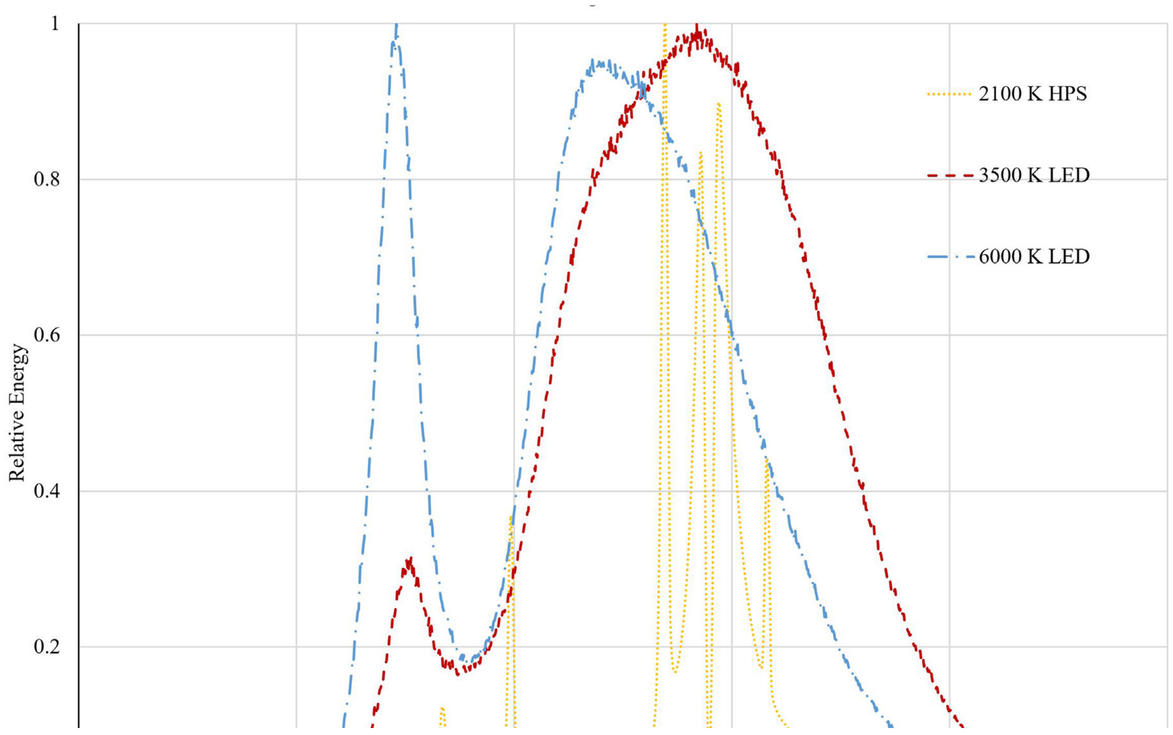


Figure 1. Spectral Power Distribution of Overhead-Lighting Types (Gibbons et al., 2015)

The color rendering capabilities and luminous efficacy of LEDs give them an edge in visibility performance. Because most of the detections in a roadway are foveal (Gibbons et al., 2012) and based on the cone detectors only (cones make up three types of photoreceptors in the eye), particularly at high speeds, an LED light source, which is a much broader spectrum source than an HPS source, provides better color contrast. This additional color contrast has been shown to provide detection benefits (Terry, 2011). Because of LED's excellent color rendering qualities, white-light-emitting LEDs have been considered as direct replacements for HPS lighting on streets and roadways. Because nighttime driving inherently involves low-light vision, typically luminance contrast prevails; however, color contrast can vastly improve an object's visibility (Lutkevich et al., 2012), especially when a source such as an LED has strong color-rendering capabilities closer to that of natural light (Gibbons et al., 2015). Figure 2 shows some of the variations that can occur in detection distances for various CCT source types (the x-axis shows source type, those shown in wattage are HPS (250 watt (W) and 400 W); and those shown by CCT in K are LED, and system light output of 25 percent, 50 percent, or 100 percent; and ASYM shows an asymmetrical distribution, which was also assessed).

> Because the standard distribution types are often quite different with LED sources, they should not be solely relied upon to select replacements for HID sources.

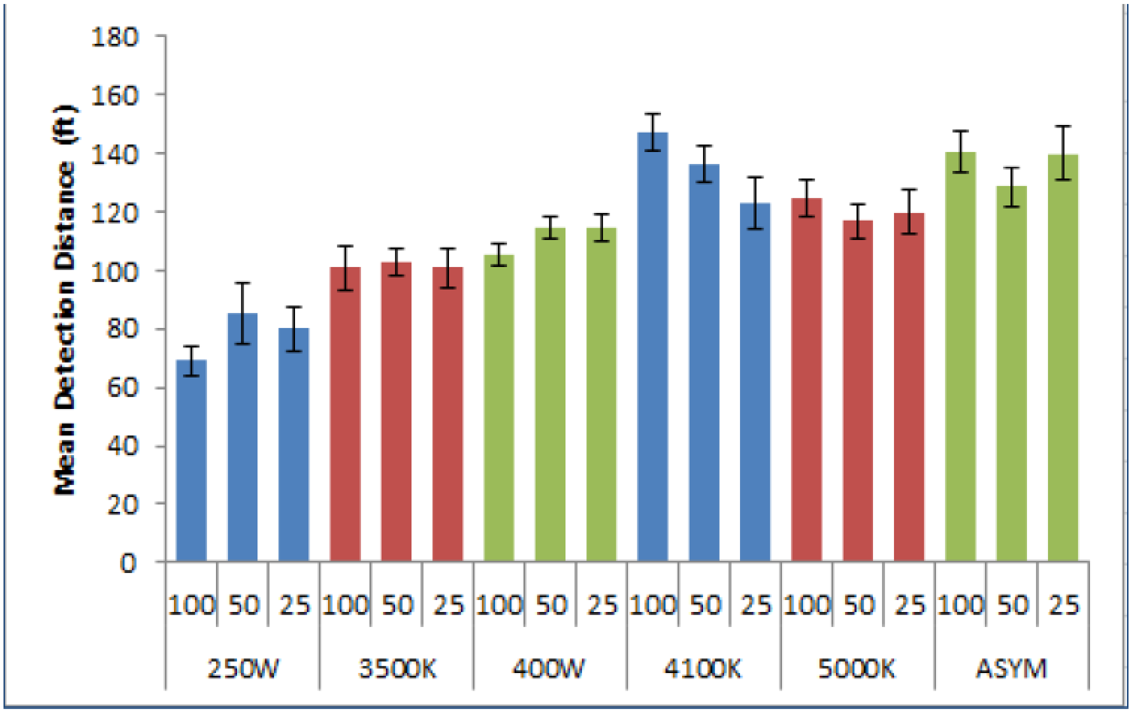


Figure 2. Mean Detection Distance Differences for Various Sources (Clanton & Associates Inc., 2014)

Throughout this guide, the figures presented may have associated error bars. These bars represent the magnitude of the standard error associated with analysis results. The standard error represents uncertainty that is associated with any data collection effort. When the error bars overlap, meaning that they are in the same range (e.g., the 3500 K LED in Figure 2), there is no statistical significance; those that are separated (e.g., 100 percent light output compared to 25 percent light output for the 4100 K LED) show statistical significance.

LEDs have some drawbacks. For example, the advent of LED lighting invites the use of more white or blue CCT lighting on roadways. The color-rendering abilities of these broader spectrum sources are much greater than the yellow associated with HPS or Low-Pressure Sodium (LPS) light sources. However, some research shows that driver vision may be negatively affected due to the adaptation of the eye when moving from darkness into an area lit by a white or blue light source (Boyce, 2009) (Goldstein, 2010). Other concerns include performance in adverse weather conditions, sky glow, and potential health impacts.

From a lighting design and specification standpoint, SSL requires a much different approach than HID technology. The life of the source is rated differently. HID sources are typically rated by the time in operation when 50 percent of the lamps had failed, where LED sources are rated by when the lumen depreciation declines to 70 percent of the initial output. Figure 3 shows test data used for predicting the life of an LED luminaire. The testing is performed for three different temperatures, a calculated life is estimated, and a rated life is determined (which can be no more than six times the test duration). This testing, however, only predicts the life of the LED and the lifetime of the driver. The life of a driver is strongly related to the case temperature. Figure 4 shows an example of driver lifetime as it relates to case temperature. Because the driver is an electronic device, it can be evaluated by mean time between failure (MTBF) testing to determine reliability and product failure rates. Operating LEDs and drivers at higher temperatures can significantly reduce expected life.

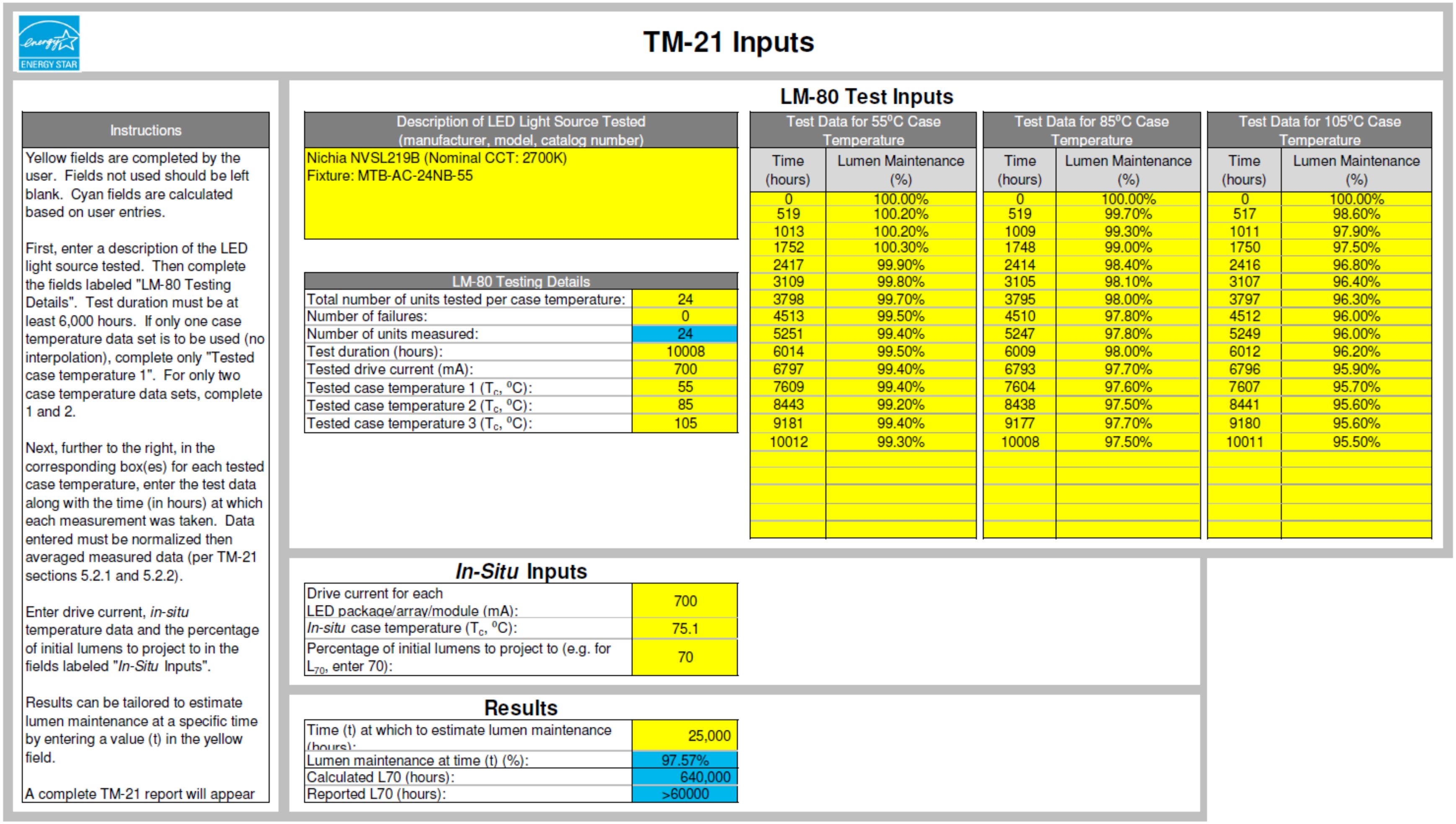
> Life of an LED can be considered as the point when the lumen output depreciates by 30 percent or when one of the components fails.

The rated life of an LED luminaire is based on the point in time when the lumen output of the LED has reduced to 70 percent of its initial lumen rating in accordance with IES LM-80. Some of these factors are quantified and included in the LED test data performed in accordance with *TM-21 Projecting Long Term Lumen Maintenance of LED Light Sources* (IES, 2011). Other data are usually available from the luminaire manufacturers. Further use of these data is discussed in Chapter 11.

Established methods of classifying photometric distribution (IES Type II, III, IV, V and short, medium, and long) are not as relevant with LED luminaires. Distribution classification methods that were often used for grouping similar HID products from an optical distribution standpoint often do not work well as descriptors for LED products. An example of an HPS luminaire and an LED luminaire distribution, both classified as Type II, and their differences are shown in Figure 5. There is also great variation between available products, as well as subjective acceptance of color and brightness, variety of control options, and different failure modes due to temperature and voltage variations. With HID streetlights, one could simply define the wattage and optical distribution (e.g., Type II, cutoff) and would get similar results from different luminaires. LED luminaires, however, require a closer review and assessment. Photometric properties of specific makes, models, and versions should be evaluated when designing a project or developing an approved products list.

1.4 KEY DIFFERENCES BETWEEN SOLID-STATE AND TRADITIONAL LIGHT SOURCES

- Spectral content and effectiveness vary. CCT only partially describes LED source spectral content.
- Photometric distribution can greatly vary between HID sources as well as among LED products.
- Rated life of luminaires is based on different performance requirements.
- Solid-state components require different considerations relating to electrical components and operations.
- Solid-state luminaires allow for much greater flexibility regarding control, output, and optical distribution. These flexibilities offer potential benefits over HID and HPS.
- Solid-state luminaires can create impacts relating to glare, environmental impacts, and subjective preferences, which should be understood and mitigated.



TM-21 Inputs

Instructions
Yellow fields are completed by the user. Fields not used should be left blank. Cyan fields are calculated based on user entries. First, enter a description of the LED light source tested. Then complete the fields labeled "LM-80 Testing Details". Test duration must be at least 6,000 hours. If only one case temperature data set is to be used (no interpolation), complete only "Tested case temperature 1". For only two case temperature data sets, complete 1 and 2. Next, further to the right, in the corresponding box(es) for each tested case temperature, enter the test data along with the time (in hours) at which each measurement was taken. Data entered must be normalized then averaged measured data (per TM-21 sections 5.2.1 and 5.2.2). Enter drive current, *in-situ* temperature data and the percentage of initial lumens to project to in the fields labeled "*In-Situ* Inputs". Results can be tailored to estimate lumen maintenance at a specific time by entering a value (t) in the yellow field. A complete TM-21 report will appear

LM-80 Test Inputs

Description of LED Light Source Tested (manufacturer, model, catalog number)
Nichia NVSL219B (Nominal CCT: 2700K) Fixture: MTB-AC-24NB-55

LM-80 Testing Details	
Total number of units tested per case temperature:	24
Number of failures:	0
Number of units measured:	24
Test duration (hours):	10008
Tested drive current (mA):	700
Tested case temperature 1 (T_c, °C):	55
Tested case temperature 2 (T_c, °C):	85
Tested case temperature 3 (T_c, °C):	105

Test Data for 55°C Case Temperature		Test Data for 85°C Case Temperature		Test Data for 105°C Case Temperature	
Time (hours)	Lumen Maintenance (%)	Time (hours)	Lumen Maintenance (%)	Time (hours)	Lumen Maintenance (%)
0	100.00%	0	100.00%	0	100.00%
519	100.20%	519	99.70%	517	98.60%
1013	100.20%	1009	99.30%	1011	97.90%
1752	100.30%	1748	99.00%	1750	97.50%
2417	99.90%	2414	98.40%	2416	96.80%
3109	99.80%	3105	98.10%	3107	96.40%
3798	99.70%	3795	98.00%	3797	96.30%
4513	99.50%	4510	97.80%	4512	96.00%
5251	99.40%	5247	97.80%	5249	96.00%
6014	99.50%	6009	98.00%	6012	96.20%
6797	99.40%	6793	97.70%	6796	95.90%
7609	99.40%	7604	97.60%	7607	95.70%
8443	99.20%	8438	97.50%	8441	95.60%
9181	99.40%	9177	97.70%	9180	95.60%
10012	99.30%	10008	97.50%	10011	95.50%

In-Situ Inputs

Drive current for each LED package/array/module (mA):	700
In-situ case temperature (T_c, °C):	75.1
Percentage of initial lumens to project to (e.g. for L_{70}, enter 70):	70

Results

Time (t) at which to estimate lumen maintenance (hours):	25,000
Lumen maintenance at time (t) (%):	97.57%
Calculated L70 (hours):	640,000
Reported L70 (hours):	>60000

Figure 3. TM-21 Inputs for Predicting Lumen Maintenance

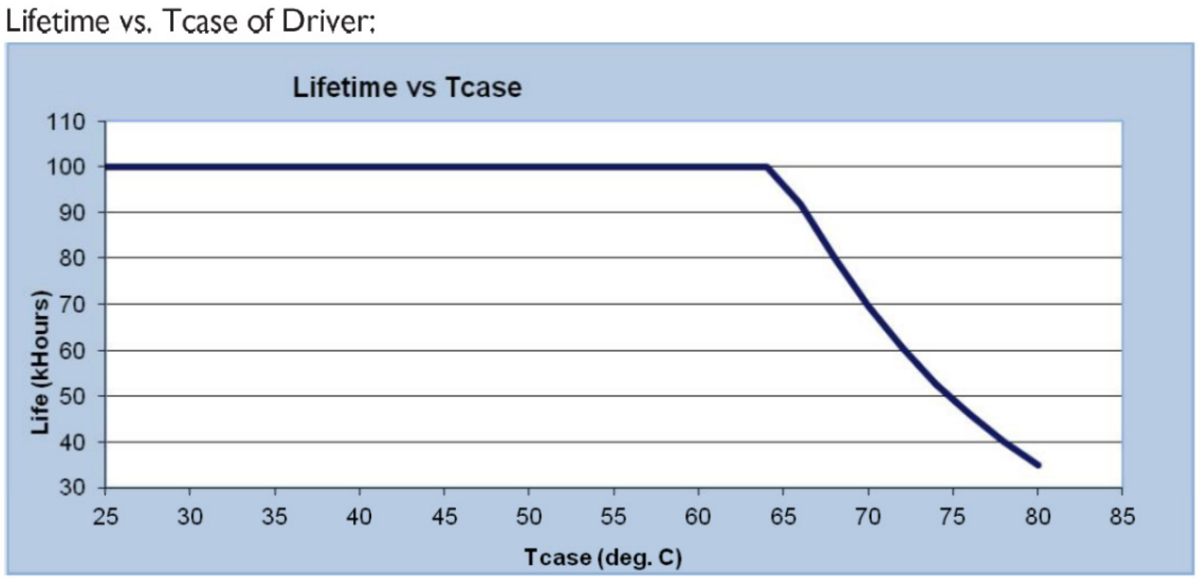


Figure 4. Example of Driver Life Determined by MTBF Analysis (T_{case} is the temperature of the case of the driver)

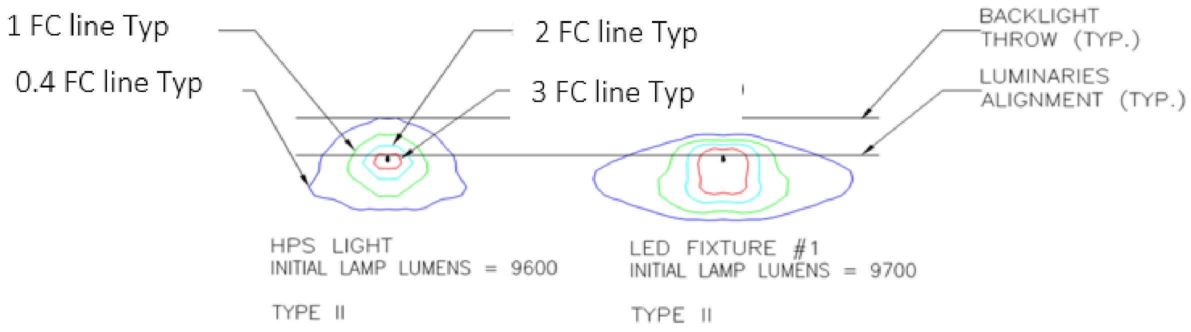


Figure 5. Comparisons of HPS and LED Luminaires using Standardized Distribution Ratings