U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

# GATEWAY Demonstrations

# Long-term Testing of LED Luminaires

**Host Site**: I-35 West Bridge, Minneapolis, Minnesota

September 2014

**Prepared for:**

Solid-State Lighting Program
Building Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

**Prepared by:**

Pacific Northwest National Laboratory

# Long-term Testing Results for the 2008 Installation of LED Luminaires at the I-35 West Bridge in Minneapolis

Final Report prepared in support of the DOE Solid-State Lighting Technology GATEWAY Demonstration Program

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U.S. Department of Energy
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September 2014

Prepared for

the U.S. Department of Energy

under Contract DE-AC05-76RL01830

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Richland, Washington 99352

PNNL-23702



PACIFIC NORTHWEST NATIONAL LABORATORY
*operated by*
BATTELLE
*for the*
UNITED STATES DEPARTMENT OF ENERGY
*under Contract DE-AC05-76RL01830*

**Printed in the United States of America**

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# Preface

**Acknowledgments**
The authors gratefully acknowledge the following individuals and their respective organizations for their important contributions to his project.

- Eric Haugaard of Cree was involved with the project from the outset in 2008, and provided technical support and input throughout, including open communication regarding the optical gel issue described in the report.
- Michael Myer of Pacific Northwest National Laboratory, co-author of the original 2009 GATEWAY report, provided ongoing data analysis and technical support through the subsequent data collections and analysis.
- Sue Zarling of the Minnesota Department of Transportation (MnDOT) was involved in the original installation in 2008 and remains engaged in the project. Sue and her colleagues at MnDOT showed particular courage in being early adopters of the technology in this critical application, and their efforts continue to provide national benefit.

**The GATEWAY Program**
This document is a report of observations and results obtained from a lighting evaluation project conducted under the U.S. Department of Energy (DOE) GATEWAY Program. The program supports evaluations and demonstrations of high-performance solid-state lighting (SSL) products in order to develop empirical data and experience with in-the-field applications of this advanced lighting technology. The DOE GATEWAY Program focuses on providing a source of independent, third-party data for use in decision-making by lighting users and professionals; this data should be considered in combination with other information relevant to the particular site and application under examination. Each GATEWAY evaluation compares SSL products against the incumbent technologies used in that location. Depending on available information and circumstances, the SSL product may also be compared to alternate lighting technologies. Though products used in the GATEWAY program may have been prescreened for performance, DOE does not endorse any commercial product or in any way guarantee that users will achieve the same results through use of these products.

# Executive Summary

This document reports on the long-term performance of a light-emitting diode (LED) system on the I-35W Bridge in Minneapolis, MN, installed September 2008. The data evaluated are in two primary categories: photometric testing (including colorimetric data in some cases) of luminaires used in the project, and illuminances measured at the installation. As of this publication 6 years hence, the I-35W Bridge remains one of the oldest exterior LED installations in continuous operation in the United States.

At the outset of this monitoring project, a plan was established for testing three luminaires prior to the installation. Two of those (designated as 200-A and 240-A, the numerical values referring to the number of LEDs on each) were installed on the bridge, and the third luminaire (200-B) was sent for long-term laboratory testing via the U.S. Department of Energy (DOE) CALiPER program, to enable future comparison of laboratory results to data from luminaires that had been installed in the field after several years of operation. These follow-up tests were conducted in April 2013.

Table ES.1 compares the power, light output, and efficacy results from the 2008 pre-installation test of luminaire 200-A to the results for the same luminaire from the 2013 test. The 2013 results shown are from the test of the luminaire after cleaning by the testing laboratory.

**Table ES.1. Long-term data for luminaire 200-A after approximately 20,300 hours of operation**

| | Aug 2008 | Apr 2013 | % Change |
|---|---|---|---|
| Power (W) | 243.9 | 233.3 | -4% |
| Light output (lm) | 16,399 | 13,194 | -20% |
| Efficacy (lm/W) | 67.2 | 56.6 | -16% |

lm is lumens; lm/W is lumens per watt.

Table ES.2 compares the power, light output, and efficacy results from the 2008 pre-installation test of luminaire 240-A to the results for the same luminaire from the 2013 test. The 2013 results shown are from the test of the luminaire after cleaning by the testing laboratory.

**Table ES.2. Long-term data for luminaire 240-A after approximately 20,300 hours of operation**

| | Aug 2008 | Apr 2013 | % Change |
|---|---|---|---|
| Power (W) | 289.3 | 278.2 | -4% |
| Light output (lm) | 18,882 | 15,653 | -17% |
| Efficacy (lm/W) | 65.3 | 56.3 | -14% |

Considering these data for the two luminaires that were tested prior to installation and then tested again after roughly 20,300 hours of operation, the average effects observed were

- a 4% reduction in input power,
- an 18% reduction in light output (independent of dirt accumulation), and
- a corresponding reduction of luminaire efficacy of 15%.

Multiple factors are contributing to the decreased light output from luminaires 200-A and 240-A. Perhaps most relevant to general LED users is the normal lumen depreciation from the LEDs, separate from any other factors that may have been unique to this project. However, for example, an optical gel bubble issue (discussed in greater detail in the report) has also contributed to the measured light output decrease; we estimate a corresponding reduction in the range of 5% to 7%. Further, a consistent reduction in input power was observed in products tested following different periods of operation; this power reduction may cause a corresponding reduction in light output that is separate from normal lumen depreciation of the LEDs. The project was not able to determine the cause of this power reduction.

After normalizing for all of the other factors, the estimated LED lumen depreciation was 11% for luminaire 200-A and 9% for luminaire 240-A. The average reduction in light output due to LED lumen depreciation for this site is therefore estimated to be 10% after 20,300 hours of operation.

Regarding luminaire 200-B, which was tested through CALiPER, Table ES.3 shows the results of the integrating sphere tests at 100 and 6000 hours.

**Table ES.3. Results for luminaire 200-B from CALiPER sphere testing at 100 and 6000 hours**

| Luminaire | 200-B | 200-B |
|---|---|---|
| Test Report # | 62722 | 62722 |
| Hours | 100 | 6000 |
| Power (W) | 246.1 | 240.5 |
| Light output (lm/W) | 16,482 | 15,659 |
| Efficacy (lm/W) | 67 | 65.1 |
| CCT (K) | 6061 | 5521 |
| $D_{uv}$ | 0.008 | 0.013 |
| x | 0.3198 | 0.3321 |
| Y | 0.3462 | 0.3666 |
| CRI | 74 | 72 |
| R9 | -25.2 | -35.5 |

CRI is color rendering index.

The manufacturer's data for the fixtures installed on the project show a rated CCT of 6000K and CRI of 75, which are consistent with the measured data for luminaire 200-B at 100 hours (measured CCT of 6061 and CRI of 74.) Over this 6000-hour period, the CCT decreased and the $D_{uv}$ increased from a slightly positive value to a greater positive value, indicating that the chromaticity coordinates shifted farther away from the blackbody curve toward the yellow-green region of the chromaticity diagram. The Δu'v' for the measured color shift from luminaire 200-B from 100 to 6000 hours was 0.0117. (See Appendix A for an explanation of these color metrics.)

Even though some color quality data was recorded for luminaires 200-A and 240-A, the specific values cannot be directly compared to the data for luminaire 200-B since the initial test was not performed using industry standard procedures. However, the initial data for luminaire 200-B were within reasonable tolerances for the initial ratings, and the data for luminaires 200-A and 240-A are very similar to each other. As their data also support the color shift trends documented for luminaire 200-B—decreasing CCT and increasing $D_{uv}$—it is reasonable to assume that these trends are typical of the luminaires installed.

During ~20,300 hours of operation, we conclude that the color properties of the luminaires in this installation

- decreased in CCT by roughly 800K,
- increased in $D_{uv}$ by roughly 0.01, moving farther above the blackbody curve, toward the yellow-green region, and
- decreased slightly in the general CRI and decreased more substantially in R9.

The factors causing the measured color shift cannot be determined within the scope of this project. The nature of the shift appears consistent with a possible change in the phosphor used in the LED packages, although other factors may have also contributed.

Dirt depreciation of the luminaires was assessed at two different times during the study: for two luminaires removed from the field in November 2009 and two more removed in May 2013. The corresponding measurements for average luminaire dirt depreciation are 4% after ~5000 hours, increasing to 12% after ~20,300 hours.

Note that these measurements represent the dirt depreciation at two specific points in time, and it is not possible to determine whether this depreciation happened linearly over the period examined or varied widely on a seasonal or other basis. Nevertheless, the data suggest that sites concerned with maintaining maximum illumination at the road surface should seriously consider instituting a regular cleaning regimen. The 12% depreciation means that more than a third of the design lifetime reduction in lumen output , i.e., 30%, has been reached by the effects of dirt alone during this period.

In terms of the illumination at the road surface, a mobile monitoring system (MMS), operated by Virginia Tech Transportation Institute, was used to take periodic measurements across the entire bridge. Illuminances measured on the ground reflect the cumulative impact of many factors (e.g., lumen depreciation, dirt, ambient temperature and other weather conditions at the time of measurement, measurement uncertainty) and the relative contribution of individual factors cannot be determined from the illuminance data alone.

Figure ES.1 shows the compiled average illuminance readings from the bridge, on the side of the southbound lanes, for the period that the MMS was used. The included illuminance trend line indicates that, over the roughly 10,000 hours of operation reflected in the chart, the measured average ground illuminance has decreased overall by ~10%, which is in general agreement (or at least does not markedly conflict) with the results of the laboratory test data reported earlier.

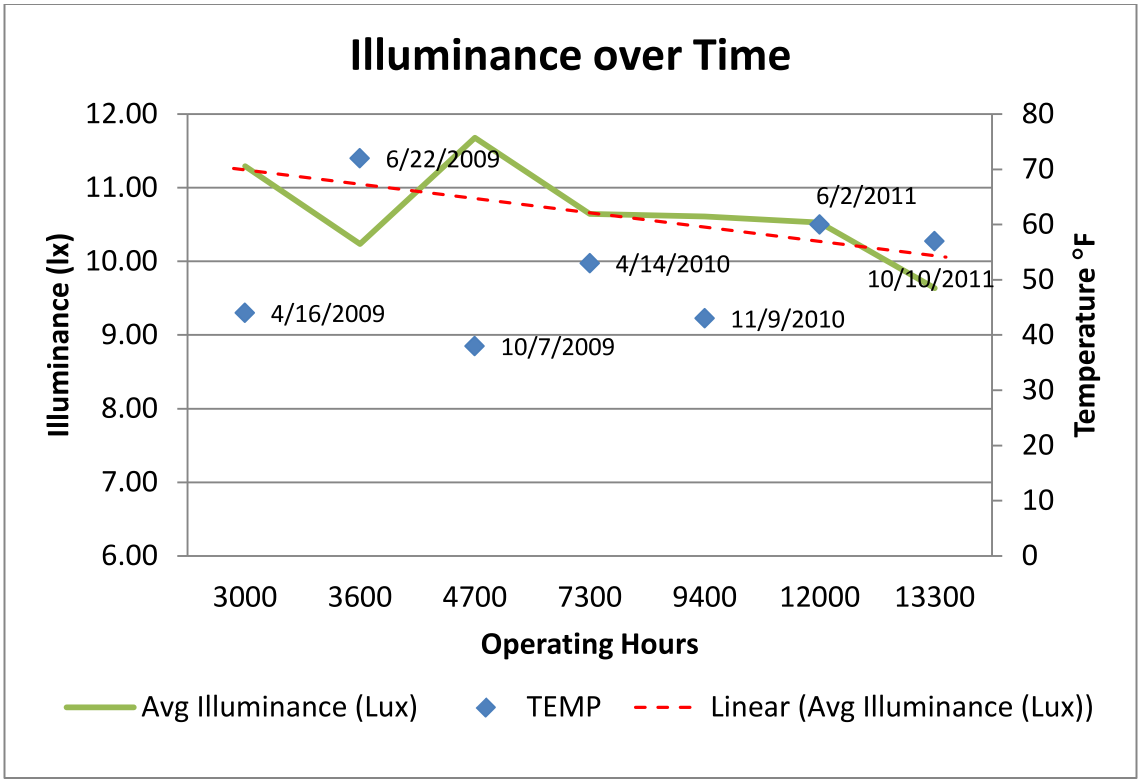


**Figure ES.1. Average illuminance readings from the MMS, southbound lanes, shown with the lowest ambient temperature reported for those same dates.**

Overall, this installation continues to be a robust and effective lighting system. A few issues have been encountered in its operation to date, but these are not unexpected given the early stage of LED development that the luminaires represent.

The entire lighting community continues to learn from this and the other installations that have been implemented since this system represented the state of the art six years ago. Readers of the report should recognize the limitations in applying long-term performance of early LED luminaires to their modern counterparts, due to continuous and ongoing advancements in the technology.

# Acronyms and Abbreviations

| | |
|---|---|
| ANSI | American National Standards Institute |
| CALiPER | Commercially Available LED Product Evaluation and Reporting |
| CCT | correlated color temperature |
| CIE | International Commission on Illumination |
| CRI | color rendering index |
| $D_{uv}$ | distance from the blackbody curve on the CIE 1960 (*u, v*) chromaticity diagram; see Appendix A |
| Δu'v' | difference between two points on the CIE 1976 (*u', v'*) chromaticity diagram; see Appendix A |
| DOE | U.S. Department of Energy |
| fc | footcandle(s) |
| HPS | high-pressure sodium |
| IES | Illuminating Engineering Society |
| LED | light-emitting diode |
| lm | lumen(s) |
| lm/W | lumens per watt |
| MMS | mobile monitoring system |
| MnDOT | Minnesota Department of Transportation |
| NEMA | National Electrical Manufacturers Association |
| SDCM | standard deviation of color matching |
| SSL | solid-state lighting |
| UCS | Uniform Chromaticity Scale |
| VTTI | Virginia Tech Transportation Institute |

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# 1. Introduction

This document reports the long-term testing results from an extended GATEWAY project that was first reported in "Demonstration Assessment of Light-Emitting Diode (LED) Roadway Lighting at the I-35W Bridge, in Minneapolis, MN," August 2009. That original report presented the results of lighting the newly reconstructed I-35W Bridge using LEDs in place of conventional high-pressure sodium (HPS) roadway luminaires, comparing energy use and illuminance levels with a simulated baseline condition. That installation was an early stage implementation of LED lighting and remains one of the oldest installations in continued operation today. A more detailed description of the bridge and other aspects of the original project are provided in the report, which is posted on the U.S. Department of Energy (DOE) Solid-State Lighting website, under GATEWAY results.

This document provides an update of the LED system's performance since its installation in September 2008. The data evaluated for this report are in two primary categories: photometric testing (including colorimetric data in some cases) of luminaires used in the project, and illuminances measured at the installation. Luminaires tested as part of this project included the following:

- Three luminaires that were tested before the installation was completed. Two of these luminaires (designated 200-A and 240-A, where the numeral indicates the number of LEDs in the luminaire) were then installed at the project site for normal operation. The third luminaire (200-B) was never installed, but was instead submitted for testing over 6000 hours of operation as part of the DOE CALiPER program.
- Two luminaires (200-C and 200-D) that were removed from the installation in November 2009 and tested as a result of a marked reduction in illuminances in the corresponding area of the bridge. These two luminaires were not the same luminaires tested before the installation. The luminaires were first tested in their as-is condition, then cleaned by the testing laboratory and re-tested.
- Two luminaires (200-A and 240-A) that were removed from the installation in May 2013 and were tested as specified in the original plan for the project. The luminaires were first tested in their as-is condition, then cleaned and re-tested. These were the same luminaires tested in August 2008, before being installed at the project site.

Results from the luminaire testing are reported in Section 3.

In addition, during the first 3 years of operation, illuminance levels on the bridge were monitored and recorded using a mobile monitoring system (MMS) designed and operated by the Virginia Tech Transportation Institute (VTTI). Seven sets of measurements were collected at various times between April 2009 and October 2011. The results from the MMS measurements are reported in Section 7.

Figure 1 presents a timeline for the data collection associated with this project.

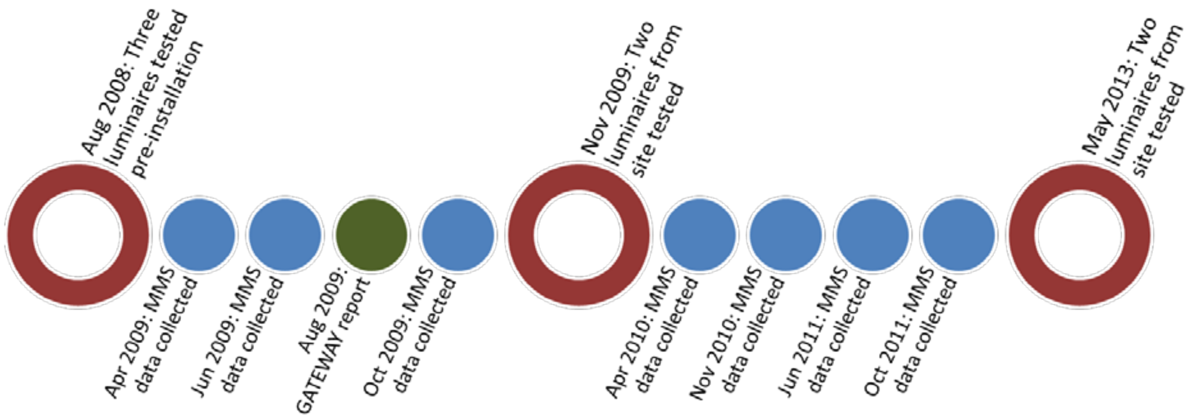


**Figure 1. Timeline of data collection and reporting for I-35 Bridge project.** Open red circles indicate luminaire testing, closed blue circles indicate MMS testing, and the closed green circle shows the publication of the original project report.

# 2. Brief Description of the Installation

The installation is described in detail in the original GATEWAY report. General characteristics are provided here for convenience.

## 2.1 Lighting System Design

Two separate spans comprise the bridge, each 1215 feet long, and each containing five 12-foot-wide lanes with a 14-foot inside shoulder and 13-foot outside shoulder. Thus, the overall bridge width is 87 feet. Poles are set on 150-foot spacing down the center of the bridge (see Figure 2), with mounting heights of 40 feet.

The bridge incorporates 16 Type V distribution 200-LED luminaires (10 LED arrays with 20 LEDs each, producing nominal 16,500 lumens) across the middle span, and 4 Type III distribution 240-LED luminaires (12 LED arrays with 20 LEDs each, producing 19,000 lumens), two mounted at each end of the bridge (one on each side). Selection of this luminaire output anticipated a future lumen depreciation of 30% (i.e., to $L_{70}$) while still meeting design criteria. At the prevailing average nighttime temperature in Minneapolis, the manufacturer projected that the luminaires would need to operate for several decades to reach an $L_{70}$ level of lumen depreciation, estimating only about a 12% loss after 20 years under the given conditions.[1]

**Figure 2. LED luminaires on the I-35 bridge**

## 2.2 Luminaires

The new luminaires were manufactured by Ruud Lighting's BetaLED™ division.[2] The LEDs and drivers were manufactured by Cree and Advanced Transformer, respectively. The LEDs are Model XR-E, generation Q5 chips. The initial laboratory-measured efficacy values for the 200-LED Type V luminaire and the 240-LED Type III luminaire were 68.0 lumens per watt and 65.3 lumens per watt, respectively. Overall, these LED luminaires

[1] As documented in the original project report.
[2] Since purchased by Cree Lighting.

were estimated to save about 13% in energy relative to the conventional system design, which assumed a baseline HPS luminaire.

## 2.3 Initial Illuminance and Power

Table 1 presents the initial illuminance results for the LED installation, measured during a site visit on the evening of September 7, 2008. (These readings were hand measurements taken by GATEWAY researchers rather than by the MMS.) For reference, the table also provides the Minnesota Department of Transportation (MnDOT) requirements from its 2006 Roadway Lighting Manual.[3] Table 2 provides the measured power use of the two LED luminaires, using respective power factors that were measured in the testing laboratory.

**Table 1. Initial illuminance levels on the bridge**

| | MnDOT Requirements | Measured Illuminance or Ratio |
|---|---|---|
| **Average** | 0.6 – 1.1[(a)] fc | 0.91 fc |
| **Maximum** | NA | 1.97 fc |
| **Minimum** | NA | 0.26 fc |
| **Avg:Min** | 3:1 – 4:1[(b)] | 3.51:1 |
| **Max:Min** | NA | 7.58:1 |

fc is footcandle.

(a) MnDOT desired results towards the higher end of this range ≈ 0.8–1.0 fc.

(b) MnDOT desired uniformity of 3:1.

**Table 2. Measured power levels for the luminaires on the bridge**

| Quantity | Distribution | Luminaire Type | Luminaire Power[(a)] (W) | Total Power (W) |
|---|---|---|---|---|
| 4 | Type III | 240-LED | 289 | 1156 |
| 16 | Type V | 200-LED | 244 | 3904 |
| | | | Overall total power | 5060 |

(a) Values were developed by taking apparent power measurements (VA) in situ and multiplying by the lab-measured power factors of 0.95 for the 200-LED luminaires and 0.94 for the 240-LED luminaires.

[3] Since updated. See http://www.dot.state.mn.us/trafficeng/lighting/2010_Roadway%20Lighting_Design_Manual2.pdf.

# 3. Luminaire Testing Results

### 3.1 August 2008 Pre-installation Laboratory Testing

Prior to the installation, three luminaires were tested at Luminaire Testing Laboratory in August 2008: two of the 200-LED luminaires and one 240-LED luminaire. Each luminaire was tested according to the IES LM-79-08 (IES 2008a) test procedure. Luminous intensity distribution was measured for each luminaire using the absolute photometry method. After testing, one of the 200-LED luminaires (luminaire 200-A) and the 240-LED luminaire (luminaire 240-A) were installed at the project site. The other 200-LED luminaire (luminaire 200-B) was sent for further evaluation as part of the DOE's CALiPER program (see section 3.2). Table 3 summarizes the testing results.

**Table 3. Data from August 2008 laboratory tests of three luminaires**

| Luminaire | 200-A | 200-B | 240-A |
|---|---|---|---|
| Test Report # | 13720 | 13721 | 13722 |
| Power (W) | 243.9 | 242.5 | 289.3 |
| Light Output (lm) | 16,399 | 16,482 | 18,882 |
| Efficacy (lm/W) | 67.2 | 68 | 65.3 |

lm is lumen(s); lm/W is lumens per watt.

### 3.2 6000-hour Testing through CALiPER

Luminaire 200-B was submitted for long-term performance testing as part of the DOE's CALiPER program. Following a burn-in period of 100 hours, the luminaire was tested in an integrating sphere to measure photometric and colorimetric performance. The luminaire was then operated for 6000 hours, during which time spot measurements of illuminance and correlated color temperature (CCT) were taken every 500 hours at five locations beneath the luminaire. Full details of the testing protocols are reported in the related CALiPER report (PNNL 2011). At the conclusion of the 6000 hour period, the photometric and colorimetric performance characteristics of the luminaire were again measured in an integrating sphere.

Table 4 shows the results of the integrating sphere tests at 100 and 6000 hours. Table 5 presents the illuminance and CCT data measured every 500 operating hours at location 3, which was directly beneath the luminaire (i.e., at nadir). The spot measurements are reported to provide an indication of the relative change over time, but they do not match the precision of the sphere data; the documented sphere measurements at 100 and 6000 hours serve as the basis for our analysis and conclusions.

**Table 4. Results for luminaire 200-B from CALiPER sphere testing at 100 and 6000 hours**

| Luminaire | 200-B | 200-B |
|---|---|---|
| Test report # | 62722 | 62722 |
| Hours | 100 | 6000 |
| Power (W) | 246.1 | 240.5 |
| Light output (lm) | 16,482 | 15,659 |
| Efficacy (lm/W) | 67.0 | 65.1 |
| CCT (K) | 6061 | 5521 |
| $D_{uv}$ | 0.008 | 0.013 |
| x | 0.3198 | 0.3321 |
| y | 0.3462 | 0.3666 |
| CRI | 74 | 72 |
| R9 | -25.2 | -35.5 |

CRI is color rendering index.

**Table 5. Illuminance and CCT measured at a single point directly beneath the luminaire at 500-hour intervals**

| Operating Hours | 100 | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Illuminance (lux) | 692.4 | 749.2 | 735.8 | 717.9 | 680.1 | 651.8 | 636.8 | 629.7 | 613.7 | 608.5 | 601.8 | 596.0 | 590.7 |
| Color Temperature (CCT) | 5573 | 5506 | 5411 | 5347 | 5320 | 5336 | 5322 | 5321 | 5334 | 5322 | 5327 | 5272 | 5246 |

## 3.3 November 2009 Laboratory Testing

### 3.3.1 Luminaires Removed from Project Site

An unexpected issue led to an early laboratory test approximately 14 months after the bridge began operation. The MMS had detected an area of the bridge where illuminance levels were rapidly decreasing relative to other areas on the bridge. To determine the source of the issue, the luminaire in this area and one next to it were removed from the site in November 2009, replaced with other units, and sent for testing. Both luminaires were 200-LED Type V distributions, and are designated herein as 200-C and 200-D. We estimate that these two luminaires had operated for approximately 5000 hours at the time they were removed from the site.

Each of these 200-LED luminaires contains two separate drivers, each of which powers half of the LEDs in the luminaire. Upon receipt of the luminaires, the laboratory found that one of the two drivers in the suspect unit had by then completely failed, resulting in half the LEDs no longer illuminating.

The laboratory proceeded with testing both of the retrieved luminaires. The unit with the two properly functioning drivers was tested first, after which one of its drivers was used as a replacement for its failed counterpart in the second luminaire. Each luminaire was tested in its as-found condition, then cleaned and re-tested. Luminous intensity distribution was measured using the absolute photometry method, but spectral power distribution was not. Table 6 shows the results of four tests for the two luminaires removed from the site in November 2009, in “as-is” (or dirty) condition and again following cleaning. The average light loss due to dirt depreciation for these two luminaires after ~5000 hours was 4%.

**Table 6. Data from November 2009 laboratory tests of two luminaires removed from the project site**

| Luminaire | 200-C | 200-C | 200-D | 200-D |
|---|---|---|---|---|
| Condition | As is | Clean | As is | Clean |
| Test Report # | 16954 | 16955 | 16956 | 16957 |
| Power (W) | 237.9 | 238.7 | 238.3 | 238.4 |
| Light output (lm) | 14,520 | 15,227 | 14,670 | 15,245 |
| Efficacy (lm/W) | 61.0 | 63.8 | 61.6 | 64.0 |

### 3.3.2 Remanufactured Luminaires

By the time of the November 2009 testing, the luminaire manufacturer had become aware of an earlier design issue that affected the performance of these luminaires. An optical gel used during the original construction to fill a void between the LED and the secondary optics tended to develop an internal bubble over time, affecting both the lumen output and distribution. To determine the relative impact of this bubble on the I-35W luminaires, following the initial dirt depreciation testing, the two luminaires were returned to the manufacturer, who essentially remanufactured them as new. Even though the optical gel was no longer in use by that time, the manufacturer still retained the associated equipment capability and was thereby able to replace the gel. Remanufacturing the luminaires in this way allowed subsequent assessment of the impact of the bubble on the performance of the luminaires.

The results for the remanufactured units are shown in Table 7. Although these were different luminaires from those tested before the installation (luminaires 200-A and 200-B), the lumen output of each after being remanufactured was very similar to the levels originally documented, and the power use of each was also very close to the originally tested luminaires. Based on these data, it appears that the bubble in the optical gel in combination with an accompanying drop in power caused an average reduction in light output of ~7%.[4]

These data suggest that the reduction in light output measured in the cleaned units from the November 2009 tests was mostly, if not completely, caused by the bubble, which means there was little to no reduction in light output due to normal lumen depreciation during the first 5000 hours of operation. The product manufacturer believes that this reduction tended to occur relatively rapidly once the bubble began forming in the optical gel.

**Table 7. Comparison of remanufactured units with cleaned units removed from site**

| Luminaire | 200-C | 200-C | 200-D | 200-D |
|---|---|---|---|---|
| Condition | Clean | Remfr | Clean | Remfr |
| Test Report # | 16955 | 17904 | 16957 | 17766 |
| Power (W) | 238.7 | 242.4 | 238.4 | 243.3 |
| Light output (lm) | 15,227 | 16,305 | 15,245 | 16,462 |
| Efficacy (lm/W) | 63.8 | 67.3 | 64.0 | 67.7 |

[4] The luminaires tested before re-manufacturing also exhibited average power use 2% lower than was both measured after the re-manufacturing, and that had been measured with luminaires 200-A and 200-B when new. We were unable to determine if the slight measured power reduction in 200-C and 200-D was related to the bubble or not, and the manufacturer did not provide further explanation when provided the opportunity. If the lumen values are normalized for equal power, the average reduction in light output due to the bubble alone was 5%.

### 3.4 May 2013 Laboratory Testing

In accordance with the original planned luminaire testing for the project, MnDOT retrieved the two luminaires that had been tested before the installation (luminaires 200-A and 240-A). Both units were tested in their "as-is" or dirty condition, then cleaned by the laboratory and tested again. Luminous intensity distribution was measured for each luminaire using the absolute photometry method. Spectral power distribution data were measured for each luminaire in an integrating sphere. We estimate that these two luminaires had operated for ~20,300 hours at the time they were removed from the site.

Table 8 provides results from the two luminaires tested in May of 2013, and shows that on average, dirt accumulation on these two luminaires reduced the light output by 12%. Section 4 discusses the effects of dirt accumulation in more detail.

**Table 8. Data from May 2013 laboratory tests of two luminaires removed from the project site, to show effect of dirt depreciation on system performance**

| Luminaire | 200-A | 200-A | 240-A | 240-A |
|---|---|---|---|---|
| Condition | As is | Clean | As is | Clean |
| Test Report # | 185287 | 185288 | 185283 | 185284 |
| Power (W) | 232.6 | 233.3 | 276.7 | 278.2 |
| Light output (lm) | 11,341 | 13,194 | 13,975 | 15,653 |
| Efficacy (lm/W) | 48.8 | 56.6 | 50.5 | 56.3 |
| Sphere test report # | 185289 | 185290 | 185285 | 185286 |
| CCT (K) | 5129 | 5178 | 5132 | 5182 |
| x | 0.3441 | 0.3425 | 0.3440 | 0.3423 |
| y | 0.3882 | 0.3867 | 0.3873 | 0.3857 |
| CRI | 70 | 70 | 70 | 70 |
| R9 | -47.2 | -47.4 | -46.9 | -46.8 |

# 4. Long-Term Data: Dirt Accumulation

## 4.1 Effect of Dirt on Light Output

Estimation of luminaire dirt depreciation (LDD) in this study entailed removing a luminaire from its installed location, delivering it to a testing laboratory with as little disturbance as possible, and testing it first in its “as-is” condition and then cleaning and re-testing it. Directly comparing the measured light output of the cleaned luminaire to that of the as-is luminaire reveals the reduction in light output due to the accumulated dirt on the luminaire. Perhaps the largest potential for error in this procedure pertains to whether all of the accumulated dirt has been successfully removed by the testing laboratory. Dirt can redirect or absorb light transmitted through the luminous surfaces, and it may also hinder thermal transfer from the luminaire heat sinks, with possible resulting impacts to light output and lifetime if the luminaires consequently run at higher temperature.

Dirt depreciation was assessed at two different times during the course of this project: for the two luminaires removed from the field in November 2009 following ~5000 hours of operation (see section 3.3 and Table 6), and for the two luminaires removed from the field in May 2013 (see section 3.3.1 and Table 8). All tested units had operated on the bridge without being manually cleaned during the period from their original installation in early September 2008 until the time they were removed.

Figure 3 shows the percentage reductions in light output due to dirt depreciation for the four luminaires tested, and illustrates increasing degradation in light output over time from dirt accumulation. Figure 4 illustrates that the average luminaire dirt depreciation after 5000 hours was 4% and that the average luminaire dirt depreciation after an estimated 20,300 hours was 12%. Note that these measurements represent the dirt depreciation at two specific points in time, and it is not possible to determine whether depreciation occurred linearly over the period studied or whether it varied widely between the testing dates. Weather conditions such as humidity, rain, fog, and wind may cause temporal and potentially sudden increases or decreases in light levels due to dirt accumulation on the luminaires. The usual expectation for field installations is that increasing dirt accumulation over time leads to increased levels of light loss as a general trend, with some fluctuation due to portions of the accumulation being removed by rain and/or wind. The data from this project are consistent with the expectation that light losses due to dirt accumulation generally increase over time.

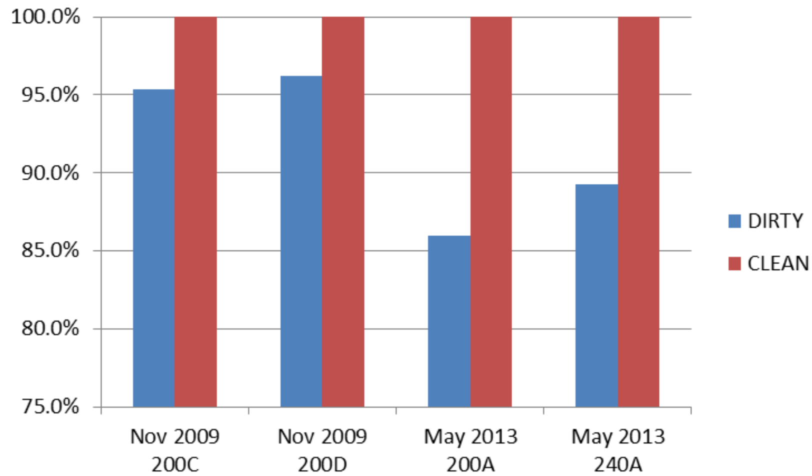


**Figure 3. Measured dirt depreciation of four luminaires.** Estimated operating time was 5000 hours for the luminaires tested in November 2009, and 20,300 hours for the luminaires tested in May 2013.

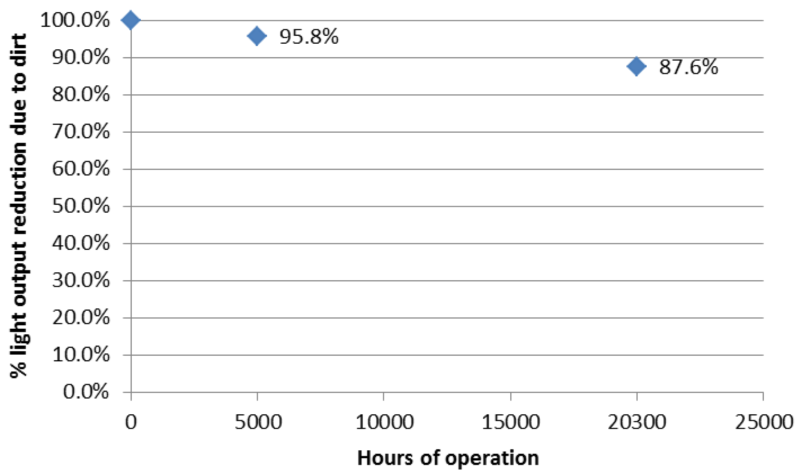


**Figure 4. Measured dirt depreciation of fixtures removed from the site**. Each data point represents the average of the two luminaires tested at each of the two periods, estimated at 5000 hours and 20,300 hours.

Although the IES does not provide specific LDD guidance for exterior environments, we used the general LDD formula (IES 2011a) which was derived for indoor environments to compare the measured results to IES estimates. The November 2009 tests occurred approximately 14 months after installation; estimated LDD values based on that time period are 0.926 for a "Clean" environment, 0.841 for a "Moderate" environment, and 0.705 for a "Dirty" environment. The May 2013 tests followed approximately 56 months of operation; estimated LDD values based on that time period are 0.87 for a Clean environment, 0.68 for a Moderate environment, and 0.36 for a Dirty environment. The measured reductions due to dirt from this project produce LDD values of 0.958 after 14 months and 0.876 after 56 months, which fairly closely align with the IES Clean condition.

## 4.2 Effect of Dirt on Intensity Distribution

Figure 5 and Figure 6 show the vertical distribution of the LED luminaires tested in May of 2013 in the "clean" and "as found" condition for the 200-A and 240-A luminaires, respectively. The "as found" distributions are indicated in red and show lower intensities than the "clean" distributions in green. The graphics reveal that dirt accumulation, while reducing output, did not significantly change the overall distribution of the luminaires, although a greater reduction is evident in the higher angles along with slightly increased intensities near the center of the distribution.

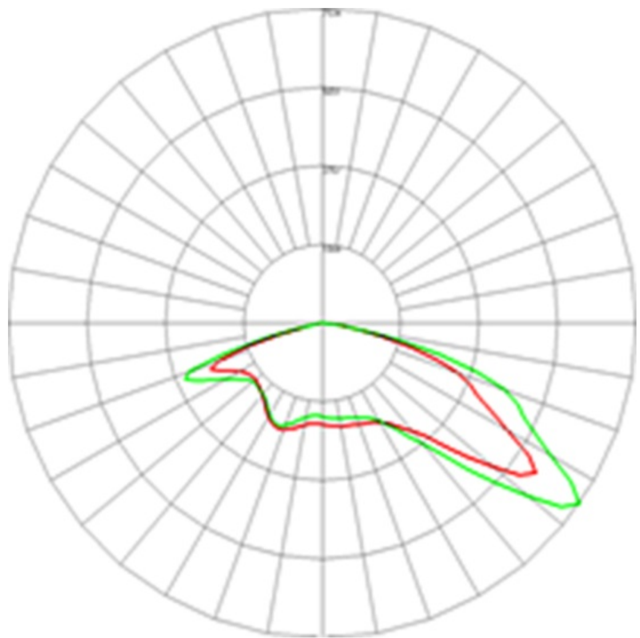

**Figure 5. Distribution effects of dirt for 200-A luminaire**. The red plot shows the luminous intensity distribution from the "as is" or dirty luminaire, and the green plot shows the distribution from the clean luminaire.

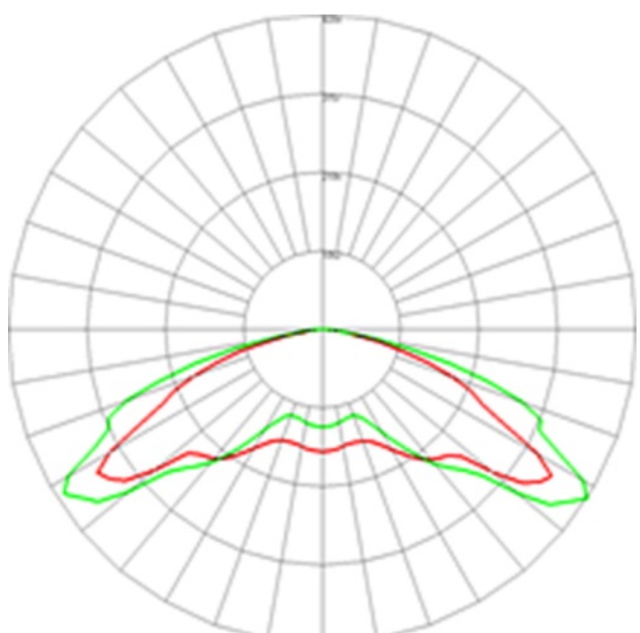

**Figure 6. Distribution effects of dirt for 240-A luminaire**. The red plot shows the luminous intensity distribution from the "as is" or dirty luminaire, and the green plot shows the distribution from the clean luminaire.

## 4.3 Effect of Dirt on Color Quality

Despite the dirt accumulation and associated reductions in lumen output, the color properties of the luminaires were not significantly affected by dirt accumulation. For the two luminaires removed from the site and tested after more than 20,000 hours of operation, the Δu'v' color difference between the as-is condition and clean condition of each luminaire was 0.001, with a decrease in CCT of about 50K due to dirt and no change in $D_{uv}$.

## 5. Long-Term Data: Power, Light Output, and Efficacy

Because the I-35W bridge installation in 2008 was one of the earliest major LED installations in the United States, at the time there were many questions about the long-term performance of this emerging technology. GATEWAY researchers therefore developed the testing plan, with the support of the host site and the manufacturer, for testing three luminaires prior to installation, then retesting two of those same luminaires after several years of operation at the site. The third luminaire was sent for long-term laboratory testing through the CALiPER program, to enable the comparison of laboratory results to data from luminaires that had been installed in the field.

Table 9 compares the power, light output, and efficacy results from the 2008 pre-installation test of luminaire 200-A to the results for the same luminaire from the 2013 test. The 2013 results shown are from the test of the luminaire after cleaning.

**Table 9. Long-term data for luminaire 200-A after approximately 20,300 hours of operation**

| | Aug 2008 | Apr 2013 | % Change |
|---|---|---|---|
| Power (W) | 243.9 | 233.3 | -4% |
| Light output (lm) | 16,399 | 13,194 | -20% |
| Efficacy (lm/W) | 67.2 | 56.6 | -16% |

Table 10 compares the power, light output, and efficacy results from the 2008 pre-installation test of luminaire 240-A to the results for the same luminaire from the 2013 test. The 2013 results shown are from the test of the luminaire after cleaning.

**Table 10. Long-term data for luminaire 240-A after approximately 20,300 hours of operation**

| | Aug 2008 | Apr 2013 | % Change |
|---|---|---|---|
| Power (W) | 289.3 | 278.2 | -4% |
| Light output (lm) | 18,882 | 15,653 | -17% |
| Efficacy (lm/W) | 65.3 | 56.3 | -14% |

Considering these data for the two luminaires that were tested prior to installation and then tested again after roughly 20,300 hours of operation, the average effects observed were

- a 4% reduction in input power,
- an 18% reduction in light output (independent of dirt accumulation), and
- a corresponding reduction of luminaire efficacy of 15%.

Table 11 compares the power, light output, and efficacy results from the 100-hour test of luminaire 240-A to the results for the same luminaire from the 6000-hour test, as tested for the CALiPER program. This luminaire was never operated at the project site, but remained in the testing laboratory during the 6000 hours of operation.

**Table 11. Long-term data for luminaire 200-B after 6000 hours of operation**

| | 100 hr | 6000 hr | % Change |
|---|---|---|---|
| Power (W) | 246.1 | 240.5 | -2% |
| Light output (lm) | 16,482 | 15,659 | -5% |
| Efficacy (lm/W) | 67.0 | 65.1 | -3% |

Summarizing these data from the three luminaires tested, input power decreased by 2% after 6000 hours of operation and by an average of 4% after 20,300 hours. Light output decreased by 5% after 6000 hours and by an average of 18% after 20,300 hours. (Extrapolating the 6000-hour data from luminaire 200-B estimates a decrease in light output of 17% at 20,300 hours, which is in line with the data from luminaires 200-A and 240-A.) Based on the discussion in section 3.3.2, we believe that the reduction in light output at 6000 hours was primarily caused by the bubble that formed in the optical gel, and that further reductions in light output beyond 6000 hours corresponded to normal lumen depreciation.

Multiple factors are contributing to the decreases in light output demonstrated by luminaires 200-A and 240-A, removed from the site for testing after approximately 20,300 hours of operation. Perhaps of most relevance for general LED users is the normal lumen depreciation from the LEDs, separate from any other factors that may have been unique to this project. However, the optical gel bubble clearly contributes to the measured light output decrease; we estimate a 5% to 7% effective reduction in light output from the bubble. Further, a consistent reduction in input power was observed in products tested following different periods of operation; this unexplained power reduction may cause a corresponding reduction in light output that is separate from normal lumen depreciation of the LEDs.

As reported above, the average reduction in light output for the two luminaires removed from the site in 2013 relative to their initial performance was 18%. To estimate the reduction due only to lumen depreciation of the LEDs, we normalized the measured output from the 2013 tests to remove the effect of the bubble (by increasing the measured light output by 5% of the initial value), and to remove the effect of the power reduction (by increasing the measured light output by the ratio of the initial power to the 2013 power). Using these normalized values, luminaire 200-A had an estimated reduction in light output due to LED lumen depreciation of 11%, and luminaire 240-A of 9% after approximately 20,300 hours. The *average* reduction in light output due to LED lumen depreciation for this site was therefore estimated to be 10% following an estimated 20,300 hours of operation.

# 6. Long-Term Data: Color Variation

Reliable color data were available for luminaire 200-B at 100 hours and 6000 hours of operation from the CALiPER testing, and for luminaires 200-A and 240-A from the April 2013 testing, after those two luminaires had been in operation for ~20,300 hours. (Preliminary color data were measured for luminaires 200-A and 240-A in August 2008 prior to their installation, but those data were not measured using currently accepted industry methods and so are not included here.) The manufacturer's data for the fixtures installed on the project show a rated CCT of 6000K and CRI of 75, which are consistent with the measured data for luminaire 200-B at 100 hours (measured CCT of 6061 and CRI of 74).

Table 12 presents the color data for these three luminaires. The two columns labeled 200-B allow a direct comparison of the color shift for that luminaire over 6000 hours of operation, and show that over that period the CCT decreased (the color appearance became warmer) and the $D_{uv}$ increased from a slightly positive value to a greater positive value (the chromaticity coordinates moved farther from the blackbody curve, toward the yellow-green). The Δu'v' value for the measured color shift from luminaire 200-B from 100 to 6000 hours was 0.0117, a shift in color that would likely be noticeable if one were comparing the colors side-by-side. However, if all luminaires shifted an equivalent amount over time, it would likely not be noticeable. (See Appendix A for an explanation of these color metrics.)

**Table 12. Comparison of color data from three luminaires**. Note that luminaires 200-A and 240-A do not have initial color data available, but were rated for 6000K CCT and 75 CRI. The data shown in the table were measured after these luminaires had operated for approximately 20,300 hours and were removed from the site for testing.

| Luminaire | 200-B | 200-B | 200-A | 240-A |
|---|---|---|---|---|
| Hours | 100 | 6,000 | 20,300 | 20,300 |
| CCT (K) | 6061 | 5521 | 5178 | 5182 |
| $D_{uv}$ | 0.008 | 0.013 | 0.018 | 0.017 |
| x | 0.3198 | 0.3321 | 0.3425 | 0.3423 |
| y | 0.3462 | 0.3666 | 0.3867 | 0.3857 |
| CRI | 74 | 72 | 70 | 70 |
| R9 | -25.2 | -35.5 | -47.4 | -46.8 |

The data for luminaires 200-A and 240-A are shaded in the table to indicate that, although they represent the color characteristics of those luminaires after 20,300 hours, the data should not be directly compared to the data for luminaire 200-B since their initial color properties were not adequately measured. However, the 100-hour data for luminaire 200-B were within reasonable tolerances for the initial ratings, and the data for luminaires 200-A and 240-A are very similar to each other. Since the data for these two luminaires are consistent with the color shift trends shown for luminaire 200-B after 6000 hours—decreasing CCT and increasing $D_{uv}$—it is reasonable to conclude that their data represent typical performance for the luminaires installed. However, the values of Δu'v' for the color shift over 20,300 hours cannot be determined for the reasons given.

Based on the data shown in Table 12, we conclude that during 20,300 hours of operation, the color properties of the luminaires in this project

- decreased CCT by roughly 800K,
- increased $D_{uv}$ by roughly 0.01, moving farther above the blackbody curve (toward the yellow-green), and
- decreased slightly in the general CRI and decreased more substantially in R9, suggesting a reduction in red content in the spectrum.

The factors causing this color shift cannot be precisely determined within the scope of this project. The nature of the shift appears consistent with a possible change in the phosphor used in the LED packages, although other factors may have also contributed.

## 7. Long-Term Data: Illuminance Testing with the Mobile Monitoring System

Details of the MMS developed by VTTI to periodically document illuminance levels on the bridge were provided in the original August 2009 project report. Seven sets of runs were recorded with the MMS, plus one incomplete set before the bridge opened in September 2008. Each set of runs involved several circuits around the bridge, recording illuminance data in each of the five lanes in both northbound and southbound directions. The frequency of readings was set at 10 hertz, or 10 readings per second, to obtain a sufficient representation of the illumination levels across the bridge.

Each run generated a large set of readings that required subsequent analysis by VTTI staff to produce the results of interest. Table 13 and Table 14 provide the compiled results from the last official run on October 10, 2011. Appendix B contains similar tables for the seven complete runs. Table 15 summarizes the compiled results from all runs, and shows that the average measured illuminance decreased by 15% during the MMS data collection (from 11.3 lux in April 2009 to 9.6 lux in October 2011), a period that spanned from an estimated 2970 to 13,320 operating hours.

**Table 13. Illuminances in southbound lanes from October 2011**

| 10-10-11 Southbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | **1st Lane** | **2nd Lane** | **3rd Lane** | **4th Lane** | **5th Lane** | **Entire Section** |
| Average | 15.5 | 12.2 | 9.1 | 6.8 | 4.8 | 9.7 |
| Maximum | 26.5 | 20.4 | 25.2 | 25.6 | 26.5 | 26.5 |
| Minimum | 5.3 | 4.1 | 3.1 | 2.6 | 2.0 | 2.0 |
| Avg:Min | 2.9 | 3.0 | 3.0 | 2.6 | 2.3 | 4.8 |
| Avg:Max | 5.0 | 5.0 | 8.2 | 9.8 | 13.0 | 13.0 |

**Table 14. Illuminances in northbound lanes from October 2011**

| 10-10-11 Northbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | **1st Lane** | **2nd Lane** | **3rd Lane** | **4th Lane** | **5th Lane** | **Entire Section** |
| Average | 15.8 | 12.8 | 8.9 | 6.1 | 4.2 | 9.6 |
| Maximum | 28.4 | 23.3 | 15.4 | 11.9 | 7.2 | 28.4 |
| Minimum | 5.2 | 4.0 | 3.5 | 2.3 | 2.3 | 2.3 |
| Avg:Min | 3.0 | 3.2 | 2.6 | 2.6 | 1.9 | 4.2 |
| Avg:Max | 5.5 | 5.9 | 4.4 | 5.1 | 3.2 | 12.5 |

**Table 15. Overall summary of MMS illuminance readings**

| | **4/16/2009 (2970 hr)** | **6/22/2009 (3590 hr)** | **10/7/2009 (4680 hr)** | **4/14/2010 (7266 hr)** | **11/9/2010 (9432 hr)** | **6/2/2011 (12,034 hr)** | **10/10/2011 (13,320 hr)** |
|---|---|---|---|---|---|---|---|
| Maximum | 34.2 | 32.5 | 32.4 | 30.6 | 31.2 | 29.4 | 27.5 |
| Minimum | 2.0 | 1.6 | 2.4 | 2.2 | 2.0 | 2.7 | 2.2 |
| Average | 11.3 | 10.2 | 11.7 | 10.6 | 10.6 | 10.5 | 9.6 |
| Avg:Min | 5.7 | 6.6 | 4.9 | 4.9 | 5.5 | 3.9 | 4.5 |

Comparing illuminance data on the road surface with the luminaire test data is complicated by a number of factors:

1. In addition to commonly understood factors like lumen maintenance and dirt depreciation, the variations in input power found in this instance, and seasonal effects like ambient temperature, snow and salt spray, also may appreciably affect lumens delivered to the target area. Lumens measured on the ground reflect the cumulative impact of all factors influencing them, and the relative contribution of individual factors cannot be distinguished from the illuminance data alone.
2. A complete set of MMS data was not collected when the bridge first opened, so the initial condition was not documented to the same extent as the subsequent MMS readings. It is thus unknown if the gel bubble issue had already begun taking effect (and if so to what extent) by the time of the April 2009 readings.
3. The testing of luminaires 200-A and 240-A provide laboratory results comparing a new system to a system with 20,300 operating hours, while the MMS data provide system performance between 2970 and 13,320 operating hours.

Despite the challenges of precisely correlating the two methods, however, the MMS did provide a valuable service in monitoring the overall lighting performance on the bridge. The MMS detected the first failing power supply (leading to its removal in November 2009) well before the performance had degraded to the point where it was visible to a typical observer on the bridge. In general, agreement with data from the laboratory testing, the MMS data also show a generally declining trend of average illuminance on the bridge during the period the system was deployed (Figure 7).

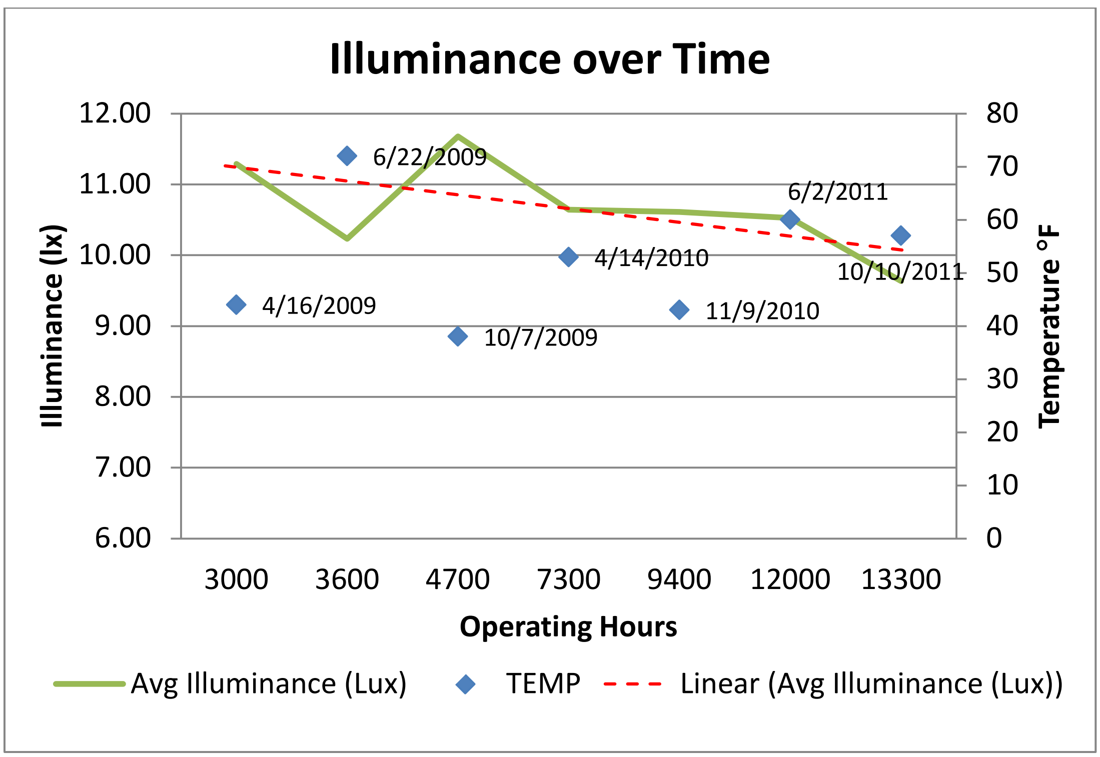


**Figure 7. Average illuminance readings from the MMS, southbound lanes, and ambient temperature data for those dates**. Temperature may affect LED output and light meters, but it does not explain all of the variation.

One issue evident in Figure 7 is the kind of "day to day" variation that is not unusual in measurements taken in actual exterior lighting environments, where contributions of the various factors affecting illuminance change over time.  Added to this is the precision of the meter(s) used, which has some percentage range of accuracy even under a given set of conditions, but that also can experience significant drift based on ambient temperature and humidity.  The chart includes the recorded low temperature for the date of each measurement[5] due to its possible influence on one or more of these constituent factors.

Because such measurement variations are commonly recognized and even accepted among lighting practitioners, the observations of primary interest are the overall trends in the data.  An illuminance trend line is therefore also included in the graphic.  Over the ~10,000 hours of operation in the chart, the measured average ground illuminance appears to have dropped ~10%, which generally agrees (or at least does not markedly conflict) with the results of the laboratory test data reported earlier, particularly given the different components likely contributing to each (e.g., the gel bubble in the laboratory test data and the varying ambient temperatures in the MMS data).

[5] Obtained from the National Climatic Data Center, www.ncdc.noaa.gov, for the site of the Minneapolis Airport.

# 8. Conclusions

As of this publication, at 6 years the I-35W Bridge in Minneapolis remains one of the oldest exterior LED installations in continuous operation in the United States. The LED luminaires represent an early state of the art in this technology, but continue to exhibit comparatively reliable operation against a traditional HPS baseline. At the current ~25,000 hours of cumulative operation, the bridge would have required at least one complete re-lamping by now had the designers chosen the conventional lighting route, with an additional number of premature failures as is typical with any common lamp-based technology.[6]

That said, the experience has not been problem-free. MnDOT reports a second power supply failure has occurred in the period since this monitoring effort concluded, requiring replacement. The noted gel bubble issue has presumably long since affected all of the original luminaires remaining on the bridge. Lumen maintenance of the luminaires has perhaps degraded at a slightly faster rate than was originally anticipated, while dirt depreciation appears to be following a relatively conventional pathway despite the manufacturer's original design attempt for the luminaires to be "self-cleaning." Finally, a slight but curious drop in power consumption (and corresponding lumen output) has been measured in all luminaires submitted for testing to date.

Nevertheless, no lighting installation, conventional or otherwise, is without issues. The causes of some of these, such as weather or line voltage spikes and fluctuations, are largely outside of the control of either the owner or product manufacturer. Even the impacts of design decisions, such as the earlier use of the optical gel in this instance, sometimes do not appear until some period in the future. The "day to day" fluctuations in lumens reaching the road surface, displayed in Figure 7, may even be driven by such factors in the early stages of installation, though over time the cumulative effects of lumen maintenance and dirt begin to dominate.

Sites concerned with maintaining maximum illumination at the road surface should seriously consider instituting a regular cleaning regimen. A 30% decline from initial output is commonly used in the LED lighting community to define luminaire lifetime; however, the average dirt depreciation measured on two luminaires in this installation after only about 4.5 years of operation amounted to ~12%. As a result, more than a third of the design lifetime reduction in lumen output has been achieved from dirt accumulation alone. While dirt depreciation is unlikely to continue to increase beyond some (as yet undetermined) maximum threshold, when combined with lumen maintenance losses and weather and other factors, it is not difficult to imagine periods when illumination levels on the road surface may already be dropping below IES recommended levels. Periodic cleaning of the luminaires may be a relatively inexpensive insurance policy where maintaining road illuminance is critical.

Along similar lines, a singular focus on the lumen maintenance characteristics of a luminaire while ignoring the collective influence of these numerous other constituent factors seems misplaced. Lumen maintenance within the luminaire is only one of many characteristics of the overall system, particularly once that luminaire is

[6] Furthermore, the previous bridge (which collapsed and was replaced) had a reported vibration problem that severely shortened the lifetime of the original HPS lamps; it is believed the new bridge design has addressed this issue but it is formally unknown since HPS luminaires have never been installed on it. Other locations have reported elimination of vibration-related failures after transitioning to solid-state products, e.g., see Seattle's MSSLC webinar presentation (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/streetlight-maintenance-webinar_4-14-2014.pdf), slide 37.

installed in a real-world environment.  Ultimately, it is not only possible that another factor will determine the luminaire end of life, but it is increasingly likely as $L_{70}$ projections extend into the distant future.

As the benefit of more field experience is gained, and the causes and impacts of the various other factors become better documented, the specification process for a given site must adapt itself accordingly.  One such example is the luminaire's suitability in meeting local conditions.  The relatively early installation on the I-35W bridge predated most of the field experience that has been gained since, possibly resulting in some otherwise preventable issues like the measured reductions in luminaire power use and corresponding output, or perhaps even the two documented power supply failures.  Without knowing the cause of these issues, it is impossible to say with certainty, for example, whether they may have been circumvented with a higher level of surge protection against local voltage transients.  As more field experience is gained, more-detailed specifications matched to the needs of a given site will help reduce or eliminate complications that negatively affect field performance.

Finally, the entire lighting community continues to learn from this and the other installations that have been implemented in the years since.  Readers of the report should recognize the limitations in applying long-term performance of early LED luminaires to their modern counterparts, due to continuous and ongoing advancements in the technology.

# Appendix A: Color Metrics

The color of a light source is often described using chromaticity coordinates, a basic principle of the International Commission on Illumination (CIE) system of colorimetry (CIE 2004), or a metric derived from them. The chromaticity coordinates of a source provide a numerical representation of the color of the light, but offer little indication of how the source will render specific object colors—changes to the chromaticity coordinates of a light source will lead to changes in the appearance of rendered objects.

Chromaticity diagrams are relative plots of hue and saturation—regardless of lightness, which is discarded as a third dimension. In essence, they are two-dimensional representations of a three-dimensional color space that is derived from color matching functions. Subsequently developed three-dimensional color spaces (CIELAB and CIELUV) are more appropriate for describing object colors and absolute appearance, whereas chromaticity diagrams are sufficient for describing the output of light sources.

As the CIE system of colorimetry has developed, the way in which chromaticity is plotted has been transformed to create a closer match to visual evaluations of color difference. That is, the plotted distance between two sets of color pairs with equal visual difference is intended to be the same. The three most commonly referenced chromaticity diagrams are the CIE 1931 (*x*, *y*), CIE 1960 Uniform Chromaticity Scale (UCS) (*u*, *v*), and CIE 1976 UCS (*u'*, *v'*), as shown in Figure A.1. While (*x, y*) coordinates are most frequently reported, color shift is most appropriately documented as the difference or change in (*u'*, *v'*) coordinates, written Δu'v', because the (*u'*, *v'*) chromaticity diagram is the most visually uniform. Nonetheless, no available chromaticity diagram perfectly represents human color perception, which itself varies from person to person. For many years, research has been ongoing to improve the methods used for documenting color difference, but as with many lighting concepts, older methods remain important for commerce.

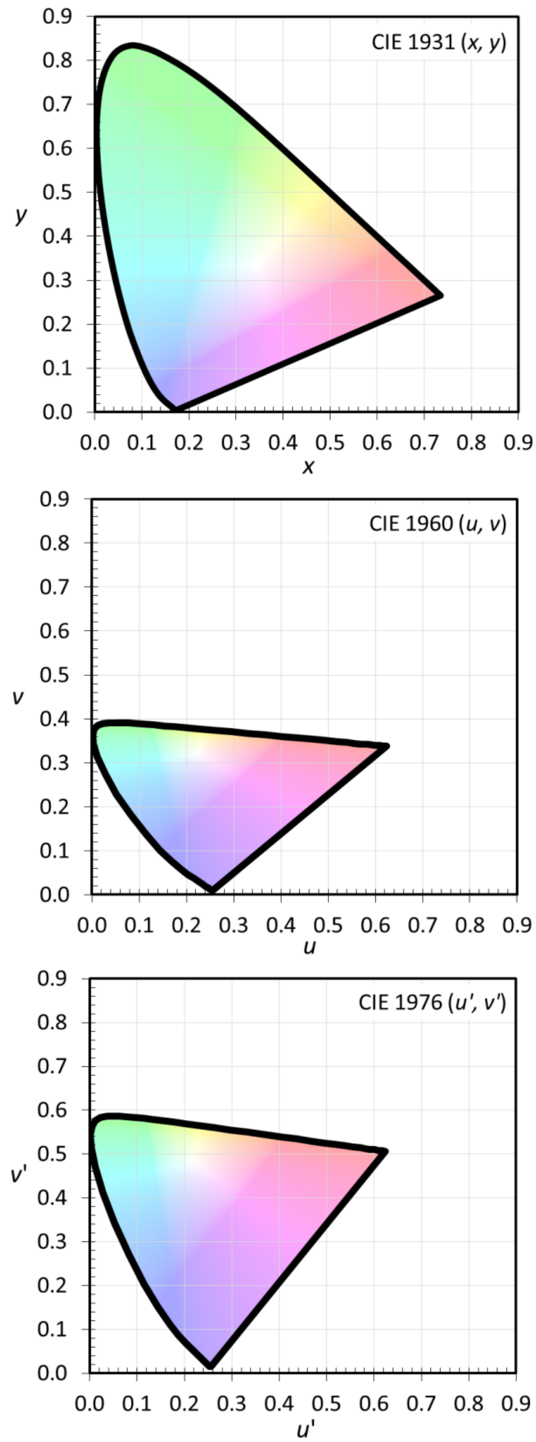


**Figure A.1. CIE 2° chromaticity diagrams. The 1960 and 1976 versions are linear transformations of the original 1931 version**. The colored backgrounds are shown for orientation only.

Correlated color temperature (CCT) and $D_{uv}$ are measures of light source color appearance derived from chromaticity coordinates. CCT and $D_{uv}$ values are calculated using the CIE

1960 ($u$, $v$) chromaticity diagram (see Figure A.2) due to the timing of the development of CCT, although the concepts are applicable in any chromaticity diagram. Either measure alone cannot accurately describe the exact color appearance of a source, but when used together the measures can be thought of as a two-dimensional coordinate system with (somewhat) visually meaningful axes. In rough terms, CCT describes a yellow-blue axis, and $D_{uv}$ describes a red-green axis. Nonetheless, reporting color shift as the change in one or both of these values is insufficient for characterizing the magnitude of the perceptual difference, especially since the ($u, v$) chromaticity diagram is not as perceptually uniform as its successor, ($u'$, $v'$).

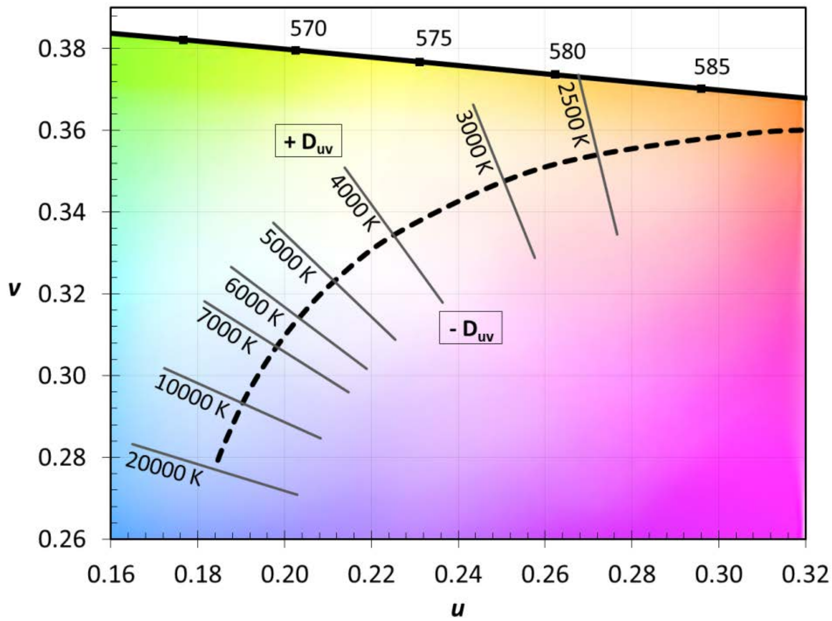


**Figure A.2. Close-up of the CIE 1960 UCS, showing lines of constant CCT, which were designed to be perpendicular to the black body locus in that particular diagram**. At a given CCT, a source with a positive value for $D_{uv}$ has a chromaticity that falls above the black body locus (appearing slightly greenish), whereas a source with a negative value for $D_{uv}$ has a chromaticity that falls below the black body locus (appearing slightly pinkish). The lines in this chart represent a $D_{uv}$ range of ±0.02, which is much greater than ANSI tolerances for white light.

Chromaticity "bins" demarcate areas on a chromaticity diagram, and are often used by manufacturers to sort products and convey nominal performance. Quadrangular bins for nominal CCT are defined by the American National Standards Institute (ANSI) Lighting Group and National Electrical Manufacturers Association (NEMA) document C78.377-2011 (ANSI 2011), as shown in Figure A.3. These quadrangles only roughly represent color appearance, and the variation within a bin is noticeable and unsatisfactory for almost all applications. That is, a source at one edge of the bin will appear very different from a source at the other end. Accordingly, manufacturers often establish much finer bins for sorting their products. Like with CCT and $D_{uv}$—as well as any color rendering metric, such as the color rendering index (CRI)—color bins have little relevance to color shift, other than being gross representations of light sources with different color temperatures.

## A.1 Color Difference Concepts

Color difference and the limits of human color tolerance are complex topics that receive considerable attention in research communities. Modern work in this field started with MacAdam ellipses, and although alternative concepts are now available, the principles are often related the original ellipses. The Δu'v' formula is currently recommended for describing color difference or color shift for light sources, and many variants of ΔE (e.g., $\Delta E^*_{ab}$, $\Delta E^*_{94}$, $\Delta E^*_{00}$, or $\Delta E^*_{CMC}$) are used to describe color difference of objects.

### Macadam Ellipses

In lighting literature, color difference is frequently described using MacAdam ellipses, although they are widely misunderstood. MacAdam ellipses were developed under strict experimental procedures, with the ellipse representing a standard deviation of color matching (SDCM) for a single, highly trained observer who made repeated matches (MacAdam 1942). These ellipses were derived throughout the 1931 (*x*, *y*) chromaticity diagram, and the conspicuous difference in size influenced subsequent chromaticity diagram revisions (see Figure A.4). As shown in Figure A.3, in the (*u'*, *v'*) chromaticity diagram, the ellipses are approximately circles, with a one-step ellipse having a radius of about 0.001—at least in the region around the black body locus (nominally white light).

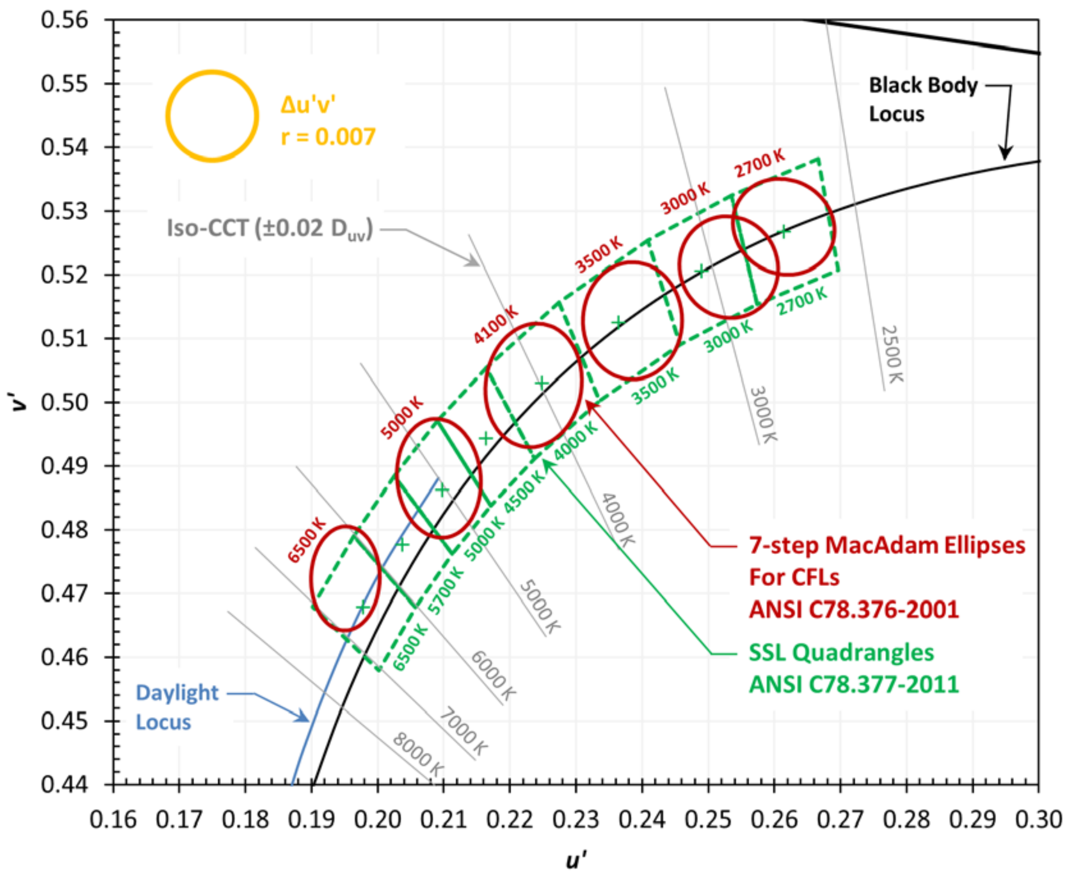


**Figure A.3. ANSI tolerances for compact fluorescent lamp (CFL) and solid state lighting (SSL) sources in the 1976 (*u'*, *v'*) chromaticity diagram**. For this diagram, MacAdam ellipses are approximately round near the black body locus, with one step equal to ~0.001.

MacAdam ellipses are often reported with a step size (e.g., seven-step), which is in reference to the multiple of the original SDCM ellipse. In this way, two pairs of chromaticity coordinates can be said to represent an x-step difference. Importantly, MacAdam's ellipses characterized the difference between the point at the center of the ellipse and a point at the edge of the ellipse, not two points at the edge. Thus, two points at opposite ends of a seven-step ellipse are correctly characterized as exhibiting a 14-step difference (see Figure A.3).

A common misinterpretation of MacAdam ellipses is that they are universally related to a *just-noticeable difference*. Under the conditions of MacAdam's experiment, a three-step difference was determined to be just noticeable (Wyszecki 1982), but that inference cannot be extrapolated to other environmental conditions that are drastically different from the small field of view under which the research was conducted. The noticeability of a difference in chromaticity depends on many factors; for example, two adjacent lamps aimed at a white wall might appear to be different colors, but when used in downlights at the opposite ends of a room, the difference might not be apparent.  Further, as is the case with all lighting metrics, chromaticity and color difference formulas are based on average observers, so individual perceptions may vary.

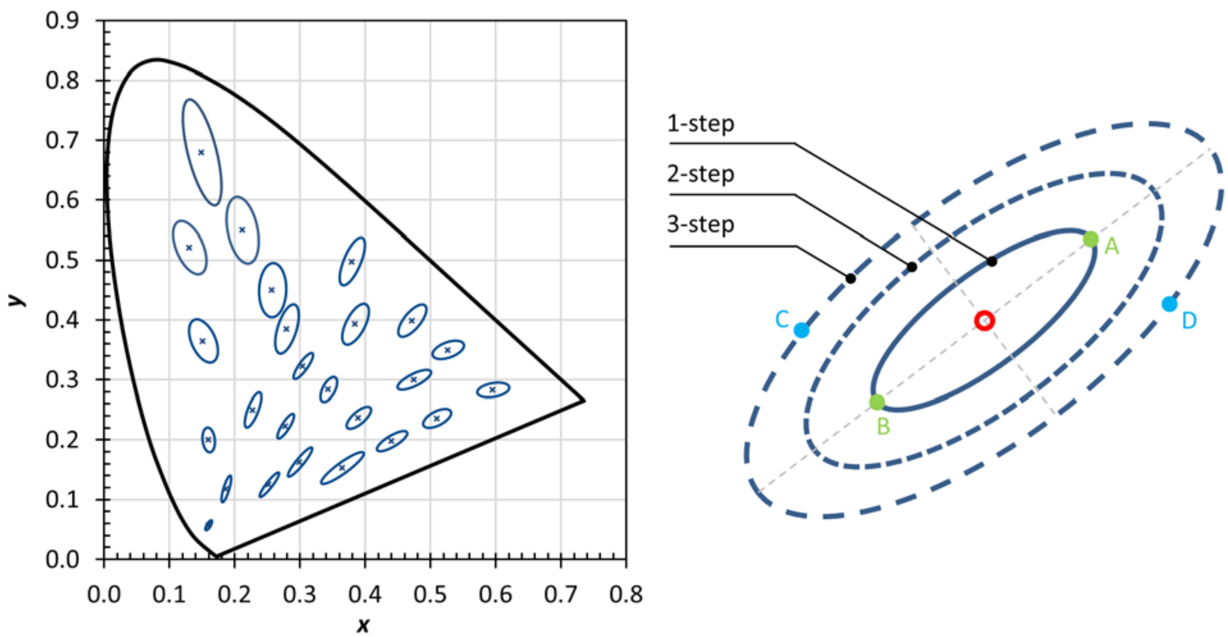


**Figure A.4. Left: 10-step MacAdam ellipses plotted in the 1931 (*x, y*) chromaticity diagram**. The different sizes of the ellipses illustrate the non-uniformity of the diagram. **Right: Enlarged image of a typical ellipse**. An x-step difference is always relative to the target chromaticity (center of the ellipse). Point A is one step different from the target, but two steps different from point B. In other words, all points encompassed by an ellipse (e.g., points C and D) are not within the specified step size tolerance of each other, but only with in the step size tolerance of the center point.

**Δu'v'**

Determining MacAdam ellipses requires several formulas, whereas Δu'v' is simply calculated as the Euclidian distance between a pair of chromaticity coordinates in the (*u'*, *v'*) chromaticity diagram. The relationship to MacAdam ellipses in the region around the black body locus—as previously described—allows for the approximation that a Δu'v' value of 0.001 is equivalent to a one-step difference. As with MacAdam ellipses, however, the noticeability of a difference depends on many factors, so there is no universal limit for what is considered an acceptable Δu'v'.

Given the mathematical simplicity of specifying color shift limits in terms of Δu'v' and the rather complex procedure for calculating a MacAdam ellipse—not to mention the many common misconceptions—both manufacturers and specifiers may benefit from using the Δu'v' terminology. One important fact to remember, however, is that neither MacAdam ellipses nor Δu'v' communicate anything about the direction of the color shift, which may or may not be important. Rather, Δu'v' quantifies the total color difference that may be the result of changes to either $D_{uv}$ or CCT (or any other two-dimensional representation of chromaticity), as shown in Figure A.5.

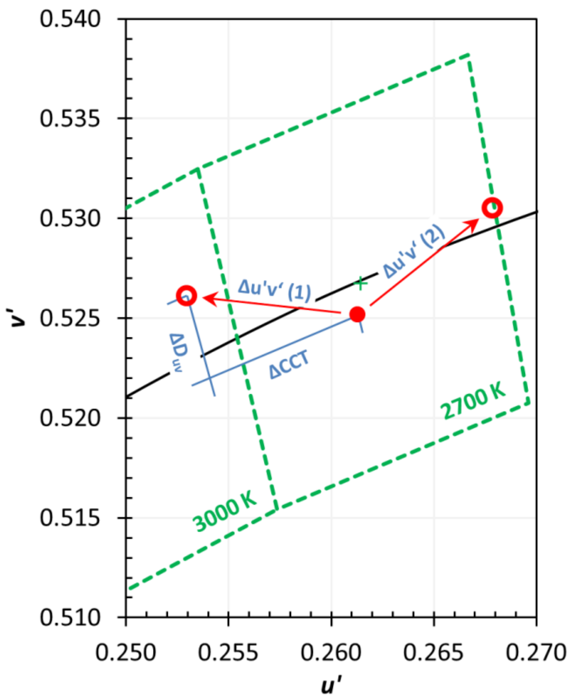


**Figure A.5. Close up of the 1976 (*u'*, *v'*) chromaticity diagram illustrating the difference between Δu'v', $\Delta D_{uv}$, and ΔCCT.** $\Delta D_{uv}$ and ΔCCT are insufficient for characterizing color difference. Only Δu'v' describes the total color difference that might be observed, although it does not describe the direction of the shift. As such, Δu'v' (1) and Δu'v' (2) would have the same value, despite shifting in different directions.

## A.2 Existing Standards for Measuring and Documenting Color Shift

Illuminating Engineering Society (IES) LM-80-08, *Measuring Lumen Maintenance of LED Light Sources* (IES 2008b), prescribes an approved method for long-term measurement of LED packages—but not complete LED lamps or luminaires (that document is in progress). While it primarily targets lumen maintenance, LM-80-08 requires that chromaticity shift be measured (and subsequently reported) over the course of the test procedure, which must last a minimum of 6000 hours. There are no specified acceptable limits for color shift, and there is no method for projecting future color shift as there is for lumen depreciation (IES 2011b). One important note with LM-80-08 is that the ambient air temperature and solder point temperature of the LED package are at equilibrium, which is unlikely to mimic real-world operating conditions.

The ENERGY STAR® program does mandate that Δu'v' at 6000 hours of operation not exceed 0.007 (EPA 2012, 2013). This is perhaps the only industry-wide criterion for color shift. It is a reasonable starting point, but may not be strict enough to ensure very high-quality lighting, especially since the lifetimes of LED products routinely far exceed 6000 hours.

Although more critical for color consistency than color stability, it is important to note that the quadrangles defined by ANSI/NEMA offer very large tolerances for nominal CCTs. For example, the 3500K bin has corner points with a Δu'v' of 0.0266, or nearly four times the ENERGY STAR tolerance for color shift. Needless to say, two lamps with the same nominal CCT designation can appear vastly different, and the difference can be exacerbated by color shift over time. Many LED chip manufacturers can offer much finer bins than the nominal CCT tolerances established in C78.377-2011.

## A.3 References

[ANSI] American National Standards Institute. 2011. ANSI_ANSLG C78.377-2011. *American National Standard for electric lamps: specifications for the chromaticity of solid state lighting products*. Rosslyn, VA: National Electrical Manufacturers Association.

[CIE] International Commission on Illumination. 2004. CIE 15-2004. *Colorimetry*. 3rd Edition. 72 p.

[IES] Illuminating Engineering Society. 2008. LM-79-08 *Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products.* 16 p.

[IES] Illuminating Engineering Society. 2008. LM-80-08 *IESNA approved method: measuring lumen maintenance of LED light sources.* 4 p.

[IES] Illuminating Engineering Society. 2011a. *The Lighting Handbook, Tenth Edition: Reference and Application,* pp 10.28-10.29.

[IES] Illuminating Engineering Society. 2011b. TM-21-11 *Projecting long term lumen maintenance of LED light sources.* 25 p.

[EPA] Environmental Protection Agency ENERGY STAR Program. 2013. *ENERGY STAR program requirements, product specification for lamps (light bulbs); Eligibility criteria version 1.0.* 25 p.

[EPA] Environmental Protection Agency ENERGY STAR Program. 2012. *ENERGY STAR program requirements for luminaires; Eligibility criteria version 1.1.* 36 p. http://www.energystar.gov/ia/partners/product_specs/program_reqs/Final_Luminaires_Program_Requirements.pdf

MacAdam, DL. 1942. *Visual sensitivities to color differences in daylight.* Journal of the Optical Society of America 32(5):247–274.

[PNNL] Pacific Northwest National Laboratory. 2011. *Long-term testing of solid-state lighting, 2011*. DOE CALiPER Program, PNNL-20889. ML Paget and AH Qiao, November 2011.

Wyszecki G, Stiles WS. 1982. *Color science, concepts and methods: quantitative data and formulae.* 2nd ed. New York: Wiley; 968 p.

# Appendix B: Mobile Monitoring System Data

## B.1 Summary of Readings

| Southbound | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 16-Apr-09 | 22-Jun-09 | 7-Oct-09 | 14-Apr-10 | 9-Nov-10 | 2-Jun-11 | 10-Oct-11 |
| Maximum | 34.16 | 32.94 | 32.53 | 30.84 | 32.36 | 28.42 | 26.52 |
| Minimum | 2.04 | 1.74 | 2.40 | 2.27 | 2.20 | 2.95 | 2.03 |
| Average | 11.27 | 10.34 | 11.62 | 10.83 | 10.84 | 10.68 | 9.69 |
| Avg:Min | 5.52 | 5.94 | 4.84 | 4.77 | 4.93 | 3.63 | 4.77 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 5.52:1.* | | | | | | | |

| Northbound | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 16-Apr-09 | 22-Jun-09 | 7-Oct-09 | 14-Apr-10 | 9-Nov-10 | 2-Jun-11 | 10-Oct-11 |
| Maximum | 34.15 | 32.07 | 32.28 | 30.37 | 29.98 | 30.42 | 28.44 |
| Minimum | 1.92 | 1.38 | 2.38 | 2.06 | 1.72 | 2.54 | 2.28 |
| Average | 11.31 | 10.13 | 11.73 | 10.45 | 10.39 | 10.38 | 9.59 |
| Avg:Min | 5.89 | 7.34 | 4.93 | 5.07 | 6.04 | 4.09 | 4.20 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 5.89:1.* | | | | | | | |

## B.2 Southbound Lanes

| 4-16-09 Southbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | 1st Lane SB | 2nd Lane | 3rd Lane | 4th Lane | 5th Lane | Entire Section |
| Average | 16.23 | 13.40 | 11.17 | 8.91 | 6.63 | 11.27 |
| Maximum | 34.16 | 26.81 | 28.50 | 30.76 | 33.77 | 34.16 |
| Minimum | 2.75 | 2.58 | 3.56 | 2.36 | 2.04 | 2.04 |
| Avg:Min | 5.90 | 5.19 | 3.14 | 3.78 | 3.25 | 5.52 |
| Max:Min | 12.42 | 10.39 | 8.01 | 13.03 | 16.55 | 16.75 |
| STDEV | 7.79 | 5.45 | 5.18 | 5.57 | 5.72 | 6.89 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 12.42:1.* | | | | | | |

| 6-22-09 Southbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | 1st Lane SB | 2nd Lane | 3rd Lane | 4th Lane | 5th Lane | Entire Section |
| Average | 14.66 | 12.35 | 10.15 | 8.44 | 6.11 | 10.34 |
| Maximum | 32.94 | 23.29 | 28.47 | 28.86 | 30.91 | 32.94 |
| Minimum | 2.12 | 2.42 | 2.94 | 2.28 | 1.74 | 1.74 |
| Avg:Min | 6.91 | 5.10 | 3.45 | 3.70 | 3.51 | 5.94 |
| Max:Min | 15.54 | 9.62 | 9.68 | 12.66 | 17.76 | 18.93 |
| STDEV | 7.08 | 5.17 | 5.08 | 5.44 | 5.24 | 6.38 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 15.54:1.* | | | | | | |

| 10-07-09 Southbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | 1st Lane SB | 2nd Lane | 3rd Lane | 4th Lane | 5th Lane | Entire Section |
| Average | 16.18 | 13.95 | 11.42 | 9.61 | 6.97 | 11.62 |
| Maximum | 29.31 | 23.58 | 28.97 | 28.48 | 32.53 | 32.53 |
| Minimum | 2.94 | 3.60 | 3.61 | 3.04 | 2.40 | 2.40 |
| Avg:Min | 5.50 | 3.87 | 3.16 | 3.16 | 2.90 | 4.84 |
| Max:Min | 9.96 | 6.55 | 8.02 | 9.37 | 13.54 | 13.54 |
| STDEV | 7.69 | 5.79 | 5.02 | 5.73 | 5.76 | 6.84 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 9.96:1.* | | | | | | |

| 04-14-10 Southbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | 1st Lane SB | 2nd Lane | 3rd Lane | 4th Lane | 5th Lane | Entire Section |
| Average | 16.28 | 13.01 | 10.54 | 8.24 | 6.10 | 10.83 |
| Maximum | 30.25 | 21.52 | 26.07 | 26.55 | 30.84 | 30.84 |
| Minimum | 4.78 | 4.52 | 3.71 | 3.01 | 2.27 | 2.27 |
| Avg:Min | 3.40 | 2.88 | 2.84 | 2.74 | 2.69 | 4.77 |
| Max:Min | 6.32 | 4.76 | 7.03 | 8.81 | 13.59 | 13.59 |
| STDEV | 7.33 | 5.32 | 4.46 | 4.60 | 4.92 | 6.43 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 6.32:1.* | | | | | | |

| 11-09-10 Southbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | 1st Lane SB | 2nd Lane | 3rd Lane | 4th Lane | 5th Lane | Entire Section |
| Average | 16.61 | 13.14 | 10.11 | 8.32 | 5.99 | 10.84 |
| Maximum | 32.36 | 22.38 | 24.39 | 25.79 | 30.67 | 32.36 |
| Minimum | 5.13 | 4.43 | 3.38 | 2.95 | 2.20 | 2.20 |
| Avg:Min | 3.24 | 2.97 | 2.99 | 2.82 | 2.72 | 4.93 |
| Max:Min | 6.31 | 5.05 | 7.22 | 8.73 | 13.94 | 14.71 |
| STDEV | 7.49 | 5.37 | 4.46 | 4.98 | 5.05 | 6.72 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 6.31:1.* | | | | | | |

| 06-02-11 Southbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | 1st Lane SB | 2nd Lane | 3rd Lane | 4th Lane | 5th Lane | Entire Section |
| Average | 16.34 | 13.44 | 10.31 | 7.87 | 5.41 | 10.68 |
| Maximum | 28.42 | 22.36 | 24.59 | 24.59 | 26.70 | 28.42 |
| Minimum | 6.20 | 5.14 | 3.97 | 3.54 | 2.95 | 2.95 |
| Avg:Min | 2.64 | 2.61 | 2.60 | 2.22 | 1.84 | 3.63 |
| Max:Min | 4.59 | 4.35 | 6.20 | 6.95 | 9.07 | 9.65 |
| STDEV | 6.74 | 5.23 | 4.31 | 4.12 | 3.01 | 6.17 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 4.59:1.* | | | | | | |

| 10-10-11 Southbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | 1st Lane SB | 2nd Lane | 3rd Lane | 4th Lane | 5th Lane | Entire Section |
| Average | 15.53 | 12.18 | 9.11 | 6.84 | 4.77 | 9.69 |
| Maximum | 26.52 | 20.45 | 25.20 | 25.63 | 26.49 | 26.52 |
| Minimum | 5.34 | 4.09 | 3.07 | 2.62 | 2.03 | 2.03 |
| Avg:Min | 2.91 | 2.98 | 2.96 | 2.61 | 2.35 | 4.77 |
| Max:Min | 4.96 | 5.00 | 8.20 | 9.77 | 13.04 | 13.05 |
| STDEV | 6.47 | 5.22 | 4.47 | 4.06 | 3.86 | 5.85 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 4.96:1.* | | | | | | |

## B.3 Northbound Lanes

| 4-16-09 Northbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | 1st Lane NB | 2nd Lane | 3rd Lane | 4th Lane | 5th Lane | Entire Section |
| Average | 18.28 | 14.37 | 10.03 | 8.12 | 5.77 | 11.31 |
| Maximum | 34.15 | 25.55 | 25.20 | 25.32 | 34.04 | 34.15 |
| Minimum | 5.50 | 4.72 | 3.18 | 2.75 | 1.92 | 1.92 |
| Avg:Min | 3.32 | 3.04 | 3.15 | 2.95 | 3.01 | 5.89 |
| Max:Min | 6.21 | 5.41 | 7.92 | 9.21 | 17.73 | 17.79 |
| STDEV | 7.88 | 5.74 | 4.38 | 4.36 | 5.24 | 7.18 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 6.21:1.* | | | | | | |

| 6-22-09 Northbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | 1st Lane NB | 2nd Lane | 3rd Lane | 4th Lane | 5th Lane | Entire Section |
| Average | 16.17 | 12.68 | 9.51 | 7.19 | 5.10 | 10.13 |
| Maximum | 31.00 | 25.05 | 20.70 | 26.77 | 32.07 | 32.07 |
| Minimum | 4.87 | 4.21 | 2.96 | 2.09 | 1.38 | 1.38 |
| Avg:Min | 3.32 | 3.01 | 3.21 | 3.44 | 3.70 | 7.34 |
| Max:Min | 6.37 | 5.95 | 6.99 | 12.81 | 23.24 | 23.24 |
| STDEV | 7.35 | 5.40 | 4.28 | 4.29 | 5.05 | 6.75 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 6.37:1.* | | | | | | |

| 10-07-09 Northbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | 1st Lane NB | 2nd Lane | 3rd Lane | 4th Lane | 5th Lane | Entire Section |
| Average | 18.19 | 15.09 | 11.05 | 8.10 | 6.23 | 11.73 |
| Maximum | 30.62 | 25.77 | 21.42 | 25.44 | 32.28 | 32.28 |
| Minimum | 5.86 | 5.06 | 3.77 | 2.90 | 2.38 | 2.38 |
| Avg:Min | 3.10 | 2.99 | 2.93 | 2.80 | 2.62 | 4.93 |
| Max:Min | 5.22 | 5.10 | 5.68 | 8.78 | 13.56 | 13.56 |
| STDEV | 7.51 | 5.95 | 4.44 | 4.37 | 5.26 | 7.13 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 5.22:1.* | | | | | | |

| 04-14-10 Northbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | **1st Lane NB** | **2nd Lane** | **3rd Lane** | **4th Lane** | **5th Lane** | **Entire Section** |
| Average | 16.43 | 13.10 | 10.00 | 7.37 | 5.38 | 10.45 |
| Maximum | 29.41 | 25.12 | 19.25 | 25.35 | 30.37 | 30.37 |
| Minimum | 4.76 | 3.80 | 3.30 | 2.47 | 2.06 | 2.06 |
| Avg:Min | 3.45 | 3.44 | 3.03 | 2.99 | 2.61 | 5.07 |
| Max:Min | 6.18 | 6.61 | 5.83 | 10.28 | 14.74 | 14.74 |
| STDEV | 7.64 | 5.95 | 4.27 | 4.27 | 4.59 | 6.72 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 6.18:1.* | | | | | | |

| 11-09-10 Northbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | **1st Lane NB** | **2nd Lane** | **3rd Lane** | **4th Lane** | **5th Lane** | **Entire Section** |
| Average | 16.53 | 13.03 | 9.57 | 7.41 | 5.41 | 10.39 |
| Maximum | 29.62 | 24.60 | 18.11 | 22.00 | 29.98 | 29.98 |
| Minimum | 5.14 | 3.94 | 3.05 | 2.47 | 1.72 | 1.72 |
| Avg:Min | 3.22 | 3.31 | 3.13 | 3.00 | 3.15 | 6.04 |
| Max:Min | 5.76 | 6.25 | 5.93 | 8.91 | 17.43 | 17.43 |
| STDEV | 7.57 | 5.87 | 4.15 | 4.22 | 4.73 | 6.68 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 5.76:1.* | | | | | | |

| 06-02-11 Northbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | **1st Lane NB** | **2nd Lane** | **3rd Lane** | **4th Lane** | **5th Lane** | **Entire Section** |
| Average | 16.87 | 13.10 | 9.97 | 7.18 | 4.78 | 10.38 |
| Maximum | 30.42 | 23.81 | 18.21 | 19.13 | 11.65 | 30.42 |
| Minimum | 5.74 | 4.62 | 3.86 | 2.97 | 2.54 | 2.54 |
| Avg:Min | 2.94 | 2.84 | 2.59 | 2.42 | 1.88 | 4.09 |
| Max:Min | 5.30 | 5.16 | 4.72 | 6.44 | 4.59 | 11.98 |
| STDEV | 7.39 | 5.48 | 4.05 | 3.12 | 1.64 | 6.34 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 5.30:1.* | | | | | | |

| 10-10-11 Northbound Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | **1st Lane NB** | **2nd Lane** | **3rd Lane** | **4th Lane** | **5th Lane** | **Entire Section** |
| Average | 15.80 | 12.81 | 8.94 | 6.13 | 4.25 | 9.59 |
| Maximum | 28.44 | 23.33 | 15.36 | 11.93 | 7.24 | 28.44 |
| Minimum | 5.20 | 3.97 | 3.49 | 2.35 | 2.28 | 2.28 |
| Avg:Min | 3.04 | 3.23 | 2.56 | 2.61 | 1.86 | 4.20 |
| Max:Min | 5.46 | 5.88 | 4.40 | 5.09 | 3.17 | 12.47 |
| STDEV | 7.12 | 5.34 | 3.67 | 2.67 | 1.40 | 6.06 |
| *Illuminance in lux. Uniformity relative to 1, e.g., 5.46:1.* | | | | | | |