DOCKETED

Docket Number:	15-AAER-06
Project Title:	Small Diameter Directional LED Lamps and General Purpose LED Lamps
TN #:	206178
Document Title:	CALiPER Report on the Photoelectric Performance of LED MR16 Lamps
Description:	Photoelectric Performance of LED MR16 Lamps
Filer:	Harinder Singh
Organization:	U.S. Department of Energy, Energy Efficiency & Renewable Energy
Submitter Role:	Public Agency
Submission Date:	9/23/2015 12:43:45 PM
Docketed Date:	9/23/2015

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

CALiPER

Report 22.1:

Photoelectric Performance of LED MR16 Lamps

August 2015

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

PNNL-24627

DISCLAIMER

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

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <http://www.ntis.gov/about/form.aspx>
Online ordering: http://www.ntis.gov

This document was printed on recycled paper.
(8/2010)

1 Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER relies on standardized photometric testing (following the Illuminating Engineering Society of North America [IES] approved method LM-79-08[1]) conducted by accredited, independent laboratories.[2] Results from CALiPER testing are available to the public via detailed reports for each product or through summary reports, which assemble data from several product tests and provide comparative analyses.[3] Increasingly, CALiPER investigations also rely on new test procedures that are not industry standards; these experiments provide data that is essential for understanding the most current issues facing the SSL industry.

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Instead, CALiPER focuses on specific groups of products that are relevant to important issues being investigated. The products are selected with the intent of capturing the current state of the market at a given point in time, representing a broad range of performance characteristics. However, the selection does not represent a statistical sample of all available products in the identified group. All selected products are shown as currently available on the manufacturer's website at the time of purchase.

CALiPER purchases products through standard distribution channels, acting in a manner similar to that of a typical specifier. CALiPER does not accept or purchase samples directly from manufacturers, to ensure that all tested products are representative of a typical manufacturing run and not hand-picked for superior performance. CALiPER cannot control for the age of products in the distribution system, nor account for any differences in products that carry the same model number.

Selecting, purchasing, documenting, and testing products can take considerable time. Some products described in CALiPER reports may no longer be sold or may have been updated since the time of purchase. However, each CALiPER dataset represents a snapshot of product performance at a given time, with comparisons only between products that were available at the same time. Further, CALiPER reports seek to investigate market trends and performance relative to benchmarks, rather than to serve as a measure of the suitability of any specific lamp model. Thus, the results should not be taken as a verdict on any product line or manufacturer. Especially given the rapid development cycle for LED products, specifiers and purchasers should always seek current information from manufacturers when evaluating such products.

To provide further context, CALiPER test results may be compared to data from LED Lighting Facts,[4] ENERGY STAR® performance criteria,[5] technical requirements for the DesignLights Consortium® (DLC) Qualified Products

---

1. IES LM-79-08, *Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*, covers LED-based SSL products with control electronics and heat sinks incorporated. For more information, visit http://www.ies.org/.
2. CALiPER only uses independent testing laboratories with LM-79-08 accreditation that includes proficiency testing, which is available through the National Voluntary Laboratory Accreditation Program (NVLAP).
3. CALiPER summary reports are available at http://energy.gov/eere/ssl/caliper-application-reports. Detailed test reports for individual products can be obtained from http://www1.eere.energy.gov/buildings/ssl/caliper/default.aspx.
4. LED Lighting Facts® is a program of the U.S. Department of Energy that showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The DOE LED Lighting Facts program is separate from the Lighting Facts label required by the Federal Trade Commission (FTC). For more information, see http://www.lightingfacts.com.
5. ENERGY STAR is a federal program promoting energy efficiency. For more information, visit http://www.energystar.gov.

List (QPL),[6] or other established benchmarks. CALiPER also tries to purchase conventional (i.e., non-SSL) products for comparison, but because the primary focus is SSL, the program can only test a limited number.

It is important for buyers and specifiers to reduce risk by learning how to compare products and by considering every potential SSL purchase carefully. CALiPER test results are a valuable resource, providing photometric data for anonymously purchased products as well as objective analysis and comparative insights. However, photometric testing alone is not enough to fully characterize a product—quality, reliability, controllability, physical attributes, warranty, compatibility, and many other facets should also be considered carefully. In the end, the best product is the one that best meets the needs of the specific application.

For more information on the DOE SSL program, please visit http://www.ssl.energy.gov.

[6] The DesignLights Consortium Qualified Products List is used by member utilities and energy-efficiency programs to screen SSL products for rebate program eligibility. For more information, visit http://www.designlights.org/.

2 Report Summary

This report is a follow-up to CALiPER *Application Summary Report 22*,[7] which investigated the photometric performance of 27 LED MR16 lamps compared to benchmark halogen lamps. Among other things, the initial report, published in 2014, found that:

- The LED MR16 lamps demonstrated systemic inaccuracy in equivalency claims (comparisons to a specific-wattage halogen MR16 lamp).
- LED MR16 lamps producing up to 600 lm were widely available. This is a considerable improvement over CALiPER testing from 2012 and earlier.
- All of the Series 22 LED products offered some efficacy advantage versus the halogen benchmarks, but the range in efficacy was substantial (38 to 90 lm/W).
- As with most types of integral LED lamps, a majority of the currently available MR16 lamps identified by CALiPER had a CRI in the low 80s. Lamps with a nominal CCT of 3000 K were prevalent. CALiPER also identified and purchased four LED MR16 lamps with CRIs in the 90s.
- The power factors of the Series 22 lamps were essentially bifurcated, with one group having a power factor around 0.70 and another group having a power factor of around 0.90. All measurements in this report are for a single lamp on a laboratory AC power supply, except for 13RT-41, which was tested on a DC power supply.

For the initial report, all testing was completed using laboratory power supplies, with all but one product tested at 12 V AC. This report examined the photoelectric performance of the same set of lamps, using commercially available transformers and dimmers as well as laboratory power supplies providing either AC or DC. The intent of the investigation was to explore several issues related to the testing and use of MR16 lamps in lighting systems. A simple goal was to examine whether characterization using laboratory power supplies instead of commercial transformers can result in misleading flicker and power quality performance characterization. More generally, the goal was to examine the range of performance that is possible for a given lamp model, based on the system to which it is connected.

This is the third CALiPER report to focus on photoelectric performance—the previous two covered PAR38 lamps[8] and retail-available A lamps.[9] This is the first CALiPER report, however, to focus on the system-level performance of low-voltage lighting, including a transformer and dimmer, using five test scenarios:

1. **Electronic/ELV** – Operation of each lamp model with an electronic transformer selected from the lamp's compatibility list (if available), and an electronic low-voltage (ELV) dimmer. The goal was to specify a system where the lamp, transformer, and dimmer were all listed as compatible, but limited available information often made this difficult.
2. **Electronic/INC** – Operation of each lamp model with an electronic transformer and a typical incandescent dimmer. The transformer was listed as compatible with the dimmer.
3. **Magnetic/MLV** – Operation of each lamp model with a typical magnetic transformer and a magnetic low-voltage (MLV) dimmer. The transformer and dimmer were considered compatible.
4. **AC Supply** – Operation of each lamp model using a laboratory power supply delivering RMS (root-mean-square) 12 V AC.
5. **DC Supply** – Operation of each lamp model using a laboratory power supply delivering 12 V DC.

[7] Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_22_summary.pdf
[8] Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_20-2_par38.pdf
[9] Available at: http://energy.gov/eere/ssl/downloads/caliper-retail-lamps-study-31-dimming-flicker-and-power-quality-characteristics

As with previous CALiPER photoelectric testing, the results from this investigation demonstrated substantial variation in the performance of LED MR16 lamps, both within one test scenario and across multiple test scenarios. The data also demonstrated the value of compatibility lists provided by manufacturers, the difficulty of retrofitting LED lamps into an existing system intended for use with halogen lamps, the relative stability of systems including a magnetic transformer (but potentially reduced performance in some aspects, such as system efficacy), and the very real possibility of generating misleading performance data when testing is performed with laboratory power supplies.

3 Introduction

As documented in *CALiPER Application Summary Report 22: LED MR16 Lamps* and the fact sheet *LED MR16 Lamps*,[10] the MR16 form factor and system requirements pose additional challenges for LEDs, compared to line-voltage products such as A lamps or PAR lamps. Besides the small size, which poses unique driver design challenges and tradeoffs, one of the most important considerations for performance—both in testing and when installed—is the fact that pin-based MR16 lamps operate at 12 V, which requires that a transformer be included in the system. Add in a dimmer, and there are three electronic devices that must all work together. This can lead to unwieldy compatibility tables, and often results in complications before, during, or after installation.

Whereas *Application Summary Report 22* examined the performance of the Series 22 MR16 lamps using laboratory power supplies set to deliver the appropriate voltage, the test protocol for this supplemental investigation included photoelectric testing of each lamp model under five different scenarios:

1. **Electronic/ELV** – Operation of each lamp model with an electronic transformer selected from the lamp's compatibility list (if available), and an electronic low-voltage (ELV) dimmer. The goal was to specify a system where the lamp, transformer, and dimmer were all listed as compatible, but limited available information often made this difficult.
2. **Electronic/INC** – Operation of each lamp model with an electronic transformer and a typical incandescent dimmer. The transformer was listed as compatible with the dimmer.
3. **Magnetic/MLV** – Operation of each lamp model with a typical magnetic transformer and a magnetic low-voltage (MLV) dimmer. The transformer and dimmer were considered compatible.
4. **AC Supply** – Operation of each lamp model using a laboratory power supply delivering RMS 12 V AC.
5. **DC Supply** – Operation of each lamp model using a laboratory power supply delivering 12 V DC.

Each scenario is discussed further in the following section. For scenarios one through three, the performance of each system was measured with a dimmer set to one of 11 test levels covering the dimming range, as well as when it was operated by a switch. For scenarios four and five, only a switch was used.

The intent of the investigation was to explore several issues related to the testing and use of MR16 lamps in complete systems. A simple goal was to examine whether characterization using laboratory power supplies instead of commercial transformers can result in misleading flicker and power quality performance characterization. More generally, the goal was to examine the range of performance that is possible for a given lamp model, based on the system to which it is connected. While system-level effects are a known phenomenon, to date there has been limited characterization of the impact of real-world system variations on energy performance. Finally, this investigation facilitates comparing the dimming, flicker, and power quality performance of MR16 lamps to other lamp types (PAR38,[11] A19[12]) that have undergone CALiPER photoelectric testing; in this case, the hypothesis was that the small-form-factor MR16 lamps would fare worse. As is standard practice for CALiPER, the goal was not to determine the best-performing products. Instead, the test results are compared against established thresholds and benchmark conventional lamps, with additional analysis focused on identifying variation and trends in performance.

[10] Available at: http://energy.gov/eere/ssl/technology-fact-sheets
[11] Available at: http://energy.gov/eere/ssl/led-par38-lamps
[12] Available at: http://energy.gov/eere/ssl/retail-replacement-lamps

4 Methods

The dimming, flicker, and power quality performance of a low-voltage LED lamp controlled by a phase-cut dimmer can be dependent on the characteristics of other components on the same electrical circuit, including other lamps or luminaires, the dimmer, and transformer. Most LED lamps are only compatible (i.e., only perform up to their full capability) with certain combinations of equipment. While this report is not exhaustive in examining potential combinations of products, the select number of unique systems does provide some indication of the possible variation in performance. Each scenario, previously introduced, is described in detail below. For more background information on dimming, flicker, and power quality, see Appendix A.

It is important to note that some of the dimmers and transformers that were used were not on the recommended list for every lamp—if the lamp manufacturer even provided such a list. Operation of any of the lamp models on a different dimmer and/or transformer may yield different results. Thus, the behavior shown in the data may not be representative of the performance of a given lamp operated by a different dimmer and transformer. While the measured performance of any given lamp could be misleading, the focus of this study was on the broader performance of the group, and on comparing and contrasting different types of equipment. The results are indicative of the general flicker, power quality, and dimming performance of LED MR16 lamps purchased in 2014—and, likely, of many low-voltage lamps that are currently available.

All of the LED lamps and three of the benchmark halogen lamps included in CALiPER *Application Summary Report 22* were included in this investigation. In total, 27 LED lamps and three benchmark halogen lamps were evaluated under all five scenarios described previously;[13] the lamp models are identified in Appendix B. In most cases, the test circuit for each lamp model was comprised of five lamp samples, in order to load the transformer to some minimum level; exceptions are noted below and in Appendix C. Regardless of how many lamp samples were connected to the lighting circuit, in all cases performance measurements (e.g., lamp power, flicker) were made for only one of the connected lamps. All except three products explicitly stated that they were dimmable; the remaining products (14-02, 14-22, and 14-29) provided no information about dimmability.

Scenario One

The focus of scenario one was to operate lamps with a recommended compatible electronic transformer and dimmer, if possible. Notably, only 12 of the 25 LED MR16 lamps tested for this scenario (and 14 of 27 total, including the two that were not tested for scenario one) provided transformer compatibility information (see Appendix C), and far fewer provided compatibility recommendations for explicit combinations of a lamp, a dimmer, and a transformer. In order to determine which transformer(s) should be used for testing, first a composite of the compatible transformer lists was created. This list was then pared down to a minimal set that still contained at least two transformers on the compatibility list for each lamp (if applicable):

- X1: B+L CV90001 (CV-10/75-12)
- X2: HATCH RS12-60M-LED
- X3: Hatch RS12-80M
- X4: Lightech LET60
- X5: Lightech LET75
- X6: Keystone KTET-75-1SCP-DIM-RJS

[13] Only 25 LED lamps were tested for scenario one, because the samples for two model types became unavailable after mishandling.

One transformer from this pared-down set was randomly chosen for testing with each lamp model. For lamps that provided compatibility information, one of the two (or more) compatible transformers on the list was chosen. If no compatibility information was provided, a transformer was randomly selected from the full set of six.

Only 8 of the 27 LED MR16 lamps included in the study provided dimmer compatibility information of any kind. All but two of the lamp models were evaluated under the control of a Lutron Diva DVELV-300P ELV dimmer, which was recommended for use with six of the eight lamps. The compatible-dimmer lists for the other two lamp models (14-13 and 14-22) did not contain the DVELV-300P. However, they both recommended use of the Lutron NovaT NTELV-600 ELV dimmer, which was therefore substituted. The complete matrix of components for each test scenario is provided in Appendix C.

Scenario Two

The focus of scenario two was to operate lamps with a typical incandescent dimmer that might be used to control halogen MR16s, and an electronic transformer compatible with that dimmer. Transformer X1 was used in this scenario to evaluate all lamp models, because it claimed compatibility with standard incandescent dimmers, including the Leviton 80800. This combination of equipment is representative of many existing installations that might be candidates for retrofit.

For this scenario, the intent was not to focus on compatibility; as such only four of the LED lamp models specified compatibility with this transformer. Also noteworthy is that three lamp models (14-05, 14-09, and 14-22)—including one of the four that provided transformer-compatibility information—were tested on transformer X1 for both scenario one and scenario two, in accordance with the random assignment procedure. These three products thus allow for anecdotal observations on the role of the dimmer in an otherwise identical system.

Scenario Three

The focus of scenario three was to operate lamps with a magnetic low-voltage (MLV) dimmer and a magnetic transformer. One magnetic transformer (X7, Halo H1499TAT) was used for all lamp models. All lamp models were controlled with a Lutron DVLV-600P MLV dimmer, which is appropriate for the specified transformer.

Scenarios Four and Five

The focus of scenarios four and five was to power the lamps as is typical when products undergo standard testing according to IES LM-79-08 at a photometry lab. The low-voltage AC and DC power for these scenarios was provided by a Chroma Model 61061. Lamps were only evaluated as controlled by a switch, for two different reasons. First, IES LM-79-08 does not specify how to operate lamps at reduced RMS voltages. Second, the electrical interaction between a phase-cut dimmer and a laboratory power supply can be significantly different than between a phase-cut dimmer and an electronic or magnetic transformer, and therefore test results may not be representative of real-world performance.

For scenario four—where lamps were supplied with RMS 12V AC—five samples were connected to the lighting circuit for all except the halogen lamps, in which case only two lamps were connected, due to power-supply-current limitations. For the fifth scenario— where lamps were supplied with 12V DC—only one lamp was connected for 11 of the lamp models, including all three benchmarks, due to power-supply-current limitations. The exact configurations are identified in Appendix C. One product (14-28) did not operate when supplied with 12V DC.

Test Apparatus and Equipment

A semi-automated test setup developed by Pacific Northwest National Laboratory was used to evaluate the dimming, flicker, and power quality performance of the lamps. Each connected lamp—typically five for each model—were installed in a Cooper Lighting Halo H1499TAT downlight, which was used for the purpose of providing a socket and interface to the measurement chamber.

The measurement system consisted of a light-impermeable box, a photosensor (UDT Model 211), a transimpedance amplifier (UDT Tramp) with a 5 V output and variable gain, a digital oscilloscope (Tektronix DPO2014), and software that was custom-developed using National Instruments LabVIEW. The system sampled and digitized 125,000 photosensor measurements to characterize the variation in luminous flux, and calculated an average output level as well as various flicker metrics. The absolute measurements of illuminance captured by the photosensor are dependent on the position of the light source in the light-impermeable box, which does not function as an integrating sphere. Test samples were not manipulated to ensure a consistent distance between their emitting surface and the photosensor or a consistent peak output from the photosensor. As a result, the raw data digitized from the photosensor were normalized to the maximum value recorded for each waveform.

Power quality calculations were made from light-source input current and voltage measurements, using a calibrated Yokogawa WT500 Digital Power Meter. The custom-developed software also controlled the WT500 and logged its measurement data.

At this time, there is no standardized test procedure for characterizing the dimming performance of LED (or other) light sources, or for measuring flicker. The lamps were allowed to warm up for approximately five minutes before measurement. Lamp temperatures and other operating characteristics (e.g., power and light output) were not monitored during this warmup time to determine stability, which is less important given the relative nature of the measurements. In order to minimize testing time, dimmable test samples were not allowed to establish a new thermal equilibrium at each dimmed measurement point. Flicker and power quality measurements were made immediately after establishing each target dimmed-output level. Measurement time per sample was minimized and relatively consistent, due to the automated data acquisition.

The transimpedance amplifier gain was adjusted for each measurement, to ensure that the peak output voltage presented to the oscilloscope for digitization was between 0.5 and 5.0 V. The average value of the photosensor measurement made for each sample when operated by a switch was used to normalize all subsequent dimmed measurements of that sample, facilitating comparisons between products for relative dimmed light output and relative efficacy.

Measurement Procedure

For each lamp model and each scenario being evaluated, flicker and power quality characteristics were first recorded when the test circuit was operated by the switch, then at a series of measurement points when operated by the specified dimmer. For this study, dimmed measurements were taken by operating the control from its maximum-to-minimum signal (i.e., high-to-low sequence) only. In all cases, output has been normalized to the level obtained when operated by the switch, which serves as a common reference point across the scenarios. However, there is no common reference point for the transformer, so dimming curves can be compared but absolute dimming level cannot.

A test operator manually adjusted the dimmer while monitoring the RMS Voltage delivered to the lamp, with the intent of taking measurements at or near 10 predetermined targets: maximum voltage, minimum voltage, and eight equally spaced voltages in between. This method was utilized because the dimmers did not have programmable presets, and physically adjusting the devices to specific positions was not repeatable. Critically, this method controls for any nonlinearity in the relationship between the dimmer position and the output signal. Thus, the resulting data is focused only on the lamp's response to the dimming control signal, and not on the translation from dimmer position to dimmer signal. In some cases, the delivered voltage was highly erratic, and the operator was forced to estimate ten equally spaced physical positions of the dimmer's slider. These cases are noted in the report. They mostly apply to scenario two (retrofit with a non-listed transformer).

The independent variable in most of the analysis is normalized mean light output—except for characterizations of mean light output versus dimmer output control signal (i.e., RMS voltage). This provides the best correlation to people's subjective experience, although it does hide differences in the range of RMS voltage range measured for the lamp and dimmer combinations. In other words, not all systems resulted in the same range of signal being received by the lamp. In some cases, the signal was highly erratic and not related to the position of the dimmer's slider.

To reiterate: mean light output for all analyses was always normalized to the output measured when the lamp was operated by a switch, whereas dimmer output signal was normalized (or rescaled) based on the extents of the RMS voltage range for each lamp-dimmer combination, which more directly relates to a user's experience of the product's performance. Although for the sake of clarity all plots are shown as continuous lines, it is important to note that measurements were taken at only 10 discrete points, and that the lines between are merely linear interpolations.

Reported Metrics

Flicker

Percent flicker and flicker index are metrics historically used to quantify flicker. Percent flicker is better known and easier to calculate, but flicker index has the advantage of being able to account for differences in waveform shape (or duty cycle, for square waveforms). Both metrics account for amplitude variation and average level, but since both are based on the analysis of a single waveform period, neither is able to account for differences in periodic frequency. Both percent flicker and flicker index were calculated from the raw waveform data and reported in this investigation. Flicker frequency was estimated from the graphical waveforms by inspection and hand calculation.

Power Quality

Power quality is commonly associated with power factor (PF) and total harmonic distortion (THD). Power factor is the ratio between active (or real, or consumed) power (measured in watts) and apparent power (measured in volt-amps [VA]). Power factor can be fundamentally degraded by displacement between voltages and current waveforms, distortion of the voltage waveform, and/or distortion of the current waveform. The PF of a system with a purely sinusoidal voltage and current can only be degraded by displacement. The PF of a system is sometimes approximated by computing the displacement between the fundamental voltage and current waveform. This calculation is sometimes referred to as the displacement power factor—as opposed to the total (or true) power factor, which accounts for all harmonic voltages and currents that comprise the apparent power.

Total harmonic distortion is a measure of waveform distortion that can be calculated for voltage (THD-V) or current (THD-I). Since PF accounts for both waveform displacement and waveform distortion, while THD is only a measure of distortion, THD is inherently limited for a given PF. THD can be calculated in at least two different ways that deliver dramatically different results:

- One method (described in ANSI C82.77-2002, IEEE 519-1992, and IEC 61000-2-2) computes the ratio of the RMS value of the 2^{nd}- to K^{th}-order voltage or current harmonics (where K is typically somewhere between 40 and 50) to that of the fundamental (1^{st}-order, or K=1) frequency component. This method is often referred to as THD (fundamental). Notably, this computation can, and often does, lead to values greater than 100%.
- A second method (described in CSA C22.2) computes the ratio of the RMS value of the 2^{nd}- to K^{th}-order voltage or current harmonics to the RMS value of all the voltage or current (i.e., 1^{st}- to K^{th}-order) harmonics. This method is sometimes referred to as TDD, or total demand distortion, and its computation will always lead to values less than 100%.

The method that results in the calculation of THD (fundamental) is more commonly used and valued. The power quality metrics reported here include (true) power, RMS current (I_{rms}), (true or total) power factor, and current THD relative to the fundamental frequency component (THD-I, fundamental).

Subjective Evaluations

In addition to the numerical data, the test operator recorded any abnormal behavior that may not have been measurable, but was still visually apparent. The operator was specifically asked to monitor the dimming smoothness, any flashing or pop-on/pop-off behavior, and audible noise. While these observations cannot be explored with numerical analysis, they are important to a full understanding of the system performance.

5 Results and Analysis

General Discussion

Scenario One: Electronic Transformer and ELV Dimmer (Maximizing Compatibility)

When operated by an electronic transformer and ELV dimmer, most of the lamps dimmed in at least a minimally acceptable way; that is, the output reduced as the dimming signal reduced. Notably, they all exhibited a linear dimming curve (except one product that dimmed erratically), which contrasts with the typical square-law dimming curve of halogen MR16 lamps and is also different from the variety seen with other CALiPER-tested lamps that underwent photoelectric evaluation. All but three of the LED products dimmed to less than 10% of the switched output. Nine of the 25 LED lamps dimmed to 2% or less.

About half of the MR16 lamp models tested provided transformer-compatibility information. By comparing these results to those of lamp models for which a transformer was randomly assigned from the pool of six—but without any compatibility guidance—some insight can be gained into the value of compatibility lists. Only one of the 12 lamps that provided compatibility information for electronic transformers did not dim in a reasonable manner, as shown in Figure 1.[14] Notably, this lamp claimed to be “compatible with electronic and conventional transformers” but did not provide a list of compatible transformers. In contrast, at least 6 of the 13 lamps that didn’t supply compatibility information exhibited substantial dead travel, limited dimming, or erratic dimming behavior (Figure 1). Notably, the two sample sets are small, with a diverse range of models in each. Because potential confounding variables (such as lamp quality) are present, it should not be assumed that lamps that provide compatibility information will always dim better than lamps that do not. Still, seeking compatibility information is always advisable.

While the products that provided transformer-compatibility information tended to dim better, there was little discernable difference in the flicker of those products compared to the group that did not provide compatibility information. In general, the flicker performance for all lamp models in this scenario was poor (Figure 2), with only four products generally having flicker index values less than that of a magnetically ballasted fluorescent lamp—with some exceptions at very low light levels. If discernable, the flicker frequency of all but one product was 120 Hz throughout the dimming range. The one exception was product 14-10, which also exhibited high values for flicker index and percent flicker.

There was a wider range in power factor for the lamps that did not provide transformer-compatibility information, but considering that the trend is the same for scenario two, this is unlikely to be related to transformer compatibility. The power factor over the dimming range for all lamps in scenario one is shown in Figure 3. The performance was highly variable, with many of the systems having a very low power factor (i.e., less than 0.50). The consequences of such a low power factor are not easily determinable, given that the lighting loads may be only one component of a building circuit, and are only one component of a building’s power system.

[14] While the lamp models are not identified in many of the charts, the line color for each lamp remains the same throughout the report. The lamp identifiers were removed because one test scenario should not be used to characterize any given lamp model.

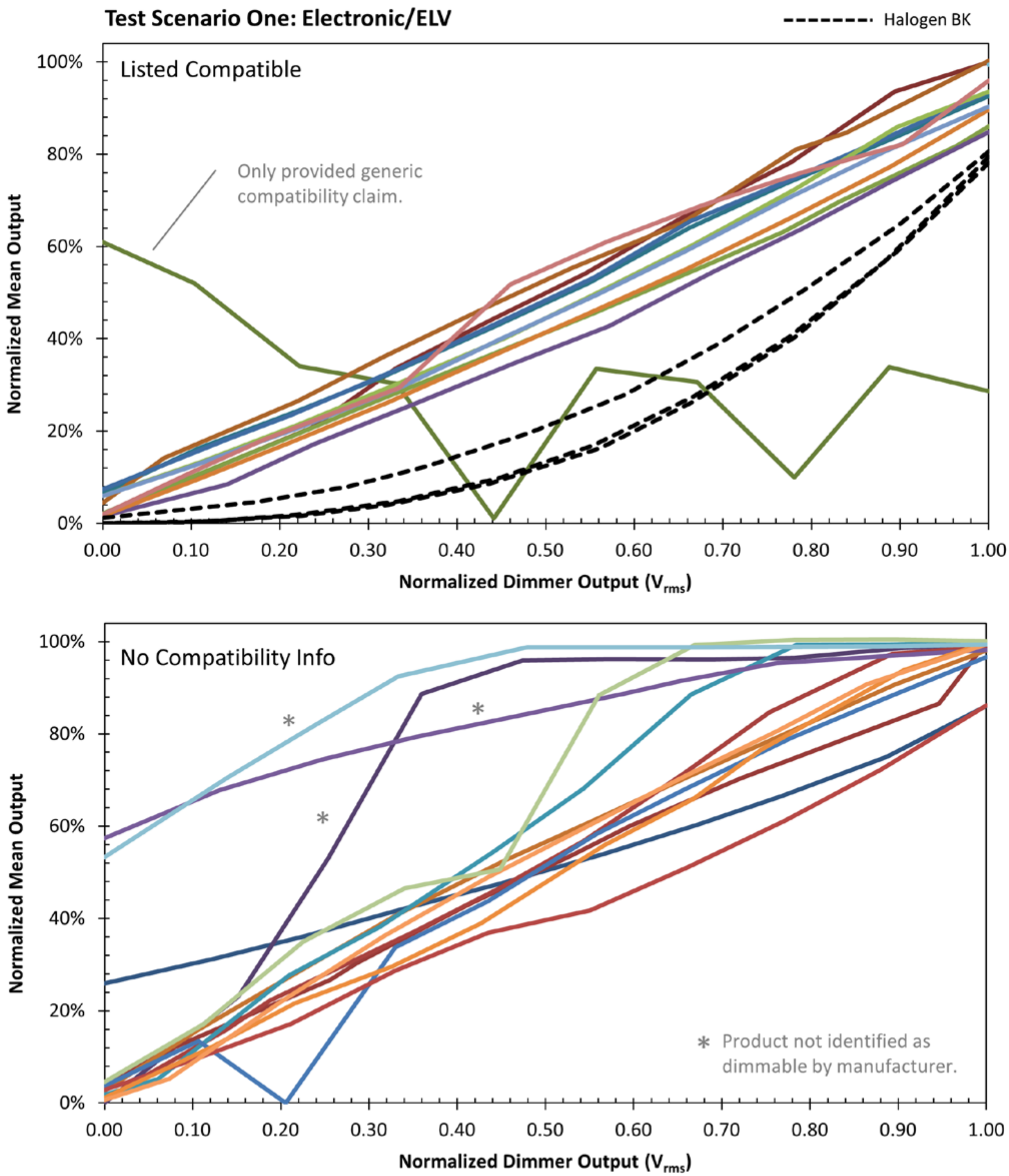

Figure 1. TOP: Light output versus dimmer voltage for lamps that provided compatibility information, scenario one. The one lamp-and-transformer combination that performed erratically only listed generic compatibility for electronic transformers, not compatibility with any specific models. **BOTTOM: Light output versus dimmer voltage for lamps that did not provide compatibility information, scenario one.** In several cases, lamps exhibited undesirable dimming behavior, such as dead travel.

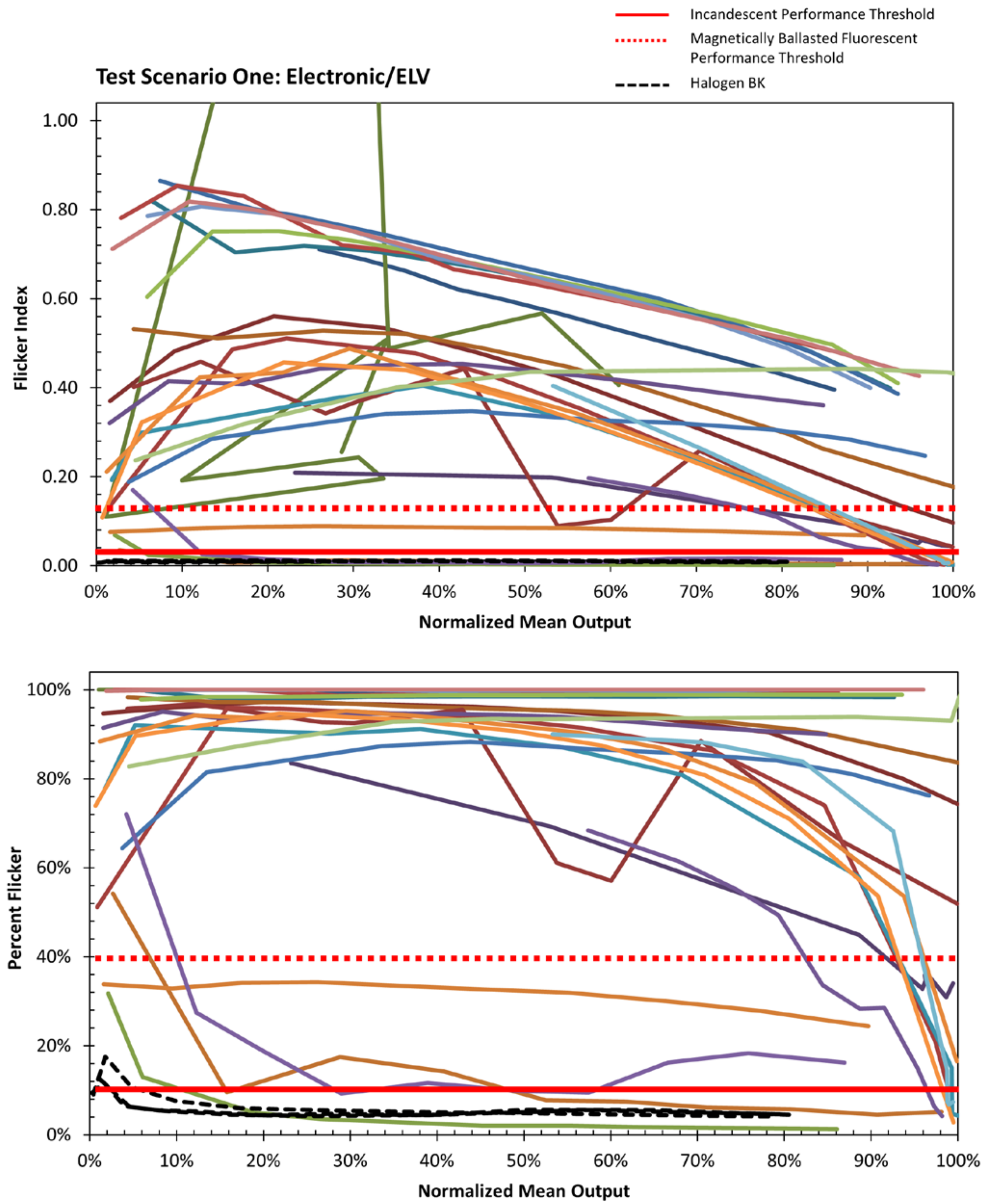

Figure 2. TOP: Flicker Index versus light output, scenario one. Few of the Series 22 LED MR16 lamp-and-transformer combinations matched the flicker performance of the halogen benchmarks. **BOTTOM: Percent Flicker versus light output, scenario one.** For both charts, mean output is normalized against the value when the lamps were operated by a switch; thus, the maximum output shown (for the dimmer only) is not 100%.

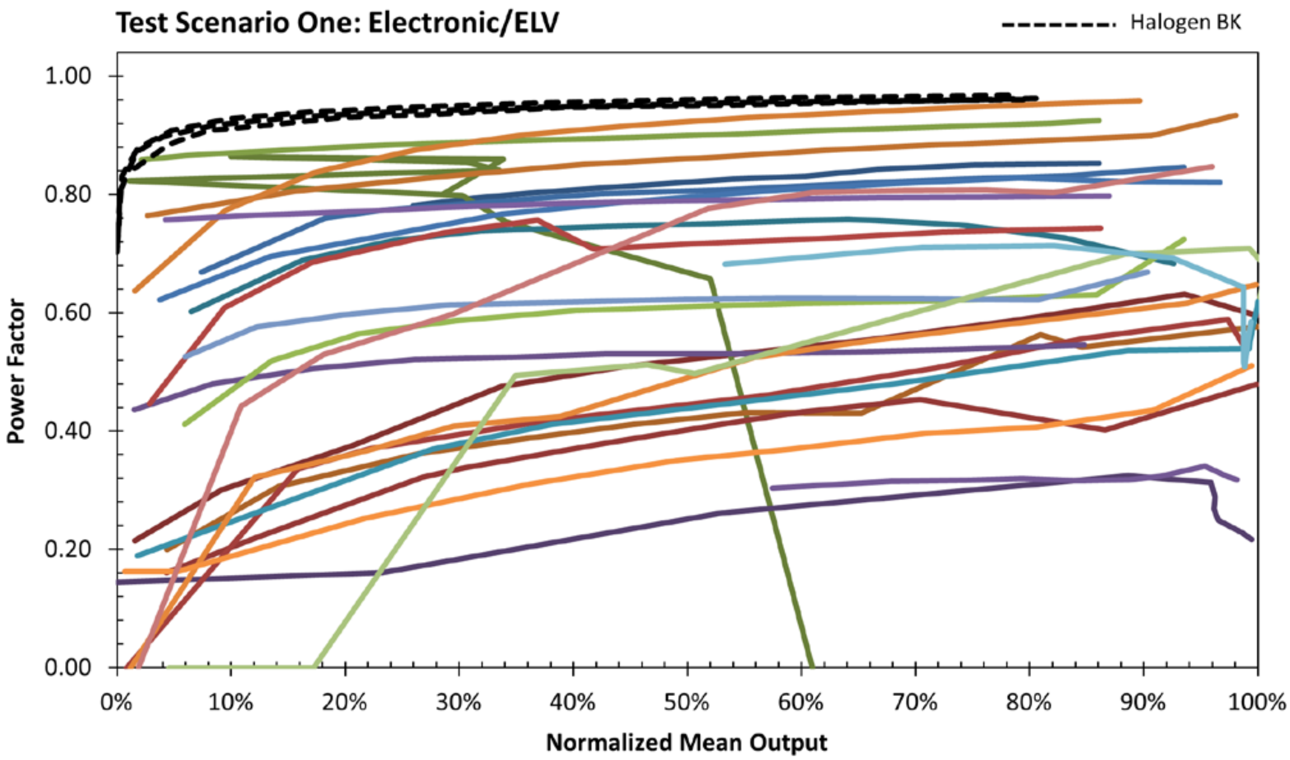

Figure 3. **Power factor versus light output for all tested lamps, scenario one.** The LED MR16 lamp-and-transformer combinations exhibited a very large range in performance, especially compared to the very consistent halogen benchmark products.

Scenario Two: Electronic Transformer with Incandescent Dimmer (Retrofit)

For this scenario, all lamp compatibility information was disregarded, and all the lamp models were connected to the same transformer (X1) and dimmer (a basic incandescent model). Figure 4 demonstrates that few of the LED lamp models dimmed in a reasonable manner. In fact, a third of the lamps dimmed in a highly non-monotonic manner, meaning that a reduction in the dimmer control did not always result in a reduction in light output; these products appear as jagged lines in Figure 4. Further, many of the LED products did not dim below 60%. Only a handful of the LED-based systems in scenario two could be considered acceptable for use.

Also worth noting in Figure 4 is that the halogen benchmarks did not have a lower output at 100% dimmer signal compared to operation by a switch, something that occurred both for scenarios one and three. The initial effect on output when replacing a switch with a dimmer was highly variable for the LED products.

Despite the drastically worse dimming performance compared to test scenario one, which also used an electronic transformer, the flicker performance was not remarkably worse (Figure 5). Interpretation of Figure 5 can be somewhat difficult, because many of the lamps dimmed so erratically. Nonetheless, the overall flicker performance remained quite poor, with most of the lamps exhibiting potentially objectionable flicker. For this scenario, five products exhibited a flicker frequency of less than 120 Hz; notably, all five of those products exhibited non-monotonic, erratic dimming behavior, so the flicker characteristics may not even be relevant. Further, one of those five products did not claim to be dimmable.

Finally, the power factor measurements (Figure 6) reveal two distinct groups of products. One group exhibited moderately low power factor that became worse at lower light outputs. The other group exhibited poor power

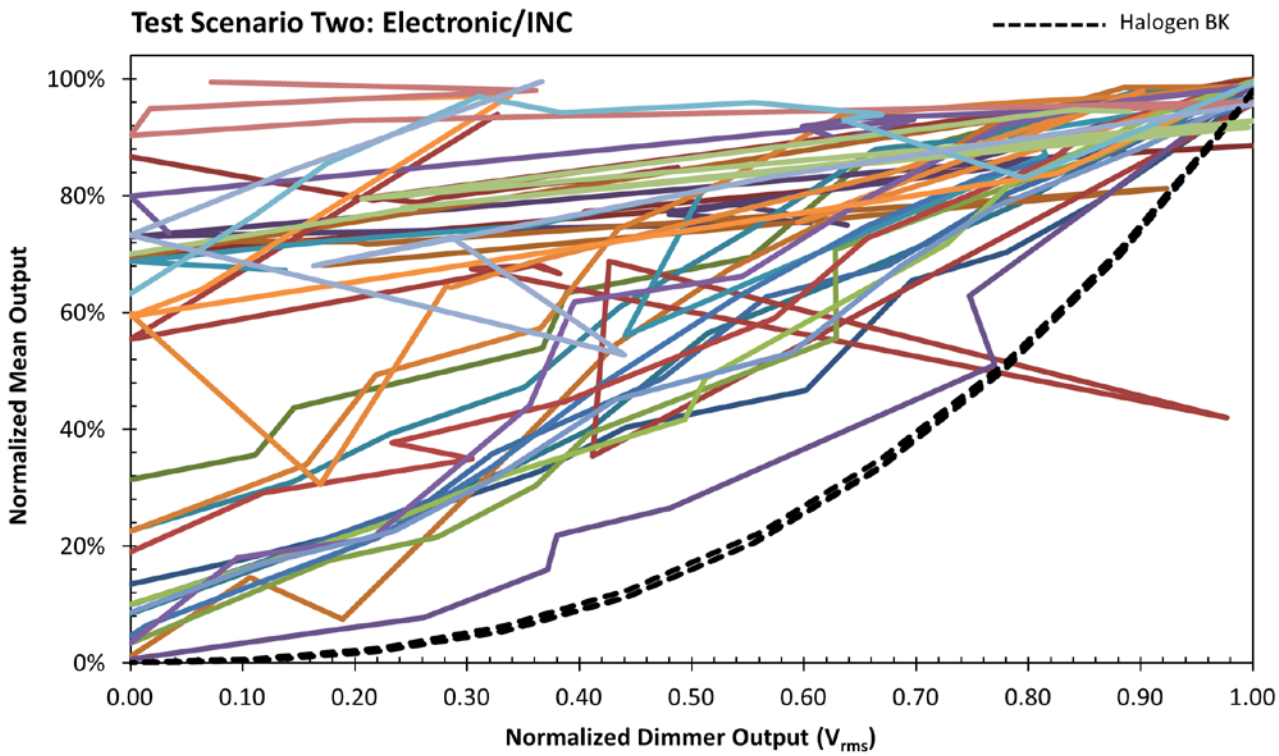

Figure 4. Light output versus dimmer voltage for all tested lamps, scenario two. Many of the LED lamp-and-transformer combinations performed erratically in this test condition, illustrating the difficulty of installing LED lamps in retrofit situations.

factor throughout the (typically limited) dimming range; many of these products also demonstrated irregular or unpredictable dimming—essentially showing a high level of incompatibility with the transformer-dimmer system.

Scenario Three: Magnetic Transformer with MLV Dimmer

Of the three real-world test scenarios, the systems using the magnetic transformer and MLV dimmer produced the least-erratic behavior, but not necessarily exemplary performance. For example, in Figure 7, which shows the dimming curves for the lamps in this test scenario, at least six products clearly exhibited substantial dead travel, and about half of the products did not dim below 10%. As with the other scenarios, none of the LED products matched the dimming curve of the halogen benchmarks, and the flicker performance of most of the lamps was rather poor (Figure 8). In contrast, most of the systems demonstrated substantially higher power factor in scenario three as compared to scenarios one and two, often increasing over the dimming range (Figure 9).

Scenarios Four and Five: AC Power Supply and DC Power Supply

As previously noted, the lamps were not dimmed using the laboratory power supply. The subsequent section explores the performance of the lamps when operated by a switch across all five test scenarios.

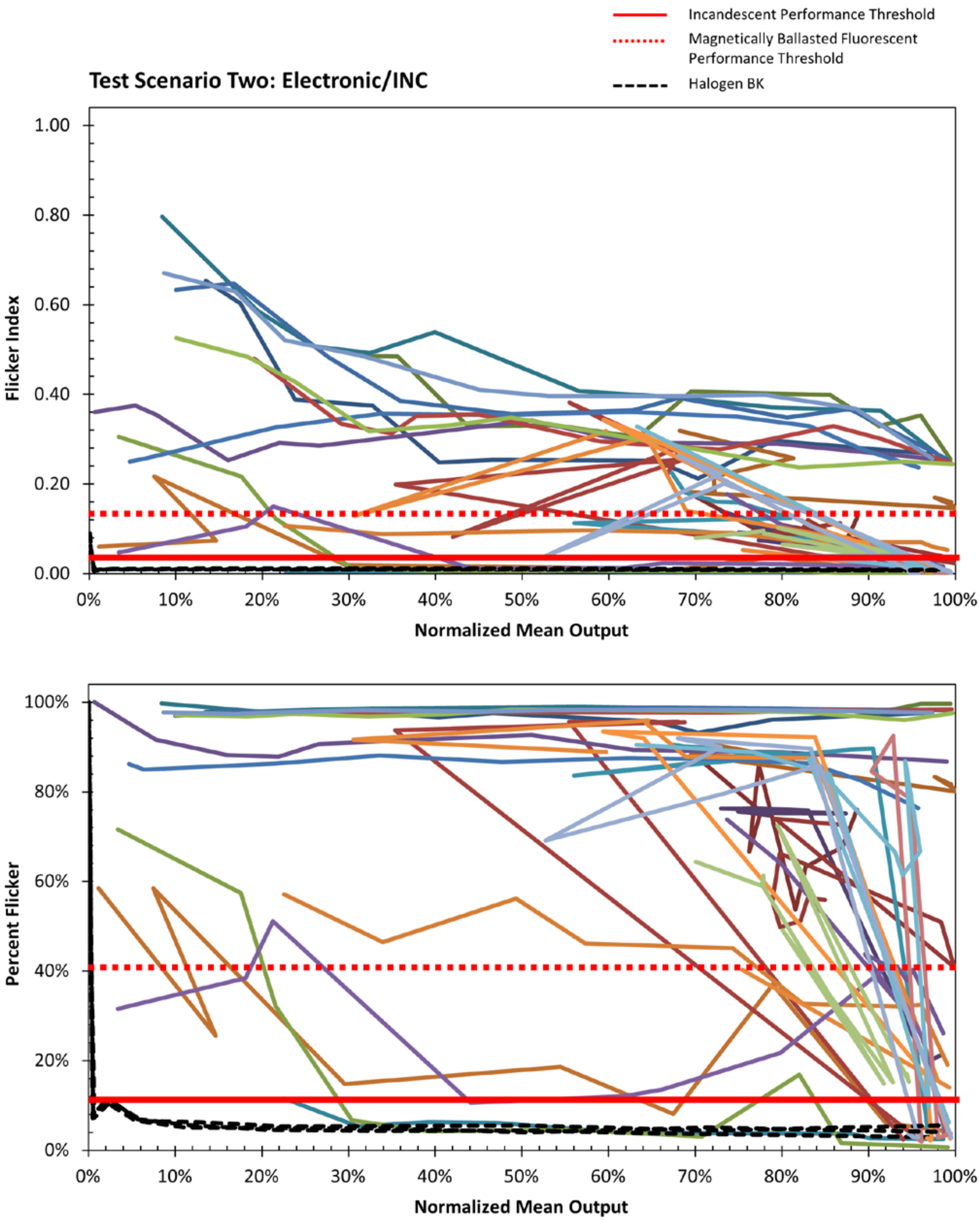

Figure 5. **TOP: Flicker index versus light output, scenario two.** Few of the Series 22 LED MR16 lamp-and-transformer combinations matched the performance of the halogen benchmarks. **BOTTOM: Percent flicker versus light output, scenario two.** For both charts, mean output is normalized against the value when the lamp-and-transformer combinations were operated by a switch; thus, the maximum output shown (for the dimmer only) is not 100%. In general, the flicker performance was similar to test scenario one.

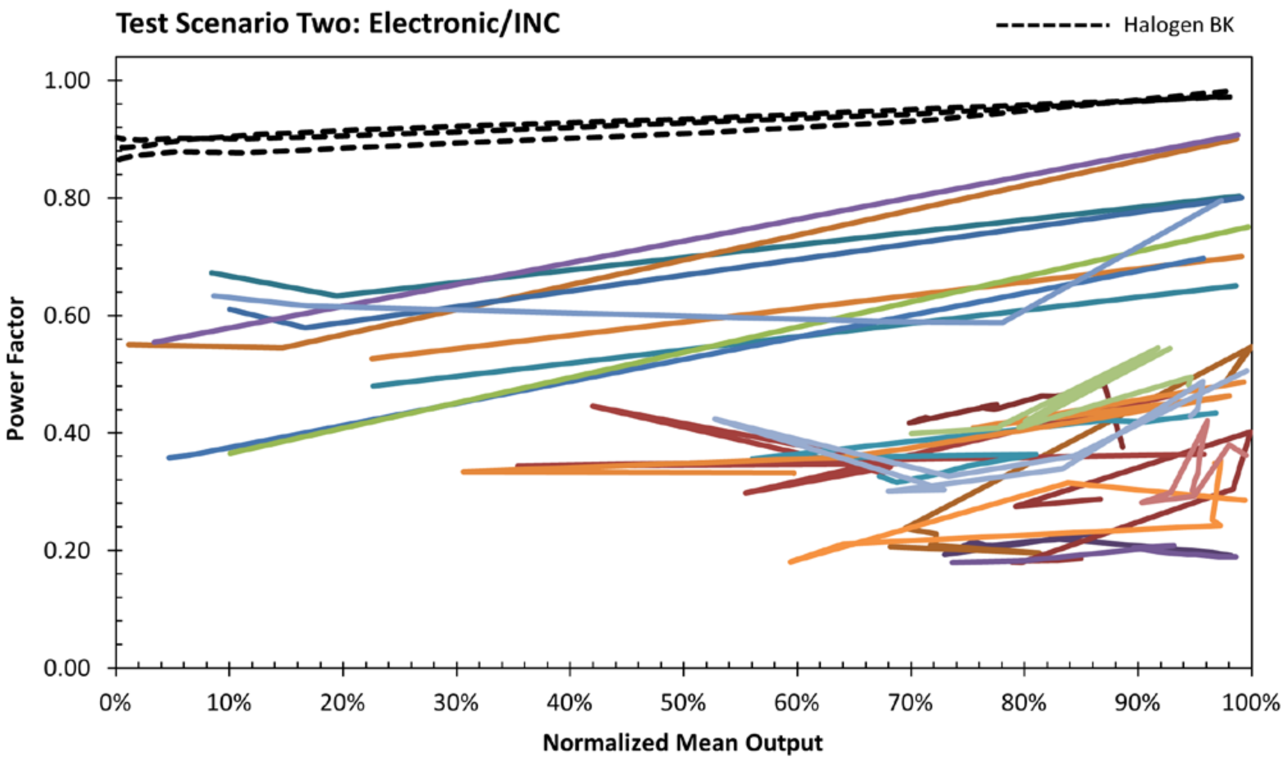

Figure 6. Power factor versus light output for all tested lamps, scenario two. The LED MR16 lamps generally fell into two categories for power factor performance (linear or erratic), which were based on the regularity/irregularity (i.e., compatibility) of the transformer/dimmer system.

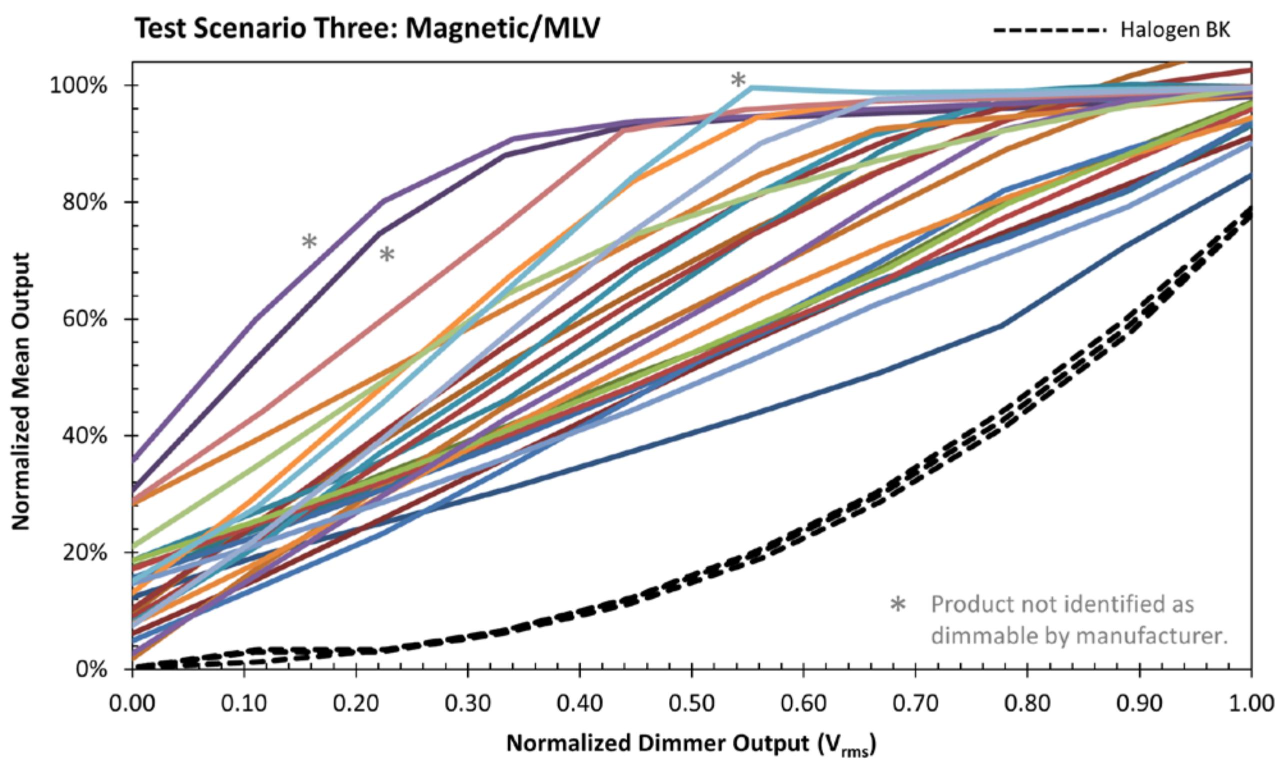

Figure 7. Light output versus dimmer voltage for all tested lamp-and-transformer combinations, scenario three. The LED lamps exhibited fewer undesirable dimming characteristics when connected to a magnetic transformer.

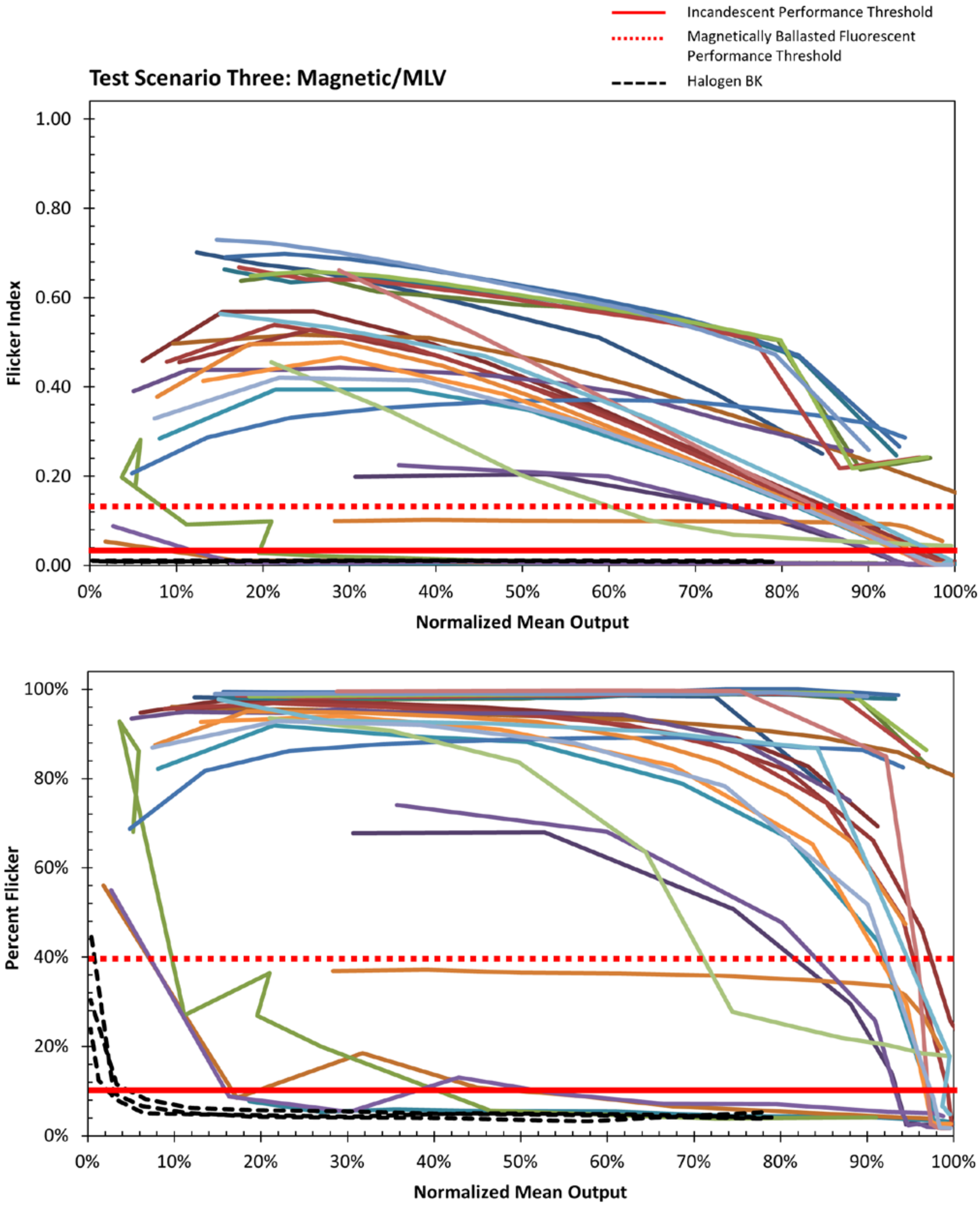

Figure 8. TOP: Flicker index versus light output, scenario three. Few of the Series 22 LED MR16 lamp-and-transformer combinations matched the performance of the halogen benchmarks. **BOTTOM: Percent flicker versus light output, test scenario three.** Flicker performance was the most consistent attribute between test scenarios one through three.

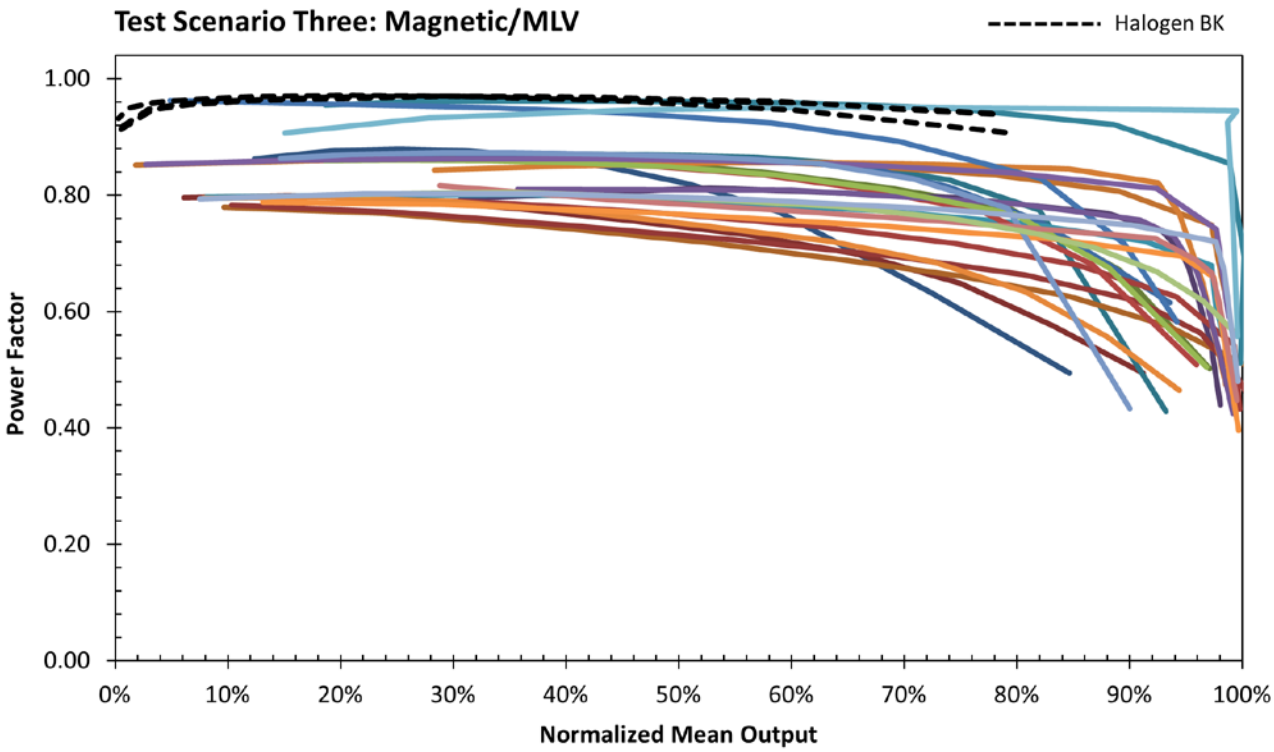

Figure 9. Power factor versus light output for all tested lamps, scenario three. The LED MR16 lamps performed most similarly to the halogen benchmarks with this equipment configuration.

Transformer Effect

All five test scenarios included measurements of lamp-transformer systems under control of only a switch. This isolates the effect of the transformer on the system. Notably, between-scenario comparisons cannot be made for light output, because the measurements were relative and normalized (i.e., the value for the switched condition of each scenario was adjusted to be 1). However, comparisons for flicker and power quality demonstrate the important role of the transformer in the overall compatibility equation.

Figures 10, 11, and 12 show the flicker, power factor, and power draw of each LED lamp model—along with the three halogen benchmarks and the average for all the LED products—across all five scenarios. Although each scenario is an independent test, the results are plotted with lines, thereby helping to identify the effect of the transformer. Mostly horizontal lines are evidence of little dependence on the choice of transformer, while sloping lines indicate a more significant transformer effect.

Flicker by Transformer

The flicker performance of most of the lamps was generally independent of test scenario, but the performance of several products strayed from their norm when operated with one of the scenario-one, -two, or -three transformers. The most notable deviations were for products 14-27 and 14-28, both of which exhibited high levels of flicker for scenario one, but much lower levels for scenarios two and three (Figure 10). While product 14-28 didn’t offer a transformer compatibility list, the transformer used for product 14-27 in scenario one—which led to substantial flicker—was on its compatibility list. In many cases, LED lamp manufacturers may not have considered flicker to be a criterion when establishing their products’ transformer compatibility.

Scenarios four and five (AC and DC) demonstrate the effect of the incoming voltage waveform on flicker. The AC power supply scenario led to flicker performance that was generally similar to the commercial transformers, with a couple of products showing some deviation. In contrast, all of the measured systems produced minimal flicker with the DC power supply, as expected.

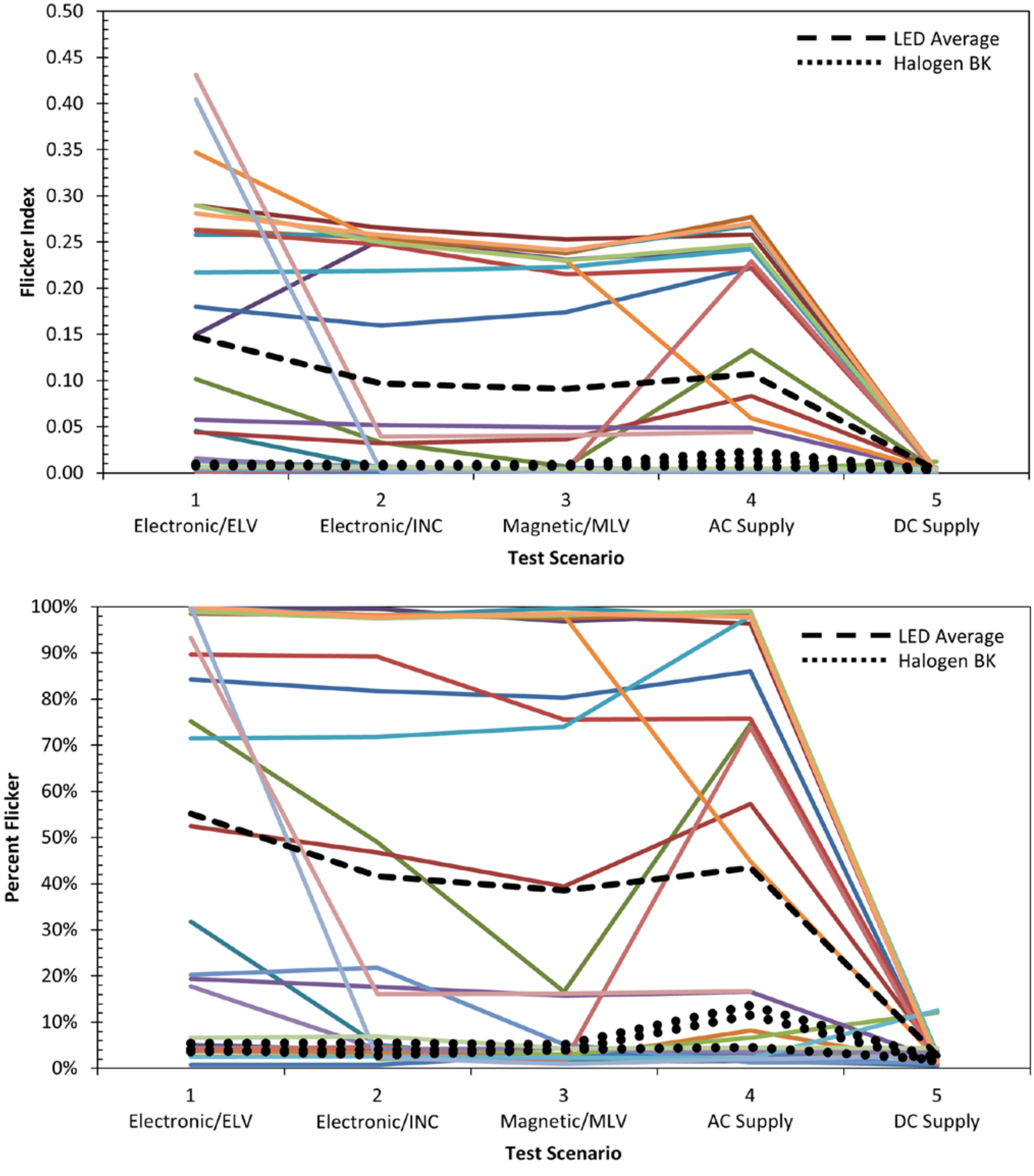

Figure 10. Comparison of flicker performance of lamps operated by a switch, for each test scenario. With some exceptions, flicker performance did not exhibit a strong dependence on the test scenario**.**

Power Factor by Transformer

As shown in Figure 11, the power factor results were more dependent on the choice of transformer than flicker was. All but one product (14-27) had a similar power factor on the two electronic transformers, but the exact performance was highly dependent on the lamp model, with power factor values ranging from 0.21 to 0.97. In contrast, the range in power factor for the LED products operated with the magnetic transformer was just 0.26 to 0.48; at the same time, the benchmark halogen lamps demonstrated only a minor dip in power factor with the magnetic transformer, compared to their performance on the electronic transformers. For scenario four, the LED products generally divided into two groups, one with power factors around 0.70 and another with power factors around 0.90; note that the wattage of the halogen lamps prevented measurement with the laboratory power supplies in some cases. With the DC power supply (scenario five), the power factor for almost all of the lamps was 1.00, as expected.

The results for THD are not shown in this report, due to measurement issues that led to unreliable data for the scenario-one tests and limited data for the scenario-two tests.

System Power Draw By Transformer

Perhaps the most notable effect of the transformer is the change in power draw of the system (Figure 12). Although there were a few exceptions, most of the products exhibited the same consistent trend, drawing almost 50% more power when connected to the magnetic transformer than when connected to the power supply. Operation with the electronic transformers (scenarios one and two) also resulted in slightly increased power draw, when operated by the switch. A few products had markedly lower power draw for scenario one than in the other configurations.

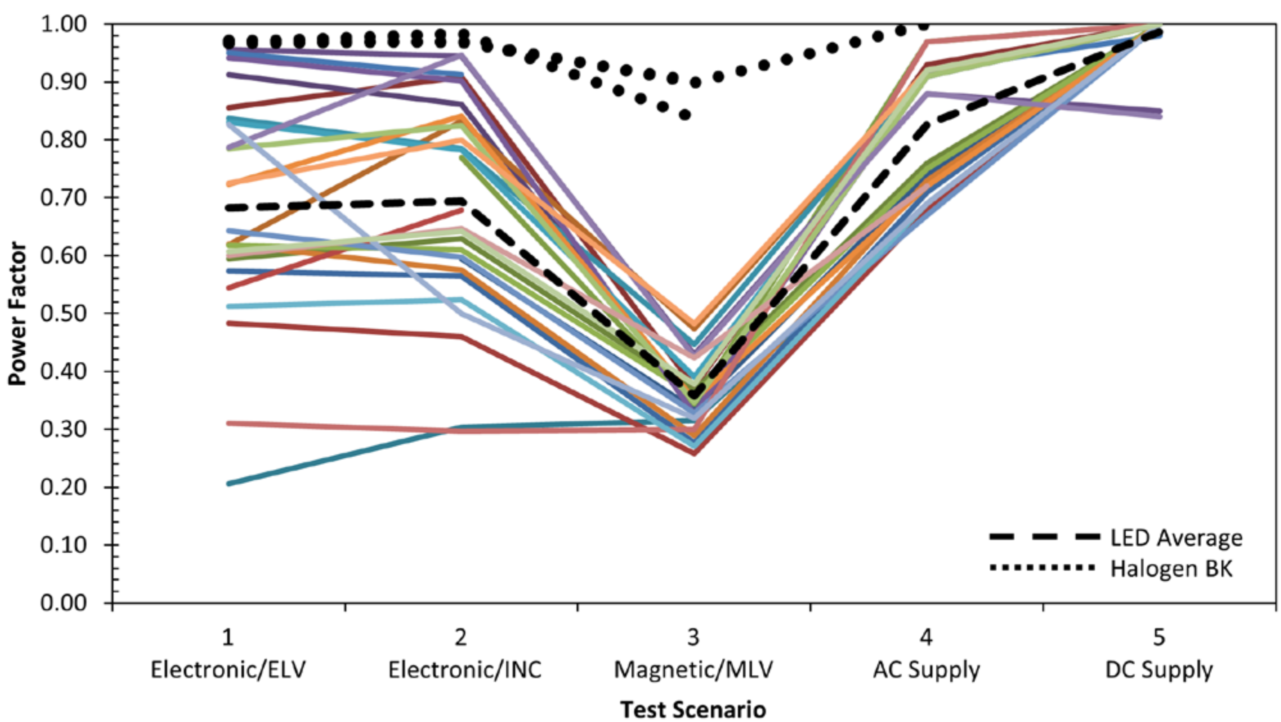

Figure 11. Comparison of power factor of lamps operated by a switch, for each test scenario. In contrast with the flicker performance, power factor varied significantly between most test scenarios.

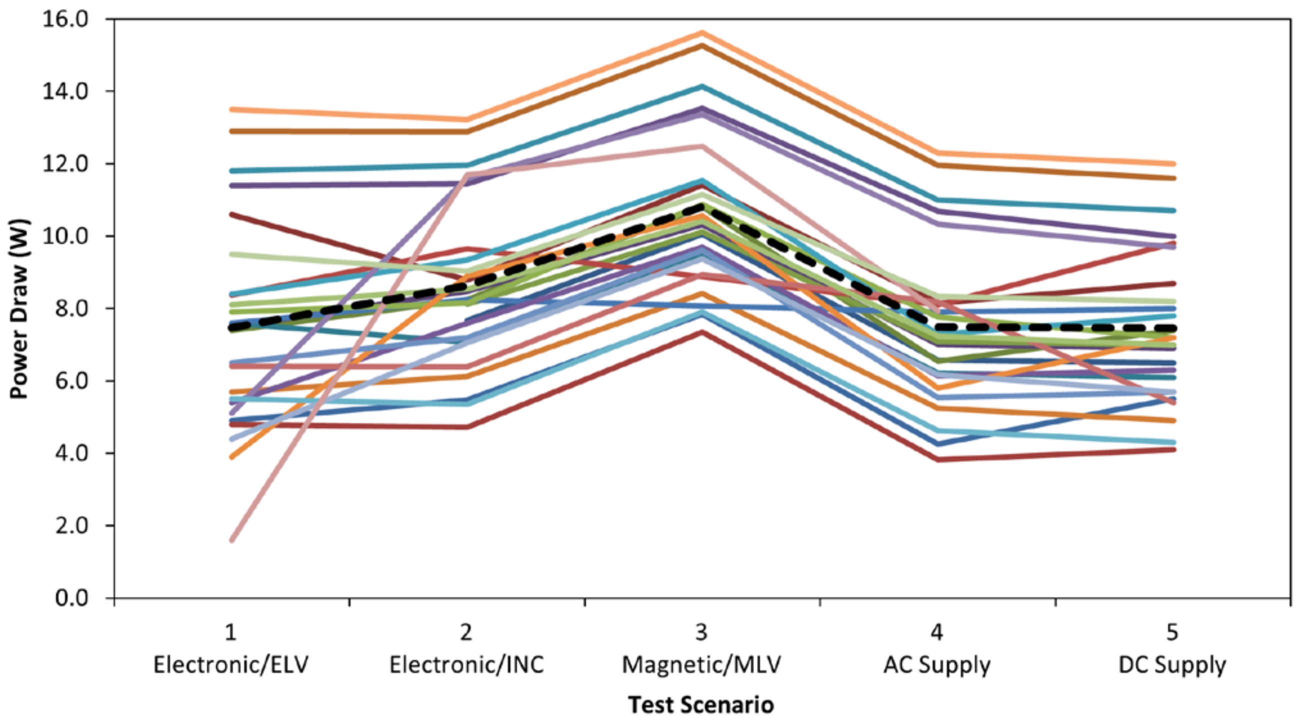

Figure 12. Comparison of power factor of lamps operated by a switch, for each test scenario. In contrast with the flicker performance, power factor varied significantly between most test scenarios.

The effect of the transformer on power draw is not captured in typical photometric testing, but the resulting difference in power draw is consequential to building energy use. There was some effect for halogen lamps, but it was much less, at about 5% difference between scenarios one, two, and three.

Dimmer Effect

Three products were tested with transformer X1 for both scenarios one and two, meaning that the only difference in the setup was the dimmer. Scenario one used an ELV dimmer, whereas scenario two used a standard incandescent dimmer. As shown in Figure 13, the dimmer had a substantial effect on the system performance. All three lamps exhibited less-desirable dimming behavior when operated by the standard incandescent dimmer than when operated by the ELV dimmer—similar to dimmer-based effects that were observed in CALiPER *Retail Lamps Report 3.1*.

Notably, one of the three products was not explicitly listed as dimmable, and demonstrated minimal dimming regardless of the dimmer. Another product exhibited reasonably similar dimming performance, whereas the third product exhibited reasonable performance with the ELV dimmer, but did not dim below 75% on the standard incandescent dimmer.

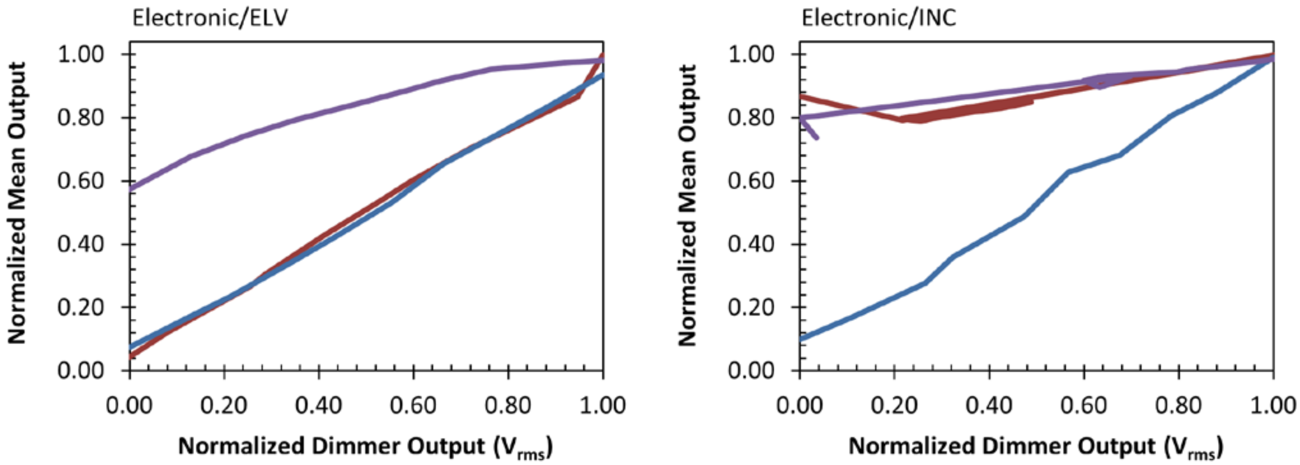

Figure 13. Comparison of dimming curves for three lamp models, all connected to transformer X1 for scenarios one (left) and two (right). The potentially substantial effect of the connected dimmer is apparent.

Subjective Observations

Dimming Smoothness

For the three scenarios where dimming was performed, there was a strong difference in perceived dimming consistency, as noted by the test operator. All of the scenario-one lamps that included a transformer compatibility list (12 of 25 LED lamps tested) exhibited smooth dimming performance. Even the 13 lamps in this scenario that didn't include compatibility information dimmed competently. In contrast, only 30% of the lamps dimmed smoothly when operated in scenario two. Nearly 80% of the lamp models were deemed to dim in a satisfactory manner by the test operated for scenario three, the magnetic transformer and MLV dimmer.

While this subjective data is strongly anecdotal, they align with expectations. Compatibility lists are provided for a reason, and ignoring them can lead to severely degraded performance. Perhaps it is even more important to consider this in retrofit situations, where other system components are often unknown, and a significant investment in time may be required to maximize system compatibility and performance. The likelihood that a combination of an LED MR16 lamp, unknown transformer, and unknown dimmer will operate smoothly and meet halogen performance expectations is low.

Flashing or Pop-On/Pop-Off Behavior

Unlike with dimming smoothness, there was no strong trend regarding the visibility of flashing or pop-on/pop-off behavior for the lamps operated in the three scenarios that included a dimmer.

Audible Noise

The presence of audible noise was greatly increased for the electronic transformer/INC dimmer scenario (85%) versus the electronic transformer/ELV dimmer (14%) or magnetic transformer/MLV dimmer (7%) scenarios. This illustrates the importance of performing mockup evaluations of LED MR16 lamps together with existing system components before committing to a significant lamp purchase.

Individual Lamp Examples

Figures 1 through 11 depict the performance of all the lamp models in only one system configuration. While these charts can and should be compared to examine system-level effects, it can also be helpful to examine the possible outcomes for a given lamp model. Figure 14 shows plots of the dimming curve, flicker index over the dimming range, and power factor over the dimming range for four LED MR16 lamps and one benchmark halogen lamp. The four LED products were chosen to demonstrate how much performance may or may not vary across the installation conditions examined in this study. For some products, there was little variation, while for others, the installation scenario dramatically affected the product performance. Product-to-product performance can vary significantly for LED MR16s, as has been noted in previous CALiPER investigations of LED products. Although the scales are not shown, they are the same as seen in Figures 1 through 9.

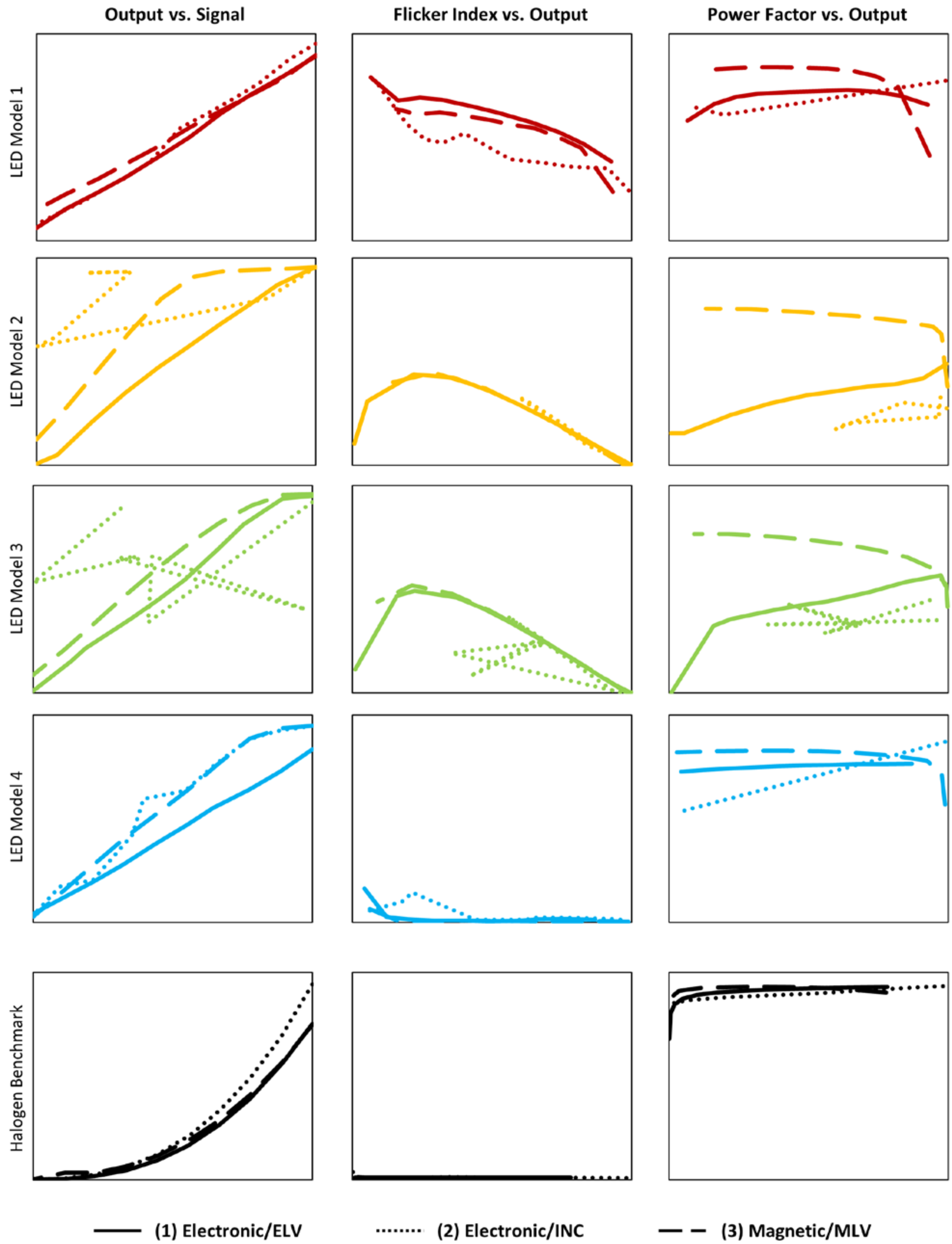

Figure 14. Graphical representation of performance for four LED MR16s lamps and one halogen benchmark lamp, scenarios one through three. Each lamp model is identified by a color, but the line colors do not correspond to the other charts in this report. For some of the LED lamps, the change in performance due to operation with different transformer-and-dimmer combinations was minimal, but for others it was substantial.

6 Conclusions

This report is a follow-up to CALiPER *Application Summary Report 22*, which investigated the photometric performance of LED MR16 lamps. The initial report found that many of the LED MR16 lamps did not perform as required by ENERGY STAR based on their equivalency claims, although they generally did provide substantial efficacy advantages compared to halogen MR16 lamps. All testing was completed using laboratory power supplies, with all but one product tested at 12 V AC. In contrast, this report examined the photoelectric performance of the same set of lamps, using commercially available transformers and dimmers as well as laboratory power supplies providing both AC and DC power.

This is the third CALiPER report to focus on photoelectric performance—the previous two covered PAR38 lamps and retail-available A lamps. This is the first CALiPER report, however, to focus on the combined system-level performance of low-voltage lighting, including a transformer and dimmer, using five test scenarios. As with previous CALiPER photoelectric testing, the results from this investigation demonstrated substantial variation in the performance of commercially available LED MR16 lamps, both within a given test scenario and across multiple test scenarios. Scenario one demonstrated the value of manufacturer-provided compatibility recommendations: lamps that provided them performed best when operated with compatible transformers and/or dimmers. In addition, the products that were tested with the same transformer, but a different dimmer, demonstrated that, while transformer compatibility is paramount, the choice of dimmer could still have an effect on the performance of low-voltage products. One important difference from previous CALiPER photoelectric testing—regardless of the scenario—was that none of the LED MR16 lamps exhibited dimming curves similar to those of the benchmark (halogen) MR16 lamps.

Scenario two demonstrated the potential problem of installing LED MR16 lamps with a typical incandescent dimmer, which is commonly found in existing halogen MR16 installations together with a potentially unknown transformer. Few of the lamps in this scenario performed adequately, and many exhibited highly erratic dimming behavior. In contrast, test scenario three demonstrated the relative stability of magnetic transformer-based systems, which eliminate the compatibility concerns of one electronic component from the system, but which draw higher system power. The greater compatibility may also come with additional tradeoffs, such as more dead travel and higher minimum dimming levels.

Scenarios four and five were included in the investigation to help understand the relevance of basic photometric testing (following LM-79) of low-voltage products. Although only a limited set of metrics could be compared, due to equipment limitations and normalization procedures, the results show that while lamp power quality measurements are unlikely to represent the installed performance of the lighting system, flicker measurements using an AC power supply may be informative. Testing with a DC power supply does not allow for evaluation of either of these important metrics.

Appendix A: Background on Dimming, Flicker, and Power Quality

Dimming

Not all LED lamps are designed to be dimmable, and those that are can exhibit different characteristics. The differences in performance are often related to the driver, which is responsible for interpreting the signal from a control device. The dimming performance of a given LED lamp can be dependent on other components in a lighting system, including the control device used and the characteristics of other light sources on the same circuit. This dependency is particularly prevalent for integral lamps controlled by phase-cut dimmers.

There is no standard definition for "dimmable," and manufacturer claims of dimmability to date cannot be construed as guaranteeing any minimum level of performance. Besides changes in light output, other performance attributes may also change during dimming, including LED package efficacy, driver efficiency, chromaticity, flicker, and power quality.

The dimming performance of LED lamps controlled by phase-cut dimmers can be affected by the choice of dimmer. Some phase-cut dimmers interfere with the normal behavior of some LED lamps, and some LED lamps interfere with the normal behavior of some phase-cut dimmers. Such compatibility issues can result in many undesirable behaviors, including:

- Lack of smoothness
- Dead travel (little or no change in light output, despite changes in dimmer setting)
- Pop-on or dropout (sudden change in light output not corresponding to the limit of the dimmer signal)
- Flashing or ghosting
- Audible noise
- Reduced lifetime or reliability of the dimmer
- Reduced lifetime or reliability of the LED product

The prevalence of these behaviors (some of which are depicted in Figure A1) in early experiences with LED products has effectively caused LED dimming performance to be highly unpredictable. More information on phase-control dimming issues and their causes, as well as suggestions for dealing with them, can be found in the GATEWAY report *Dimming LEDs with Phase-Cut Dimmers: The Specifier's Process for Maximizing Success*,[15] and in the National Electrical Manufacturers Association (NEMA) Lighting Systems Division document LSD 49-2010, *Solid State Lighting for Incandescent Replacement—Best Practices for Dimming.*[16]

Flicker

All conventional light sources—including incandescent, high-intensity discharge, and fluorescent—modulate luminous flux and intensity, whether visible or not. Many terms are used when referring to this time variation, including "flicker," "flutter," and "shimmer." LED flicker characteristics are primarily a function of the LED driver. Dimming an LED source can increase or induce flicker, most notably when phase-cut controls are used and/or pulse-width modulation (PWM) is employed within the driver to reduce the average light output from the LED source.

Low-frequency flicker can induce seizures in people with photosensitive epilepsy, and the flicker in magnetically ballasted fluorescent lamps used for office lighting has been linked to headaches, fatigue, blurred vision,

[15] Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2013_gateway_dimming.pdf

[16] Available at: https://www.nema.org/Standards/Pages/Solid-State-Lighting-for-Incandescent-Replacement-Best-Practices-for-Dimming.aspx

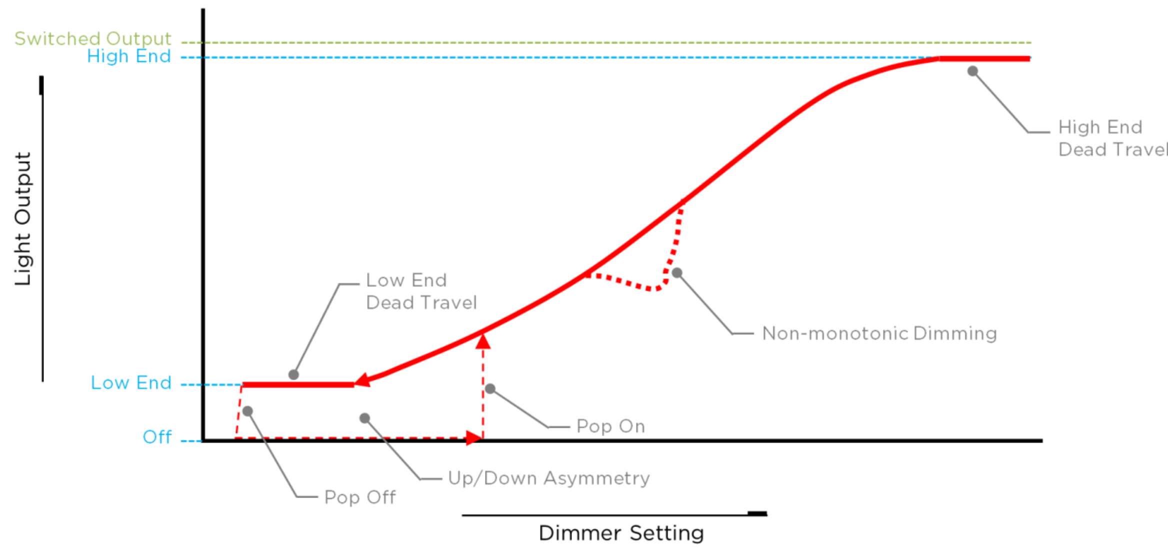

Figure A1. Potential behaviors when dimming LED lamps or luminaires. The plot shows light output (from zero to maximum) versus the dimmer setting (referring to the dimmer conduction time, phase angle, mechanical position of a knob, or V_{rms}). Many other behaviors are not shown. Adapted from NEMA SSL 6-2010, *Solid State Lighting for Incandescent Replacement – Dimming*.

eyestrain, and reduced visual task performance for certain populations. Flicker can also produce hazardous phantom-array effects—which may lead to distraction when driving at night, for example—or stroboscopic effects, which may result in the apparent slowing or stopping of moving machinery in an industrial setting.

The photometric flicker found in electric light sources is typically periodic, with its relative-light-output-versus-time waveform characterized by variations in amplitude, average level, periodic frequency (cycles per unit of time), shape, and, in some cases, duty cycle. The IES has defined two metrics for quantifying flicker: Flicker index and percent flicker. More information on flicker can be found in a DOE Fact Sheet on the topic.[17]

Flicker frequency is an important factor in evaluating the severity of the risk from flicker. At very low frequencies of 3 to 70 Hz (number of light modulations per second), the flickering light can trigger epileptic seizures in some populations. From 70 Hz to 100 Hz, the flicker is visible to many individuals. Above 100 Hz, flicker may cause headaches, trigger migraines, reduce visual task performance, or cause malaise, among other issues. These potential maladies may be a concern with frequencies up to approximately 1250 Hz; even though the number of individuals who can visually decipher the flicker at higher frequencies is small, the neurological system is still able to detect the flicker, and thus it may contributing to a physiological reaction.

Power Quality

Electric power is delivered through a complex system of generators, transmission lines, and distribution networks to widely varying end-use circuits comprised of interconnected loads. Power quality broadly describes the fitness of electric power to drive electric loads in a manner that allows them to function as intended without significant reduction in performance or lifetime. Power quality is a system characteristic, not a component characteristic. The power quality of an electric system is determined by the characteristics of the system components—including generators, switching devices, transformers, and ultimately loads—and how those interconnected components interact with each other.

[17] Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/flicker_fact-sheet.pdf

Electric power can be of poor quality in many ways, including (but not limited to) poor synchronization of the voltage frequency and phase across subsystems, transient increases or decreases to the root mean square (RMS) voltage that occur over time frames ranging from milliseconds to minutes (or more, in the case of outages), and harmonic distortions to voltage or current waveforms. There are many potential causes of poor-quality power, including (but not limited to) network or load switching events, currents induced by lightning strikes, and reactive (energy-storing) or non-linear loads.

Power quality is a significant potential concern for multiple stakeholder groups and may lead to higher financial costs as well as possibly degraded performance of, or damage to, electric networks and loads. Electric utilities are most affected by power quality, and as a result are most broadly concerned about new equipment deployment and other changes in electric systems. Degradation in the power quality of a utility system or subsystem can result in resonance in distribution networks, increased transmission and distribution losses, a need to install transmission and distribution infrastructure with higher power/current handling capability, and possibly even a need for increased generation capacity.

Building owners and operators need to beware of significant connected-load changes that might degrade building power quality and lead to potentially higher electricity costs resulting from a utility “power factor charge,” or to safety-related issues resulting from increased neutral-wire currents. Building occupants may also be affected by degraded power quality, which can lead to increased electrical-service interruptions and associated downtime—resulting from a greater occurrence of circuit-breaker trips or power-supply overloads and resets. Further, distorted input-voltage waveforms can also lead to degraded equipment performance, or in rare cases outright failure. Concerns about power quality have led to the development of equipment specifications by various standards organizations.[18] To date, the CALiPER program is not aware of any LED installations that have led to problematic reductions in the power quality of the building.

[18] In North America, ANSI C82.77-2002 currently contains perhaps the most appropriate power quality performance recommendations specifically for lighting equipment.

Appendix B: Series 22 Product Identification

Table B1. Make and model for the Series 22 MR16 products included in the photoelectric testing

DOE CALiPER Test ID	Brand	Model
14-01	Green Creative	7MR16G3DIM/930FL36
14-02[1]	Nu Vue Lighting	NV/MR16/6.1/WW/FL/53/CT
14-03	Soraa	MR16-65-B01-12-930-36
14-04	TerraLUX	TLL-R16A-A2030NFD
14-05	Dauer LED	LED-MR16-4XBD-WW-15 (487054)
14-06	GE Lighting	LED7DMR16D/830/15 (69919)
14-08	Philips Lighting	10MR16/END/S15 3000 12V DM (414755)
14-09	Soraa	MR16-65-B01-12-830-10 (00265)
14-10	Toshiba	5MR16/30DSP-T
14-11	Acculamp	ALSMR16 450L 36 DIM
14-13	CREE Lighting	LM16-50-30K-25D
14-14	Cyber Tech Lighting	LB10MR16/D/WW
14-15	E2 Lighting	E2MR0727K-40D
14-17	Feit Electric	BPEXN/LED
14-18	Green Creative	7MR16G3DIM/830NF25
14-19	Han Star LED	PLM16D
14-22[1]	Nu Vue Lighting	NV/MR16/5.1/WW/NFL/53/CX
14-23	OSRAM	LED7MR16/DIM/830/NFL25 (78420)
14-24	Philips Lighting	10MR16/END/F24 3000 DIM Model 9290002194
14-25	Shenzhen Kingliming Technology	MR 16 5W COB
14-26	Soraa	MR16-75-B01-12-830-25
14-27	TCP	LED7MR1630KNFL
14-28	Toshiba	9MR16/30GNF-UP
14-29[1]	Turolight	HD-MR16/9W/30/FL25/GU5.3
13RT-39	GE Lighting	LED7XDMR16830/25
13RT-41	EcoSmart	ECS 16 WW V2 NFL
13RT-44	Verbatim	M16ES-L500-C30-B30
BK14-31	Litetronics International	L-3804
BK14-32	Osram Sylvania	50MR16/B/NFL25 (58320)
BK14-33	Osram Sylvania	37MR16/IR/NFL25/C 12V (58634)

1. No information provided about dimmability.

Appendix C: Equipment Configuration

Table C1. Combinations for test scenario one: (electronic transformer/ELV dimmer, maximizing compatibility).

Lamp ID	Number of Connected Lamps	Electronic Transformer	Listed?[2]	Dimmer	Listed?[2]
13RT-39	(No Data)[1]	X3 Hatch RS12-80M	Yes	Lutron Diva DVELV-300P	No
13RT-41	5	X6 Keystone KTET-75-1SCP-DIM-RJS	No	Lutron Diva DVELV-300P	No
13RT-44	5	X2 Hatch RS12-60M-LED	Yes	Lutron Diva DVELV-300P	No
14-01	5	X4 Lightech LET60	Yes	Lutron Diva DVELV-300P	No
14-02	5	X5 Lightech LET-75	No	Lutron Diva DVELV-300P	No
14-03	5	X5 Lightech LET-75	Yes	Lutron Diva DVELV-300P	Yes
14-04	5	X2 Hatch RS12-60M-LED	Yes	Lutron Diva DVELV-300P	No
14-05	5	X1 B&L Technologies CV90001	No	Lutron Diva DVELV-300P	No
14-06	(No Data)[1]	X3 Hatch RS12-80M	Yes	Lutron Diva DVELV-300P	No
14-08	5	X4 Lightech LET60	No	Lutron Diva DVELV-300P	No
14-09	5	X1 B&L Technologies CV90001	Yes	Lutron Diva DVELV-300P	Yes
14-10	5	X2 Hatch RS12-60M-LED	No	Lutron Diva DVELV-300P	No
14-11	5	X2 Hatch RS12-60M-LED	Yes	Lutron Diva DVELV-300P	Yes
14-13	5	X5 Lightech LET-75	Yes	Lutron NovaT NTELV-600	Yes
14-14	5	X2 Hatch RS12-60M-LED	No	Lutron Diva DVELV-300P	No
14-15	5	X3 Hatch RS12-80M	Yes	Lutron Diva DVELV-300P	Yes
14-17	5	X2 Hatch RS12-60M-LED	No	Lutron Diva DVELV-300P	No
14-18	5	X3 Hatch RS12-80M	No	Lutron Diva DVELV-300P	No
14-19	5	X2 HATCH RS12-60M-LED	No	Lutron Diva DVELV-300P	No
14-22	5	X1 B&L Technologies CV90001	No	Lutron NovaT NTELV-600	Yes
14-23	5	X4 Lightech LET60	Yes	Lutron Diva DVELV-300P	Yes
14-24	5	X3 Hatch RS12-80M	Yes[3]	Lutron Diva DVELV-300P	No
14-25	5	X6 Keystone KTET-75-1SCP-DIM-RJS	No	Lutron Diva DVELV-300P	No
14-26	5	X4 Lightech LET60	Yes	Lutron Diva DVELV-300P	Yes
14-27	5	X3 Hatch RS12-80M	Yes	Lutron Diva DVELV-300P	No
14-28	5	X3 Hatch RS12-80M	No	Lutron Diva DVELV-300P	No
14-29	5	X6 Keystone KTET-75-1SCP-DIM-RJS	No	Lutron Diva DVELV-300P	No
BK14-31	5	X4 Lightech LET60	Yes	Lutron Diva DVELV-300P	No
BK14-32	5	X5 Lightech LET-75	Yes	Lutron Diva DVELV-300P	No
BK14-33	5	X6 Keystone KTET-75-1SCP-DIM-RJS	Yes	Lutron Diva DVELV-300P	No

1. The lamps were not available for this test scenario.
2. *No* indicates that no compatibility information was provided, not that listed information was not followed.
3. Transformer-compatibility information provided, but operation with dimmer had additional stipulations.

Table C2. Combinations for test scenario two (typical electronic transformer with compatible incandescent dimmer).

Lamp ID	Number of Connected Lamps	Electronic Transformer		Dimmer
13RT-39	5	X1	B&L Technologies CV90001	Leviton 80800
13RT-41	5	X1	B&L Technologies CV90001	Leviton 80800
13RT-44	5	X1	B&L Technologies CV90001	Leviton 80800
14-01	5	X1	B&L Technologies CV90001	Leviton 80800
14-02	5	X1	B&L Technologies CV90001	Leviton 80800
14-03	5	X1	B&L Technologies CV90001	Leviton 80800
14-04	5	X1	B&L Technologies CV90001	Leviton 80800
14-05	5	X1	B&L Technologies CV90001	Leviton 80800
14-06	5	X1	B&L Technologies CV90001	Leviton 80800
14-08	5	X1	B&L Technologies CV90001	Leviton 80800
14-09	5	X1	B&L Technologies CV90001	Leviton 80800
14-10	5	X1	B&L Technologies CV90001	Leviton 80800
14-11	5	X1	B&L Technologies CV90001	Leviton 80800
14-13	5	X1	B&L Technologies CV90001	Leviton 80800
14-14	5	X1	B&L Technologies CV90001	Leviton 80800
14-15	5	X1	B&L Technologies CV90001	Leviton 80800
14-17	5	X1	B&L Technologies CV90001	Leviton 80800
14-18	5	X1	B&L Technologies CV90001	Leviton 80800
14-19	5	X1	B&L Technologies CV90001	Leviton 80800
14-22	5	X1	B&L Technologies CV90001	Leviton 80800
14-23	5	X1	B&L Technologies CV90001	Leviton 80800
14-24	5	X1	B&L Technologies CV90001	Leviton 80800
14-25	5	X1	B&L Technologies CV90001	Leviton 80800
14-26	5	X1	B&L Technologies CV90001	Leviton 80800
14-27	5	X1	B&L Technologies CV90001	Leviton 80800
14-28	5	X1	B&L Technologies CV90001	Leviton 80800
14-29	5	X1	B&L Technologies CV90001	Leviton 80800
BK14-31	5	X1	B&L Technologies CV90001	Leviton 80800
BK14-32	5	X1	B&L Technologies CV90001	Leviton 80800
BK14-33	5	X1	B&L Technologies CV90001	Leviton 80800

Table C3. Combinations for test scenario three (magnetic transformer/MLV dimmer).

Lamp ID	Number of Connected Lamps	Magnetic Transformer	MLV Dimmer
13RT-39	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
13RT-41	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
13RT-44	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-01	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-02	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-03	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-04	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-05	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-06	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-08	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-09	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-10	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-11	5 (No Power Data)	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-13	5 (No Power Data)	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-14	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-15	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-17	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-18	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-19	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-22	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-23	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-24	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-25	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-26	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-27	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-28	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
14-29	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
BK14-31	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
BK14-32	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P
BK14-33	5	QE001292AS (Halo H1499TAT)	Lutron DVLV-600P

Table C4. Combinations for test scenarios four and five (RMS 12V AC and 12V DC).

Lamp ID	Number of Connected Lamps (AC)	Number of Connected Lamps (DC)
13RT-39	5	1
13RT-41	5	5
13RT-44	5	5
14-01	5	5
14-02	5	5
14-03	5	1
14-04	5	5
14-05	5	5
14-06	5	5
14-08	5	1
14-09	5	1
14-10	5	5
14-11	5	5
14-13	5	1
14-14	5	5
14-15	5	5
14-17	5	1
14-18	5	5
14-19	5	5
14-22	5	5
14-23	5	5
14-24	5	1
14-25	5	5
14-26	5	1
14-27	5	5
14-28	5	(Did not operate)
14-29	5	5
BK14-31	2	1
BK14-32	2	1
BK14-33	2	1