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The Energy and Operational Impacts of Using 0-10V Control for LED Streetlights

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Comments

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Abstract

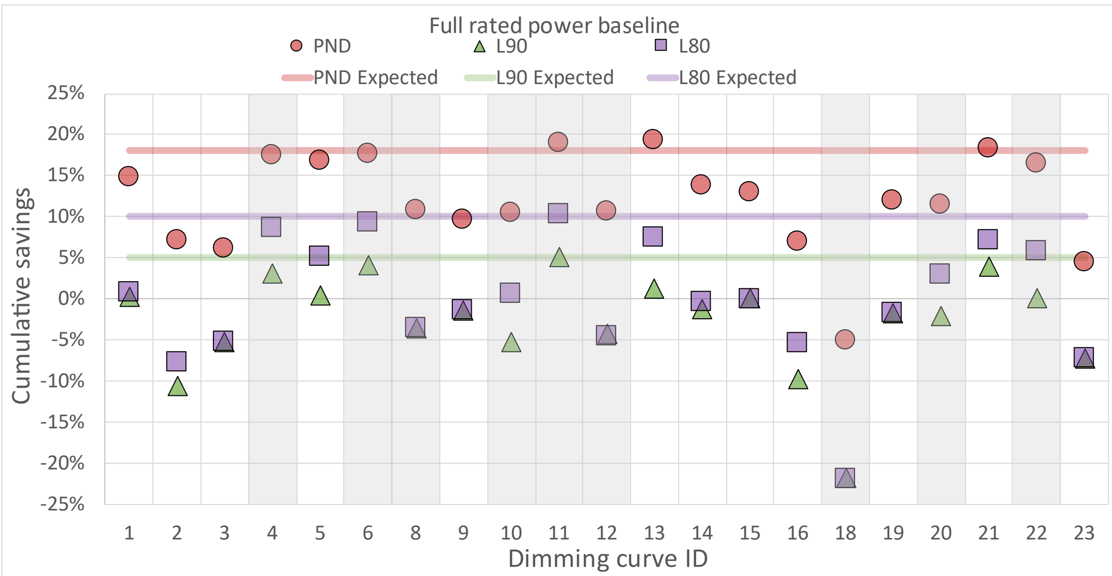
Lighting systems have historically utilized either a proprietary control method, or one of a handful of standardized methods (e.g., 0-10V, DALI, DMX512) aimed at facilitating vendor interoperability. The utility and market success of the standardized methods has been limited for a variety of reasons. Although 0-10V is presently the most commonly available control interface for indoor and outdoor products in North America – even after the emergence of LED products and "connected lighting systems" with more modern network interfaces and luminaire-level sensors and intelligence – the use of 0-10V methods has significant tradeoffs. For instance, it is difficult to predict relative luminaire light output and input power at any particular control voltage, and performance across luminaires is inconsistent. This study characterizes 23 LED streetlights that claimed dimmability via a 0-10V interface, quantifies the performance variation found in market-available LED drivers, and explores the potential impact of the most recent 0-10V voluntary standard (ANSI C137.1-2022). Notably, the tested products were all manufactured prior to the release of this standard, and thus do not make compliance claims. Variation in response to 0-10V control voltages was expected to be more significant across different make/model luminaires than different units of the same make/model; the test population was structured based on this expectation. The 23 tested luminaires comprised 21 unique make/model streetlights from 14 different manufacturers. Three samples of one make/model streetlight were included in the test population to facilitate a limited exploration of unit-to-unit variation. The 21 unique make/model luminaires contained 20 unique make/model LED drivers from eight different driver manufacturers. Luminaire input power and current were measured at 11 control voltages (0.5 V and 1–10 V in 1 V increments).

Variation in the luminaire response to 0-10V control signals was substantial. Across all the luminaires and tested control voltages, the range of relative power draw was on average ~53 percentage points. Nineteen of the 21 LED drivers were evaluated for ANSI C137.1-2022 voluntary standard compliance and 9 of the 19 were found to be noncompliant. The range of relative power draw across the 12 luminaires containing ANSI C137.1-2022 compliant LED drivers at a tested control voltage was on average ~47 percentage points. From this limited testing, it appears that adoption of the ANSI C137.1-2022 voluntary standard will have a positive impact on market-available products (i.e., a reduced variation in response to a given control voltage) but will not necessarily result in uniform or predictable performance.

If controllers that operate luminaires with 0-10V interfaces are not calibrated to the unique control signal responses of those luminaires, and controllers are configured with the expectation of a linear response from 0% relative light and power at a 0V control signal to 100% relative light and power at a 10V control signal – as is common in real-world products and system configurations – then unexpected lighting levels or energy performance are likely to occur. When implementing energy saving control strategies, such unexpected energy performance may compromise the realization of energy saving goals. This study explored the potential impact of using 0-10V control on the two predominant energy saving control strategies for outdoor lighting: a Part-Night Dimming (PND) strategy that dims light output for part of the night and a Constant Light Output (CLO) strategy that trims excess initial light output and subsequently compensates for lumen depreciation over luminaire lifetime. Based on the sample this study characterized, luminaires that use 0-10V control for a PND strategy that targets a reduction in energy use and cost of 18% would see an average reduction of only 12%. Similarly, our evaluation of two CLO strategies – L_{90} at 20 years and L_{80} at 16 years – shows, on average, an increase in energy use and cost of 2% and no savings, respectively, rather than the expected savings of 5% and 10%, respectively. The use of ANSI C137.1-2022 compliant LED drivers is not a sufficient substitute for calibrating luminaire controller output to the actual 0-10V dimming curve of a given make/model luminaire. On average, ANSI C137.1-2022 compliant LED drivers do not improve the energy or cost savings delivered by a PND strategy, only marginally improve the savings delivered by an L_{90} at 20 years CLO strategy, and improve the savings delivered by the L_{80} at 16 years CLO strategy from 0% to 5% – only half of the expected 10% savings. Figure below shows the cumulative energy and cost savings delivered by these three lighting

control strategies, relative to a full rated power baseline, for each of the 0-10V dimming curves characterized in this study.

The results of this study can help the lighting industry and standards developing organizations to better understand and possibly resolve the shortcomings of 0-10V products and consider what is best for the industry – namely, accurate and consistent dimming performance across all luminaires in a lighting system, guaranteeing the delivery of expected light levels, energy, and cost savings. This report makes recommendations consistent with these goals to lighting and LED driver manufacturers, lighting software developers, standards developing organizations, and system designers and specifiers. While this study focused on LED streetlights, similar results are to be expected for other luminaires that utilize 0-10V control signals, as the underlying phenomena are not a function of lighting application.



Cumulative energy and cost savings delivered by dimming curves from all luminaires characterized in this study, for one Part-Night Dimming (PND) strategy (red) and two Constant Light Output (CLO) strategies – L_{90} at 20 years (green), L_{80} at 16 years (violet) – relative to the full rated power baseline. The gray shaded columns represent ANSI C137.1-2022 noncompliant products. Notably, L-3, L-9, and L-23 are three units of the same make/model streetlight.

Introduction

Methods for using an analog low voltage signal to dim light sources were first developed in the 1980s for controlling fluorescent lamp ballasts. Multiple standards for such methods have been developed, each of which has been generally referred to as a 0-10V control method. Simplicity and low cost of implementation has made these methods a popular option for both specifiers and manufacturers. Over the last 40 years, a variety of more advanced lighting control methods have been developed, and some of them even standardized (e.g., DALI, DMX512). While these methods offer greater capabilities, they can be proprietary, complex to configure, and costly to implement. The utility and market success of the standardized methods has been limited for a variety of reasons. In some cases, performance aspects that are key to meeting lighting design goals are not covered by a standard, leading to varying product implementations that can yield unpredictable and unsatisfying results. Compliance testing tools and processes for the standardized methods have not been available or mandated for most of their existence, and as a result, manufacturer interpretations have varied. These varying implementations and interpretations can result in specification and commissioning challenges ranging from difficult-to-predict performance to undesirable outcomes that may or may not be correctable in the final installation. Standards developers have attempted to address some of these limitations. For example, the [Digital Illumination Interface Alliance](#) (DIIA) introduced a [certification program](#) for the DALI-2™ specification in 2017; this improved interoperability and led to more predicable performance among certified products, but has not led to widespread adoption of DALI-2™ by the lighting industry. Of the 139,902 entries in the DesignLights Consortium Qualified Products List (DLC QPL) for Outdoor Luminaires on October 28, 2023, only 22,059 (~15%) offer DALI as a control method while the vast majority of the products (134,939) offer 0-10V as a control method. More recently, the DIIA introduced D4i™, an extension of the DALI-2™ certification program. D4i™ LED drivers have the capability to store and report a wide range of luminaire, energy, and diagnostics data in a standardized format.

In recent years, LED technology has revolutionized the lighting industry. While dimmability was an expensive feature for all previous energy-efficient lighting technologies, it has become a baseline capability for many LED products, including LED streetlights. For example, of the 139,902 entries in the DLC QPL for Outdoor Pole/Arm-Mounted Area and Roadway Luminaires on October 28, 2023, only 144 (~0.1%) were marked "Not Dimmable." The emergence of "connected lighting systems" with more modern network interfaces and luminaire-level sensors and intelligence was anticipated by many to mark the beginning of the end of analog control. However, 0-10V interfaces continue to be the most commonly available luminaire control option with these more "digital" systems, in large part due to its low cost and simplicity. 0-10V control does not require any configuration for basic functionality, and its simple approach to communicating control signals is reliable and subject to few issues, which are well-known and installation-dependent. However, the simplicity of 0-10V methods comes with a significant trade-off; although the communication of the 0-10V control signal is typically reliable, the interpretation of that control signal by a luminaire is not. Perhaps the most basic lighting control requirement is the ability to reliably set the relative light output of a luminaire or a group of luminaires to a desired level (e.g., 50% or 90% of maximum output). 0-10V standards have historically only specified driver (and ballast[1]) output power levels at the high and low end of the control voltage range, and not explicitly defined the relationship between the luminaire input control signal and output luminous flux (the "dimming curve") for the full control signal range. As a result, it is difficult to predict relative luminaire light output and input power at a given control voltage, and in practice, performance is inconsistent across LED drivers and the luminaires they power.

While this inconsistency has long been acknowledged by experts in the field, it is not accounted for in standard practice product development, specification, and configuration. End-users continue to regularly see unexpected and undesirable performance. Most commercially available controllers assume the load that they are controlling has a simple linear relationship between control signal and input power (or output light level) that spans the entire control voltage range. Some controllers provide options for fundamental non-linear relationships (e.g., exponential/logarithmic), but few offer the ability to define custom non-linear relationships. These custom relationships would allow for the control signal sent to each unique luminaire make and model to be "calibrated" according to the luminaire relationship between 0-10V control signal and input power (and associated light level). Such calibration requires the characterization of this relationship for each luminaire – yielding what is often referred to as a "dimming curve"– and the ability for the luminaire controller to assign the appropriate dimming curve to a given luminaire during the commissioning process. While neither capability is technically challenging, they do require some implementation effort and associated cost for the luminaire and controller manufacturer, as well as the commissioning agent. To date, neither has become standard practice.

Varying luminaire responses to input control signals and the lack of a standard practice to compensate for (or even acknowledge) these variations lead to unexpected and undesirable lighting performance. Some examples include:

[1] LED drivers are discussed in this report, but the concepts also apply to ballasts.

- Energy and cost savings goals associated with common lighting control strategies (e.g., Part-Night Dimming, Constant Light Output) may not be realized.
- Adjacent luminaires with different LED drivers that dim to different light levels when provided with the same control signal might compromise visibility or be visually unappealing.
- Dead zones in the dimming curve, where the control signal is changing but light levels are not, may lead users to think that one or more aspects of the lighting control system are not functioning as intended.

This report quantitively exposes variations in the response of commercially-available streetlights to 0-10V control signals, evaluates the potential impact of those variations on energy use and cost, and explores how well the ANSI C137.1-2022 voluntary standard might mitigate such variations.

Background

0-10V control voluntary standards specify how an analog low-voltage control signal should be created, and how a driver should interpret the control signal and thereby adjust its output power to the light source – typically by changing amplitude of DC output current or by pulse width modulation of the output current. Analog 0-10V control requires the connection of two low-voltage wires between the control and the driver. The 0-10V DC voltages that serve as control signals can be created in two different ways, current-sourcing and current-sinking, as shown in Figure 1. In both approaches, a control current is passed through multiple resistors and the resulting voltage drop across the resistors creates the control voltage. In the current-sourcing method, the control sources current to the driver; in the current-sinking method, the driver sources current to the control. Both 0-10V control method implementations have been standardized. The Entertainment Services and Technology Association standardized a current-sourcing method (ESTA E1.3) that specifies a driver output of “full” (i.e., maximum) when the control signal is 10 V and “zero” (i.e., minimum) when it is 0 V [ESTA 2016]. Between these two voltage limits, the standard specifies that the “receiver shall vary between minimum and maximum.” ESTA E1.3 compliant products are typically used in theatrical and entertainment dimming systems. Meanwhile, the International Electrotechnical Commission (IEC 60929 Annex E) and ANSI C82.11 Annex A both standardized a current-sinking method that has been used by the architectural lighting industry to control fluorescent and HID lighting for over 35 years [IEC 2014; ANSI 2017]. The standard specifies a driver output of “maximum” when the control signal is 10 V and unspecified “minimum” level when the control signal is 1 V. Between these two voltage targets, the standard specifies “arc power rising from minimum to maximum value.” Notably, an off (i.e., zero power) state is not specified. As a result, line voltage to the driver is typically switched in installations to ensure the ability to create an off state.

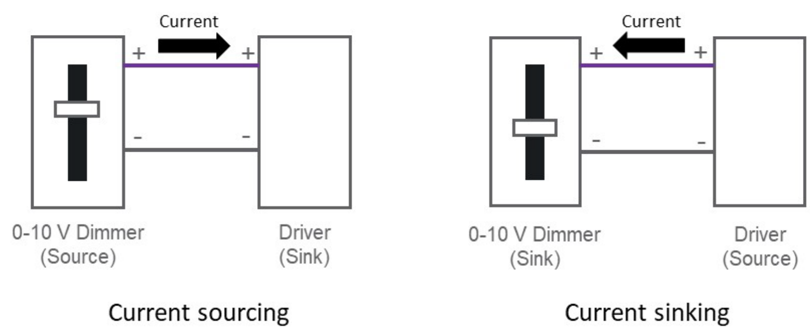


Figure 1. Two ways in which analog 0-10 V dimming can be achieved; in the current sourcing method, the dimmer sources current to the driver while in the current sinking method, the dimmer sinks current sourced by the driver.

In recent years, the National Electrical Manufacturers Association (NEMA) ANSI C137 Lighting Systems Committee launched an effort to improve 0-10V control by reducing the performance variation seen in commercial products and corresponding likelihood of unexpected light levels and energy use that have long been reported by experienced end-users. This effort resulted in the release of ANSI C137.1-2019, and more recently ANSI C137.1-2022 [ANSI 2019, ANSI 2022], a voluntary standard for 0-10V control of LED drivers that builds upon previous current-sinking specifications (i.e., IEC 60929 and ANSI C82.11). It requires LED drivers to reach maximum output at either 8 V or 9 V and retains the requirement to provide an unspecified "minimum" output at 1 V. Between these two voltage targets, the standard specifies that "output power of LED driver shall rise monotonically as control voltage rises from low control voltage to high control voltage." It also states that the dimming curve shall be "linear or logarithmic" in shape. Although logarithmic dimming curves are actually exponential in shape, they are commonly referred to as logarithmic because they are designed to account for the logarithmic nature of perceived brightness as a function of light output. The "minimum" output varies in the marketplace; while most LED drivers can dim to 10% of full output, some can only dim to 30%, some can dim to 1% or even lower, and some ambiguously claim to be able to "dim to off," which says nothing about the minimum relative output before turning off. In addition, the standard specifies control voltage targets for standby mode as ≤ 0.5 V and for power on between 0.8 V – 1.2 V, as well as output-value (rate of) change time (i.e., the time from power ON to output power or the time to change from one output value to another).

Notably, 0-10V methods only define how a driver should respond to a control signal. They do not define how a control signal should be created in response to user requests or needs. Multiple input-output relationships define how the lighting system responds to user requests or needs. The first relationship is between control input (e.g., user interface, automated control system) and the control output (i.e., control signal), which depends on the design of the user interface or control system; while this relationship is often assumed to be linear, it frequently is not. The second relationship is between the control signal and driver power, which depends on the driver design. The final relationship is between driver power and luminous flux, which depends on the lighting technology used, but is usually linear for LED sources. These relationships can be represented by stimulus-response curves, which are helpful to understand lighting device behavior.

Despite the typically linear relationship between LED driver power and luminous flux, the relationship between the control input and LED driver output power is not always linear, but rather depends on the combination of the other two response curves, as shown in Figure 2. While most end-users assume that all three relationships are linear, product developers offer user interfaces, controllers, and drivers with non-linear relationships – in some cases highlighting the non-linear behavior as a differentiating feature of the product, and in other cases as a configurable option for the product. Typically, non-linear relationships are utilized to achieve better stimulus resolution over a portion of the stimulus-response curve.

As shown in the non-linear examples in Figure 2, logarithmic relationships offer better resolution at lower levels of stimulus, at the expense of worse resolution at the higher levels of stimulus. For example, if the stimulus is a 0-10V control signal, and the device that creates the control signal can only create 0.5 V steps along the 10 V range, then the linear stimulus-response relationship produces a consistent 5% increase in the response for each stimulus step, resulting in a minimum stimulus resolution of 5%. However, in the case of the logarithmic stimulus-response relationship, each incremental stimulus step produces a response step that starts very small and grows steadily until it reaches 5% in the vicinity of 8 V for our example (i.e., 80% of the stimulus range), and then exceeds 5% for the remainder of the stimulus range. Better resolution at low end is advantageous if the aim is to make fine adjustments to the response at the low end, as can be the case in some lighting applications (e.g., in restaurants or other environments where low light levels are used to create desirable atmosphere). However, worse resolution at the high end of the stimulus range is a problem for lighting applications that target adjustments in that regime (e.g., most energy-saving control strategies).

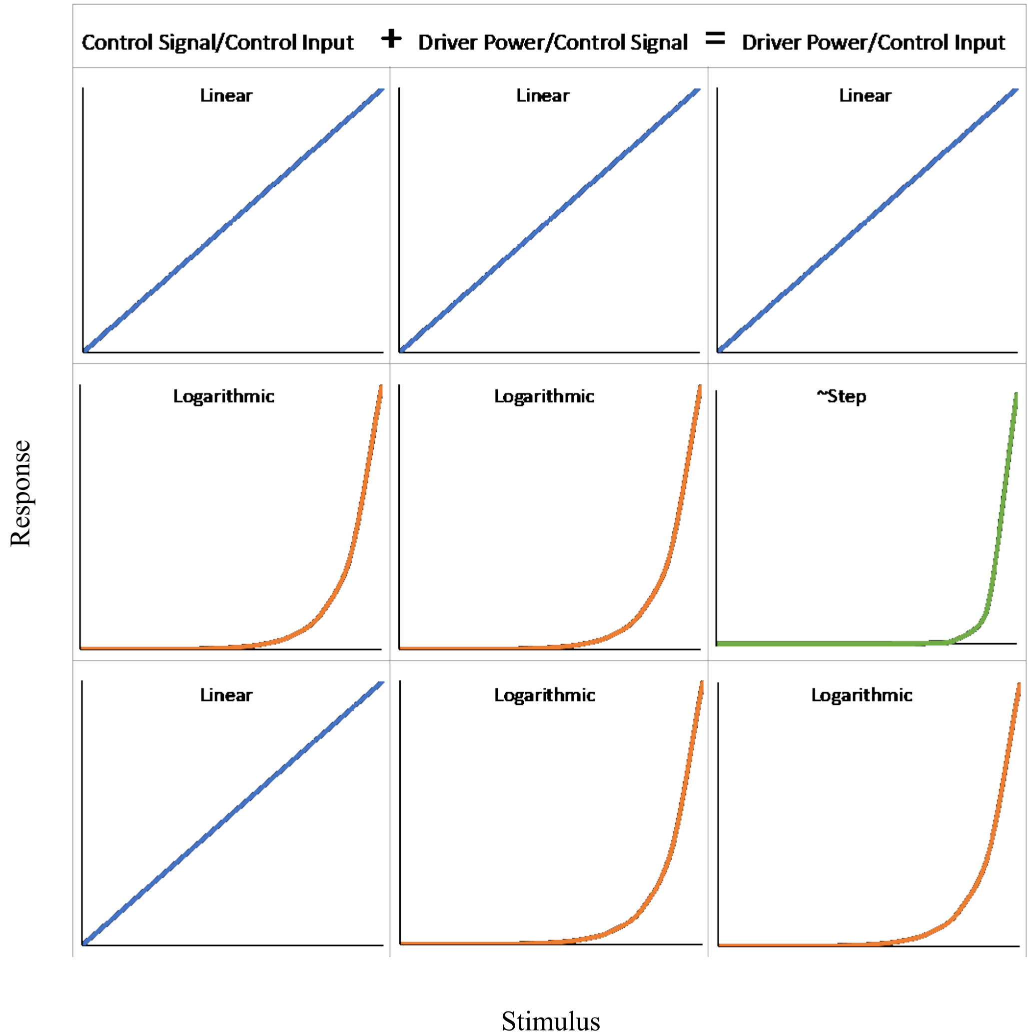


Figure 2. LED luminaire dimming curves that result from three different combinations of control input and driver power curves. In all cases, the stimulus is shown on the horizontal (x) axis, and the response is shown on the vertical (y) axis.

Test Setup, Implementation, and Procedure

This study explores the response of commercially available LED outdoor cobrahead-style luminaires (typically used for streetlighting applications) with ANSI C136.41 receptacles to 0-10V control signals. A test setup consisting of a power meter, a multimeter, and a 0-10V residential wallbox dimmer measured the power drawn by a luminaire under test at different control voltages. The luminaires were powered via a junction box that facilitates the measurement of luminaire current and power draw by the power meter. The current-sink dimmer was used to set the control voltage. The dimmer was wired to a custom-made jig compatible with the ANSI C136.41 receptacle. The multimeter measured the voltage across the output wires of the dimmer. The 0-10V control signal was delivered via the ANSI 136.41 compliant receptacle, and luminaire input power was measured at varying control signal settings. Figure 3 shows a high-level block diagram of the test setup implementation.

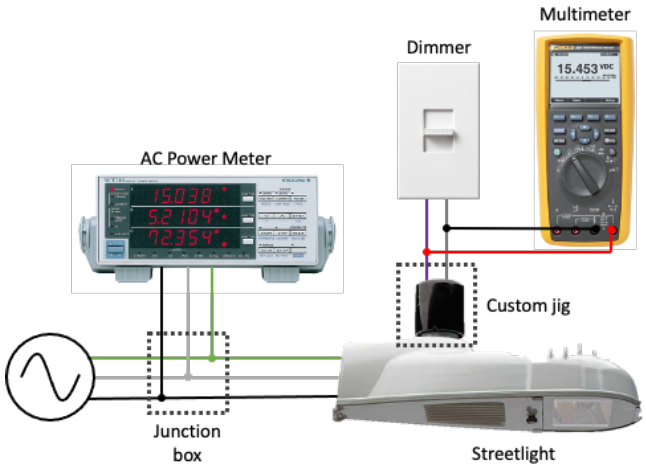


Figure 3. Block diagram of the test setup implementation.

This setup was implemented in the Pacific Northwest National Laboratory (PNNL) Connected Lighting Test Bed (CLTB) by using a Yokogawa WT210 power meter, Lutron NFTV-WH 0-10V mechanical slider dimmer, and Fluke 287 True RMS multimeter. Although the Yokogawa WT210 and Fluke 287 were calibrated by the respective manufacturers (prior to purchase) to ensure the initial accuracy of the measuring equipment satisfied manufacturer performance claims, neither was subsequently calibrated by an accredited laboratory. Table 1 provides key rated characteristics of these three hardware components.

Table 1. Key rated characteristics of the primary test setup equipment.

Yokogawa WT210 Power Meter		Voltage range: 0–600 V Current range: 0–20 A Sample rate: 50 kS/s Power accuracy at 45-66Hz: 0.1% of reading + 0.1% of range
Fluke 287 True RMS Multimeter		Voltage range: 0–1000 V Current range: 0–10 A DC voltage accuracy: 0.025% DC current accuracy: 0.05%
Lutron NFTV-WH 0-10V Dimmer		Dimmer type: slide Preset option: no Control current: 30 mA max Current-sink control method

The slider dimmer produced a 0.5 V control signal at its lowest dimming position and created an air gap "off" when slid further to its endpoint. Luminaire input power and current were measured at 11 control voltages (0.5 V and 1–10 V in 1 V increments) by manually changing the dimmer position as well as with shorting caps. Luminaire light output was not measured. However, it is well-known that the relationship between input power and light output (i.e., luminous flux) is linear and monotonic for LED light sources over most of their operating range [Jingting Wei et al. 2013]. The power and current data were manually recorded from the Yokogawa power meter at each control voltage.

Test Units, Results, and Analysis

Dimming performance of 23 luminaires that claimed 0-10V dimming was characterized in a laboratory environment. Variation in response to 0-10V control voltages was expected to be more significant across different make/model luminaires than different units of the same make/model. The test population was structured based on this expectation. The 23 tested luminaires comprised 21 unique make/model streetlights from 14 different manufacturers. Three samples of one make/model streetlight were included in the test population to facilitate a limited exploration of unit-to-unit variation. The 21 unique make/model luminaires contained 20 unique make/model LED drivers from eight different driver manufacturers. The rated maximum power draw for the set of products ranged from 25 to 161 W. The tested products all had ANSI C136.41 receptacles internally wired to the control pins of the driver but varied by luminaire and LED driver make/model. The luminaires and LED drivers had varying rated maximum power draws. All of the LED driver manufacturers claimed a linear dimming curve for their products. Whereas the LED driver in the three samples of one make/model luminaire claimed a dimming range of only 30–100%, all the others claimed a range of 10–100%. Datasheets for 12 of the 21 unique products provided dimming curves that enabled determination of low- and high-control voltages, along with corresponding relative output values. Laboratory testing was conducted at the PNNL CLTB in March 2019. Luminaire and driver information for all products is shown in Appendix A.

Given that the luminaires and LED drivers have different rated maximum input power, relative luminaire input power and relative LED driver output power were calculated at each control voltage as shown below:

1. *Relative luminaire input power (%) = (Measured input power / rated maximum input power) * 100%*
2. *Relative LED driver output power (%) = ((Measured input power * rated driver efficiency) / rated maximum output power) * 100%*

Luminaire Power Draw

Luminaire maximum power draw was evaluated when a) controlled by a shorting cap and b) subjected to a 10 V control signal. A shorting cap creates a "no-control signal," always-on scenario which is different from the 10 V control signal scenario. The measured luminaire power draw when controlled by a shorting cap was higher than the manufacturer rated (maximum) input power for all but two luminaires (L-7 and L-21), as shown in Figure 4. Most luminaires were within 10 percentage points of the manufacturer rating. However, there was substantial overall variation, ranging from a relative (to the manufacturer rating) luminaire power draw of ~55% (for L-7) to ~125% (for L-18), a span of 70 percentage points. Across all luminaires, the average difference between luminaire maximum power draw when controlled by a shorting cap and when subjected to a 10 V control signal was ~4 percentage points.

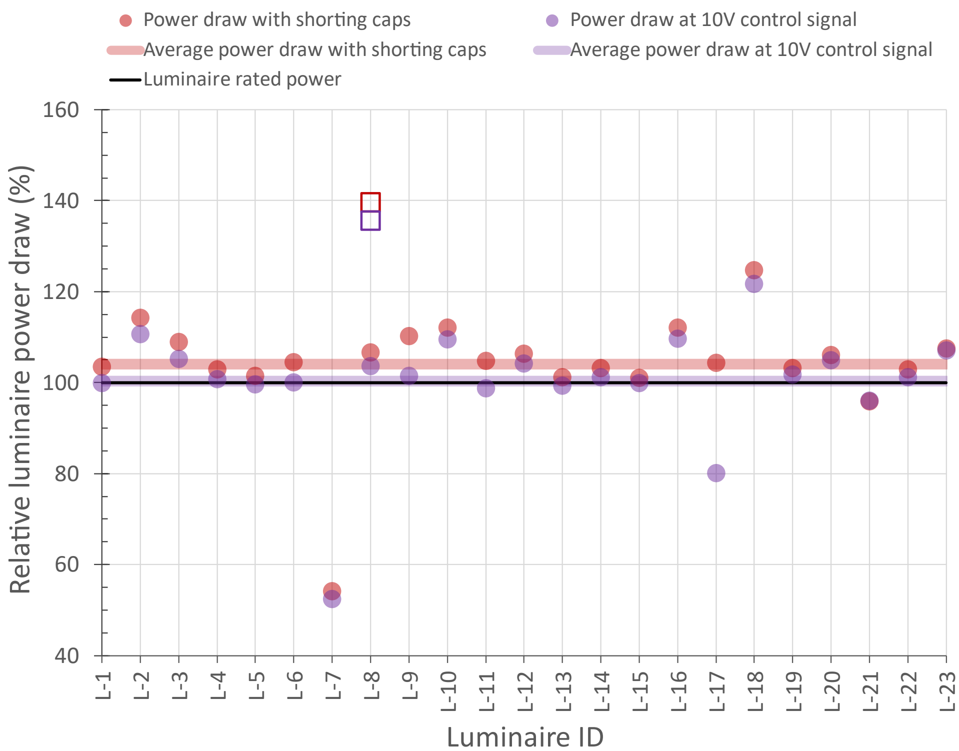


Figure 4. Relative (to manufacturer rating) luminaire input power draw when a) controlled by a shorting cap vs. b) subjected to a 10 V control signal. Two calculations are shown for L-8: one (box markers) based on an erroneous "nameplate" sticker applied to the luminaire, and a second (circle markers) based on (true) datasheet ratings. Notably, L-3, L-9, and L-23 are three units of the same make/model streetlight.

When subjected to a 10 V control signal, the measured power draw of all but three luminaires (L-7, L-17, and L-21) was higher than the manufacturer rating. Across all luminaires, the average difference was ~0.5 percentage points. Once again, however, there was substantial variation between luminaires, which ranged from a relative luminaire power draw of ~50% (for L-7) to ~120% (for L-18), a span of 70 percentage points. All luminaires drew more power when a shorting cap was used than when subjected to a 10 V control signal. For most luminaires, the difference between the shorting cap and 10 V control signal measurements was on the order of a few percentage points. However, for luminaires L-9 (~10 percentage points) and L-17 (~25 percentage points), this difference was more substantial. In Figure 4, two sets of relative luminaire power draw calculations are shown for luminaire L-8. The initial set – shown by unfilled square markers – was calculated relative to a rated input power of 55 W that was derived from an attached "nameplate" sticker. The resultant relative luminaire power draw of almost 140% when controlled by a shorting cap raised safety concerns and led to further investigation. Review of documentation found on the manufacturer website showed that the luminaire actually had a rated input power of 72 W. The second set of calculations – shown by circle markers – was derived from this 72 W rating.

Figure 5 shows the dimming curve of each luminaire, along with the commonly "expected" linear response from 0% relative power at a 0 V control signal to 100% relative power at a 10 V control signal. Most luminaires exhibited a "dead band" (i.e., a lack of response to the varying input control signal) above 8 V and below 1 V. While the three luminaires rated for 30–100% were indeed unable to reduce their relative power draw below 30%, most of the other luminaires were able to dim to 10%, and a few were able to dim to less than 10%. Two results are shown for luminaire L-8. The brown dashed line depicts the relative luminaire power as derived from the erroneous luminaire "nameplate" sticker rating of 55 W. The correct response, based on the 72 W rating, is plotted separately.

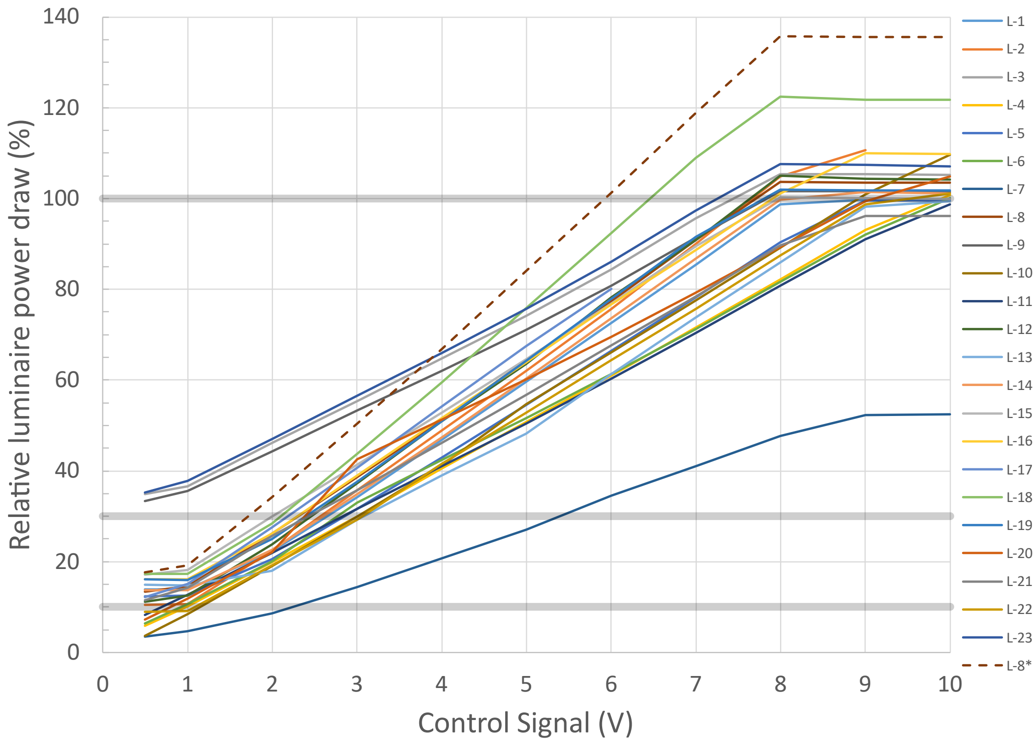


Figure 5. Dimming curves for all luminaires along with an "expected" linear curve (thick red line). Horizontal threshold lines are highlighted at 10%, 30%, and 100% of rated maximum input power. *A second (dashed) curve for luminaire L-8 shows the response relative to the incorrect 55 W nameplate rating.

Figure 5 partially reveals the causes of the significant deviations from manufacturer ratings for luminaires L-7 and L-17 seen in Figure 4. Luminaire L-7 responds to the full range of 0-10V control signal inputs, but never draws more than ~50% relative input power. An inspection of the LED driver in L-7 reveals that it has rated output power of 40 W, while the luminaire has a rated input power of 55 W, and only draws 30 W in the presence of a 10 V control signal, so an undersized LED driver possibly contributes to the poor dimming performance. The dimming curve for Luminaire L-17 stops at a control signal of 6 V, revealing what appears to be an LED driver inability to source enough current for the 0-10V dimmer to produce control signals above 6 V, resulting in a maximum relative luminaire power draw of only ~80%.

Dimming curve variations across luminaires can be more clearly visualized using a violin plot (see Figure 6), where each violin shows the distribution of luminaire responses at a given distinct 0-10V control signal (i.e., 0.5 V or an integer value from 1–10 V). The variation in relative luminaire power draw was greatest for an 8 V control signal. The variation seen at lower control signals is the result of varying LED driver minimum power ratings (i.e., 10% or 30%, relative to rated maximum power), and the variation seen at higher control signals is the result of luminaires reaching their maximum power draw at different points in the dimming curve (i.e., at 8 V, 9 V, or 10 V).

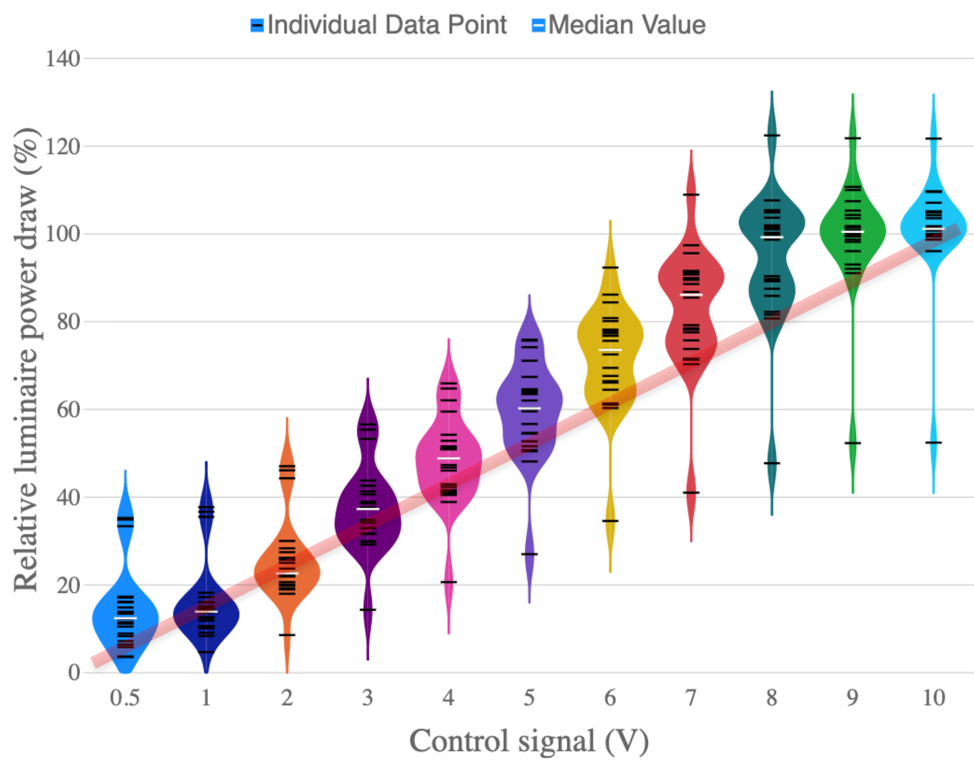


Figure 6. Variation in the relative luminaire power draw at 11 distinct 0-10V control voltages. The horizontal width of each violin-style histogram denotes the frequency of values, and the vertical length shows their range. Black barcode stripes represent measured values, white stripes highlight median values, and the thick red line shows an "expected" linear dimming curve.

LED Driver Output Power

Relative LED driver output power was calculated at each control voltage using manufacturer-reported driver efficiency. The 21 unique make/model LED luminaires contained 20 unique make/model LED drivers. Datasheets for two of the LED driver make/models could not be found, and as a result they were not included in this analysis, so 18 unique make/model LED drivers were analyzed. All 18 make/model drivers claimed a linear dimming curve, 17 of them claimed a dimming range of 10–100%, and one claimed a range of only 30–100%. A total of 21 LED driver units were analyzed (one unique luminaire instance of 16 LED drivers, two unique luminaire instances of one LED driver, and three identical luminaire instances of the one LED driver that claimed a 30–100% dimming range). The characteristics of some LED drivers are captured on multiple manufacturer datasheets. Sometimes a "product family" datasheet contains information about multiple LED drivers. Basic characteristics are typically captured on a brief datasheet, and sometimes an "extended" datasheet contains additional details. For LED drivers with efficiency curves, LED luminaire power was calculated by dividing the LED driver output power by the LED driver efficiency at that output power level, and the resulting LED luminaire power vs. LED driver output power curve was used to create LED driver output power vs. control signal curves.

The LED drivers exhibited substantial differences in the calculated relative output power at higher control voltages, as shown in Figure 7. This can be attributed to the fact that rated luminaire input power is typically lower than rated LED driver output power (drivers have some internal losses and are generally oversized). This difference between the rated power of LED driver and luminaire can vary with different driver/luminaire make/model combinations. There were a few exceptions, where the rated luminaire input power is higher than the rated LED driver output power, and in some of these cases, the LED driver output power exceeded its rated maximum value. For one LED driver, the "basic" datasheet only stated a single (presumably nominal or best-case) efficiency, while the "extended" datasheet contained an efficiency vs. load curve. Output power for this LED driver was calculated using efficiency values from both documents, as shown by the dashed and solid black lines that track closely on the graph and reach a relative LED driver output power of ~100% at a control signal of 8 V. The dotted line was calculated from the single efficiency value that was stated in the "basic" datasheet, and the solid line was calculated using an efficiency curve found in the "extended" datasheet, which only characterized efficiency between 60% and 100% load; the efficiency below 60% load was assumed to be equal to the efficiency at 60%.

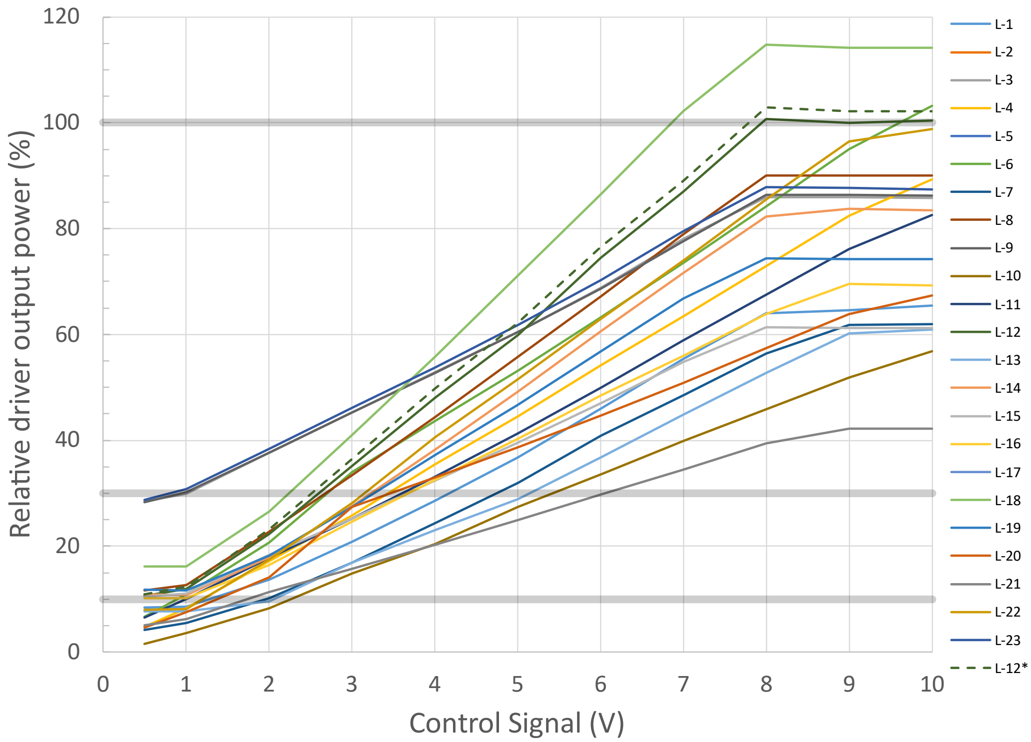


Figure 7. LED driver dimming curves, based on relative driver output power, as calculated from the rated driver efficiency. Horizontal threshold lines are highlighted at 10%, 30%, and 100% of rated maximum input power, and a thick red line shows an "expected" linear dimming curve. Two curves for L-12 (dark green, solid and dashed) show the response based on rated efficiency data found in two different manufacturer documents.

Luminaire manufacturers and lighting designers/specifiers might assume that a given make/model LED driver will always deliver the same dimming performance. However, the dimming performance of an LED driver can vary with the amount of connected load (i.e., the power required by LED array to produce a given luminous flux). Figure 8 shows the dimming curves for two different luminaire models from the same manufacturer (L-18 and L-19), which have the same make and model LED driver. The variation in LED driver performance can clearly be seen by comparing the two curves. For example, when a control signal of 5 V was provided to these luminaires, luminaire L-18 exhibited a relative input power draw of 76%, while luminaire L-19 exhibited a relative input power draw of 64%. The variation was most pronounced at control signals of 8 V and above, where luminaire L-18 exhibited 122% of its rated power and luminaire L-19 exhibited 101% of its rated power.

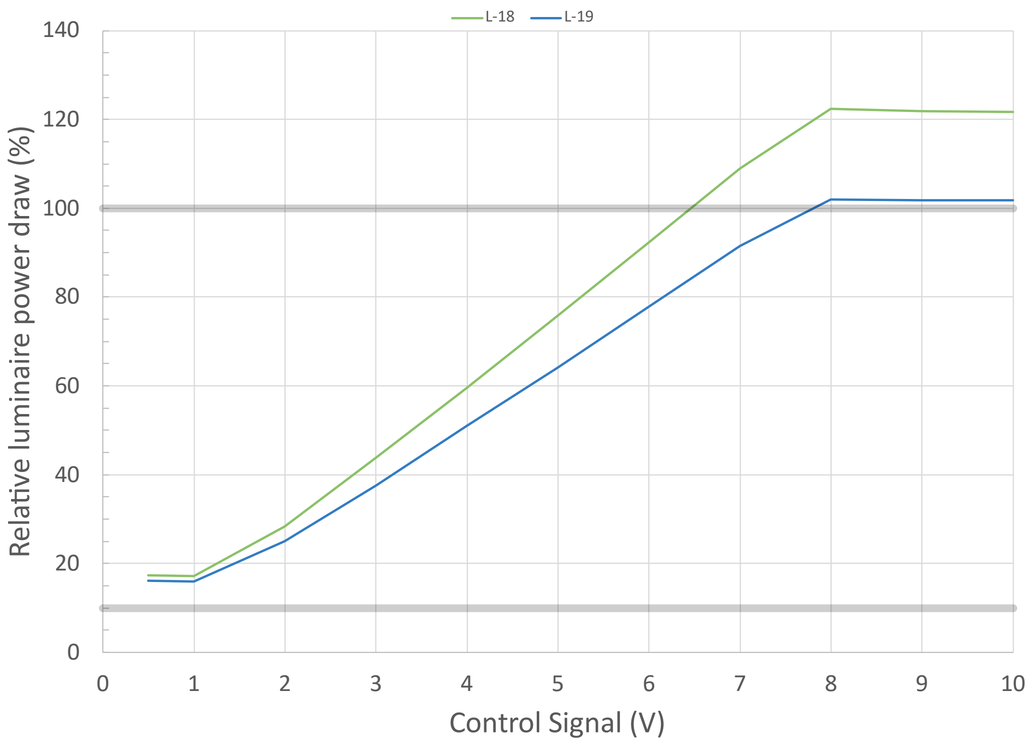


Figure 8. Dimming curves for luminaires L-18 and L-19. Horizontal threshold lines are highlighted at 10% and 100% of rated maximum input power, and a thick red line shows an "expected" linear dimming curve.

Luminaire manufacturers prefer to use the same make/model LED driver in as many luminaire make/models as possible to simplify design and manufacturing processes. A potentially undesirable ramification of this practice was exposed in the analysis of these two luminaires, as shown in Figure 9, where measured luminaire input power draw and calculated LED driver output power are plotted against control voltage. The two luminaires had rated input powers of 54 W (luminaire L-18) and 42 W (luminaire L-19), and the LED driver they both used had rated output power of 50 W. As noted previously, luminaire L-18 presents a larger load to the LED driver than luminaire L-19. While the rated input power of luminaire L-19 is less than (i.e., within the specified capability of) the rated output power of the LED driver, the rated input power of luminaire L-18 is higher than (i.e., exceeds the specified capability of) the rated output power of the LED driver, even if the driver efficiency is 100%. The LED driver output power in both cases is calculated using its rated efficiency at maximum load (86.8%), as stated in the datasheet. At a control signal of 10 V, where the luminaire should be operating at its maximum input power, luminaire L-18 drew 65 W (120% of its rating) while its LED driver delivered 57 W (114% of its rating), while luminaire L-19 drew 42 W (100% of its rating), and its LED driver delivered 37 W (74% of its rating).

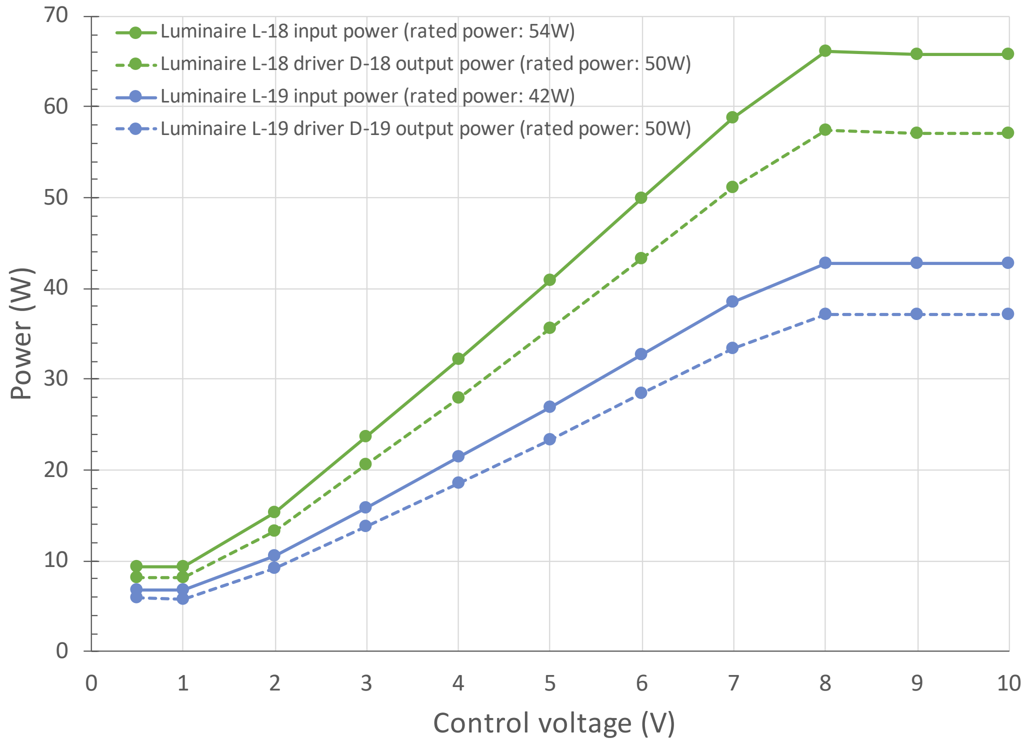


Figure 9. Luminaire input power and LED driver output power as a function of control voltage for luminaires L-18 and L-19. The luminaires are different models from the same luminaire manufacturer; both models use the same make/model LED driver.

ANSI C137.1-2022 Compliance Analysis

The ANSI C137.1-2022 voluntary standard defines performance requirements for LED drivers, but not LED luminaires. To explore the potential impact of the standard, the performance of the LED drivers evaluated in this study was compared with key standard requirements, which are summarized in Figure 10. Notably, the tested products were all manufactured prior to the release of this standard, and thus do not make compliance claims.

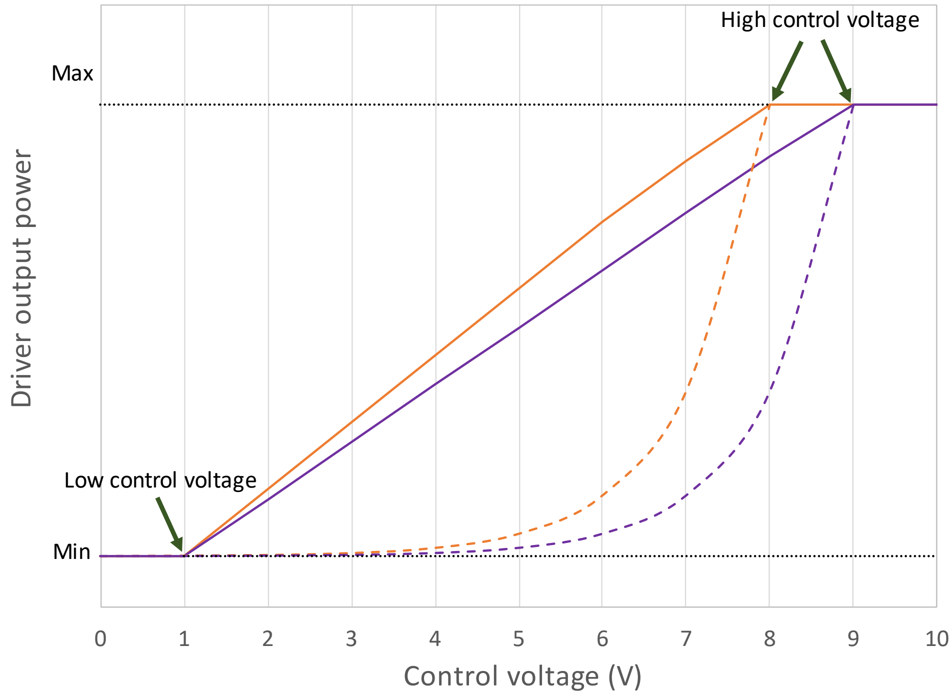


Figure 10. Key ANSI C137.1-2022 voluntary standard requirements for LED drivers with linear (solid) or logarithmic (dashed) dimming curves, which must reach maximum output at either 8 V (orange) or 9 V (purple) control signal voltage.

Nine of the 21 LED driver units, representing nine unique make/model LED drivers, were found to be noncompliant with ANSI C137.1-2022 requirements, as shown in Figure 11. The LED driver make/model installed in two different make/model luminaires was compliant in one luminaire, and noncompliant in the other luminaire. The LED driver that claimed a 30%–100% dimming range and was evaluated in three units of the same make/model luminaire passed all requirements for all three units.

Three types of non-compliance were identified, each represented by a different marker in Figure 11. Eight of the nine noncompliant LED driver units, each representing a unique make/model LED driver, are characterized by a single curve in the figure. One non-compliant LED driver that had both a "basic" and "extended" datasheet was analyzed in two different ways, and is characterized by two curves in the figure, shown in black. If the output power of this LED driver is calculated using the single efficiency value found in its "basic" datasheet, it appears to deliver more power at its high voltage control point than the manufacturer rating, as shown by the black dashed line and empty square. If the output power of this LED driver is calculated based on the efficiency curve provided in its "extended" datasheet, it appears to be compliant in the high control voltage range, as shown by the black solid line. Either way, this LED driver failed to reach rated minimum output power at 1 V.

Seven of the nine noncompliant LED drivers failed a single criterion, while the remaining two failed multiple criteria. Six LED drivers were found to be noncompliant because they failed to reach rated maximum output power at 8 V or 9 V, and one of these also delivered more power at its high voltage control point than the manufacturer rating. Three LED drivers were found to be noncompliant because they failed to reach rated minimum output power at 1 V, and one of these also delivered more power at its high voltage control point than the manufacturer rating.

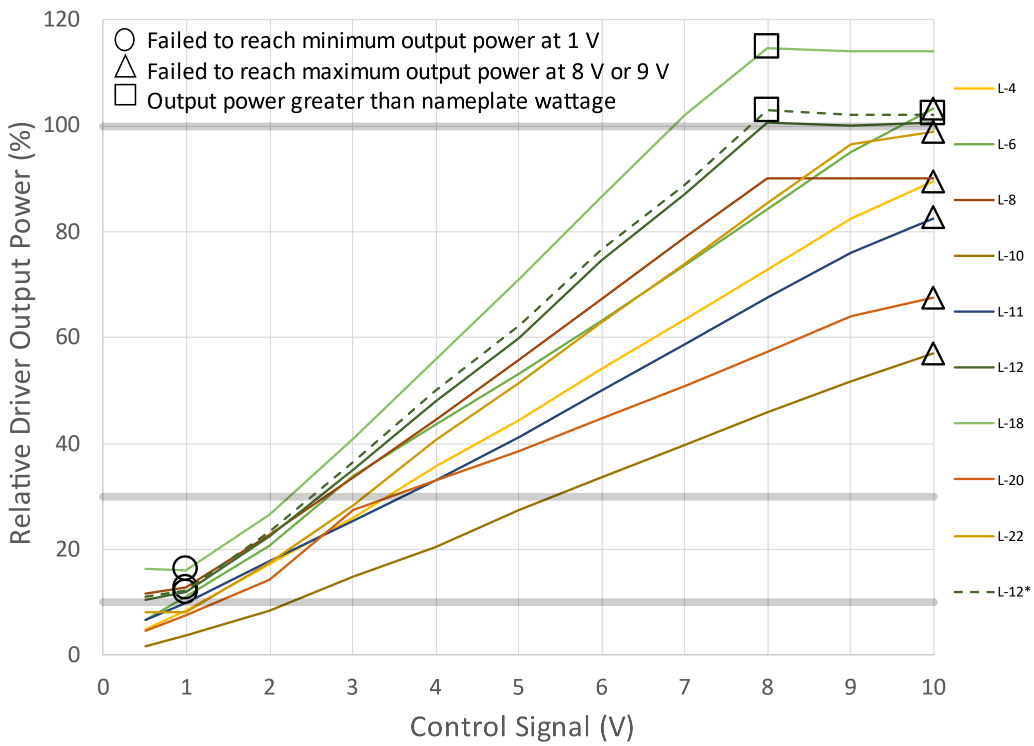


Figure 11. Dimming curves for LED drivers that were found to be non-compliant with ANSI C137.1-2022 voluntary standard requirements. Each shaped marker represents a failed criterion. Horizontal threshold lines are highlighted at 10%, 30%, and 100% of rated maximum input power. Two curves for L-12 (dark green, solid and dashed) show the response based on rated efficiency data found in two different manufacturer documents.

Sixteen of the 21 LED driver units, representing 13 unique make/model LED drivers, were manufactured by National Electrical Manufacturers Association (NEMA) members. The LED driver make/model installed in two different make/model luminaires was manufactured by a NEMA member, as was the LED driver that claimed a 30%–100% dimming range and was evaluated in three units of the same make/model luminaire.

Twelve of the 16 LED driver units manufactured by NEMA members, representing 10 of their 13 unique make/model LED drivers, complied with ANSI C137.1-2022 voluntary standard requirements, as shown in Figure 12. All noncompliant LED driver units were unique models. Three of the four noncompliant LED driver units were manufactured by the same NEMA member. All LED driver units manufactured by non-NEMA manufacturers were found to be non-compliant.

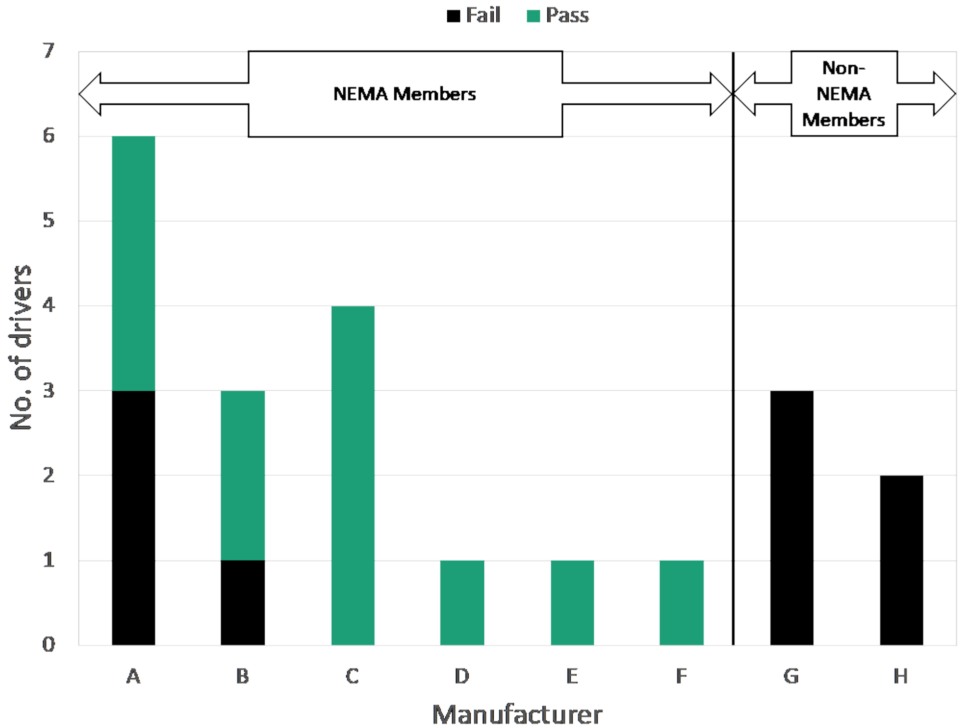


Figure 12. ANSI C137.1-2022 voluntary standard pass (green) /fail (black) results for all evaluated LED driver units, as a function of LED driver manufacturer.

Table 2 summarizes the variation at each control voltage for four different luminaire categories. For each category, the minimum, maximum, and average range of variation is shown (in percentage points) along with the corresponding control voltage. For example, for the group of all 23 luminaires, at a control voltage of 0.5 V, the variation between the lowest relative power draw (3.7%) and the highest relative power draw (35.3%) yielded a relative power draw range of 31.7 percentage points. This range (31.7 percentage points) is the smallest range calculated for any control voltages, and thus it is included in Table 2. Range of variation is chosen as the reported metric, rather than statistical metrics such as standard deviation, to better inform designers and specifiers of potential impacts. In real-world lighting installations, populations of one or more make/model products are installed. Although performance variation across different units of the same make/model might be random and exhibit a normal distribution, this variation is expected to be small compared to variation between make/models. The make/models that are chosen for an installation are not chosen randomly and even if they were, there is no practical reason that any variation in their performance should be normally distributed. In practice, what matters is how the chosen luminaire make/models perform, not how an average or a luminaire within 1-standard deviation performs. Thus, an understanding of worst-case scenarios, represented by the extremes (i.e., the range of performance), is more useful than any statistical metric.

The expectation of smaller variation across units vs. across makes/models is verified to a limited degree by the results presented here. The luminaires with a driver minimum relative power rating of 30% were analyzed independently of luminaires with a driver minimum relative power rating of 10% for two reasons: to separate the variation resulting from different minimum relative power ratings from the variation resulting from different responses to the 0-10V control voltage, and because all the luminaires with a driver minimum relative power rating of 30% were of the same make/model. The relative power draw range for these luminaires varied from a minimum of ~2 percentage points (at a control voltage of 0.5 V) to a maximum of ~6 percentage points (at a control voltage of 7 V), resulting in an average variation across all control voltages of ~4 percentage points. Notably, while this variation between different unit samples of the same luminaire was small, it was still measurable and arguably substantial. However, this unit-to-unit variation was much smaller than the variation exhibited by the population of luminaires of varying make/model (i.e., those with a driver minimum relative power rating of 10%). For those luminaires, the relative power draw range varied from a minimum of ~13 percentage points (at a control voltage of 1 V) to a maximum of ~75 percentage points (at a control voltage of 8 V), resulting in an average variation across all control voltages of ~46 percentage points.

Table 2. Variation in relative power draw (as percent of rated maximum input power) for four luminaire categories and two minimum driver relative power rating subcategories. The anomalous L-7 luminaire only drew 55% of its rated input power at a 9 V control signal, so calculations were performed with and without L-7 for relevant categories.

Luminaire Category	Driver Minimum Relative Power Rating	Including Anomalous L-7 Luminaire			Excluding Anomalous L-7 Luminaire		
		Minimum Range (Percentage Points)	Maximum Range (Percentage Points)	Average Range Percentage Points)	Minimum Range	Maximum Range	Average Range (Percentage Points)
All Luminaires	10%	13.5 @ 1 V	74.7 @ 8 V	45.9	9.8 @ 1 V	41.7 @ 8 V	24.3
	30%	1.9 @ 0.5 V	6.1 @ 7 V	4.3	-	-	-
	All	31.7 @ 0.5 V	74.7 @ 8 V	52.6	27.0 @ 4 V	41.7 @ 8 V	31.0
Luminaires with ANSI C137.1 Compliant Drivers	10%	13.5 @ 0.5 V	57.7 @ 9 V	37.1	4.5 @ 1 V	17.8 @ 7 V	13.0
	30%	1.9 @ 0.5 V	6.1 @ 7 V	4.3	-	-	-
	All	31.7 @ 0.5 V	60.0 @ 8 V	47.5	13.6 @ 10 V	29.1 @ 2 V	23.3
Luminaires with ANSI C137.1 Compliant Drivers with High Control Voltage of 8 V	10%	0.4 @ 5 V	5.0 @ 2 V	2.0	-	-	-
	30%	1.9 @ 0.5 V	6.1 @ 7 V	4.3	-	-	-
	All	7.1 @ 10 V	22.0 @ 2 V	13.4	-	-	-
Luminaires with ANSI C137.1 Compliant Drivers with High Control Voltage of 9 V	10%	11.3 @ 1 V	57.7 @ 9 V	35.6	3.6 @ 1 V	15.7 @ 5 V	11.6

One luminaire (L-7) showed particularly poor performance, with a relative power draw of only ~55% at its maximum control voltage, likely due in part to a design or manufacturing flaw resulting in the use of an undersized LED driver. As a result, the performance of this luminaire might arguably be the result of more than just 0-10V response variation. If the data from this luminaire is removed from the 10% analysis, the relative power draw range varied from a minimum of ~10 percentage points (at a control voltage of 1 V) to a maximum of ~42 percentage points (at a control voltage of 8 V), resulting in an average variation across all control voltages of ~24 percentage points.

The relative power draw range across all the luminaires varied from a minimum of ~32 percentage points (at a control voltage of 0.5 V) to a maximum of ~75 percentage points (at a control voltage of 8 V), resulting in an average variation across all control voltages of ~53 percentage points. If L-7 is removed from the analysis, the relative power draw range varied from a minimum of ~27 percentage points (at a control voltage of 4 V) to a maximum of ~42 percentage points (at a control voltage of 8 V), resulting in an average variation across all control voltages of ~31 percentage points. More variation is seen at lower control voltages because the evaluated LED drivers had two different minimum relative power ratings (i.e., 10% and 30%), and the variation seen at higher control voltages is the result of different luminaires reaching their maximum power draw at different control voltages (i.e., 8, 9, or 10 V).

Twelve of the 21 LED drivers in total were found to be compliant with the ANSI C137.1-2022 voluntary standard; notably, this count includes the three identical make/model LED drivers. The relative power draw range for the 12 luminaires with compliant LED drivers, at a tested control voltage, varied from ~32 percentage points (at a control voltage of 0.5 V) to ~60 percentage points (at a control voltage of 8 V), resulting in an average variation across all control voltages of ~47 percentage points. If the data for the anomalous L-7 luminaire (which presented its LED driver with a load that exceeded its rated output) is removed from the analysis, the relative power draw range for the remaining 11 luminaires varies from ~14 percentage points (at a control voltage of 10 V) to ~29 percentage points (at a control voltage of 2 V), resulting in an average variation across all control voltages of ~23 percentage points.

These 11 luminaires (with compliant LED drivers, not including L-7) can be further divided into two groups according to their LED driver's high control voltage (i.e., 8 V or 9 V). Some luminaires with a compliant LED driver that reached its high output power at 8 V had a driver minimum relative power rating of 30%, while others had a minimum rating of 10%. For luminaires with a compliant LED driver with a minimum relative power rating of 30%, the relative power draw range varied from a minimum of ~2 percentage points (at a control voltage of 0.5 V) to a maximum of ~6 percentage points (at a control voltage of 7 V), resulting in an average variation of ~4 percentage points for these identical make/model LED drivers. For the LED drivers with a minimum relative power rating of 10%, the relative power draw range varied from a minimum of ~0.5 percentage points (at a control voltage of 5 V) to a maximum of ~5 percentage points (at a control voltage of 2V), resulting in an average variation of ~2 percentage points.

All luminaires with a compliant LED driver that reached its high output power at 9 V had a driver minimum relative power rating of 10%. For these luminaires, the relative power draw range varied from a minimum of ~11 percentage points (at a control voltage of 1 V) to a maximum of ~58 percentage points (at a control voltage of 9 V), resulting in an average variation of ~36 percentage points. If L-7 is removed from the 10% analysis, the relative power draw range varied from a minimum of ~4 percentage points (at a control voltage of 1 V) to a maximum of ~16 percentage points (at a control voltage of 5 V), resulting in an average variation of ~12 percentage points.

The average variation for all luminaires with compliant LED drivers (including those with both 8 V and 9 V high control voltage targets) was substantially higher (i.e., ~23 percentage points) than the average variation for the 8 V group (i.e., ~13 percentage points) and the 9 V group (i.e., ~12 percentage points). The higher average variation for the 8 V group when compared with the 9 V group can be attributed to some LED drivers in the 8 V group having a minimum relative power rating of 30% and others having a minimum relative power rating of 10%. These results suggest that specifying just one high control voltage (either 8 V or 9 V) and one relative LED driver output at the low control voltage target (e.g., 10% or 30%) can substantially reduce, if not eliminate, the large variation in relative power draw at a given control voltage and improve dimming uniformity across products.

Energy Performance Impact

Unexpected or varying response of streetlights to 0-10V control signals will result in unexpected lighting or energy performance. Lights that are dimmed in response to resident complaints or in order to execute control strategies may not deliver the expected lighting levels, possibly compromising resident satisfaction and safety. Lights that are subject to adjustments in electricity costs based on expected reductions in energy use may be over- or under-billed. In city deployments with tens of thousands of streetlights, the variation in dimming performance could have a substantial impact on expected energy use and cost. Typically, both streetlight operators and electric utilities will be unaware of deviations from expected energy use and cost, as the energy use of streetlights in the U.S. is typically not metered, and energy cost is estimated based on expected usage.

The following sections quantify the impact of using 0-10V control to implement the predominant energy saving control strategies for outdoor lighting: a Part-Night Dimming (PND) strategy that dims light output for part of the night and two versions of a Constant Light Output (CLO) strategy that trims excess initial light output and subsequently compensates for lumen depreciation over luminaire lifetime. Notably, CLO strategies are likely to be the most impacted by 0-10V dimming curves, as they largely operate in the 8–10 V control signal range where real-world dimming curves most noticeably deviate from linear expectations. A moderate city-wide streetlight deployment of 20,000 streetlights is considered, where each luminaire has a rated input power of 100 W. Streetlights are assumed to be controlled by a dusk-to-dawn photocell that limits operation to an average duration of 11 hours every night of the year. Energy costs are calculated using a simple rate of 11.34¢ per kWh, the U.S. national average in 2021 [EIA 2021]. The operator of this system expects an annual energy use of 8030 MWh and energy cost of $910,602. Energy savings derived from the control strategy are calculated by comparing the energy use with two baselines: "full rated power" and "10 V control signal." For the "full rated power" baseline, lights are operated all night at 100% of rated power (i.e., not based on measurement data from this study using shorting cap or dimming control signal). For the "10 V control signal" baseline, lights are operated all night with a control voltage of 10 V. Although these two baselines might be assumed to be equivalent, this study shows that not to be the case, as luminaire response to a 10 V control signal varies. Operating the lights with a 10 V control signal for the baseline (i.e., no PND) subjects the baseline energy use to this variation.

Expected energy savings are compared with the variation in savings that can result from the use of 0-10V control, and the impact of specifying luminaires with LED drivers that comply with ANSI C137.1-2022 is analyzed. It was assumed – as is commonly the case in the real world – that luminaire responses to 0-10V control signals were not characterized and calibrated. In such cases, the most common expectation is that the relationship between control voltage and input power is perfectly linear between 0 V and 10 V, (e.g., 10 V and 5 V control signals would deliver relative power levels of 100% and 50%, respectively). While lighting systems integrators might make different assumptions if they specified luminaires with LED drivers that comply with ANSI C137.1-2022, those assumptions are likely to vary given the nature of the standard, and as a result are not considered here. Given that ANSI C137.1-2022 allows dimming curves to reach their peak output prior to the 10 V maximum (i.e., at 8 or 9 V), compliance is not expected to significantly improve the performance of the CLO strategies.

Part-Night Dimming

In the PND scenario, luminaires are operated with a 10 V control signal – which is expected to result in a relative light and input power level of 100% – for 7 hours and operated with a 5 V control signal – which is expected to result in a relative light and input power level of 50% – for 4 hours. Actual dimming levels were calculated based on dimming curves from the luminaires tested in this study.

The operator of our example streetlight system expects this PND strategy to reduce their annual energy use to 6570 MWh. Based on our analysis, if this operator did not calibrate their luminaire response to a 0-10V input signal, they might see a worst-case annual energy use of 8436 MWh (28% higher than expected) and a best-case annual energy use of 6465 MWh (2% lower than expected). On average – that is, across many such lighting system installations, or for a random distribution of all the luminaires and dimming curves seen in this study – the operator might see an annual energy use of 7081 MWh (7% higher than expected).

The operator of our example streetlight system expects this PND strategy to deliver a relative energy savings of 18%. On average, however, they might only see a relative energy savings of 12% (6 percentage points less than expected), relative to the "full rated power" baseline and 13% (5 percentage points less than expected), relative to the "10 V control signal" baseline. Based on the variation in dimming curves seen in this study, the relative savings observed by the operator might vary between -5% (23 percentage points less than expected) and 19% (1 percentage point more than expected), relative to "full rated power" baseline, and between 13% (5 percentage points less than expected) and 19% (1 percentage point more than expected), relative to "10 V control signal" baseline. Table 3 summarizes PND performance, including the cost impact for a simple rate of 11.34¢ per kWh.

Table 3: Expected and actual (best, average, worst) PND performance for one–year operation of the example 20,000 luminaire streetlight system.

					Full Rated Power Baseline				10 V Control Signal Baseline			
						Energy Savings				Energy Savings		
Performance	Light Level (%)		Energy Use (MWh)	Energy Cost ($)	Baseline Energy Use (MWh)	MWh	$	%	Baseline Energy Use (MWh)	MWh	$	%
Expected	100	50	6570	745,038	8030	1460	165,564	18	8030	1460	165,564	18
Best	96	48	6465	735,285	8030	1565	175,316	19	7950	1485	169,646	19
Average	103	64	7081	802,191	8030	949	108,410	12	8191	1110	124,399	13
Worst	122	76	8436	956,642	8030	-406	-46,040	-5	9774	1338	151,729	14

The impact of ANSI C137.1-2022 on this control strategy is minimal; on average the energy savings of compliant LED drivers is the same as all LED drivers (12%). Based on the results of this study, the annual energy savings observed by operators who specify compliant LED drivers will vary between 4% and 19% (vs. the -5% to 19% variation seen for all LED drivers) relative to the "full rated power" baseline and between 11% and 19% (vs. 14% to 19%) relative to the "10 V control signal" baseline.

CLO for 20 Years at L_{90}

In this scenario, luminaires that claim a lumen maintenance of 90% over a 20-year period (L_{90}) are operated to produce a constant light output over that period by adjusting relative power levels. Lights are dimmed by 10% at the time of deployment and their electrical power is linearly increased by 10 percentage points over 20 years to compensate for lumen depreciation. Luminaires are initially operated with a 9 V control signal – which is expected to result in a relative light and input power level of 90%. The control signal is adjusted yearly by 0.05 V increments until year 20, when luminaires are operated with a 10 V control signal – which is expected to result in a relative input power level of 100%. Actual dimming levels were calculated at control signals between 9 V and 10 V (interpolating for intermediate voltages) based on dimming curves from the luminaires tested in this study. Based on cumulative energy use over the strategy period, the three dimming curves that delivered the best, (closest to) average, and worst performance are highlighted in the results.

The operator of our example streetlight system expects that this CLO strategy will reduce their 20-year energy use from 160.6 GWh to 152.6 GWh and reduce their energy cost from $18.2M to $17.3M. Based on our analysis, if this operator did not calibrate their luminaire response to a 0-10V input signal, they might see a 20-year energy use of as much as 195.6 GWh (28% higher than expected) and as low as 150.3 GWh (2% lower than expected). On average – across many such lighting system installations, or for a random distribution of all the luminaires and dimming curves seen in this study – the operator might see a 20-year energy use of 164.5 GWh (8% higher than expected). Figure 13 illustrates energy use for all dimming curves.

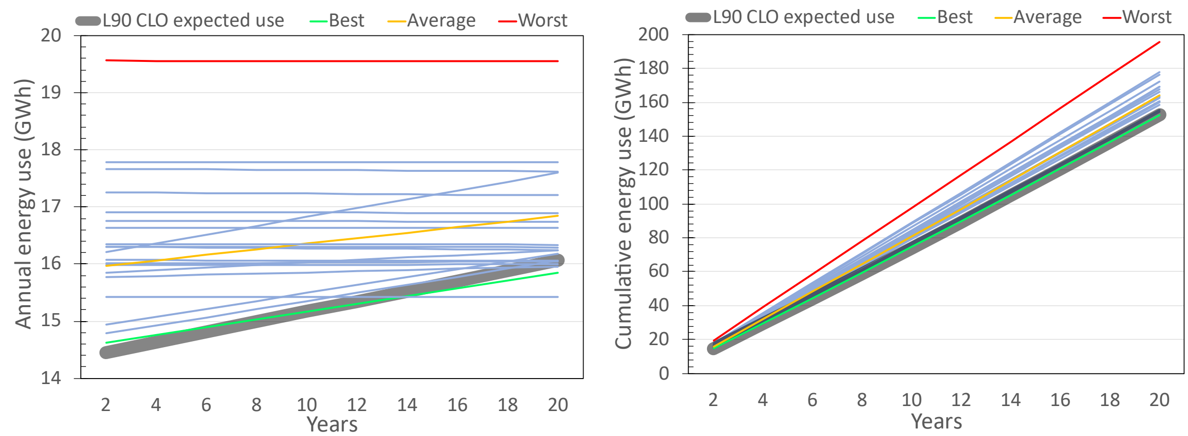


Figure 13: Annual (left) and cumulative (right) energy use for 20,000 streetlights (each with a rated power of 100 W) operated 11 hours each night, based on dimming curves from all tested luminaires, highlighting those with best (green), average (yellow), and worst (red) performance, and compared with expected (thick gray) performance.

The operator of our example streetlight system expects this CLO strategy to deliver a cumulative 20-year energy savings of 8 GWh. On average, however, they might see a cumulative 20-year energy use increase of 3.9 GWh (11.9 GWh more than expected) relative to the “full rated power” baseline and energy savings of only 1.7 GWh (6.3 GWh less than expected) relative to the “10 V control signal” baseline. Based on the variation in dimming curves seen in this study, the cumulative 20-year savings observed by the operator might vary between -35 GWh (43 GWh less than expected) and 10.3 GWh (2.3 GWh more than expected) relative to the “full rated power” baseline and between -0.06 GWh (8.06 GWh less than expected) and 4.04 GWh (3.96 GWh less than expected) relative to the “10 V control signal” baseline. Figure 14 illustrates cumulative energy and cost savings for all dimming curves.

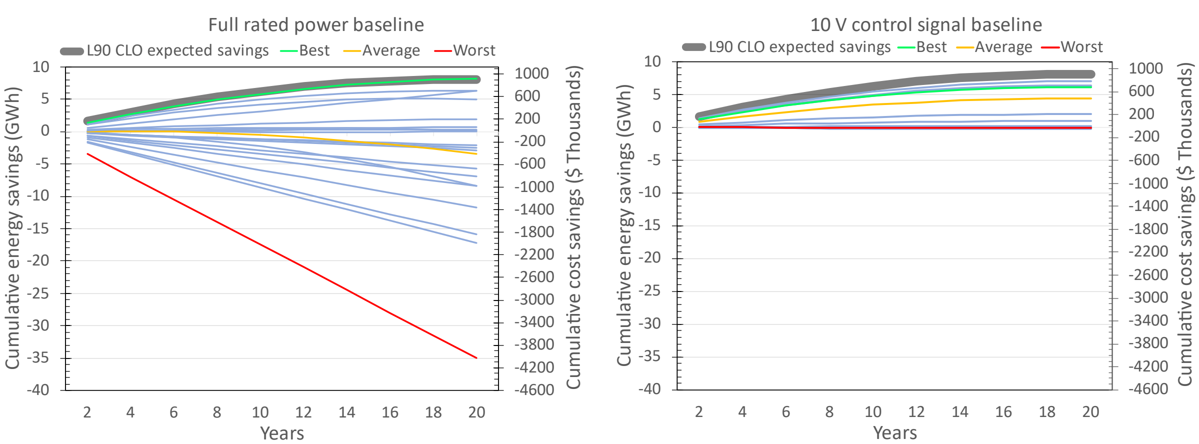


Figure 14: Cumulative energy and cost savings for the CLO for 20 years at L_{90} strategy, relative to a full rated power (left) and a 10 V control signal (right) baseline, for dimming curves from all tested luminaires, highlighting those with best (green), average (yellow), and worst (red) performance, and compared with expected (thick gray) performance.

The operator of our example streetlight system expects this CLO strategy to deliver a relative annual energy savings that starts at 10% in the first year and is reduced by 0.5 percentage points every subsequent year, culminating in a relative 20-year savings of 5%. On average, however, they might only see a relative 20-year energy savings of -2% (7 percentage points less than expected), relative to the “full rated power” baseline and

1% (4 percentage points less than expected), relative to the "10 V control signal" baseline. Based on the variation in dimming curves seen in this study, the relative 20-year savings observed by the operator might vary between -22% (27 percentage points less than expected) and 5% (as expected), relative to the "full rated power" baseline and between 0% (5 percentage points less than expected) and 3% (2 percentage points less than expected), relative to the "10 V control signal" baseline. Figure 15 illustrates relative energy savings for all dimming curves. Table 4 summarizes CLO L_{90} at 20-year performance, including the cost impact for a simple rate of 11.34¢ per kWh.

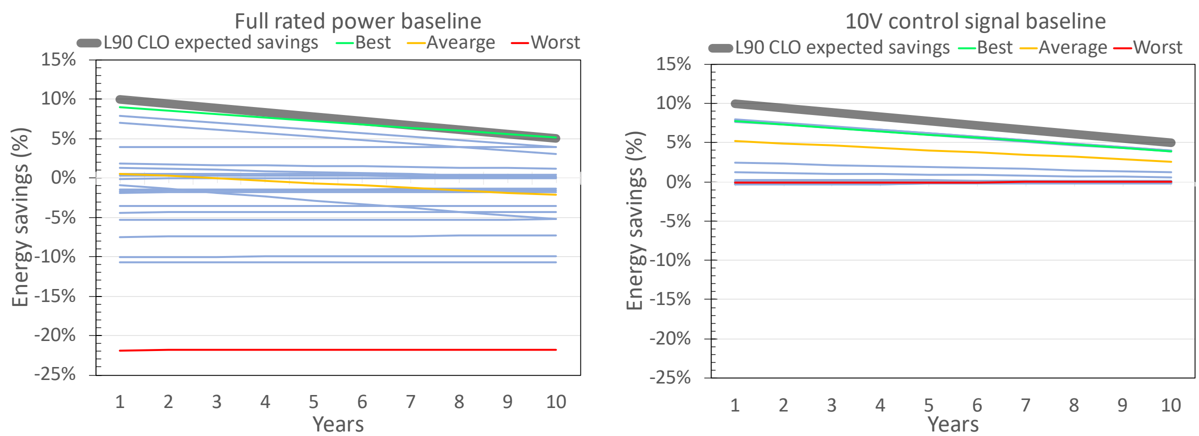


Figure 15: Annual energy savings for the CLO for 20 years at L_{90} scenario, relative to a full rated power (left) and a 10 V control signal (right) baseline, for dimming curves from all tested luminaires, highlighting those with best (green), average (yellow), and worst (red) performance, and compared with expected (thick gray) performance.

Table 4: Expected and actual (best, average, worst) energy performance for the example 20,000 luminaire streetlight system operated using the CLO for 20 years at L_{90} control strategy.

					Full Rated Power Baseline				10 V Control Signal Baseline			
						Energy Savings				Energy Savings		
Performance	Light Level (%) Y1	Light Level (%) Y20	Energy Use (GWh)	Energy Cost ($)	Baseline Energy Use (GWh)	GWh	$	%	Baseline Energy Use (GWh)	GWh	$	%
Expected	90	100	152.6	17.3M	160.6	8.0	910.6K	5	160.6	8.00	910.6K	5
Best	91	96	150.3	17.1M	160.6	10.3	1171.6K	5	154.3	4.04	457.73K	3
Average	101	103	164.5	18.6M	160.6	-3.9	-444.9K	-2	166.2	1.68	190.67K	1
Worst	122	122	195.6	22.2M	160.6	-35.0	-3962.8K	-22	195.4	-0.06	-7.15K	0

Specification of ANSI C137.1-2022 compliant LED drivers does not deliver "expected" performance, but the requirements that it imposes do reduce the range of possible performance. Some end-users who require ANSI C137.1 compliance may understand the unpredictability of the 0-10V dimming curve and calibrate the control-signal to power relationship for the products they deploy. However, others might still desire or attempt to set their control signals based on a simpler assumption. For example, an end-user who expected to achieve the 10% variation in relative power that is necessary to implement this CLO strategy by varying the control signal between 9 V and 10 V, might look at the 8 V or 9 V high control signal requirement in ANSI C137.1 and just shift that 1 V variation down (i.e., vary the control signal between either 7 V and 8 V or 8 V and 9 V over the 20-year period).

Table 5 summarizes the energy savings performance that would result from such an approach, where the control voltage is varied from an initial value of 8 V (i.e., instead of 9 V) to a final value 9 V (i.e., instead of 10 V) for year 20, and compares it to the results from all LED drivers. On average, the specification of ANSI C137.1 LED drivers for this CLO scheme delivers a nearly negligible improvement in energy savings (-1% vs. -2%) relative to the "full rated power" baseline, and no improvement (1% vs. 1%) relative to the "9 V control signal" baseline. The range of actual savings shrinks from 27 (i.e., 5% to -22%) to 17 percentage points (i.e., 8% to -9%) when compared to the "full rated power" baseline, and actually increases slightly from 3 (i.e., 3% to 0%) to 5 percentage points (i.e., 5% to 0%) when compared to the "9 V control signal" baseline.

Table 5. Expected and actual (best, average, worst) energy savings for the example 20,000 luminaire streetlight system operated using the CLO for 20 years at L_{90} control strategy, for ANSI C137.1 compliant drivers vs. all drivers.

		Full Rated Power Baseline			0-10V Baseline*		
Driver	Expected	Best	Average	Worst	Best	Average	Worst
All	5%	5%	-2%	-22%	3%	1%	0%
ANSI C137.1 compliant	5%	8%	-1%	-9%	5%	1%	0%

* 10 V for all drivers, 9 V for ANSI C137.1 compliant drivers

CLO for 16 Years at L_{80}

In this scenario, luminaires that claim a lumen maintenance of 80% over a 16-year period (L_{80}) are operated to produce a constant light output over that period by adjusting relative power levels. Lights are dimmed by 20% at the time of deployment and their electrical power is linearly increased by 20 percentage points over 16 years to compensate for lumen depreciation. Luminaires are initially operated with an 8 V control signal – which is expected to result in a relative light and input power level of 80%. The control signal is adjusted yearly by 0.125 V increments until year 16, when luminaires are operated with a 10 V control signal – which is expected to result in a relative input power level of 100%. Actual dimming levels were calculated at control signals between 8 V and 10 V (interpolating for intermediate voltages) based on dimming curves from the luminaires tested in this study. Energy performance was calculated using dimming curves from all luminaires tested in this study, as well as an "expected" linear dimming curve associated with expected performance. Based on cumulative energy use over the strategy period, the three dimming curves that delivered the best, (closest to) average, and worst performance are highlighted in the results.

The operator of our example streetlight system expects that this CLO strategy will reduce their 16-year energy use from 128.5 GWh to 115.6 GWh, and reduce their energy cost from $14.5M to $13.1M. Based on our analysis, if this operator did not calibrate their luminaire response to a 0-10V input signal, they might see a 20-year energy use of as much as 156.7 GWh (35% higher than expected) and as low as 114.4 GWh (1% lower than expected). On average – across many such lighting system installations, or for a random distribution of all the luminaires and dimming curves seen in this study – the operator might see a 20-year energy use of 128.6 GWh (11% higher than expected). Figure 16 illustrates energy use for all dimming curves.

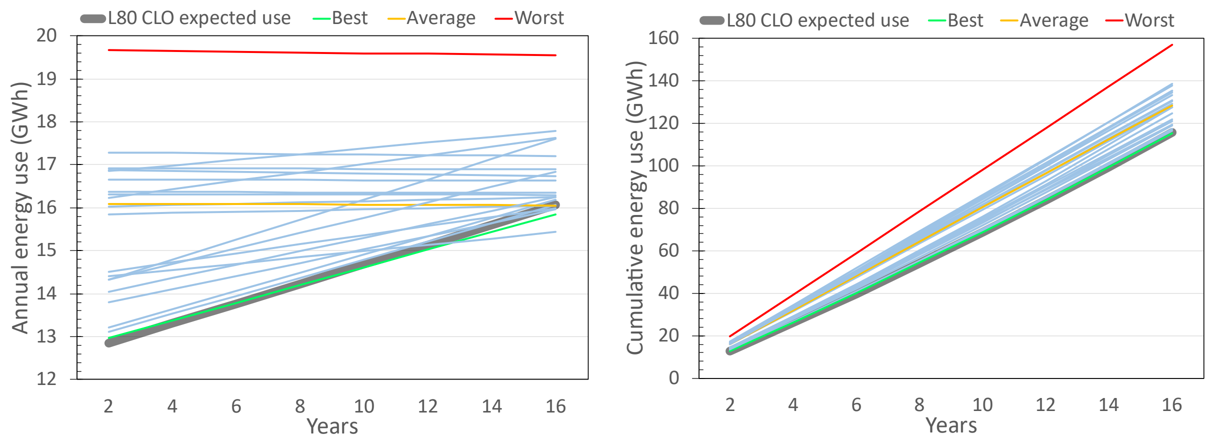


Figure 16: Annual (left) and cumulative (right) energy use for 20,000 streetlights (each with rated power of 100 W) operated 11 hours each night based on dimming curves from all tested luminaires, highlighting those with best (green), average (yellow), and worst (red) performance, and compared with expected (thick gray) performance.

The operator of our example streetlight system expects this CLO strategy to deliver a cumulative 16-year energy savings of 12.8 GWh. On average, however, they might see a cumulative 20-year energy use increase of 0.15 GWh (12.95 GWh more than expected) relative to the "full rated power" baseline and only 4.33 GWh (8.47 GWh less than expected) relative to the "10 V control signal" baseline. Based on the variation in dimming curves seen in this study, the cumulative 16-year savings observed by the operator might vary between -28.2 GWh (41.0 GWh less than expected) and 14.0 GWh (1.2 GWh higher than expected) relative to the "full rated power" baseline and between -0.34 GWh (13.14 GWh less than expected) and 9.01 GWh (3.79 GWh less than expected) relative to the "10 V control signal" baseline. Figure 17 illustrates cumulative energy and cost savings for all dimming curves.

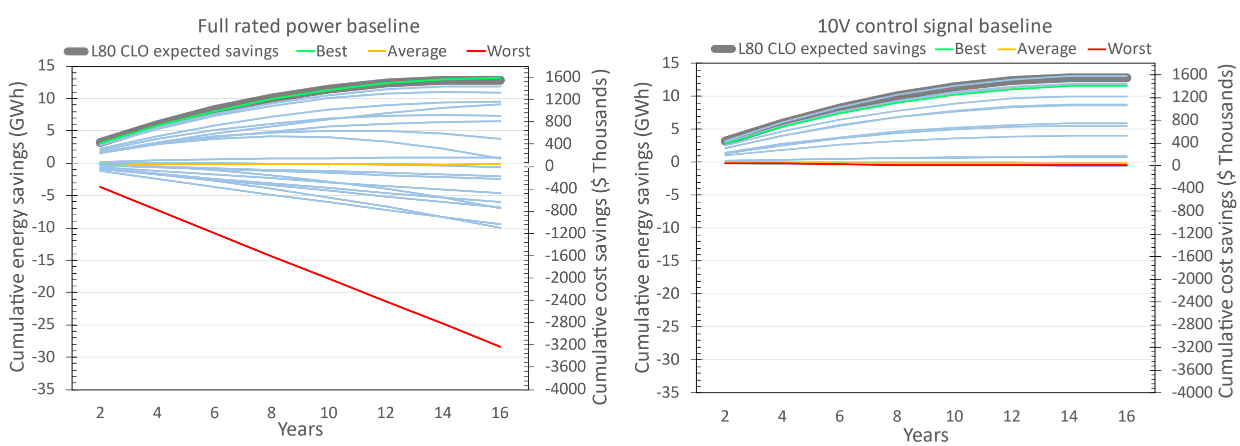


Figure 17: Cumulative energy and cost savings for the CLO for 16 years at L_{80} scenario, relative to the full rated power baseline (left) and 10 V control signal baseline (right) for dimming curves from all tested luminaires, highlighting those with best (green), average (yellow), and worst (red) performance, and compared to expected (thick gray) performance.

The operator of our example streetlight system expects this CLO strategy to deliver a relative annual energy savings that starts at 20% in the first year and is reduced by 1.25 percentage points every subsequent year (e.g., 18.75% in the second year, 17.5% in the third year), culminating in a savings of 10% over the full 16-year period. On average, however, they might see zero 16-year energy savings (10 percentage points less than expected), relative to the "full rated power" baseline and 3% (7 percentage points less than expected), relative to the "10 V control signal" baseline. Based on the variation in dimming curves seen in this study, the relative 16-year savings observed by the operator might vary between -22% (32 percentage points less than expected) and 11% (1 percentage point higher than expected), relative to the "full rated power" baseline and between 0% (10 percentage points less than expected) and 7% (3 percentage point less than expected), relative to the "10 V control signal" baseline. Figure 18 illustrates relative energy savings for all dimming curves.

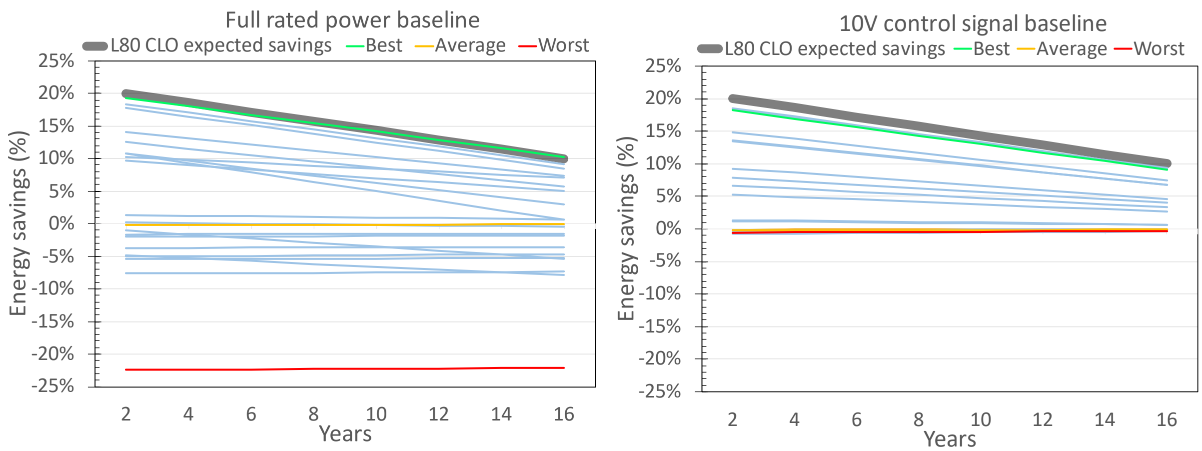


Figure 18: Annual energy savings for the CLO for 16 years at L_{80} scenario, relative to the full rated power baseline (left) and 10 V control signal baseline (right) for dimming curves from all tested luminaires, highlighting those with best (green), average (yellow), and worst (red) performance, and compared to expected (thick gray) performance.

Table 6: Expected and actual (best, average, worst) energy performance for the example 20,000 luminaire streetlight system operated using the CLO for 16 years at L_{80} control strategy.

					Full Rated Power Baseline				10 V Control Signal Baseline			
						Energy Savings				Energy Savings		
Performance	Light Level (%)		Energy Use (GWh)	Energy Cost ($)	Baseline Energy Use (GWh)	GWh	$	%	Baseline Energy Use (GWh)	GWh	$	%
	Y1	Y16										
Expected	80	100	115.6	13.1M	128.5	12.8	1456.9K	10	128.0	12.80	1456.9K	10
Best	81	96	114.4	13.0M	128.5	14.0	1593.2K	11	123.4	9.01	1022.1K	7
Average	96	103	128.6	14.6M	128.5	-0.15	-17.56K	0	133.0	4.33	490.9K	3
Worst	122	122	156.7	17.8M	128.5	-28.2	-3203.1K	-22	156.4	-0.34	-38.60K	0

Table 6 summarizes CLO L_{80} at 16-year performance, including the cost impact for a simple rate of 11.34¢ per kWh. Once again, specification of ANSI C137.1-2022 compliant LED drivers does not deliver expected performance, but it does reduce the range of possible performance. While some end-users who require ANSI C137.1 compliance may appreciate the unpredictability of the 0-10V dimming curve – and calibrate the control-signal to power relationship for products they deploy – some might still desire, or attempt to set their control signals based on, a simpler assumption. In one imagined simpler approach for this CLO strategy, an end-user who previously expected to achieve the 20% variation in relative power that is necessary to implement the strategy by varying the control signal between 8 V and 10 V, might look at the 8 V or 9 V high control signal requirement in ANSI C137.1 and vary the control signal between either 6.4 V and 8 V or 7.2 V and 9 V over the 16-year period.

Table 7 summarizes the energy savings performance that would result from such an approach, where the control voltage is varied from an initial value of 7 V (i.e., instead of 8 V) to a final value 9 V (i.e., instead of 10 V) for year 16, and compares it to the results from all LED drivers. On average, the specification of ANSI C137.1 LED drivers for this CLO scheme delivers similar improvement in savings relative to "full rated power" baseline (from 0% to 5%), and relative to "9 V control signal" baseline (from 3% to 7%). The range of actual savings shrinks from 33 (i.e., 11% to -22%) to 19 (i.e., 15% to -4%) percentage points when compared to the "full rated power" baseline, and from 7 (i.e., 7% to 0%) to 6 (i.e., 12% to 6%) percentage points when compared to the "9 V control signal" baseline.

Table 7. Expected and actual (best, average, worst) energy savings for the example 20,000 luminaire streetlight system operated using the CLO for 16 years at L_{80} control strategy, for ANSI C137.1 compliant drivers vs. all drivers.

		Full Rated Power Baseline			0-10V Baseline*		
Driver	Expected	Best	Average	Worst	Best	Average	Worst
All	10%	11%	0%	-22%	7%	3%	0%
ANSI C137.1 compliant	10%	15%	5%	-4%	12%	7%	6%

* 10 V for All drivers, 9 V for ANSI C137.1 compliant drivers

Summary and Recommendations

From the evaluation of 23 commercially-available LED streetlights in this study, it was clear that the relative (as compared to rated) luminaire power draw for streetlight products at a given 0-10V control signal voltage can vary substantially.

- Across all of the luminaires and tested control voltages, the average range of relative power draw at a tested control voltage was ~53 percentage points, with extremes of ~32 percentage points at a control voltage of 0.5 V and ~75 percentage points at a control voltage of 8 V.
- One luminaire (L-7) showed particularly poor performance, with a relative power draw of only ~55% at its maximum control voltage. An undersized LED driver possibly contributed to the poor dimming performance. The average relative power draw range, excluding luminaire L-7, was ~31 percentage points.
- The variation seen at lower control voltages is partially the result of LED drivers having two different minimum relative power ratings (i.e., 10% and 30%), and the variation seen at higher control voltages is partially the result of different luminaires reaching their maximum power draw at different control voltages (i.e., 8 V, 9 V, or 10 V).

Variation in response to 0-10V control voltages was expected to be more significant across different make/model luminaires than across different units of the same make/model luminaire, and the results in the limited sample were consistent with this expectation. The average range of relative power draw at a tested control voltage for 3 units of the same make/model luminaire with a minimum relative power rating of 30% was ~4 percentage points, while the average range of relative power draw at a tested control voltage for 20 make/model luminaires with a minimum relative power rating of 10% was ~46 percentage points.

The performance of an LED driver is dependent on its connected load (i.e., the LED array). Two luminaires, L-18 (rated input power of 54 W) and L-19 (rated input power of 42 W), used the same make/model LED driver with a rated output power of 50 W. At a control signal of 10 V, luminaire L-18 drew 65 W (120% of its rating) and its driver delivered 57 W (114% of its rating), while luminaire L-19 drew 42 W (100% of its rating), and its driver delivered 37 W (74% of its rating). This shows that using the same make/model LED driver will not always lead to identical dimming performance and end-users can still experience performance variation across luminaires. Also, operating the LED driver outside of its rated range can compromise its electrical performance in one or more ways (e.g., lower electrical efficiency, higher electrical current, higher operating temperature), potentially leading to reduced component or system lifetime.

The 23 luminaires evaluated in this study contained 21 unique make/model LED drivers; one driver was found in three luminaires. Nineteen of the 21 unique make/model LED drivers were evaluated for ANSI C137.1-2022 voluntary standard compliance, including the make/model found in three luminaires; LED driver efficiency information necessary for evaluating compliance was unavailable for two of the LED drivers.

- Slightly more than 50% (10 out of 19 evaluated) of the unique make/model LED drivers were found to be compliant with ANSI C137.1-2022, including one make/model found in 3 luminaires.
- The average range of relative power draw across the 12 luminaires containing ANSI C137.1-2022 compliant LED drivers at a tested control voltage was ~47 percentage points, with extremes of ~32 percentage points at a control voltage of 0.5 V and ~60 percentage points at a control voltage of 8 V. Notably, poor-performing luminaire L-7 had a compliant LED driver. If luminaire L-7 is excluded, the average range across the remaining 11 luminaires was ~ 23 percentage points.

It appears that the ANSI C137.1-2022 voluntary standard will have an impact on market-available products if manufacturers choose to develop products that comply with its requirements, and thus reduce some of the historical performance variation. However, the standard in its current form will not necessarily result in uniform or predictable performance. While ANSI C137.1-2022 compliance reduces average relative power draw variation – from ~53 percentage points for all products to ~47 percentage points for compliant products, or from ~31 percentage points to ~23 percentage points if luminaire L-7 is excluded – the variation remains substantial. Notably, while the standard defines a control-voltage target for minimum output power, it does not specify relative LED driver output at the low control voltage, so luminaire manufacturers and lighting specifiers will still have to evaluate LED driver claims independently. Similarly, while the standard defines a control-voltage target for maximum output power, it does not specify a limit for relative LED driver output at the high control voltage. In either case, such a requirement could specify a range of allowable percentages, rather than a single fixed percentage. Until then, end-users might continue to discover that their luminaires draw unexpected power when their 0-10V control is set to minimum or maximum output.

The observed variation in response of streetlights to 0-10V control signals can have a substantial impact on luminaire energy performance and cost. Payback calculations for control strategies that are made with expected savings might be significantly shorter than the actual payback times. In order to quantify this impact, an energy analysis was performed for a medium-sized city installation of 20,000 streetlights that implemented a PND strategy (whereby luminaires are dimmed to 50% for 4 hours out of 11 hours of operation) or one of two CLO strategies (L_{90} at 20 years and L_{80} at 16 years).

- A PND strategy that should deliver an annual energy and cost savings of 18% was estimated to only deliver an average savings of 12% to 13%, depending on the baseline condition.
- An L_{90} at 20 years CLO strategy that should deliver a cumulative energy and cost savings of 5% at the end of the strategy period was estimated to only deliver an average cumulative savings of -2% to 1% at the end of the strategy period, depending on the baseline condition.
- An L_{80} at 16 years CLO strategy that should deliver a cumulative energy and cost savings of 10% at the end of the strategy period was estimated to only deliver an average cumulative savings of 0% to 3% at the end of the strategy period, depending on the baseline condition.

The deployment of luminaires with ANSI C137.1-2022 compliant 0-10V LED drivers does not deliver expected performance, even if dimming curve expectations of linear performance from 0 to 10 V are adjusted to 0 to 9 V for the L_{90} at 20 years CLO strategy or 0 to 8 V for the L_{80} at 16 years CLO strategy. The use of ANSI C137.1-2022 compliant drivers does, however, reduce the range of possible performance. On average, compliant LED drivers deliver the same performance as all LED drivers for the PND strategy, and a marginal impact on performance for the CLO L_{90} at 20 years strategy (slightly better when compared to the "full rated power" baseline and no impact when compared to the "9 V control signal" baseline). For the CLO L_{80} at 16 years strategy, compliant drivers deliver, on average, an improvement in energy savings that is substantial (5% at the end of strategy period as opposed to 0% for all drivers), but still only half of the expected energy savings (10%). In short, the use of ANSI C137.1-2022 compliant LED drivers is not a sufficient substitute for calibrating luminaire controller output to the actual 0-10V dimming curve of a given make/model luminaire.

Figure 19 summarizes the cumulative energy and cost savings delivered by these three lighting control strategies, relative to both baseline conditions, for all dimming curves characterized in this study.

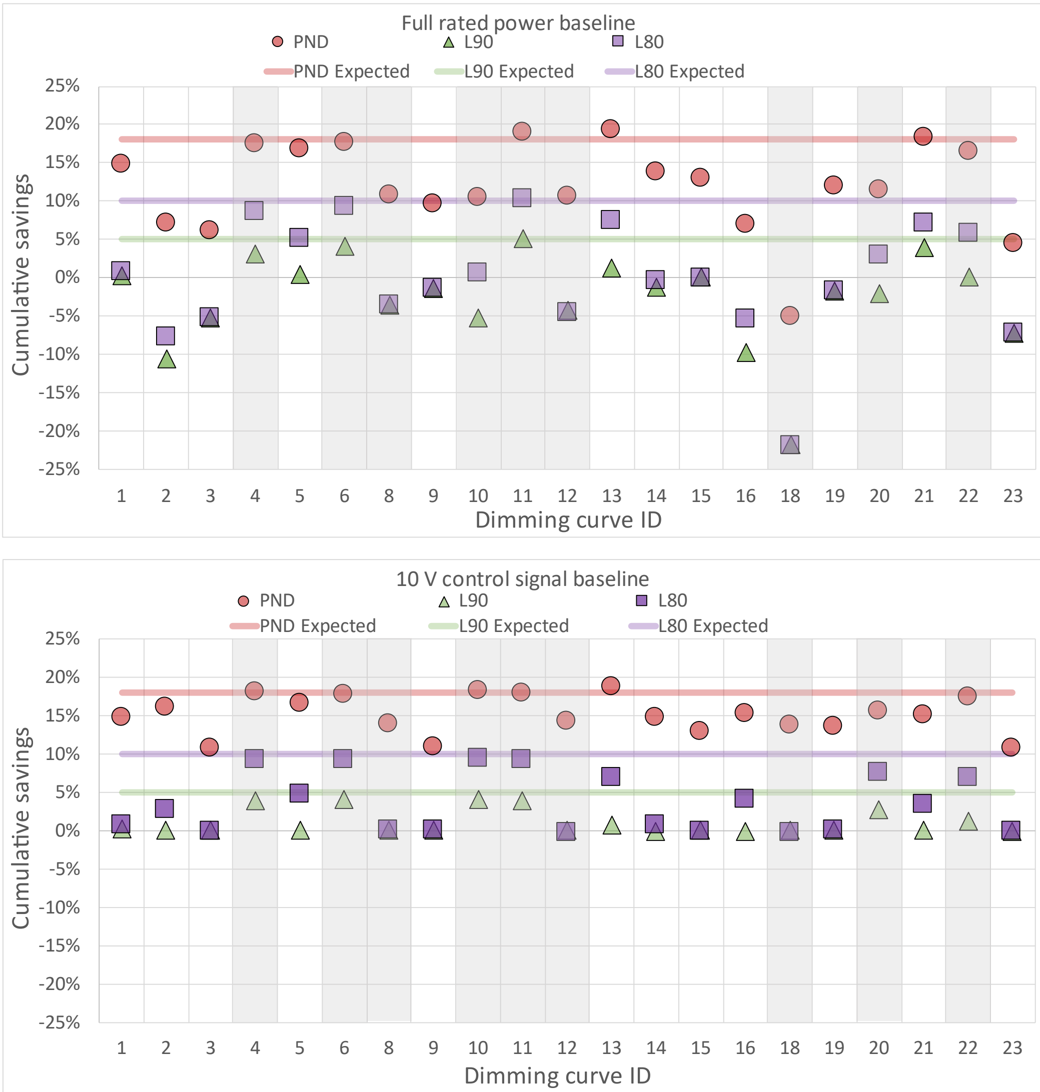


Figure 19: Cumulative energy and cost savings delivered by dimming curves from all luminaires characterized in this study, for one PND strategy (red) and two CLO strategies – L_{90} at 20 years (green) and L_{80} at 16 years (violet) – relative to the full rated power baseline (top) and 10 V control signal baseline (bottom). The gray shaded columns represent ANSI C137.1-2022 noncompliant products.

The following recommendations are offered to key stakeholders, in order of minimum to maximum expected positive impact. Notably, while this study focused on LED streetlights, similar results are to be expected for other luminaires, as the underlying phenomena is not a function of lighting application.

- Driver manufacturers should:
  - design products that comply with the ANSI C137.1-2022 voluntary standard and contribute to its refinement,
  - provide dimming curves (output power and efficiency vs. control signal) for their 0-10V products in their basic product documentation, and
  - transition to standardized digital methods of control (e.g., DALI D4i™, ANSI C137.4-2021) that do not have the same unpredictable performance and variation as 0-10V control.
- Luminaire manufacturers should:
  - ensure that LED driver output power ratings are compatible with luminaire load power requirements,
  - use LED drivers that comply with the ANSI C137.1-2022 voluntary standard,
  - provide dimming curves (output power and light level vs. control signal) for their 0-10V products in their basic product documentation, and
  - transition to LED drivers that utilize standardized digital methods of control (e.g., DALI D4i™, ANSI C137.4-2021) that do not have the same unpredictable performance and variation as 0-10V control.
- Connected lighting system developers should:
  - create a means for adjusting control signals sent to luminaires with LED drivers that comply with the ANSI C137.1-2022 voluntary standard to reflect a high control voltage expectation of 8 V or 9 V.
  - create a means for easily storing multiple luminaire 0-10V dimming curves into their central management and lighting controller software,
  - create mechanisms in their central management or lighting controller software for uploading external dimming curves or systematically capturing luminaire dimming curves by sweeping the control signal input and measuring its input power, for luminaires or luminaire controllers that are capable of monitoring input power, and
  - enable the assignment of available dimming curves to specific luminaire types, such that the 0-10V control signal sent to the luminaire can be "calibrated" to ensure that the luminaire draws the desired relative power and delivers the associated relative light level.
- Standards development organizations should consider modifying ANSI C137.1 to:
  - define a single 0-10V high control voltage, either 8 V or 9 V, and
  - define a relative driver output power requirement or range at the single 0-10V high control voltage (e.g., 100% of full output) and at a specified 0-10V low control voltage (e.g., 8–12% of full output).

- Lighting designers and specifiers should:
    - specify luminaires with LED drivers that comply with the ANSI C137.1-2022 voluntary standard,
    - request dimming curves for all specified 0-10V luminaires and specify connected lighting systems that have the ability to "calibrate" lighting controller output to the actual 0-10V dimming curve for all deployed make/model luminaires, and
    - consider specifying DALI D4i™ and/or ANSI C137.4-2021 compliant drivers to achieve accurate and consistent dimming performance across all luminaires in the system and thus guarantee the delivery of expected energy and cost savings.
- Owners/operators of existing connected lighting systems that use 0-10V control should:
    - obtain dimming curves for all deployed 0-10V luminaires from the luminaire manufacturer or via laboratory testing, and manually adjust lighting controller setpoints to account for actual 0-10V response, as opposed to expected response,
    - inquire about or request connected lighting system software updates that facilitate the ability to "calibrate" lighting controller output to actual 0-10V dimming curves for all deployed make/model luminaires, and
    - replace luminaires that have failed or reached their end of life with luminaires that contain LED drivers that comply with the ANSI C137.1-2022 voluntary standard.

References

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[ANSI 2017] *ANSI C82.11-2017, American National Standard for Lamp Ballasts—High Frequency Fluorescent Lamp Ballasts*.

[ANSI 2019] *ANSI C137.1-2019, American National Standard for Lighting Systems—0-10V Dimming Interface for LED Drivers, Fluorescent Ballasts, and Controls*.

[ANSI 2022] *ANSI C137.1-2022, American National Standard for Lighting Systems—0-10V Dimming Interface for LED Drivers, Fluorescent Ballasts, and Controls*.

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[Jingting Wei et al. 2013] Wei, Jingting, Zechun Yi, Li Wang, Lilin Liu, Hao Wu, Gang Wang, and Baijun Zhang. “White LED light emission as a function of current and junction temperature.” In *2013 10th China International Forum on Solid State Lighting* (ChinaSSL), pp. 166-169. IEEE, 2013., doi: 10.1109/SSLCHINA.2013.7177340

Appendix A: Nominal Data for Evaluated Products

Luminaires			LED Drivers			
Manufacturer	Model Number	Rated Input Power (W)	Manufacturer	Model Number	Rated Output Power (W)	Rated Dimming Range
Beacon	VP-S/24NB-55/4K/T3/ UNV/PCRU/SF2/BBT	55	Thomas Research	LED40W-054-C07000-D 3	37.8 (max)	10-100%
Cree	BXSPR-A-0-2-F-C-U-S-N	42	Signify/Philips	XI050C150V038CNH1	50	10-100%
Cree	BXSPR-B-HT-2ME-A-40K -UL-SV-N-Q9	54	Signify/Philips	XI050C150V038CNH1	50	10-100%
Cree	BXSP-C-HT-2ME-F-40K-U L-SV-N-Q9	139	Driver information not available	Driver information not available	Driver informati on not available	Driver informati on not available
Eaton	SAM-VERD-A016-D-U-T2 -4N7-10K-AP	36	Osram	OT50W/UNV/1250C/2D IMLT2/P6	50 (max)	10-100%
Eaton	SAM-VERD-G-A028-D-U-T2-4N7-10K-AP	103	Samsung	PSDV151104A	150	10-100%
EOI	ESU-DA013M03242M	55 (luminaire sticker) 72 (manufactu rer datasheet)	Signify/Philips	XI075C070V105CNY1M	75 (nominal)	10-100%
ESL Vision	ESL-AL-75W-150	75	MeanWell	HLG-80H-48B	81.6 (rated)	10-100%
Eye Lighting	RW-L740-37-UK-RE2	75.91	Driver not accessible	Driver not accessible	Driver not accessibl e	Driver not accessibl e
GE	ERL1003E140AGRAY	25 (typical)	GE	85237-D050MP25X47V 1SM	50 (max)	10-100%
GE	EALS010D3AW740NAC 1GRAYH	99	GE	GED150MC/VD1P700S	150	10-100%
GE	ERLH015E140DGRAYR 010	161 (typical)	GE	GED150MC/VD1P1050 S	150 (max)	10-100%
LED2 Lighting	ARD-35WD-T2-30-N-5P-SC-UNV-SV	35	MeanWell	HLG-60H-C350B	70 (rated)	10-100%

LED Roadway Lighting	NXT72M573HB7GY3UL X2HPDH5	158	Signify/Philips	Xitanium 150W 0.35-0.7A Prog GL sXt	150	10-100%
Leotek	GCJ1-20G-MV-NW-2-GY-465-PCR7-WL	45	LiteON	PA-1600-31SL	63	10-100%
Leotek	GCJ2-20G-MV-NW-2-GY-1A-PCR7-WL	73	LiteON	PA-1600-48SL	63	10-100%
Leotek	GCM2-40F-MV-NW-3-GY-1A-PCR7-CR-WL	136 (luminaire sticker) 138 (specsheet)	Signify/Philips	XI150C105V140CNF1	150	10-100%
Neptun	LED-777060-L2-UNV	60 (rated)	MeanWell	HLG-60H-42B	60.9 (rated)	10-100%
RAB Lighting	TBLED3T48NRG/D10/7PR	48	RAB Lighting	RD-052-A1400-R	52	10-100%
Schreder	12LED NW-48W-5.5klm	48 (typical)	Osram	OT 50/120-277/1A2 2DIMLT2 P	50 (max)	30-100%
Signify/Philips	RFM-108W48LED4K	106 (typical average)	Signify/Philips	LEDINTA0700C210DO	150 (max)	10-100%

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