
ASSIST *recommends...*

Dimming: A Technology-neutral Definition

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Abstract

This issue of *ASSIST recommends* describes a technology-neutral definition of dimming for lamps and lighting systems used in residential and hospitality interior applications. The proposed definition is based on the common expectations of dimmable products from end users in these applications.

Introduction

This document recommends a technology-neutral definition for the dimming of lamps and lighting systems used in residential and hospitality interior applications. The objective of this recommendation is to establish guidelines for the description and meaningful comparison of dimmable products. Although the electrical compatibility between the light source (e.g., a lamp) and the controlling device (i.e., the dimmer) is important to the safe and successful dimming functionality of a lighting system, for the purpose of this document those aspects are considered independent of end users' expectations of dimming and are therefore not included in the proposed definition.

This recommendation was developed by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute in collaboration with members of the Alliance for Solid-State Illumination Systems and Technologies (ASSIST). The suggested audiences for this document are lamp and luminaire manufacturers, designers and specifiers, program and incentive managers, and purchase decision-makers.

Background

Presently, an increasing number of non-incandescent lighting products are being marketed as dimmable, yet despite recent industry efforts, there is no accepted, industry-wide definition or characterization method of such products (NEMA 2010a, 2010b, 2011a, 2011b, 2011c). With the increasing availability of dimmable lighting products, there has been a corresponding increase in reports of compatibility issues between components (e.g., lamps and dimmers).

In general, *dimming* refers to the property of a light source (e.g., a lamp or a luminaire) to vary in intensity between fully on and a minimum value when so desired by the end user. NEMA 64-2012 defines continuous dimming as “a lighting control strategy that varies the light output of a lighting system over a continuous range from full light output to a minimum light output without flickering in imperceptible steps” (NEMA 2013). As can be expected, many products in the market satisfy this basic concept of dimming; however, the industry currently lacks a more expansive definition with formal requirements that would create an expected and consistent “dimming experience” for the user. Without a more formal definition, many factors could differ between products during the dimming process. For example, the actual maximum and minimum values could be

different because of the choice of light source and dimmer combination. Similarly, the rate of change between the extremes could also be different and could depend on the direction of change (maximum to minimum vs. minimum to maximum). Furthermore, some light sources could exhibit undesirable behaviors such as pop-on, drop out, dead travel, non-monotonic¹ change in light output, color shift, flicker, or audible noise (Rea 2000; ASSIST 2011a; ASSIST 2011b; ASSIST 2011c, NEMA 2010a, 2011a). The lack of consistency in performance among products makes the pairing of lamps and dimmers difficult and can eventually lead to end user dissatisfaction.

The first step to a practical but precise definition of dimming, and by extension the definition of what constitutes a dimmable product, is understanding the contextual purpose of dimming, the end user's needs and expectations, and the technological implications of the light source and control devices both individually and as a system. For purposes of the definition proposed in this document, the focus is placed on the expectations from the end user because those are often independent of the lighting technology used.

A literature review and technology and human factors evaluations were conducted in the laboratory to develop the proposed dimming definition described herein. Characteristics such as minimum and maximum lamp light output, and dead travel were identified as the most relevant aspects of a system's dimming profile. A maximum allowable flicker criterion was deemed equally important for a positive subjective evaluation. System efficacy and audible noise are also included as parameters to consider in a dimmable system, in recognition that these issues are important to the end-user experience, albeit related more to the technology itself or non-visual in nature.

Proposed definition of dimming

Dimming profile

The dimming profile of a lamp/dimmer combination generally refers to the relative change of light output as a function of dimmer setting. More specifically, a dimming profile can be broken up into smaller aspects that can have a measurable effect on the user's dimming experience. The relevant aspects considered in this document include the minimum and maximum dimming levels,

¹These and other terms relevant to dimmable systems are defined in the appendix.

the amount of dead travel, and the rate of change of light output between the minimum and maximum levels (Figure 1). It is important to characterize the dimming profile of a lamp/dimmer combination because it can vary greatly depending on the specific lamp and dimmer used, and potentially the number of lamps in the circuit. This variability is especially possible with new LED- and compact fluorescent-based products.

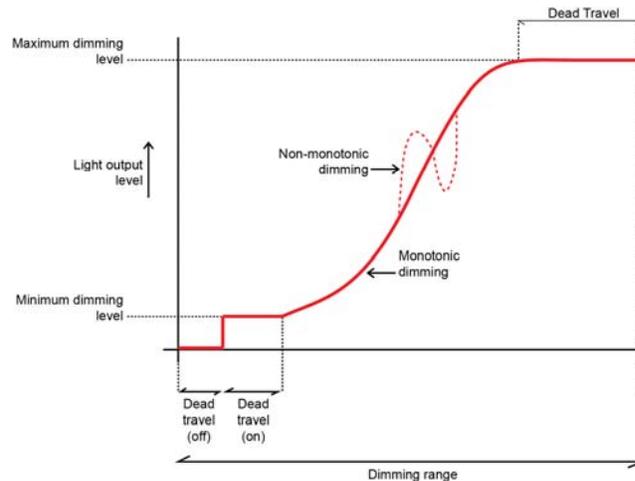


Figure 1. Idealized dimming profile showing the minimum and maximum dimming levels, dead travel, and rate of change of light output as a function of dimmer range. Not all of these elements may be present in a given product’s dimming profile.

The most apparent characteristic in a dimming profile is the rate of change of light output as a function of dimmer setting, also known as the dimming curve. Because of the approximately logarithmic response of the visual system to brightness, dimming curves that resemble a square function are generally rated favorably by most end users (Rea 2000; LRC 2013). The square function, also known as square law curve, is used by many dimmer manufacturers as a guide for the design of their products (Rea 2000). Other dimming curves are certainly possible, including positive and negative square functions, S-shaped, and straight linear curves. In a recent study, observers evaluated different dimming curves in a simulated residential room. The results showed that different dimming curves can be equally acceptable as long as attention is paid to the other aspects of the dimming profile, specifically the minimum light level and perceived dead travel, particularly at the top end (LRC 2013). The following sections discuss acceptability of various amounts of measured dead travel over the dimming curve, defined here as any period during dimming where the measured light output did not vary at all. It is important to keep in mind that some dimming curves may have more perceived dead travel than others due to shallow slope.

The dimming should also be monotonic; that is, the light level should not increase at any point along the curve when the dimmer is traveling down (or decrease at any point when the dimmer is traveling up).

Based on these results and until further information is available, so long as the dimming profile is monotonic and meets the dead travel and range requirements (discussed in the following sections), no limitation on the detailed shape is recommended at this time.

Minimum dimming level

Arguably, the minimum light level attainable with a dimmable system is the primary selection criterion by the end user. Although in principle the amount by which an end user might dim the lighting in a room may change depending on the desired effect, recent human factors evaluations in a dining room application showed that the absolute minimum light level is independent of the task and the initial light level (LRC 2013). The evaluations were conducted in a room outfitted as a residential dining room. Observers were asked to set the light to a minimum acceptable level: first, for a reading task of high contrast, 12-point font size simulating a menu in a restaurant; and second, for a leisurely ambiance setting for casual conversation. In both cases, the observers dimmed the light in the room to approximately 14 lx measured horizontally on the dining table, independently of the initial light level, which ranged from 100 lx to 240 lx. The initial light levels selected for the evaluations were not much different than those typical in many residential applications where the average can reach over 300 lx (Rea 2000). However, these results indicate that defining the minimum light level as a percentage of the maximum light output from the lamp or luminaire can be problematic when multiple sources are in the space (i.e., to get the same light level by dimming one lamp to 10% would require dimming two lamps down to 5%, etc.). Therefore, any benchmark for a relative minimum dimming level in percent from maximum will not satisfy *all* end users until such a time when lighting products can reliably dim to 0%. As technologies improve and more lamp/dimmer combinations are able to achieve lower minimum dimming levels, the minimum to maximum percent value should be revised to a lower number in order to encourage the development of products that meet most users' expectations. Until such time, ASSIST recommends that dimmable products (e.g., a lamp and dimmer combination) reach a minimum light output of no more

than 5% of the maximum output to meet the expectations of residential users (5% of 300 lx = 15 lx).

Maximum dimming level

Most, if not all, dimmers cut down the line voltage applied to the lamp in the circuit so that even when the dimmer is at its maximum setting, the lamp circuit does not receive full mains voltage. Although this condition is often of no significant consequence, it typically results in the lamp producing a lower light output than what it would normally produce at rated voltage (i.e., when not connected to a dimmer). Specifically in some LED replacement lamps, depending on the driver circuit topology and design, it is also possible that the slightly lower input voltage is interpreted by the regulating circuit as a need for compensation, resulting in the lamp producing more light than what it would at nominal input voltage. While this situation may not be considered in principle a problem, it is counterproductive for dimming purposes. In general then, it would be reasonable to expect that at no dimming setting below the maximum would the lamp produce more light than at the maximum setting. In general, too, it would be reasonable to limit the reduction in light output due to the dimmer when at the maximum setting. Knowing this reduction in light output is important for design purposes and energy savings calculations, as it also reduces the lamp luminous efficacy in at least the same proportion. Thus, an approach to quantifying the reduction in light output of a lamp/dimmer combination due to the dimmer would be to compare the light output of the lamp at rated input voltage (e.g., 120 Vac) to the light output of the lamp/dimmer combination when the dimmer is at its maximum setting. Based on recent human factors evaluations (LRC 2013) and published results (Rea 2000), it is reasonable to assume that a 10% reduction of light output will not be objectionable to the end user, if at all noticeable. Therefore, ASSIST recommends that the maximum light output of a lamp/dimmer combination be no less than 90% of the lamp's light output when operated at rated input voltage.

Dead travel

Dead travel occurs when there is no actual or perceived change in light output from a dimmable lamp while there is a change in the dimmer setting. Defining tolerances for dead travel is difficult because, firstly, human visual sensitivity to changes in light varies with absolute light level (Rea 2000); in other words, the tolerance needs to change according to where in the dimming profile the dead

travel occurs. Secondly, defining dead travel tolerances involves not only detection of dead travel by end users, but also determining the acceptability of such dead travel conditions. Recent human factors evaluations (LRC 2013) found that on average, when the light was on, 20% or more measured dead travel at the beginning, middle, and end of dimmer travel was noticeable to over half of the participants. Those who noticed the dead travel found it “somewhat” to “very” distracting. During these evaluations, dead travel was defined as any period during dimming where the measured light output did not vary at all, and subjects were asked to state whether they perceived any change in light output. Based upon these data and to maximize the acceptability from end users, ASSIST recommends limiting measured dead travel to no more than 10% of the dimmer travel at both the beginning and end of the dimmer setting (e.g., mechanical position of the dimmer actuator). While dead travel in the middle of the dimmer travel has not been reported in lamp/dimmer systems to date, it also was found to be undesirable to end users. Therefore, ASSIST recommends limiting dead travel in the middle of the dimmer setting to no more than 10%.

Flicker

Flicker during dimming can happen because of a number of reasons. Some dimmers, for example, modify the shape of the input electrical waveform to the lamp, which can result in changes in the temporal characteristics of the light output. In other cases, certain lamp technologies, particularly those which produce light from a gas discharge, can become unstable when operated at lower than rated power. Flicker also can result from the electrical interactions between the dimmer and the electric or electronic circuits controlling the lamp’s current. Regardless of the reason, flicker has been consistently identified as a potential but undesirable consequence of dimming (Rea 2000, NEMA 2010a), and thus needs to be considered as a key parameter in any proposed definition of dimming. Flicker can be perceived directly when the temporal changes in light output occur at frequencies below 100 Hz.² For frequencies of 100 Hz or higher, flicker can be perceived indirectly in the form of stroboscopic effects. For those conditions, which can extend to over 3000 Hz, the probability of detection by observers and their rating of acceptability depend on both the frequency as well as the percent flicker (%) of the temporal characteristics of the light source’s

² The frequency denoted here refers to the actual temporal characteristics of the light output and not to the electrical frequency at which the light source is being operated. For example, an incandescent lamp operated on a 50 Hz mains will produce flicker at 100 Hz. The same lamp operated on a 60 Hz mains will produce flicker at 120 Hz.

output (ASSIST 2012). Based on the literature and the evaluations conducted by Bullough et al. (2011, 2012a, 2012b), it is clear that more than 10% flicker below 100 Hz could be noticeable and unacceptable to end users. For frequencies equal to or above 100 Hz, ASSIST recommended a calculation method to quantify the predicted acceptability of noticeable stroboscopic effects from a light source based on the percent flicker and the frequency (ASSIST 2012). The same equations can be used to determine either the maximum percent flicker, or the minimum frequency, needed to minimize the detection of stroboscopic effects for a given reference criterion. Following the rationale in ASSIST (2012), ASSIST recommends that dimmable lamps or luminaires produce a calculated acceptability rating greater than zero for frequencies equal to or greater than 100 Hz. The tradeoff between frequency and percent flicker can be simply calculated using the equations in ASSIST (2012).

System efficacy

As explained previously, because of the light output loss due to the dimmer circuit, and because of the additional electrical losses introduced by the dimmer, the luminous efficacy of the lamp/dimmer combination is expected to always be lower than that of the lamp when operated at rated input voltage. Thus, when evaluated for the purpose of energy savings calculations or energy efficiency programs and incentives, the luminous efficacy (lm/W) of a dimmable lamp or luminaire should be measured while operated by a suitable dimmer control. Arguably, the reduction in luminous efficacy of the lamp/dimmer combination when at minimum light output is not of particular concern because the total input power would be significantly lower, which would ensure further energy savings compared with a lamp at maximum output. Therefore, ASSIST recommends that the luminous efficacy of a dimmable lamp or luminaire be measured when operated at full output with a suitable dimmer.

Audible Noise

Like flicker, audible noise from either a lamp or dimmer has been identified as potential but undesirable to end users (Rea 2000, NEMA 2010a). Regardless of the source, a maximum acceptable audible noise level from a dimmable system should be identified in the interest of reducing end user dissatisfaction. Although strictly speaking, audible noise does not impact the visual experience from a dimmable system, it is included here as an additional measure to define a dimmable product that would be rated favorably by most users. In a recent

attempt to address the issue of audible noise from dimmable products, NEMA (2010a) defined the maximum level of audible noise from a lamp to be no higher than 24 dBA. While in the past the lighting industry has used the 24 dBA criterion to categorize electromagnetic fluorescent ballasts, this limit still requires human factors testing to verify its applicability to different scenarios; however, it probably is a reasonable starting point for the amount of noise expected from a dimmable product. Since dBA is a unit of sound pressure (as a weighted value) in a similar way that lux is a unit of illuminance, a methodology for the setup and measurement of audible noise from a lamp or dimmer needs to be clearly outlined for consistent and repeatable noise measurements. At the time of this writing, ASSIST recommends consulting established test procedures from organizations such as ANSI and ISO. It is important to emphasize here that the measurement of audible noise is, by itself, not a measure of the acceptability of that noise level. Noise level and acceptability of that noise will depend on the application. One lamp by itself may pass the 24 dBA criterion, but ten lamps used together may create an unacceptable noise level, depending on the space and tasks.

Aspects of dimming that depend on the application

Dimming is an important feature of residential and commercial lighting systems because it allows users to set the desired ambiance by adjusting light levels in a space, typically with the added benefit of reducing the connected electric load. These two objectives, achieving a desired lighting effect and energy savings, summarize the need for dimming in most applications. The specific expectations from a dimmable lighting system are then contextual. For example, the acceptable range of light levels will depend on the final use of the space (e.g., reading vs. audiovisual presentations in a meeting room) or the intent of dimming (e.g., when dimming is used as part of a control strategy to reduce energy use in commercial areas due to availability of daylight or in times of no occupancy). Similarly, the acceptability of changes in light source properties, such as color shift, may also depend on the context. While color shift may be expected from incandescent lamps and desirable in residential and hospitality applications where the warmer tone of dimmed lamps can create an inviting atmosphere, color shift from fluorescent lamps is often not desirable and dimming is limited to a range in which color shift is not detectable (Rea 2000). Notwithstanding the potential desirability of lamp color shift in certain applications, recent studies have shown that for residential general illumination, lamps with the ability to shift

in color similarly to the way incandescent lamps do while dimming were equally rated to those lamps that did not shift in color (LRC 2013).

Summary

Table 1 summarizes the criteria for acceptable dimming based on users' expectations of dimming.

Table 1. Criteria for acceptable dimming based on users' expectations of dimming.

Dimming profile	No limitation on the detailed shape as long as the dimming profile is monotonic and meets the dead travel and range requirements.
Minimum light level	No more than 5% of the maximum light output ³ .
Maximum light level	No less than 90% of full light output at rated voltage (i.e., not on a dimmer).
Dead travel	No more than 10% of dimmer travel at the top and bottom, or middle of the dimmer setting.
Flicker	For frequencies below 100 Hz, less than 10% flicker; for frequencies equal to or above 100 Hz, a calculated acceptability rating greater than zero, following the procedure put forward in <i>ASSIST recommends...Flicker Parameters for Reducing Stroboscopic Effects from Solid-state Lighting Systems</i> (ASSIST 2012).
Audible noise	Audible noise is an important parameter to consider in the definition of dimmable products; however, at the time of writing, no specific measurement method or noise criterion has been established. See page 11 for a discussion on this issue.
System efficacy	To be measured at maximum output when operated on a compatible dimmer.

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³ A 5% minimum dimming level would provide sufficient dimming for most residential applications where the average light level is up to 300 lx. For the given geometry of the human factors testing conducted, participants dimmed the lighting to 14 lx (on average). See page 8 for further information.

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About ASSIST

The Alliance for Solid-State Illumination Systems and Technologies (ASSIST) was established in 2002 by the Lighting Research Center as a collaboration among researchers, manufacturers, and government organizations. ASSIST's mission is to enable the broad adoption of solid-state lighting by providing factual information based on applied research and by visualizing future applications.

Appendix – Glossary of common dimming terms

dBA: Decibel-A weighting, a measurement of sound pressure level from environmental noise. The dBA curve approximates the human ear frequency sensitivity and is used in noise control regulations.

Dead travel: A range of dimmer settings that have the same light output. Dead travel occurs when there is no actual or perceived change in light output from a dimmable lamp while there is a change in the dimmer setting. Also see *dimmer travel*.

Dimmer: A device used to control the intensity of light emitted by a light source by controlling the voltage or current available to it.

Dimmer setting: An adjustment to the dimmer intended to change the light output of a lamp or luminaire. A setting at the highest possible level should correspond to the maximum light output achievable (which may be lower than the maximum light level when the lamp or luminaire are not connected to a dimmer). A setting at the lowest possible level should correspond to the minimum light level achievable.

Dimmer travel: The action or path of a dimming device moving from maximum to minimum or minimum to maximum. The stopping point is the dimmer setting (see definition above). A dimmable lamp will change its light output along the course of dimmer travel.

Dimming profile: Generally, the relative change of light output as a function of dimmer setting. More specifically, the smaller aspects that can have a measurable effect on the user's dimming experience, including the minimum and maximum dimming levels, the amount of dead travel, and the rate of change of light output between the minimum and maximum levels. A lamp's dimming profile can be different from one dimmer to another.

Drop out: The point above the minimum dimmer setting at which the voltage to the lamp ceases, turning the light off (i.e., the lights "drop out" before the dimmer slider or knob reaches the bottom).

Maximum dimming level: The maximum light output achievable at the highest dimmer setting.

Minimum dimming level: The minimum light output achievable at the lowest non-off dimmer setting.

Monotonic dimming: Refers to the light output change in relation to the direction of the dimmer setting. To achieve monotonic dimming, the light output should not change in an inverse relationship to the direction of dimmer setting (either higher or lower).

Percent flicker: A relative measure of the cyclic variation in output of a light source (percent modulation). It is given by the expression $100 \frac{A-B}{A+B}$, where A is the maximum and B is the minimum output during a single cycle.

Pop-on: Lowest dimmer setting above minimum at which the lamp transitions from off to a dimmed state.

Square function, square law: A presumed relationship between brightness and measured illuminance. The square law curve for adaptation used by many controls manufacturers shows, for example, that a measured illuminance of 25% of the original illuminance is perceived as a brightness of 50% of the original level.