# Exploring flicker in Solid-State Lighting:
# What you might find, and how to deal with it

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## Introduction

Traditional commercial electric light sources running on alternating current (AC) power modulate light output. Whether perceptible or not, incandescent, halogen, metal-halide, and fluorescent light sources modulate luminous flux, typically periodically, but otherwise with characteristics that are functions of the light source design and construction.

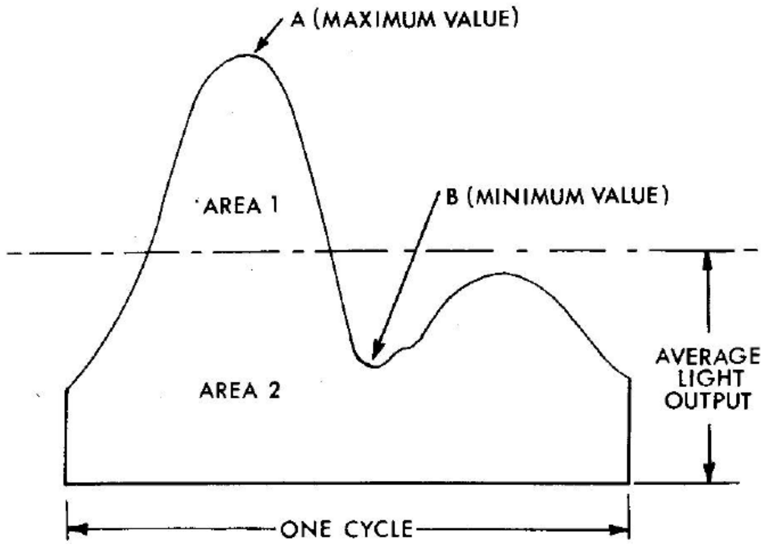
Light modulation has many names, including flicker, flutter, and shimmer. The Illuminating Engineering Society of North America (IESNA) Lighting Handbook defines flicker – the most commonly used term – as "the rapid variation in light source intensity" (Rea, 2000). However, photometric flicker should not be confused with electrical flicker, which refers to noise on AC distribution lines that can directly create additional (light) modulation on resistive (incandescent) loads. In cases of electrical flicker, the AC line is the source of the modulation, rather than characteristics of the light source design and construction.

Measurement of light modulation, or (photometric) flicker, is not a standard practice for commercially available light sources. However, as light-emitting diode (LED) lamps and luminaires continue their significant penetration of the lighting market, apprehension is rising over the possibility for, and amount of, flicker found in some of these products. Photometric flicker from 60Hz magnetically -ballasted fluorescent, metal halide, and high-pressure sodium lamps has been an ongoing concern of the lighting community because of the possible connection to headaches, distraction, fatigue, lower productivity, and annoyance in a small but significant population. No standard procedure currently exists for measuring luminous flux modulation from light sources, and while metrics for quantifying the amount of flicker have been developed by industry bodies, they are not widely understood or used, and appear to have inadequacies that may be exposed by solid-state lighting (SSL) technology.

This paper presents the measured flicker found in a variety of traditional lighting technology products, as well as a sample of commercially available SSL products, and addresses the question of whether SSL sources modulate luminous flux any differently than the traditional sources the lighting industry has been built on.

## Photometric Flicker

According to the IESNA, lighting experts have proposed and used two metrics for photometric flicker (Rea, 2000). Percent flicker, defined by Eq. 1 with reference to Figure 1, is the best known of the two metrics and is commonly used in lighting research literature, where it is also referred to as peak-to-peak contrast, Michelson contrast, or even just "modulation". Flicker index, defined by Eq. 2, also with reference to Figure 1, is generally preferred over and/or considered more reliable than percent flicker by lighting researchers when comparing periodic waveforms with different shapes or duty cycles. These viewpoints are easily justified, as flicker index is mathematically able to account for differences in shape or duty cycle that the more simplistic percent flicker cannot. Nevertheless, flicker index is less known, and rarely found in lighting research literature, perhaps due in part to the integral math required and the related need for accurate sampling of complex waveforms.




*Source: IESNA Lighting Handbook, 9$^{th}$ Edition (Rea 2000)*

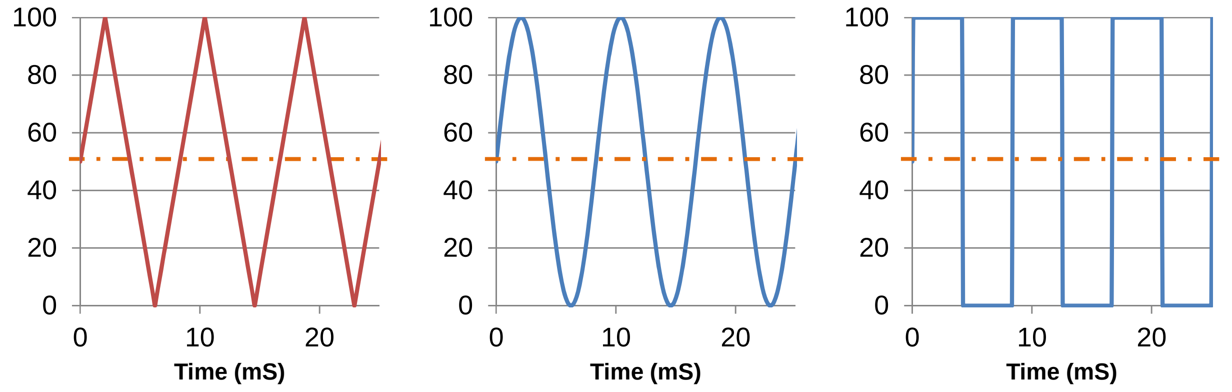
**Figure 1. Periodic Waveform Reference for Traditional Flicker Metrics**

Percent Flicker = 100% x (Max-Min) / (Max + Min) = 100% x (A-B) / (A+B) Eq.1

Flicker Index = Area above Mean / Total Area = Area 1 / (Area 1 + Area 2) Eq.2

## Calculating Percent Flicker and Flicker Index

The best way to understand the differences between the existing flicker metrics and their relationship(s) to other waveform properties is to look at some examples. Figure 2 shows three different 120 Hz periodic waveforms on an arbitrary magnitude scale. The familiar shapes and mathematical representations of these basic triangle, sine, and square waveforms make for simple calculations of waveform properties and flicker metrics. All three waveforms have identical average values, which, if these were measurements of luminous flux from a light source, would equate to identical average luminous flux. On the arbitrary magnitude scale, both the triangle and sinusoidal waveforms have identical reference levels of 50, while the square waveform has a maximum level of 100, and minimum level of zero. Percent flicker calculations for all three waveforms are identical (100%), while flicker index calculations produce different results (0.25, 0.318, and 0.500 respectively for triangle, sinusoidal, and square waveforms), demonstrating the primary difference between the two metrics.




- Reference Level = 50
- Peak-Peak Amplitude = 100
- Shape = Triangle
- Duty Cycle = N/A
- Frequency = 120 Hz
- Average Level = 50
- Percent Flicker = 100%
- Flicker Index = 0.250

- Reference Level = 50
- Peak-Peak Amplitude = 100
- Shape = Sine
- Duty Cycle = N/A
- Frequency = 120 Hz
- Average Level = 50
- Percent Flicker = 100%
- Flicker Index = 0.318

- Maximum Level= 100
- Peak-Peak Amplitude = 100
- Shape = Square
- Duty Cycle = 50%
- Frequency = 120 Hz
- Average Level = 50
- Percent Flicker = 100%
- Flicker Index = 0.500

**Figure 2. Waveform Properties & Flicker Metrics for Simple Periodic Waveforms**

The key observation of note is that flicker index accounts for obvious differences in waveform shape, while percent flicker does not. Furthermore, simple periodic waveforms which transition faster from their low levels to their high levels have higher flicker index values, as seen over the progression from triangle to sinusoidal to square waveform. Simply put, among otherwise similar simple periodic waveforms, square waveforms will always have the highest flicker index.

## Percent Flicker vs. Flicker Index

Table 1 summarizes the differences in how percent flicker and flicker index account for various periodic waveform properties. As a final note of comparison, percent flicker is extremely simple to determine – requiring only the measurement of maximum and minimum values with respect to a reference and simple math. Flicker index, on the other hand, requires the accurate measurement of waveform shape with respect to a reference and more complex integral math. These differences perhaps explain some of the historical use of both metrics in lighting research.

**Table 1.** Comparison of Existing Flicker Metrics

| | Percent Flicker | Flicker Index |
|---|---|---|
| Average | Yes | Yes |
| Peak-to-peak amplitude | Yes | Yes |
| Shape/Duty Cycle | No | Yes |
| Frequency | No | No |
| Complexity | Simple | Moderate |

The ability of percent flicker to account for many waveform properties (other than shape, or duty cycle) raises the possibility of using percent flicker as a proxy for those properties when exploring how flicker index varies for different waveform shapes, or square wave duty cycles. Figure 3 shows the dependency of the flicker index metric on waveform shape for sine, triangle, and square (50% duty cycle) waveforms. Note the following observations:

1. For a given level of percent flicker, triangle waveforms have the lowest flicker index, followed by sinusoidal waveforms, and capped by square waveforms. In any comparison of simple periodic waveforms, squares will always have the highest flicker index for a given percent flicker.

2. The separation in flicker index for the different waveform shapes diminishes at lower percent flicker levels, converging at 0% flicker and flicker index = 0, both indicative of no waveform modulation.

3. The maximum flicker index for simple periodic waveforms = 0.5.

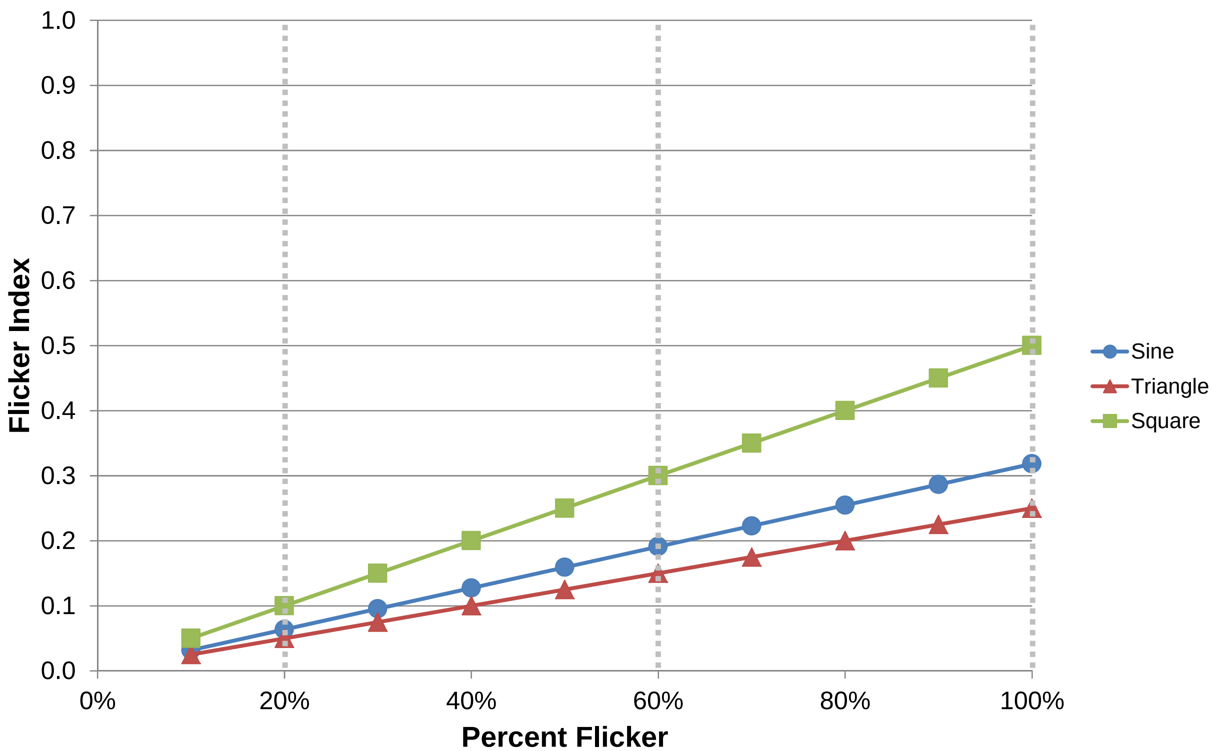



**Figure 3. Flicker Index vs. Percent Flicker for Simple Periodic Waveforms**

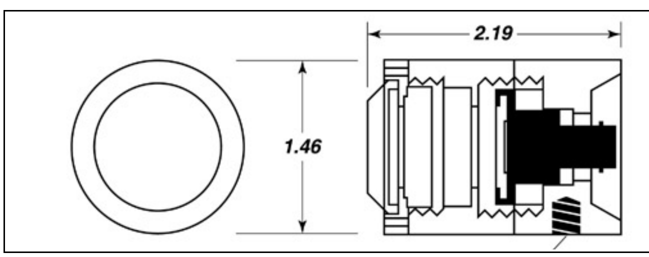
## Measuring Flicker

Any analysis of photometric flicker requires first the ability to measure, accurately and precisely, the modulation of luminous flux emitted from a light source. At present, a standard procedure for measuring luminous flux modulation does not exist. This task is unlikely to be viewed as overly challenging for those skilled and experienced in instrumentation, although some nuances must be taken into consideration to ensure accuracy and precision.

Photosensors capable of measuring visible light over a wide dynamic range have long existed in the marketplace. Standard practice for many sensor applications includes the digitization of the (typically) analog sensor output, thereby facilitating the use of a wide range of digital signal processing software. The data sampling and processing requirements for this application are well within the range of (relatively) inexpensive and commonly available hardware and software.

A simple system consisting of a light-impermeable box (Figure 4), photosensor (Figure 5), transimpedance amplifier (Figure 6), and digital oscilloscope (Figure 7) was assembled for measuring and digitizing photometric flicker. The system was configured, as summarized in Table 2, with an emphasis on capturing even very high-frequency luminous flux modulation.

**Figure 4**. Light-Impermeable Box




| | |
|---|---|
| Photometric filter accuracy (%) | < 1.0 |
| CIE Vλ function $f_1'$ (%) | < 3.0 |
| Dynamic range (lux) | $10^{-2}$ to $5x10^{5}$ |
| Typical (555nm) response (A/lux) | $3.2x10^{-9}$ |

**Figure 5**. UDT Model 211 Photosensor and Key Performance Characteristics


| | |
|---|---|
| Gain (Volts/Amp) | $10^{3}$-$10^{10}$ |
| Noise (mV RMS) | 0.5 |
| Current Range (Amps) | $10^{-2}$-$10^{-13}$ |
| Overall Accuracy (%) | ± 2 |
| Typical Input Impedance (Ω) | 0.001 |
| Output Impedance (Ω) | < 1 |
| Output Voltage Range (V) | ± 5 |

**Figure 6**. UDT Tramp Transimpedance Amplifier and Key Performance Characteristics

| | |
|---|---|
| -3dB Analog Bandwidth (MHz) | 100 |
| Hardware Bandwidth (MHz) | 20 |
| Max. Sample Rate (GS/s) | 1 |
| Max Record Length (points) | 1M |
| Input Impedance (kΩ) | 101 |
| Max. Input Voltage | ±40 |

**Figure 7**. Tektronix DPO2014 Digital Oscilloscope and Key Performance Characteristics

**Table 2**. Data Acquisition Configuration Summary

| | |
|---|---|
| Sample rate (MS/s) | 100,000 |
| Sampling period (uS) | 1 |
| Sampling window (mS) | 125 |
| Record length (samples) | 125,000 |
| Number of records | 10 |

## Flicker in traditional lighting technologies

The performance evaluation of any new technology should start with a clear understanding of how the incumbents perform. Table 3 categorizes 22 unique traditional lighting technology sources evaluated for flicker to form a baseline understanding of traditional lighting technology. The measured luminous flux modulation and calculated flicker metrics for a subset of these sources (shown in Table 4) are shown in Figures 8-11.

**Table 3**. Categorical Summary of Traditional Technology Sources Tested

| | |
|---|---|
| Incandescent | 7 |
| Halogen | 3 |
| Metal Halide | 1 |
| Fluorescent | 11 |

**Table 4**. Examples of Traditional Lighting Technology Sources Tested

| | |
|---|---|
| Incandescent, Halogen, Metal Halide |  |
| Magnetically Ballasted Fluorescent |  |
| Electronically Ballasted Fluorescent |  |

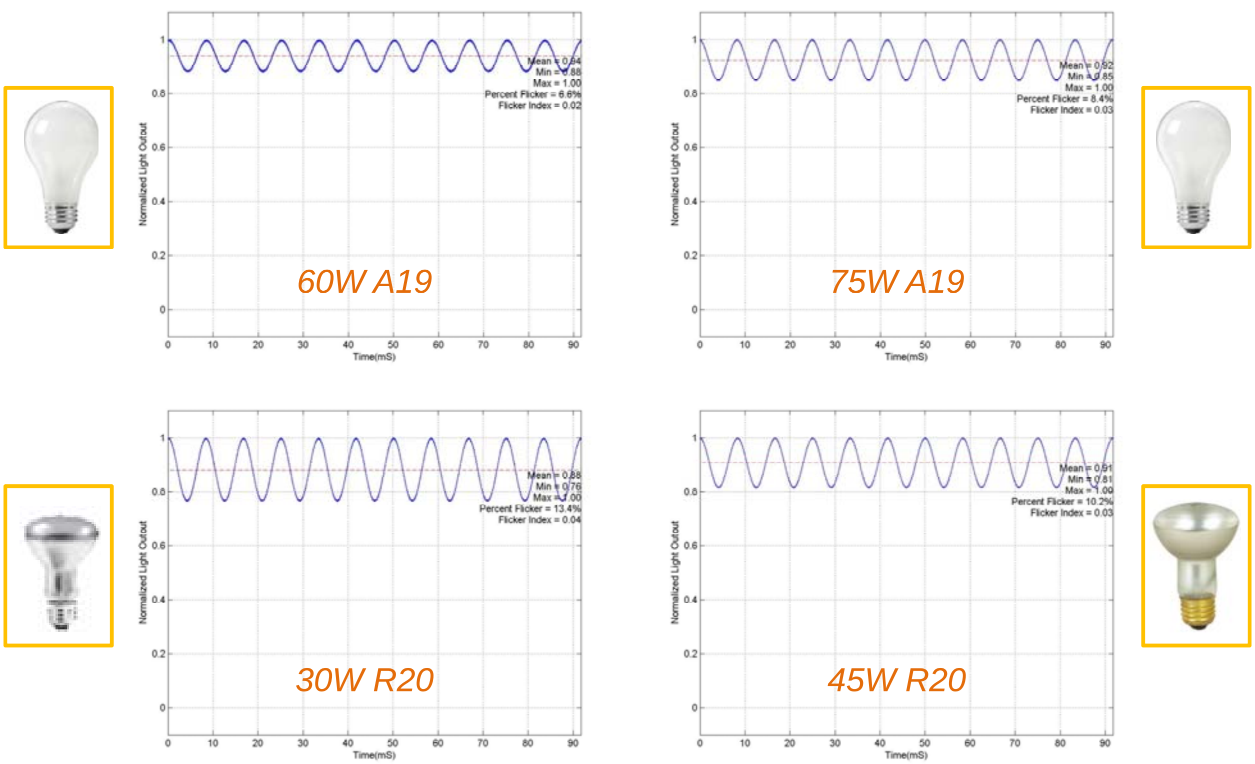



**Figure 8**. Examples of Incandescent Lighting Flicker

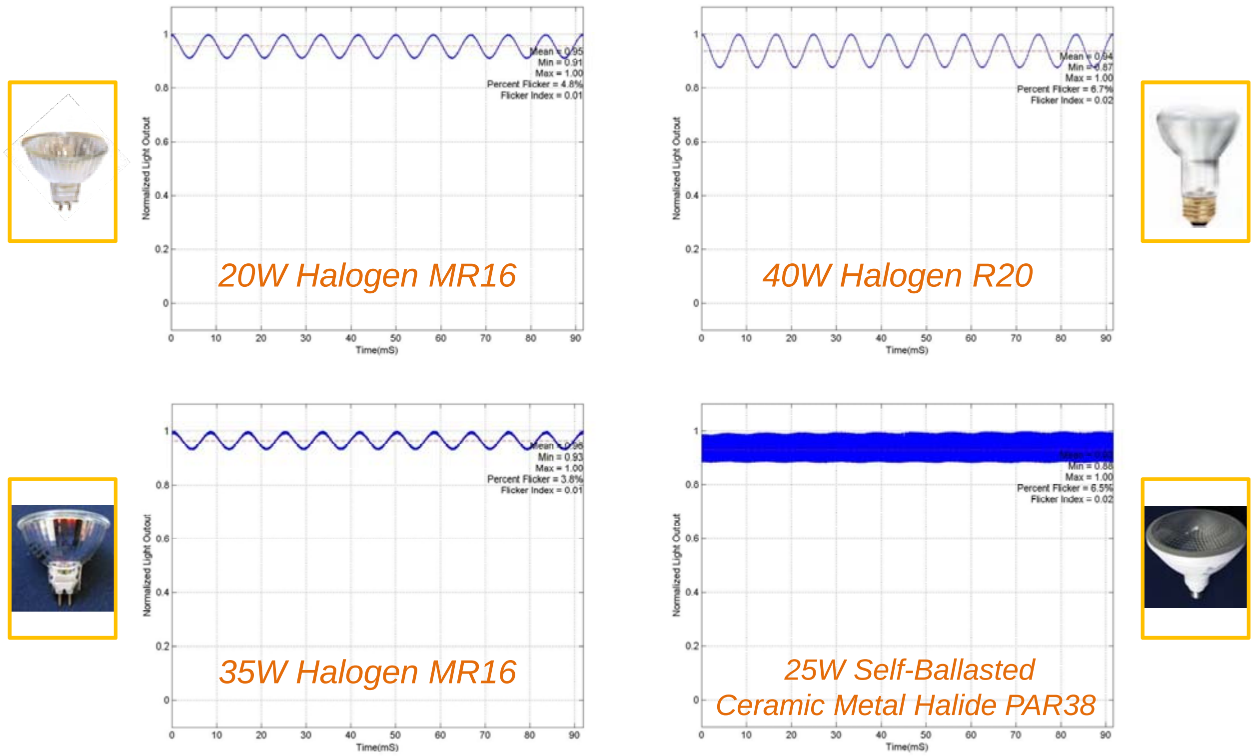



**Figure 9**. Examples of Halogen, Metal Halide Lighting Flicker

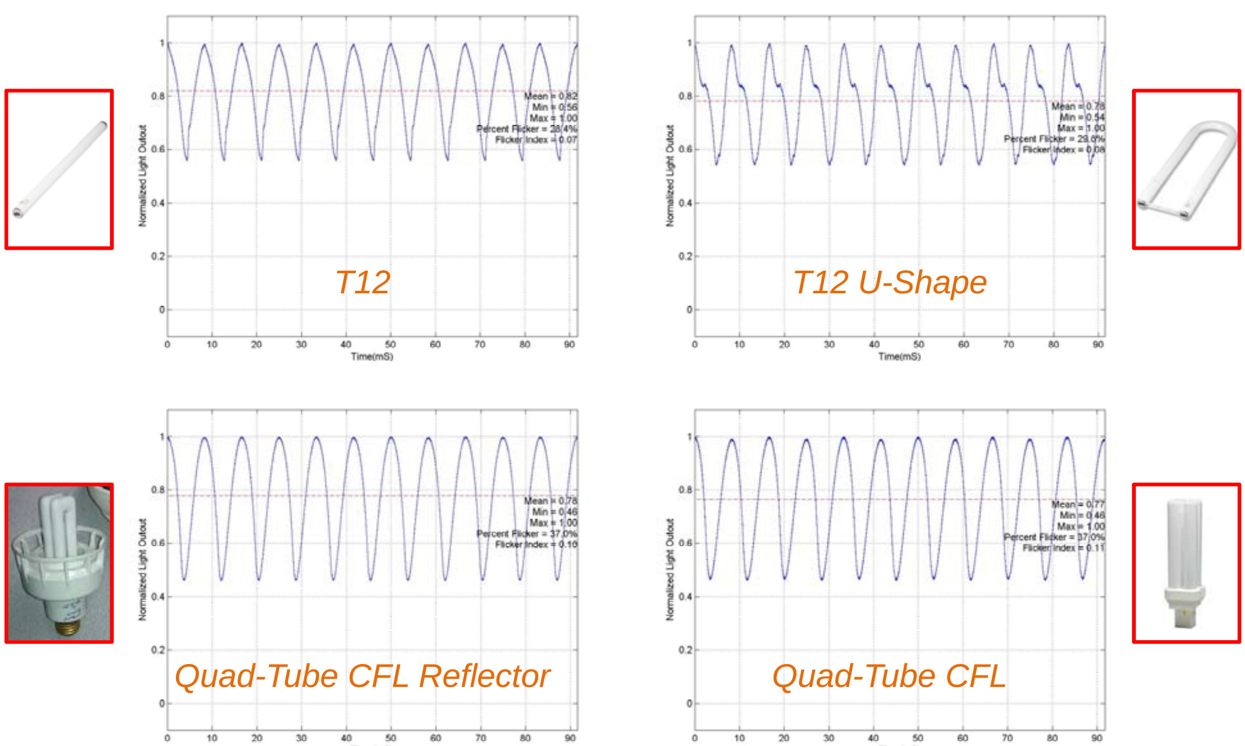



**Figure 10**. Examples of Magnetically Ballasted Fluorescent Lighting Flicker

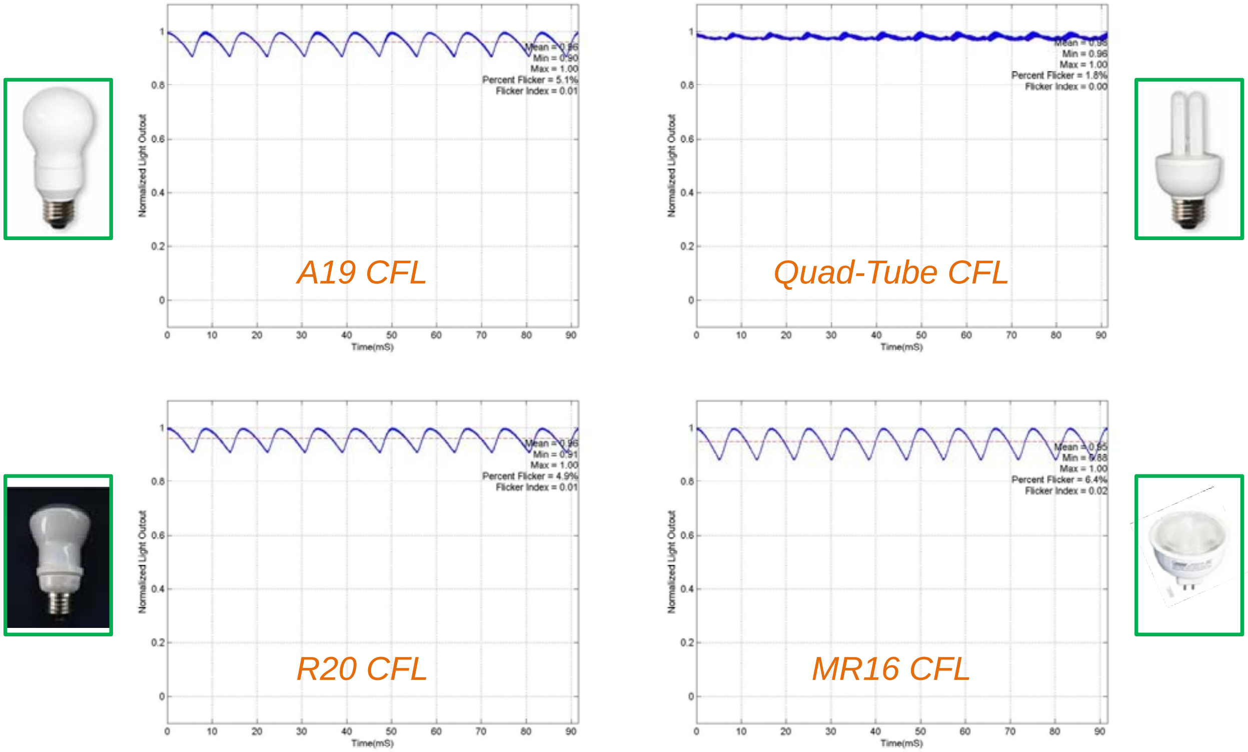



**Figure 11**. Examples of Electronically Ballasted Fluorescent Lighting Flicker

Combining percent flicker and flicker index in an iconic scatter plot of all the aforementioned traditional lighting technology samples creates a frame of reference for discussing flicker. In Figure 12, an icon for each of the traditional lighting technology samples reviewed is plotted such that the x-axis corresponds to the measured percent flicker, and the y-axis corresponds to the measured flicker index. A rectangle has been drawn which encloses all plotted sources, thereby forming a flicker frame of reference for traditional technologies. As expected, incandescent sources crowd one corner of the rectangle and the magnetically ballasted fluorescent sources occupy the opposite corner. The examples shown here occupy an area enclosed by a maximum percent flicker of 40%, and a maximum flicker index of 0.15, hereby referred to as the flicker frame of reference.

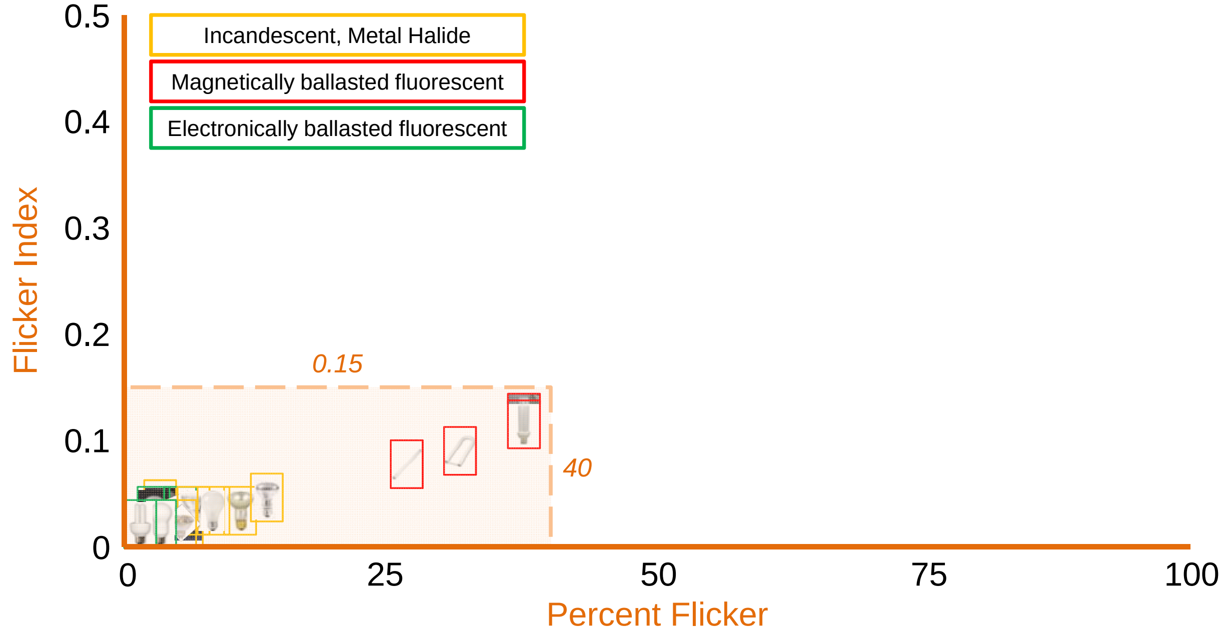



**Figure 12. Traditional Lighting Technology Flicker Frame of Reference**

## Flicker in emerging solid-state lighting products

Table 5 categorizes 93 unique SSL products evaluated in this study. The products consisted mostly of integral replacement lamps, but also included some other product types for comparison and as a precursor to future study.

The flicker index distribution for all tested SSL products reveals that almost half of the products had very low (< 0.05) flicker index values, and nearly 2/3 were under 0.20 (Figure 13). The remaining products were either distributed almost evenly across the range of 0.2-0.4 or part of a denser cluster with flicker index scores of 0.4-0.5. No products had a flicker index > 0.5 or the comparative threshold set by a square wave with 50% duty cycle. A review of the individual luminous flux waveforms, displayed in Appendix A, shows that the fundamental frequency (if clearly visible) for almost all products is 120 Hz.

A plot of flicker index vs. percent flicker for all SSL products is shown in Figure 14. The variation in shape captured by flicker index becomes more pronounced for otherwise similar waveforms with higher percent flicker. This can be seen here in the increasing spread of flicker index values at greater than 50% flicker levels.

Figure 15 implies a coarse inverse relationship between flicker index and luminous flux. A wide range of flicker index values can be seen, however, at any given level of luminous flux. One hypothesis might be that smaller products, such as MR16s (which typically have lower levels of luminous flux, and which necessarily have less physical space for integrated electronics), can be expected to perform more poorly.

**Table 5**. Categorical Summary of Tested SSL Products

| Replacement | | Other | |
|---|---|---|---|
| A-lamp/G-lamp | 18 | Decorative | 1 |
| R/PAR lamp | 27 | Downlight | 3 |
| MR16 | 20 | Linear | 1 |
| Decorative | 7 | Module | 14 |
| Other | 1 | Troffer | 1 |

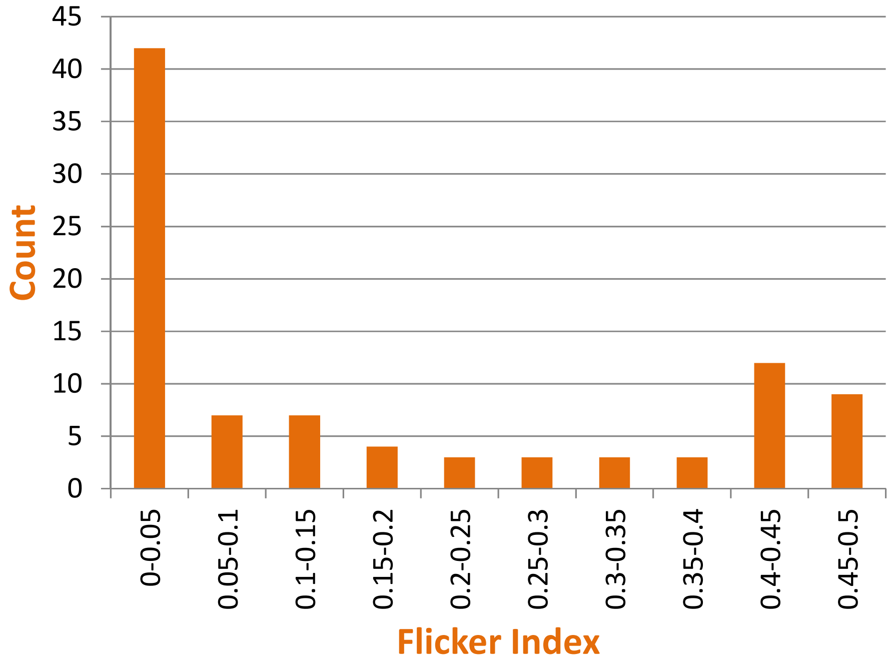



**Figure 13**. Flicker Index Histogram for All Tested SSL Products

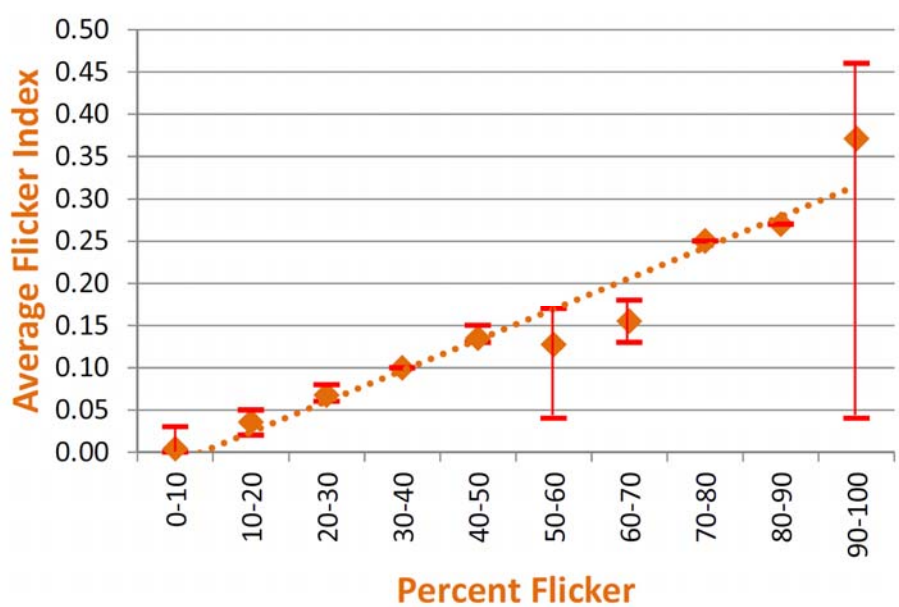



**Figure 14**. Flicker Index vs. Percent Flicker for All Tested SSL Products

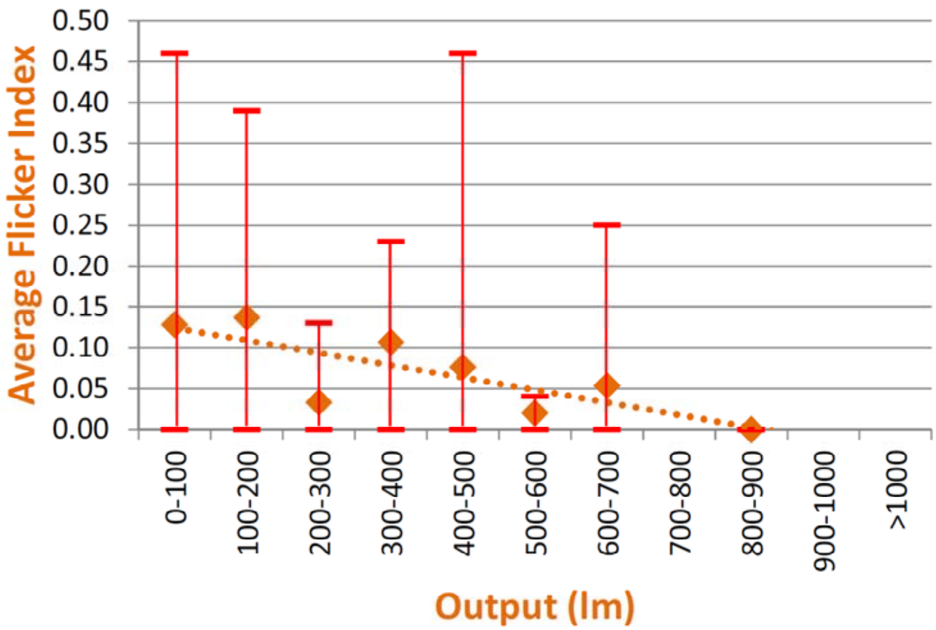



**Figure 15**. Flicker Index vs. Luminous Flux for All Tested SSL Products

The measured luminous flux modulation and calculated flicker metrics for a subset of these products, across various source categories, are shown in Figures 16-20.

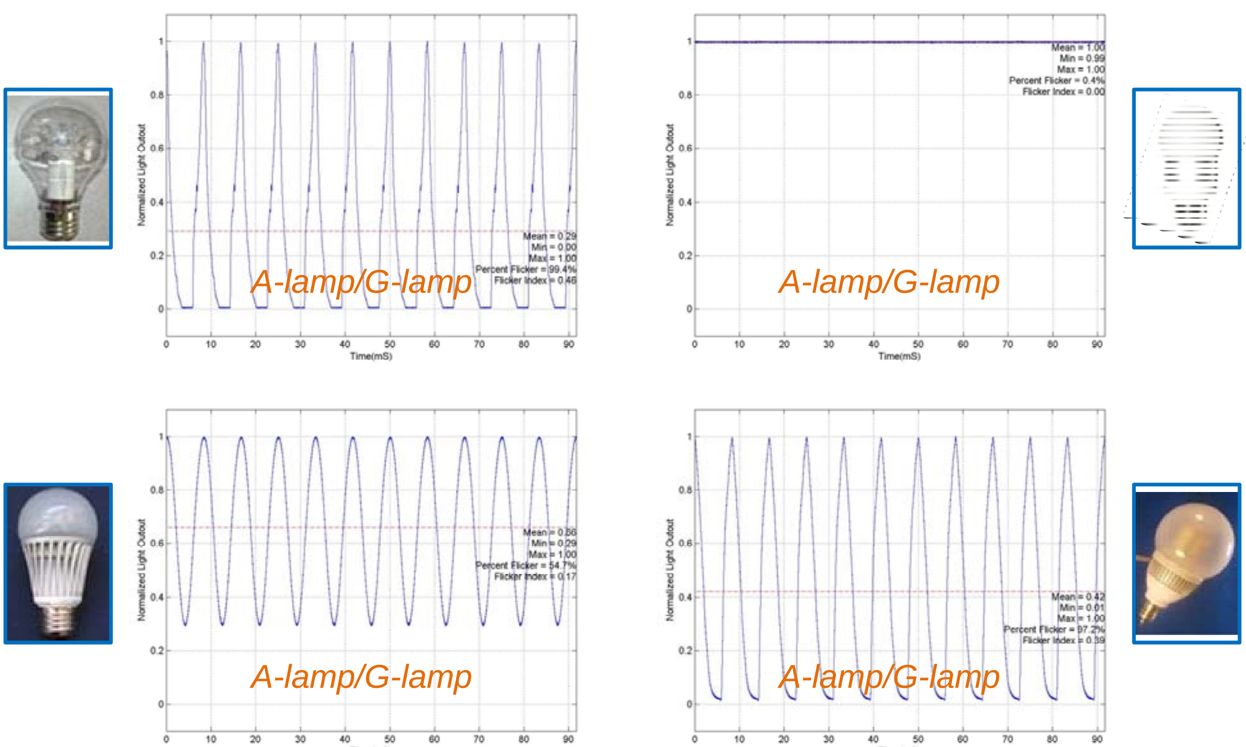



**Figure 16**. Examples of SSL A-Lamp/G-lamp Flicker

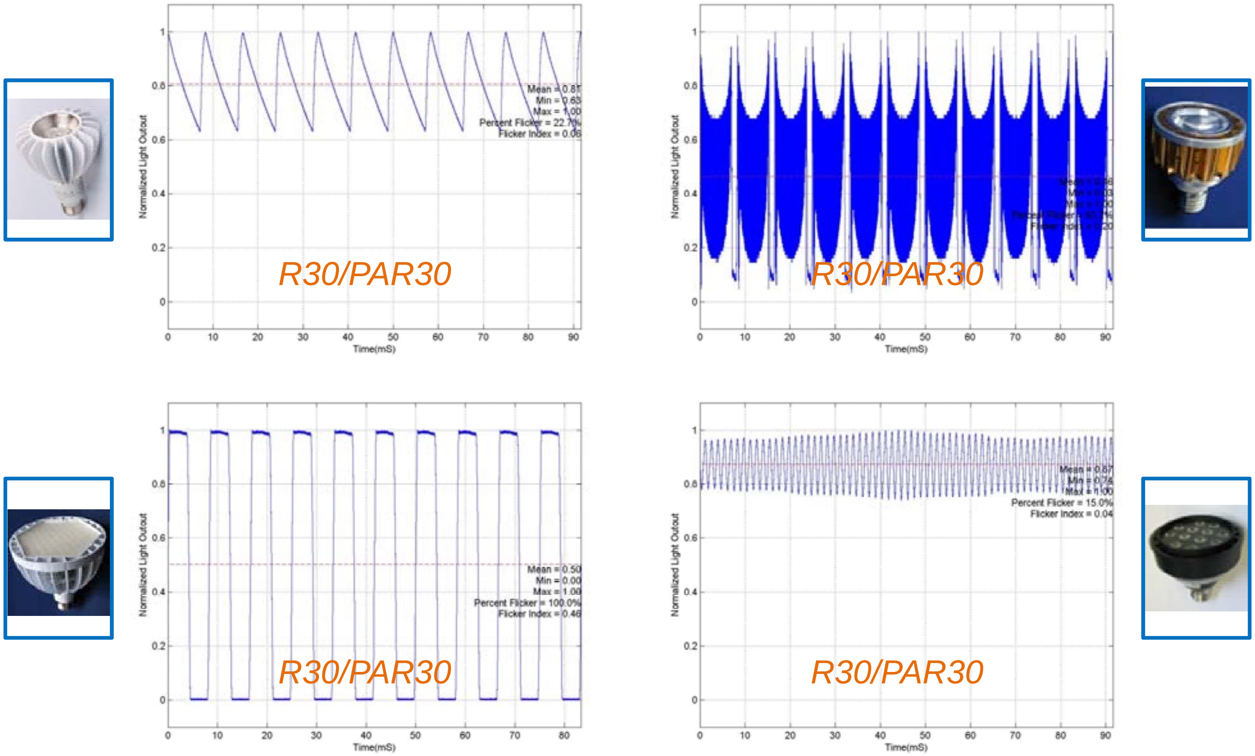



**Figure17**. Examples of SSL R/PAR Lamp Flicker

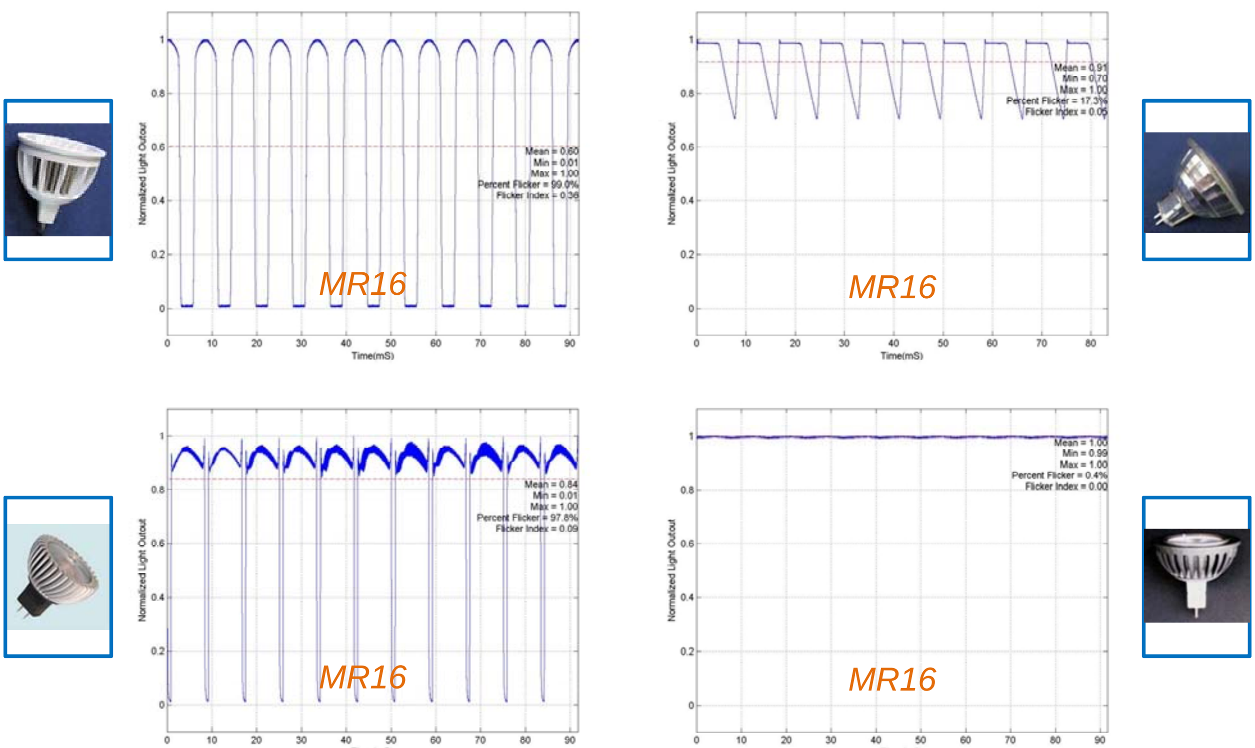



**Figure 18**. Examples of SSL MR16 Flicker

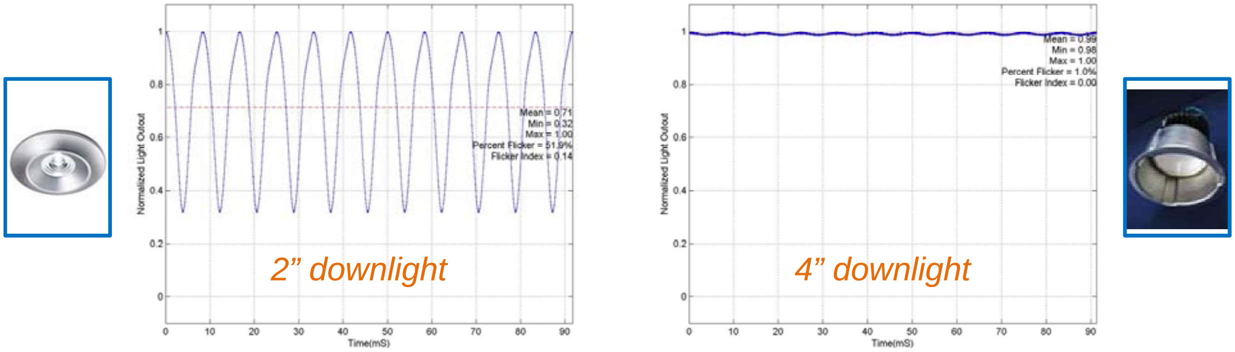



**Figure 19**. Examples of SSL Downlight Flicker

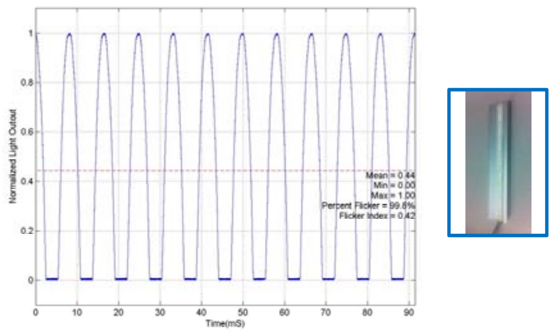



**Figure 20**. Flicker Typical of All Tested SSL Modules Marketed As Containing “AC LEDs”

The flicker frame of reference introduced and discussed previously was updated to include most of the SSL product examples shown in Figures 16-20 (Figure 21). Figure 21 graphically summarizes many previous observations:

- Some SSL products currently on the market have equal or better (as noted by the lower arrow in Figure 21) flicker performance than traditional lighting technology.
- Some SSL products currently on the market are clearly well outside (as noted by the upper arrow in Figure 21) the flicker frame of reference established by traditional lighting technology, and modulating luminous flux in previously unseen manners.
- Flicker index and percent flicker correlate fairly well at lower levels of percent flicker (< 40). However, shape variation captured by flicker index separates otherwise similar (same percent flicker) products at higher levels of percent flicker.
- SSL products currently on the market exhibit wide variation in flicker performance.

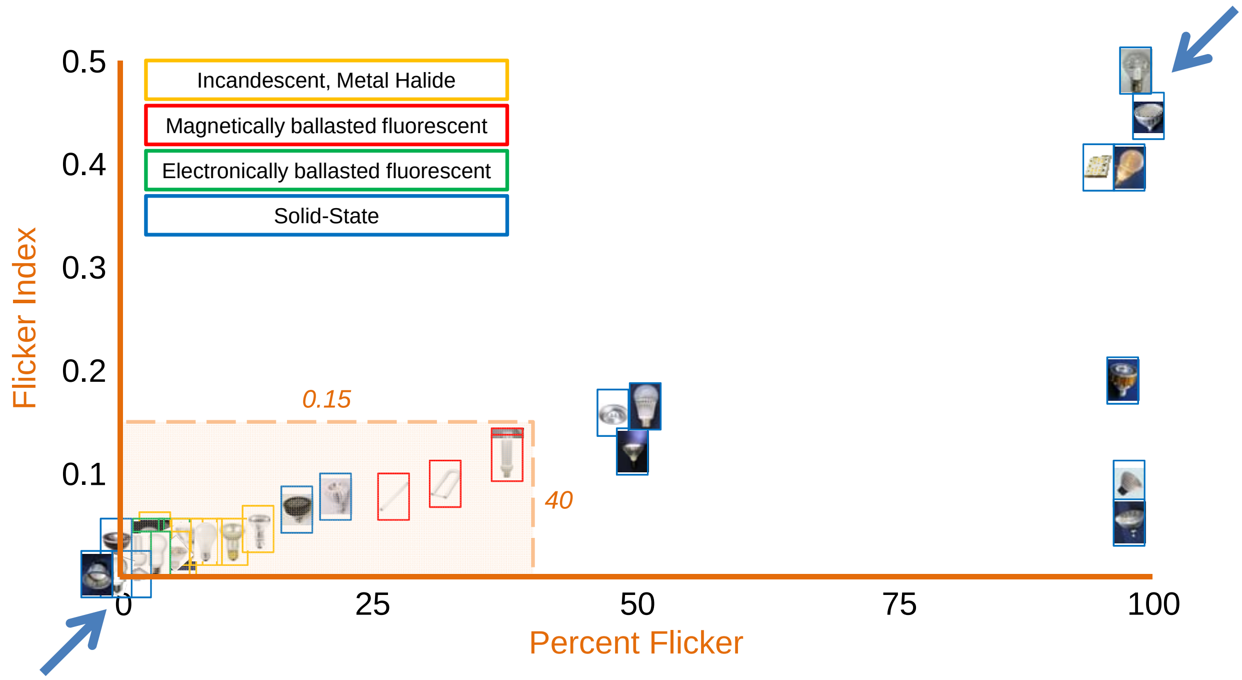



**Figure 21.** Examples of SSL Products on the Flicker Frame of Reference

It is apparent from the snapshot taken here that some SSL light products already on the market are modulating light output in ways different from the electric lighting technologies that the industry is familiar with and has relied on in the past. Although efforts were to evaluate products representative of the current state of the market, the analyses and comparisons made here are not statistically significant representations of any product category. A visual review of modulated light waveforms from these SSL products, however, shows heretofore unseen peak to peak amplitudes, waveform shapes, duty cycles, and frequencies, as well as a large amount of product to product variation. Further analysis using percent flicker and flicker index confirm that many SSL products on the market are outside of the frame of reference established by traditional technologies.

## Flicker in application – Why should we care?

The rapid modulation of light can result in a number of negative physiological responses. They include:

- **Headaches and eyestrain**. Dr. Wilkins et al found that the number of headaches experienced by office workers in spaces lighted with 50Hz magnetically ballasted fluorescent lighting dropped by a factor of 2 when the luminaires were equipped with high-frequency electronic ballasts instead (Wilkins et al 1989)

- **Neurological problems including photosensitive epilepsy**. Even short exposures of visible modulation in the 3 to 70 Hz range may cause seizures in sensitive people. This affects approximately 1 in 4000 individuals aged 5 to 24. Onset usually begins around puberty, and 75% of these individuals remain sensitive for life. (Fisher et al, 2005)

- **Reductions in visual performance**. Veitch and McColl in 1995 found that 100-120 Hz modulation (not perceived as flicker) from magnetically-ballasted fluorescent lighting systems reduced group average performance on visual tasks, when compared to performance under high-frequency electronic ballasts. This occurred for reading, both for paper tasks and for text on computer screens.

- **Distraction**. The periphery of the visual field is more sensitive to flicker, and the rapid modulation may draw a driver's gaze toward a flickering sign or toward a car with flickering taillights, for example. Drawing the eye away from the task ahead could be dangerous for the driver or objects and people in the driver's path.

- Hazard from the strobe effect of flickering light sources interacting with moving machinery, resulting in an apparently different rate of motion, or even appearance of being stopped. This hazard has been recognized in industrial applications for decades. (IES RP-7: Recommended Practice for Lighting Industrial Facilities, 2001.)

- Disruptive behaviors in individuals with autism. Children with autism are especially sensitive to changes in their environment, and flicker from lighting can result in increased repetitive behaviors.[i] Rates of autism in children in the US are approximately 1 in 110. (Fenton and Penney, 1985)

### What makes flicker worse?

The following conditions contribute to a higher risk of adverse responses to flicker:

- Duration of exposure (longer is worse)

- Area of the retina receiving stimulation (greater is worse)

- Location in visual field (central is worse because it projects to a greater area of the visual cortex, even though flicker is less noticeable in the fovea)

- Brightness of the flash (higher luminances are worse; scotopic luminances produce low risk, high mesopic and photopic luminances produce higher risk)

- Contrast of the flash with the surround luminance (higher is worse)

- Color contrast of flash (deep red is worse)

These issues of health, perception, and performance may be an annoyance for some individuals, a hazard for others, and some may remain unaffected. It is important that the susceptible populations are identified, the probability of occurrence quantified, and the severity of the consequences assessed. Ideally, a risk matrix is needed to help professionals designing lighting assess potential populations and applications of concern. This, in conjunction with a reliable, lighting technology-neutral flicker metric, would help these designers and engineers choose low-flicker products and avoid others for particular settings.

### Where Flicker matters

*General lighting*. Avoid high modulation or light levels of flicker in luminaires that provide general lighting in spaces, since general lighting fills most of the visual field and is unlikely to be mitigated by other non-flickering sources of light. This may include overhead lighting in corridors, offices, classrooms, laboratories, etc.

*Spaces where children or susceptible populations spend considerable time***.** Avoid flicker in luminaires used in spaces where children or individuals with greater sensitivity are likely to spend longer periods of time. This includes hospitals, clinics, medical offices, classrooms, daycare centers, etc.

*Task lighting***.** Avoid task lights that flicker, because the light from the luminaire may fill most of the visual field, and be providing the highest luminances in the field of view.

*Industrial spaces with moving machinery***.** Task lighting on machinery should NOT produce high levels of flicker. If HID luminaires driven by magnetic ballasts are used overhead, their flicker can be mitigated by daylight from skylights; or, luminaires with overlapping coverage areas can be powered on separate phases of a three-phase electrical distribution system.

### Where flicker is less important

*Parking lots/roadways where users are moving in a motor vehicle or spending short periods of time.* Flicker is less problematic with short exposures.

*Accent light on artwork***.** As long as the ambient lighting in a space doesn't flicker, flicker from low levels of accent lighting on artwork may not be noticeable or problematic. Sensitive users may notice the strobe effect when their gaze moves as they scan across the room. This may be somewhat distracting, depending on the relative modulation of the accent lighting relative to the viewer's adaptation luminance.

*Places where the distraction of flashing may be an advantage***.** Controlled flicker, such as flashing of an LED marker light on a bicycle may provide sufficient distraction to enhance visibility. It may be prudent to avoid the prominent sensitivity ranges for photosensitive epilepsy, however.

### Conclusion

The data presented in this paper indicate great variability in waveforms (flicker profiles) from commercially available LED products. Flicker is therefore a key attribute that the practitioner needs to consider in evaluating LED products. A standardized measurement procedure and reporting protocol is needed to help the practitioner in that effort, but industry consensus methods are not currently available. In the meantime, a spinning top "flicker checker" is a simple tool the practitioner can use when viewing products, to identify those that exhibit flicker. Visual assessment by the lighting practitioner of LED lighting products in their intended application is always recommended.

Anyone who specifies lighting products needs to be aware of the possibility of finding unfamiliar levels of flicker in some SSL products, and understand how to specify lighting systems for susceptible populations in both indoor and outdoor spaces. While flicker may be acceptable in certain applications, this is still an area for investigation. Definitive guidance cannot be given at this time, but the purpose of this paper is to show examples of the waveform variability that exists in current commercially available LED products, and to identify some of the health and performance issues that may result from exposure to too much flicker, including applications and user populations where caution is warranted.

An IEEE Standards Working Group, IEEE PAR1789 "Recommending practices for modulating current in High Brightness LEDs for mitigating health risks to viewers" has been formed by Prof. Brad Lehman of Northeastern University to advise the lighting industry, ANSI/NEMA, IEC, EnergyStar® and other standards groups about the emerging concern of flicker in LED lighting. IEEE PAR1789 activity is currently focused on three areas. An Education sub-committee disseminates the ongoing work in IEEE PAR1789, primarily through the development of a series of white papers, conference presentations, and journal articles. The Defining Measures for Flicker sub-committee is focused on developing a new, technology-neutral metric for flicker. The known health risks from flickering light sources are being documented by a Hazard Analysis sub-committee, which will subsequently set its sights on developing and refining a risk assessment matrix, which should be an invaluable tool for guiding the lighting industry towards designing and specifying SSL products safely.

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