Flicker in Solid-State Lighting: Measurement Techniques, and Proposed Reporting and Application Criteria

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Abstract

Solid-state lighting is already bringing energy-efficiency, excellent colour, long life, controllability, unique optics and forms to architectural lighting. However, the flicker found in some SSL systems can be a significant barrier to adoption. Furthermore, the pairing of dimming controls with SSL sources can increase flicker, or even induce it in sources that do not flicker in switched mode.

Flicker has been shown to induce photosensitive epilepsy, migraines and headaches, and increased autistic behaviours in certain people. Reduced task performance, stroboscopic or phantom array motion effects, distraction, and annoyance are other possible consequences. Modulation depth, frequency, and waveform shape have been shown to affect flicker sensitivity, and are known to be dependent upon exposure time and a number of visual factors. Yet, flicker is rarely reported in product literature, and there is little to no guidance for architectural lighting practitioners in applying LED products that may flicker.

The authors have developed a means for measuring and reporting lighting flicker. The data analysis techniques are presented, as well as measurements from many conventional and SSL products operated using simple switches and dimming controls. Using data from previous and current flicker research, a straw-person standard is proposed based on flicker index and flicker frequency. Guidelines are presented to help guide practitioners in their evaluation of lighting products and conversations about flicker with manufacturers and clients.

Keywords: Flicker, flicker index, % flicker, flicker frequency, flicker waveforms, solid-state lighting, LED driver, LED dimming, PWM, flicker metrics, applications.

1 Introduction

Light modulation has many names, including flicker, flutter, and shimmer. The Illuminating Engineering Society of North America (IES) 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.

Photometric flicker was an issue when magnetically-ballasted fluorescent and high-intensity discharge (HID) luminaires were common, before the mid-1990s. Research at that time identified flicker of the light source to be related to migraines, headaches, autistic behaviours, reduced visual performance and comfort, along with other possible neurological health issues (IEEE 2010). When high-frequency electronic ballasts were introduced for energy efficiency, the negative effects of flicker were reported less frequently and largely disappeared from public discourse. With the introduction of LED products to the marketplace, flicker has re-emerged as a consideration, partly because the time-modulation of LED light output has been frequently observed to be greater than the modulation seen with fluorescent or HID sources. For LED sources, flicker is primarily determined by the LED driver. Some driver designs produce little to no detectable flicker at full or dimmed outputs; others flicker noticeably at both full and dimmed output; still others produce little to no flicker at full output but flicker objectionably when dimmed. (Some LED products produce flutter or instability while the dimming level is changing, but that disappears when the dimming level is fixed.)

All light sources modulate light, or flicker, to some degree, usually as a consequence of their drawing power from AC mains sources (i.e. 60Hz AC in North America). However, some variations in light output can be visible to some individuals, and may affect some populations even if it isn’t visible to them. The flicker created by electrically powered light sources is typically periodic. A periodic waveform can be characterized by at least four parameters: its amplitude modulation (i.e., the difference between its maximum and minimum levels over a periodic cycle), its average value over a periodic cycle (also called the DC component), its shape or duty cycle (the percentage of time spent at its maximum vs. minimum level over a periodic cycle, typically only used to characterize square waves), and its periodic frequency. Researchers have known that light sources with low frequency flicker, such as 3 to 70 Hz, can have serious neurological consequences, including photosensitive epilepsy, for some populations. Frequencies of 100 Hz, which occurs with 50 Hz power in Europe, are recognized as contributing to headaches and migraine. Frequencies of 120 Hz are annoying and distracting at the very least for some populations, especially when there is large amplitude modulation in the light output. LED sources can exhibit flicker with 100% modulation, which may be visible and may have health consequences at frequencies higher than 120 Hz, but the research community does not know how combinations of the four parameters render the light modulation hazardous or harmless (IEEE 2010).

At present, a standard procedure for measuring flicker does not exist, 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. Flicker measurements for a wide range of products have been made by the Pacific Northwest National Laboratory (PNNL) using a test setup consisting primarily of light-impermeable box, an analogue photosensor with matching transimpedance amplifier and digital oscilloscope, together with digital signal processing software. This allowed the capture of even very high-frequency luminous flux modulation.

2 Metrics for Photometric Flicker

According to the IES, 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.

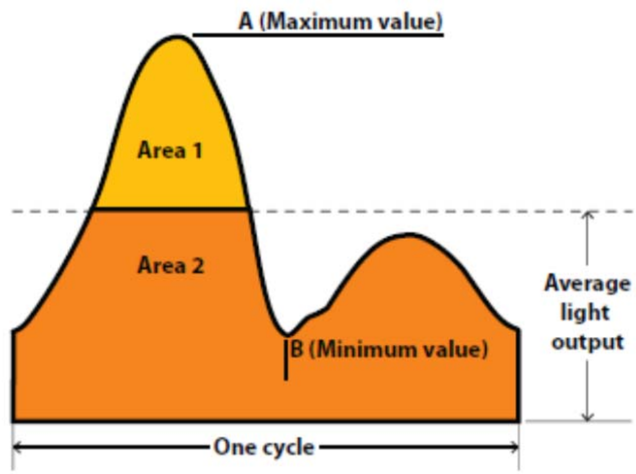

Figure 1: **Periodic Waveform Reference for Traditional Flicker Metrics**
Source: IES Lighting Handbook, 10th Edition

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

2.1 Calculating Percent Flicker and Flicker Index

Some examples will help the reader understand the differences between the existing flicker metrics and their relationship(s) to other waveform properties. 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 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.

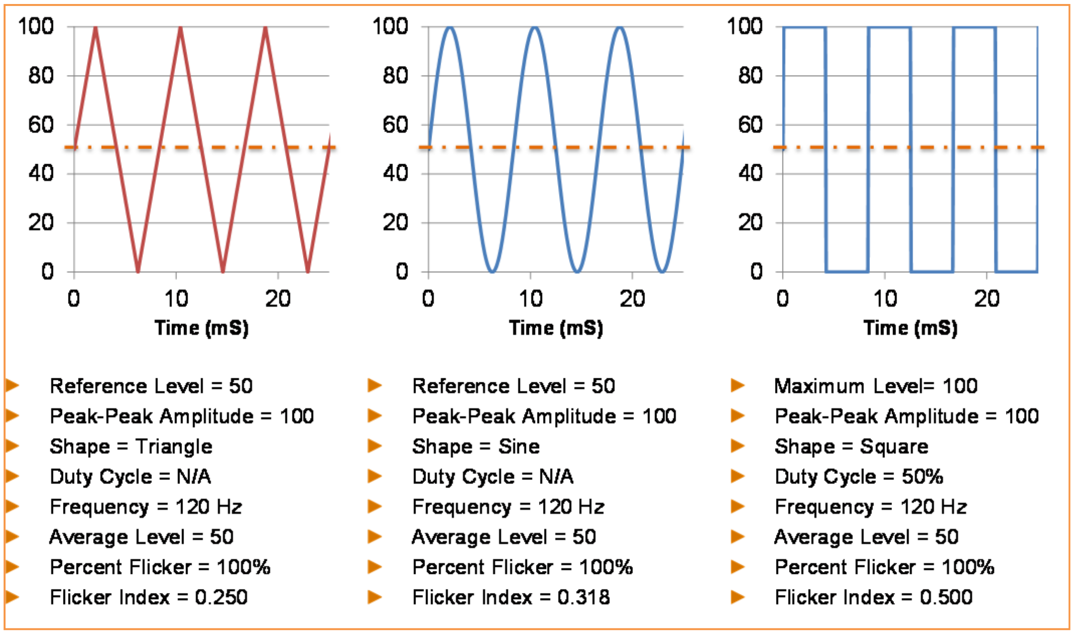

Figure 2: Waveform Properties & Flicker Metrics for Simple Periodic Waveforms

The key observation is that flicker index accounts for 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.

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.

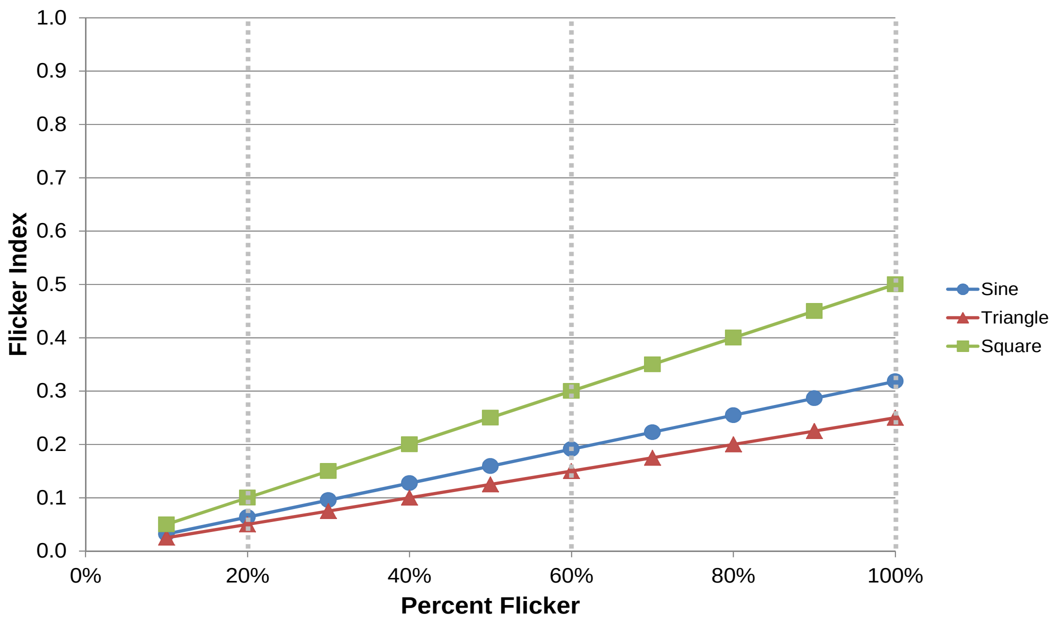

Figure 3: Flicker Index vs. Percent Flicker for Simple Periodic Waveforms

3 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) analogue 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.

4 Flicker in traditional lighting technologies

The performance evaluation of any new technology should start with a clear understanding of how the incumbents perform. Table 2 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 are shown in Figures 4-7.

Table 2: Categorical Summary of Traditional Technology Sources Tested

Incandescent	7
Halogen	3
Metal Halide	1
Fluorescent	11

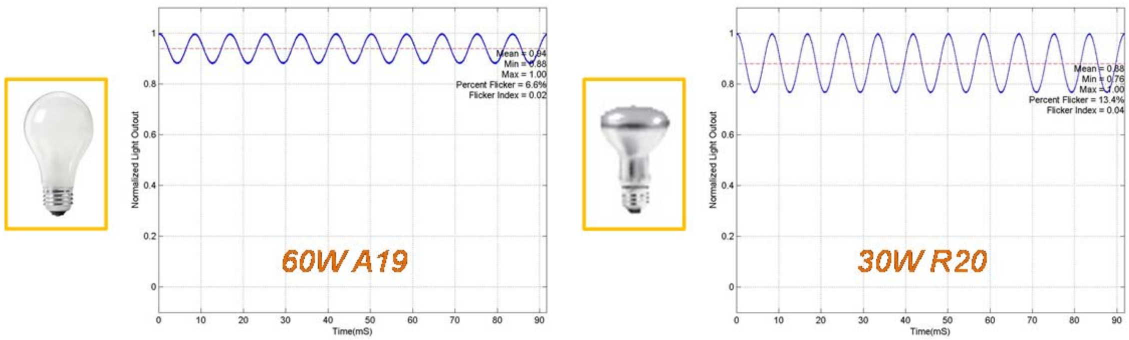

Figure 4: Examples of Incandescent Lamp Flicker

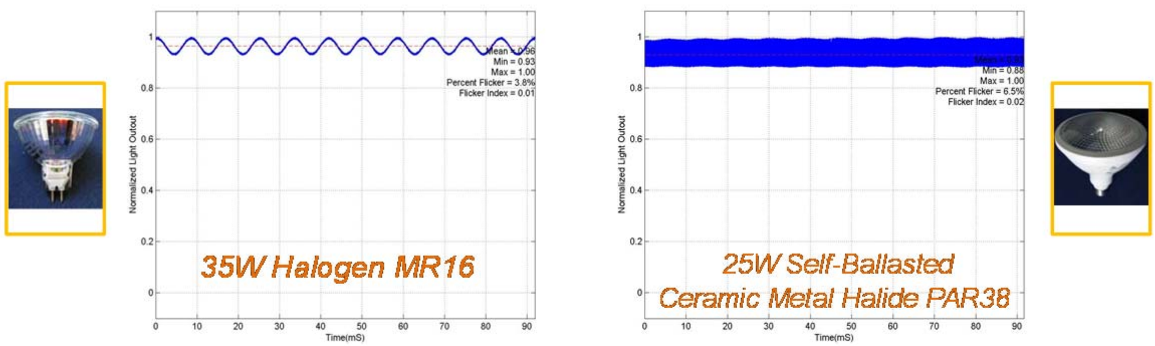

Figure 5: Examples of 12V Halogen and 120V self-ballasted (high-frequency) Metal Halide Lamp/System Flicker

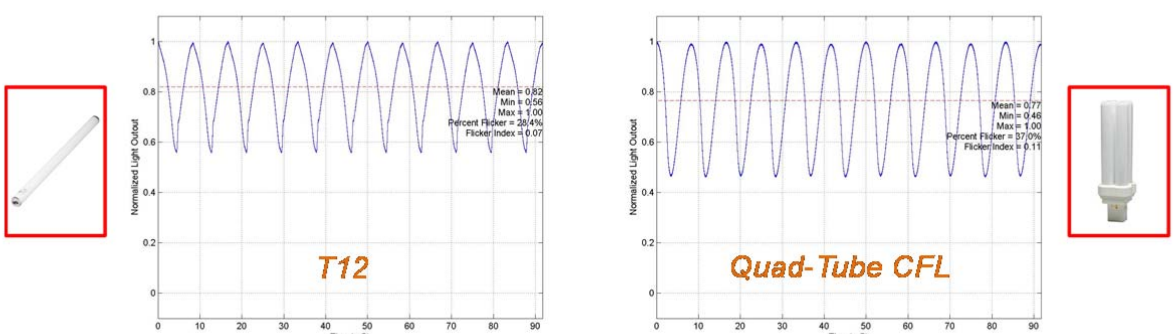

Figure 6: Examples of Magnetically Ballasted Fluorescent Lamp/System Flicker

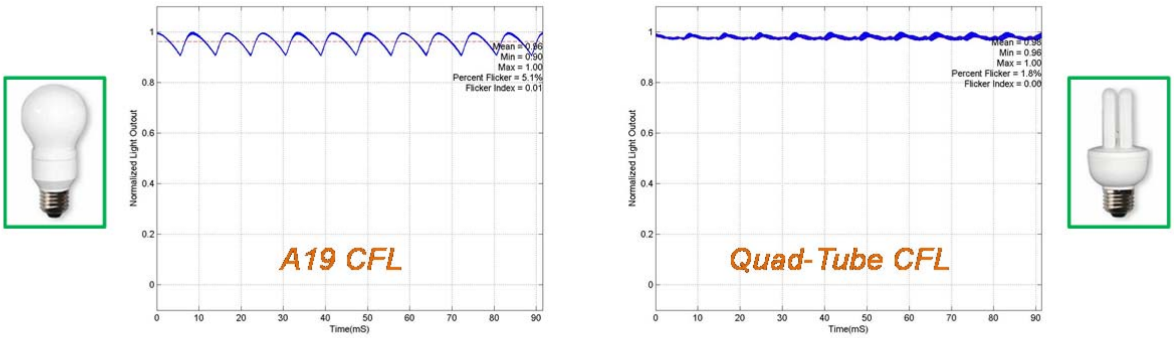

Figure 7: Examples of Electronically Ballasted Fluorescent Lamp/System Flicker

Combining percent flicker and flicker index in an iconic scatter plot of all the traditional lighting technology samples creates a frame of reference for discussing flicker. In Figure 8: , 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.

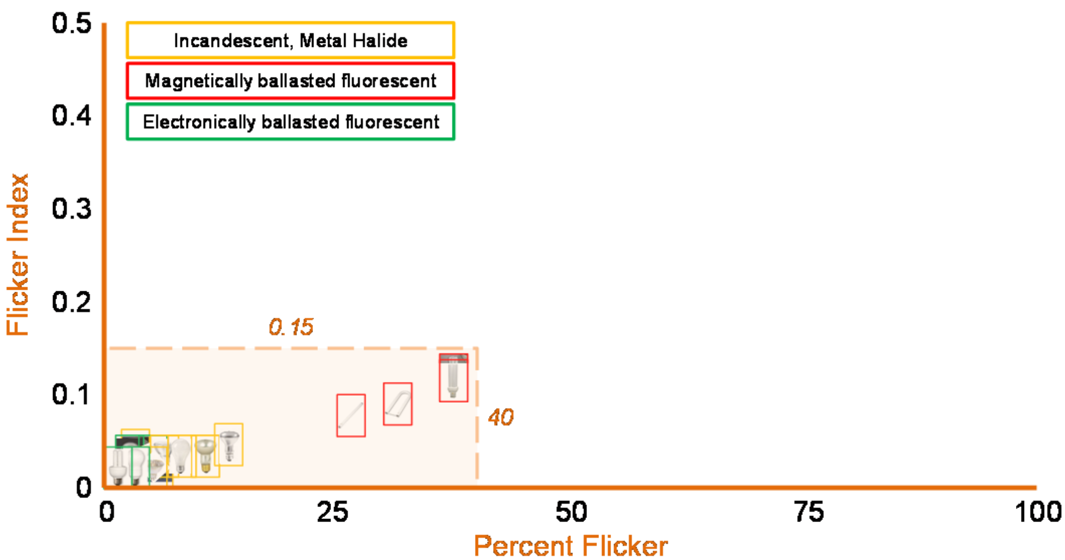

Figure 8: Traditional Lighting Technology Flicker Frame of Reference

Table 3 categorizes 93 unique SSL products evaluated for flicker. The products consisted mostly of integral replacement lamps, but also included some other product types for comparison.

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 9). The remaining products were either distributed almost evenly across the range of 0.2-0.4 or part of a 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 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 10. 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.

Table 3: 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

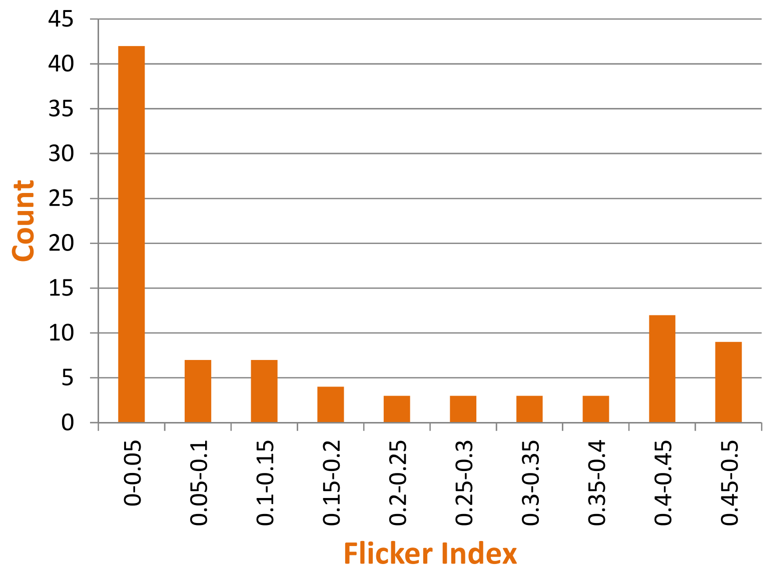

Figure 9: Flicker Index Histogram for All Tested SSL Products

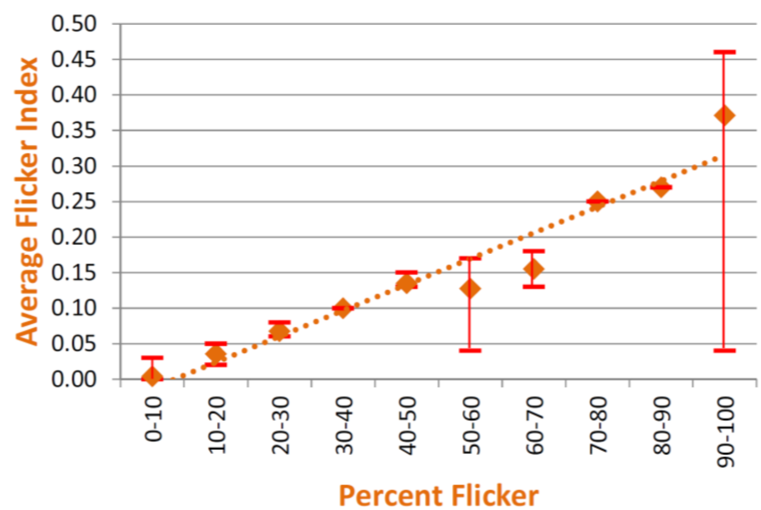

Figure 10: Flicker Index vs. Percent Flicker for All Tested SSL Products

The measured luminous flux modulation and calculated flicker metrics for a subset of these products, across various source categories, are shown in the following figures.

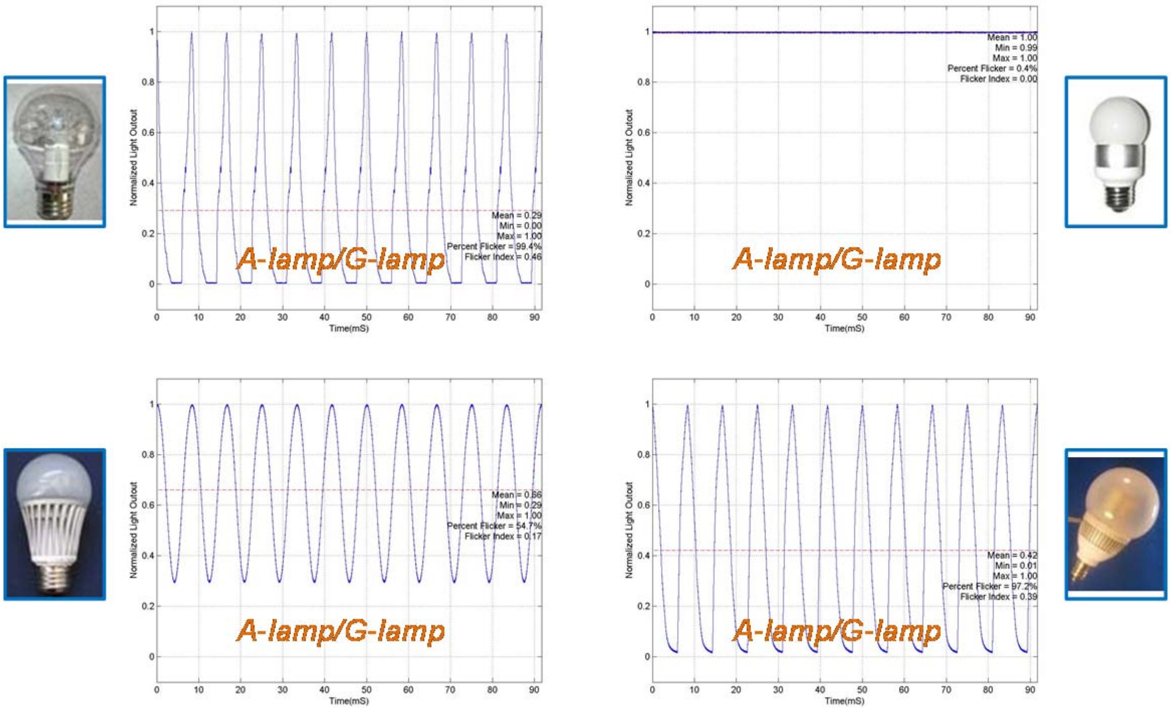

Figure 11: **Examples of SSL A-Lamp/G-lamp Flicker**

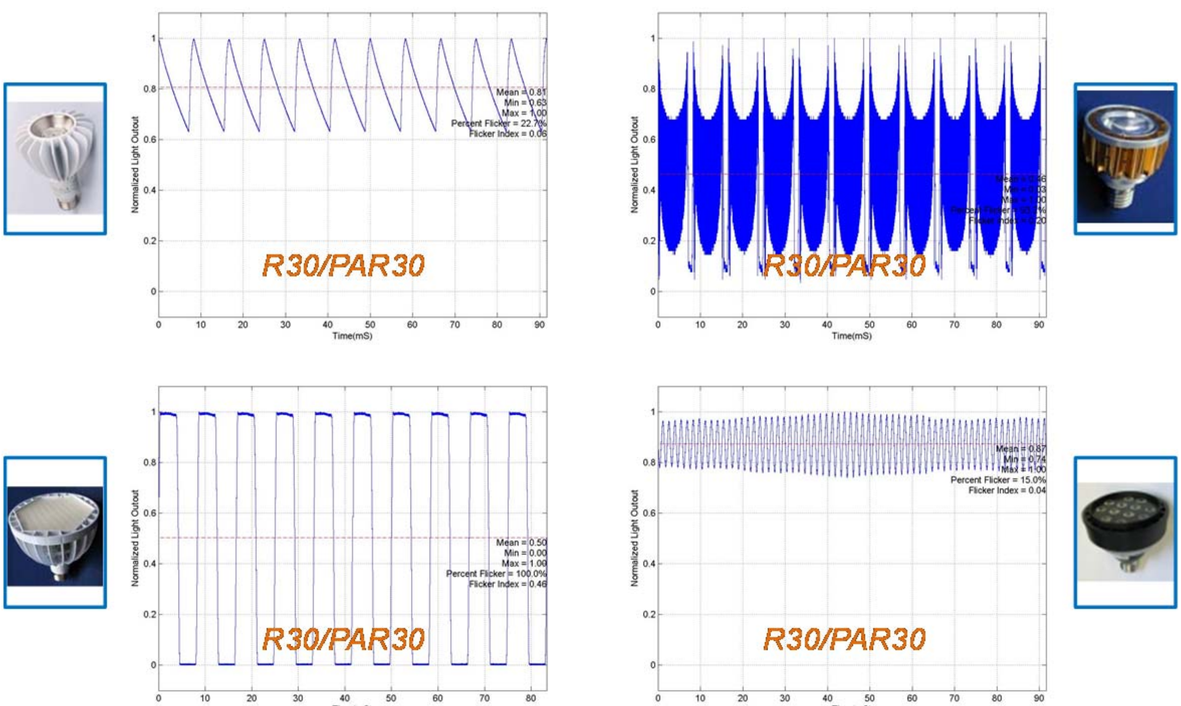

Figure 12: Examples of SSL R/PAR Lamp Flicker

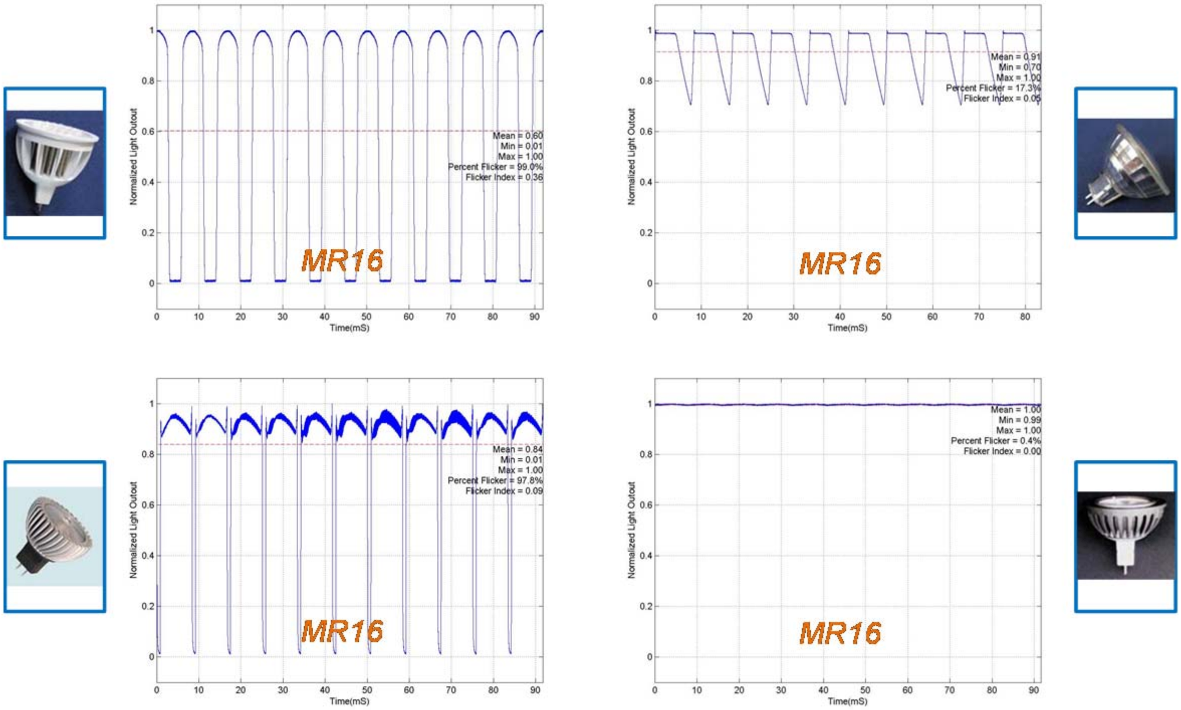

Figure 13: Examples of SSL MR16 Flicker

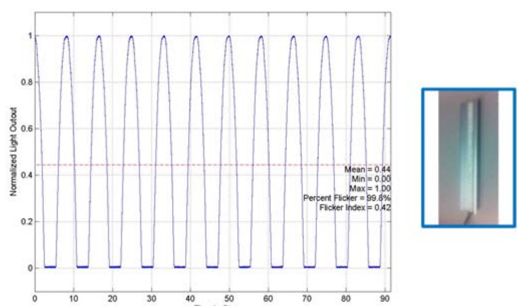

Figure 14: Flicker Typical of All Tested SSL Modules Marketed As Containing "AC LEDs"

The flicker frame of reference introduced and discussed previously was updated in Figure 15 to include most of the SSL product examples shown in Figures 11-14. Figure 15 graphically summarizes many previous observations:

- Some SSL products currently on the market have equal or better (as noted by the lower arrow) flicker performance than traditional lighting technology.
- Some SSL products currently on the market are clearly well outside (as noted by the upper arrow) 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.

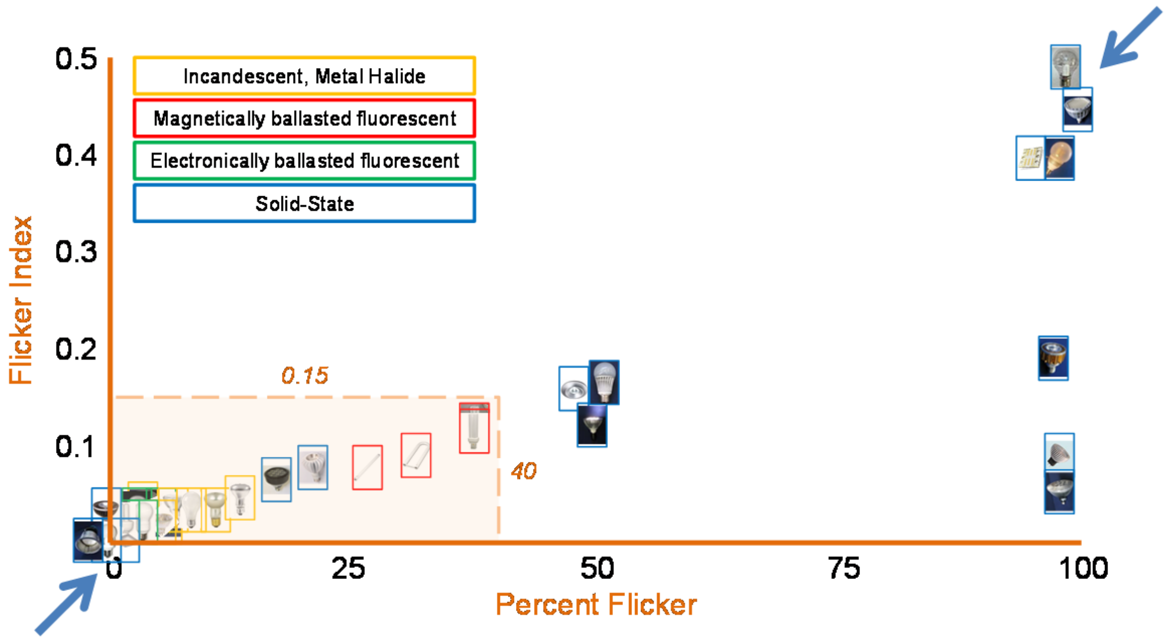

Figure 15: Examples of SSL Products on the Flicker Frame of Reference

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 unfamiliar 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.

5 Effect of dimming on SSL Products

Dimming a SSL source can induce or increase flicker, as shown in the Figure 16. Some SSL sources that exhibit little to no flicker at full output on a switch can exhibit flicker when dimmed. The amount and characteristics of this induced flicker is typically dependent on the techniques used by the LED driver to implement dimming. Interaction between the dimming control and the LED driver can further impact the flicker exhibited by SSL sources, especially for phase-control dimmers. This suggests that any evaluation of flicker should be done at both full output and at one or more dimmed levels.

Pulse-width modulation (PWM) dimming circuits by definition induce flicker in SSL systems. Flicker perception is reduced for higher PWM frequencies, so flicker is far less detectable when dimming is performed using a PWM frequency of 1000 Hz compared to 300 Hz, for example. Not all LED drivers implement dimming using PWM. Some LED drivers use Constant Current Reduction (CCR), which reduces the DC offset current in the LEDs. Other drivers use a combination of PWM and CCR techniques for dimming.

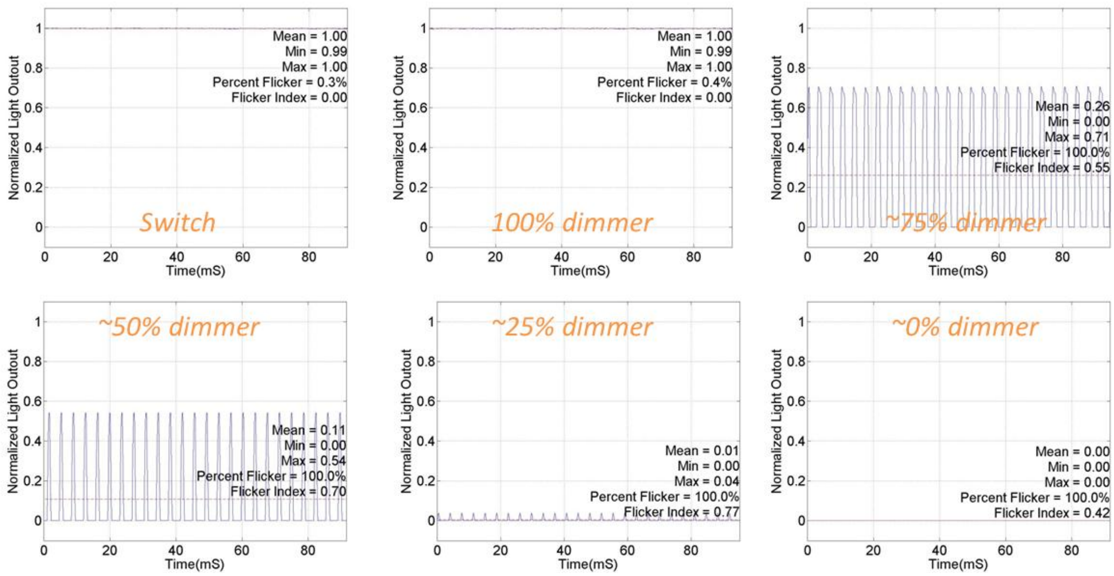

Figure 16: Example of flicker waveforms from a recessed LED troffer with 0-10V PWM dimming driver, exhibiting a flicker frequency around 250 Hz.

6 A proposed flicker metric and values

Ideally, a metric based on a Fourier analysis of the flicker waveform would be preferred because of its ability to account for all four periodic waveform parameters with a single metric. However, the use of Fourier analysis on time-sampled waveforms adds another degree of measurement and computation complexity that must be standardized to ensure apples-to-apples comparisons. A two-phase approach is suggested: the first, near-term proposal uses existing metrics to minimize development time; the second, follow-up approach would incorporate the use of a Fourier analysis based metric. Given that neither percent flicker nor flicker index account for variations in frequency, the use of either must be accompanied by a flicker frequency dependency. We propose that in the near-term, a flicker index criteria that is relaxed for higher flicker frequencies can be suitable for classifying light sources for architectural applications. Flicker index is preferred to percent flicker because it includes the effect of duty cycle, a particularly important consideration given the prevalence of PWM techniques used to dim LEDs.

It is hoped that this “strawperson” criteria will generate discussion and accelerate the adoption of flicker criteria by industry agencies creating performance standards. In the USA, the Environmental Protection Agency’s (EPA) EnergyStar® Program has proposed a flicker standard for SSL products, with input from various stakeholders. Invited laboratory partners are evaluating products for the proposed criteria, and instituting round robin testing to ensure labs can product consistent results. The laboratories are financially motivated to participate, as is the international lighting industry. It is expected this will lead the industry to develop a standardized test procedure for flicker. Other agencies such as the California Public Utilities Commission are also considering flicker criteria.

The anchor point for the proposal is the performance of magnetically ballasted linear fluorescent lamps, which set a maximum flicker index at twice the input AC frequency (100 or 120Hz). The maximum flicker index should be relaxed for waveforms with higher periodic frequencies. In the interests of simplicity, this frequency dependency should be linear. The slope of this line should be set with consideration to findings in relevant flicker studies:

- Incandescent lamps, with less than flicker index of <0.05 (<15% flicker) are known to not produce problematic flicker as long as the frequency is above 100Hz (IEEE 2010). PNNL measured incandescent lamps at .03 flicker index, 6-10% flicker, 120 Hz.

- Magnetically ballasted linear fluorescent lamps are known to be related to migraine and headaches when operated at 100Hz (Wilkins 1989). Flicker index is approximately 0.09 (30% flicker).
- Recent research by Wilkins and Roberts suggests there is no effective perceptual difference between a phantom array and the stroboscopic effect from flicker when the human observer's eye is moving, or when an object is moving in the field of view. They suggest that under nighttime driving conditions, 10% flicker (approximately 0.03 flicker index for a theoretical sine wave) at 120Hz is insufficient for reliable flicker detection, but at 20% flicker (approximately 0.06 flicker index), nearly 100% of subjects accurately detected flicker at that frequency. (A phantom array is an artefact of flicker where a discrete image is reproduced across the visual field as the eye moves, rather like animal tracks in the snow.)
- Vogel, Sekulovski, and Perz (Vogels 2011) tested threshold flicker perception under combinations of movement, modulation depth, duty cycle, and frequency with square wave stimuli. Their data suggests that an average reduction in detection would be achieved with a flicker index value < 0.10 at 100 Hz, flicker index value < 0.15 at 200 Hz, and < 0.25 at 400 Hz. Note that there is variation in the sensitivity of individuals, so these average values may evoke a flicker response in some people. (They also reported that no stroboscopic effect was described by subjects at 400 Hz, 90% duty cycle at all modulation depths.)
- Work by Bullough, Sweater Hickcox, Klein, Lok, and Narendran (Bullough 2011) suggests the following: Detection of flicker by over 60% of subjects occurs at <250 Hz, 50% duty cycle, >10% flicker; and also at <2000 Hz, 50% duty cycle, 100% flicker. Flicker was considered unacceptable at 100 Hz, 50% duty cycle, >20% flicker; and also at <400 Hz, 50% duty cycle, 100% flicker. Flicker was detected by 70% of subjects at <300 Hz, 50% duty cycle, >25% flicker. High acceptability was recorded at 1000 Hz or higher, 50% duty cycle, 5% to 100% flicker. It was further noted that 5% flicker received high ratings of acceptability for all frequency conditions, at 100 Hz or greater. All of these data points are plotted in Figure 17.
- In a followup paper reporting on visual performance under flickering illumination, Bullough, Skinner, and Sweater Hickcox (Bullough 2012) observed that task performance error rates went up under detectable flicker of 100 Hz/50% duty cycle/100% flicker, and 100 Hz/50% duty cycle/25% flicker, compared to the baseline of 1000 Hz/50% duty cycle/100% flicker. It is not clear from this study whether error rates would drop further under even higher frequencies.
- In a recent exploratory work on LED recessed troffers through the US Department of Energy's CALiPER Program, PNNL asked 18 observers to evaluate flicker from pairs of luminaires installed in a mockup office space. Table 4 shows combinations of flicker index, % flicker, and frequency that produced responses of "Low to moderate flicker" or "Moderate to bad flicker." All of the "moderate to bad flicker" responses were for dimmed LED products that appeared to use PWM techniques.

Table 4 Observer flicker responses and metrics from PNNL CALiPER LED troffer study. All but the top two rows correspond to luminaires in dimmed a state.

	Flicker Index	% Flicker	Approx. Flicker Frequency
Low to moderate flicker	0.07	21.6	120 Hz
	0.07	23.6	120 Hz
	0.05	16.3	120 Hz
	0.59	100	480 Hz
	0.04	13.2	120 Hz
Moderate to bad flicker	0.77	100	270 Hz
	0.76	100	260 Hz
	0.77	100	250 Hz

The data points from the studies listed above have been translated into a table of flicker index and flicker frequency, and have been plotted in Figure 17 according to whether they produced imperceptible flicker, an acceptable level of flicker, low to moderate flicker, or moderate to bad flicker. The authors then interpreted the results in an effort to separate somewhat ambiguous definitions of flicker into guidance for application. An orange line has been drawn to differentiate between combinations likely to produce no flicker issues ("Allowed for applications") or problematic flicker issues ("Not Allowed for applications"). The upturn of the orange line at 800 Hz is shown to suggest that flicker of 800Hz or greater is unlikely to produce harmful effects, but this needs confirmation by researchers, since there are few data points in that range.

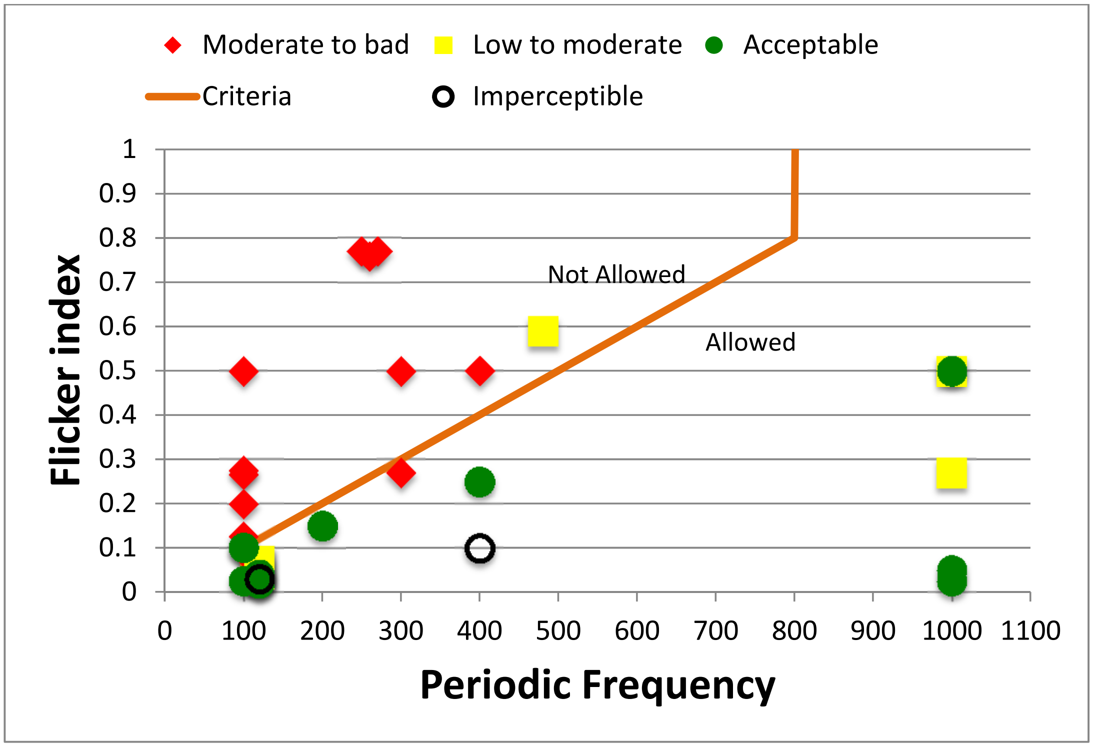

Figure 17: Plot of flicker index and flicker frequency using data points from a past and recent flicker studies. Black circles indicate imperceptible flicker, green data points indicate acceptable flicker, yellow indicate possible flicker detection causing issues in some applications, and red data points indicate responses of unacceptable flicker. Note: For some SSL products, including some of the examples in Figures 11 and 13, the Periodic, or flicker frequency may not be obvious. In order to allow for evaluation of these products, a stricter alternative criterion – perhaps a maximum percent flicker of 20% - may be required.

7 Flicker in application

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

- Headaches and eyestrain. Dr. Wilkins et al (Wilkins 1989) 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.
- 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 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 (Wilkins 2013). 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 2001).
- Disruptive behaviours in individuals with autism. Children with autism (currently estimated by the US Centre for Disease Control at 1 in 88 children) are especially sensitive to changes in their environment, and flicker from lighting can result in increased repetitive behaviours (Fenton 1985).

7.1 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)
- Colour 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.

7.2 Where flicker matters

For the following applications, lighting specifiers should recommend lighting systems that fall below the line in Figure 17, with less than 0.1 flicker index at 100Hz, less than 0.3 at 300 Hz, less than 0.5 at 500 Hz, for example. If the light system uses PWM dimming with 100% flicker, with a flicker index of 0.8 or higher, then a minimum frequency of 800 Hz is recommended. In no cases is it advisable to have flicker frequencies of less than 100 Hz.

- 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. and is likely to affect a wide population that may include those who suffer from migraines and headaches.
- 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. It may be advisable to avoid PWM dimming techniques in these applications, altogether.
- 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 to reduce the effective depth of modulation.

7.3 Where flicker is less important, or even advantageous

For the following applications, flicker requirements can likely be relaxed. Flicker frequency should always remain at or above 100 Hz, but higher flicker index (perhaps 20%?) above the line in Figure 17 may be acceptable.

- Parking lots/roadways where users are moving in a motor vehicle or spending short periods of time. Flicker is less problematic with short exposures, and probably at lower illuminances.
- 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. Traffic signals may incorporate a strobe light to increase conspicuity of the signal. It may be prudent to avoid the prominent sensitivity ranges for photosensitive epilepsy, however.

8 Conclusion

The data presented in this paper demonstrate the great variability in flicker found in commercially available LED products. Flicker is therefore a key attribute that the practitioner needs to consider in evaluating LED products. 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.

A standardized measurement procedure and reporting protocol is ideally needed to help the practitioner in that effort, along with clear application specific guidelines for deploying lighting products with known flicker characteristics. In the meantime, a spinning top "flicker checker" or a rapidly-waved pencil are simple tools the practitioner can use when viewing products, to identify those that exhibit flicker. Visual assessment of LED lighting products by the lighting practitioner and representative occupants in their intended application is always recommended. While new flicker research holds the promise of identifying when and where different levels of flicker are acceptable for various user populations, some means for classifying products currently on the market is needed to help educated practitioners and novices identify light sources that are going to minimize their risk in most circumstances.

This paper presents a conservative approach to developing a minimum recommended performance criteria for flicker, taking into consideration the performance of known lighting systems, and incorporating results from significant researchers in the field. It is hoped this will minimize the chance that inappropriate lighting products are installed in applications where flicker can be a significant health hazard or where it can hinder productivity and human comfort.

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