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An analytic-numerical image flicker study to test novel flicker metrics

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Abstract

The IEEE P2020 Automotive Image Quality working group is proposing new metrics and test protocols to measure image flicker. A comprehensive validation activity is therefore required. Light source flicker (often LED flicker), as captured in a camera output, is a product of camera exposure time, sensitivity, full well capacity, readout timing, HDR scheme, and the light source frequency, duty cycle, intensity, waveform and spectrum. The proposed LED flicker metrics have to be tested and validated for a sufficient number of combinations of these camera and lighting configurations. The test space of the combinations of camera and lighting parameters is unfeasibly large to test with physical cameras and lighting setups. A numerical simulation study to validate the proposed metrics has therefore been performed. To model flicker, a representative pixel model has been implemented in code. The pixel model incorporates exposure time, sensitivity, full well capacity, and representative readout timings. The implemented light source model comprises an hybrid analytic-numerical approach that allows for efficient generation of complex temporal lighting profiles. It simulates full and half wave rectified sinusoidal waveforms, representative of AC lighting, as well as pulse width modulated lighting with variable frequency, duty cycle, intensity, and complex edge rise/fall time behaviour. In this article, both initial results from the flicker simulation model, and evaluation of proposed IEEE metrics, are presented.

Introduction

In recent years, in many lighting applications, LED lighting has begun to replace more traditional lighting sources, such as incandescent and fluorescent lights, primarily because of its low cost, high efficiency and design flexibility. Specifically within the automotive environment, LED lights are now commonly used in vehicle headlamps and signals, and are also being used in traffic lights, speed signs, temporary road markings etc.

Typically, the brightness of LEDs is controlled by Pulse Width Modulation (PWM). Using this method, the output brightness can be controlled by varying both the duty cycle and frequency of modulation. This technique has many advantages, including higher dimming ratio capability than current modulation, and avoids LED colour shifts at low current levels.

As has been previously described in the literature [1, 2, 3, 5], the simultaneous development of PWM driven LED lighting and the evolution of automotive imaging has led to the increasingly widespread phenomenon of so-called LED flicker. A full description of the mechanism of LED flicker has been described in detail in previous studies [5]. Briefly, flicker is an artifact observed in digital imaging where a light source or a region of an imaged scene appears to flicker (i.e. the light may appear to switch on and off, or modulate in terms of brightness or color), even though the light source appears constant when viewed directly by a human observer.

The implications of flicker vary. In some applications, flicker may only be considered as an annoyance or distraction to the driver. However, in other applications, a flickering headlamp may be mistaken for a turn signal, or for Advanced Driver Assistance (ADAS) systems - flicker can increase the difficulty of detecting traffic signals, speed signs, or safety messages.

The IEEE P2020 Automotive Image Quality Working Group [2] was established to define standards for automotive imaging applications. Within the scope of this work, LED flicker has been identified as a topic where existing image quality standards are insufficient. Hence, the IEEE P2020 working group are actively working on standard test procedures and metrics for camera LED flicker assessment.

Defining metrics for LED flicker measurement

As of writing, test procedures and metrics for LED flicker are still under development. However, a number of key metrics have been identified. These include the Flicker Modulation Index:

$$\mathrm{FMI} = 100 \times \frac{X_{\max} - X_{\min}}{X_{\max} + X_{\min}} \tag{1}$$

where $X_{\max}$ is the maximum measured signal, $X_{\min}$ is the minimum measured signal of the PWM light source for the entire captured video sequence. A lower number indicates less flicker in the output image.

Flicker Detection Index (FDI) is a measure of the probability that a flickering light will be distinguishable from the background light level, and is defined as:

$$\mathrm{FDI} = \mathrm{Prob}\left(\frac{X_{\mathrm{meas}} - X_{\mathrm{ref,off}}}{X_{\mathrm{ref,off}}} \geq \text{flicker threshold}\right) \tag{2}$$

where X_{meas} is the instantaneous measured flickering signal level, $X_{\mathrm{ref,off}}$ is the reference background light level or "off" light level, and flicker threshold is the minimum defined acceptable Weber Contrast level (Note that both Weber and Michelson contrast are used, for FDI and FMI respectively). A higher number indicates better flicker mitigation, with a value of 1.0 indicating that in all frames measured, the flickering light source can be distinguished from the background/off light level.

Modulation Mitigation Probability (MMP) is defined as

$$\mathrm{MMP} = \mathrm{Prob}((\overline{X_{\text{ref,on}}} - \delta \cdot \overline{X_{\text{ref,on}}}) \leq X_{\text{meas}} \leq (\overline{X_{\text{ref,on}}} + \delta \cdot \overline{X_{\text{ref,on}}})) \quad (3)$$

where X_{meas} is the measured flickering signal level, $X_{\text{ref,on}}$ is the reference expected light level, and δ is the defined acceptable threshold level. A higher number indicates better flicker mitigation, with a value of 1.0 indicating the light level was measured within a target threshold for all video frames measured.

A full description of the test protocols and metrics is beyond the scope of this study. However, these proposed metrics are proposals for new image quality assessment standards, and as such, will have to be thoroughly validated prior to publication.

Flicker metric validation challenges

One of the main challenges regarding flicker is the lack of standardization of PWM frequencies and duty cycles. Before the widespread adoption of LEDs, cameras were vulnerable to banding and flicker effects from AC light sources. AC driven light sources modulate at 50 Hz or 60 Hz, depending on geographical location. As a result, banding effects could be mitigated by setting the camera exposure time to be an integer multiple of half of the AC lighting period (i.e. for 60 Hz regions, setting the exposure time to an integer multiple of 8.333 ms would ensure no visible flicker from lighting). However, LED lights have very few restrictions in terms of frequency and duty cycle choice. The main restriction is that the PWM frequency has to be greater than 90 Hz [4], to avoid flicker being visible to the human visual system. Under current requirements, once this restriction is met, engineers are free to choose whichever combination of frequency and duty cycle meets their application requirements. The impact on camera systems is typically not considered.

This presents a significant challenge when it comes to validating proposed LED flicker metrics. Given the lack of constraints on LED light parameters, the test space of the combinations of camera and lighting parameters is unfeasibly large to test with physical cameras and lighting setups. As an illustrative example, consider a camera capturing video at 30 frames per second, imaging a PWM driven LED light. The beat frequency of the flickering light as captured by the camera is effectively the modulus of the flickering light source and the camera capture frame rate [1]. If the PWM frequency is 180.0 Hz, the beat frequency at the camera will be 0 Hz i.e. the light does not flicker. However, if the frequency of the PWM light is 180.5 Hz, the light source, as imaged by the camera, will modulate with a frequency of 0.5 Hz. This is approximately the same frequency at which standard turn signals operate. In other words, a 0.5 Hz difference in LED frequency completely changes the characteristics of the flicker as captured by the camera.

Based on this, it is clear that simulation will be required, to fully validate the proposed flicker metrics. This paper outlines the flicker model developed by the IEEE P2020 working group, and presents the results of the flicker model validation study.

Simulation

To replicate the varying effects of flicker, a hybrid analytic-numerical simulation has been implemented in Python. It consists of a set of illumination and sensor models, with multiple adjustable parameters for each.

LED model

For this study, two major illumination models are considered: a) a PWM driven LED and b) a rectified AC driven model. The base signals are assumed to reach a maximum value of 1 a u and are defined by one period on the unit interval $[0,1]$, and then scaled by a given frequency f. The PWM model supports various rising and falling edges with a set duty cycle. The possible shapes are a step, linear or a capacitance loading curve. Figure 1 shows an example of the linear and capacitance curves, with additional parameters. The AC model supports leading and trailing edge dimming as well as half and full wave rectification, as can be seen in Figure 2. Both models allow scaling of the maximum intensity via a contrast parameter, a DC lighting offset, as well as a phase offset. A full description of the parameters is given in table 1.

Table 1: LED Model parameters

Parameter	Description
	Both models
Frequency f	Frequency of the signal.
Offset	Constant offset corresponding to DC lighting.
Contrast	Scales the maximum intensity of the LED waveform.
Phase offset φ	Phase offset of the signal in degrees
	PWM model
Duty cycle (DC)	Fraction of the full period during which the signal is above 50% intensity.
Rise/Fall curve	Shape of the rising and falling edge of the waveform. Either step, linear edge or capacitance loading curve.
Half load cycle HLC	Fraction of the full period the signal requires to reach 50% intensity. For a given RC time constant τ and the frequency f this can calculated via $(\mathrm{HLC}) = \ln(2) \cdot f \cdot \tau$
	AC model
Rectification	Full or half rectification of the AC signal.
Dimming Mode	Supports no dimming, leading edge dimming and trailing edge dimming.
Dimming Cycle	Fraction of a half-period where the signal is set to 0.

The complexity of the models waveforms renders a purely numerical approach, i.e. a simple sampling of the waveform with high temporal resolution, unfeasible. We developed a combined analytical and numerical approach. The analytical part of our hybrid sensor model is based on symbolic integration of the waveforms, which are all given by piece-wise combinations of elementary functions. The limits of integration are given by the recording duration, the frame rate, a timing offset and the exposure time. For exposures over multiple periods of the T-periodic waveform $f(t)$ the following identity reduces the calculation to a few evaluations of the integrated waveform $F(t) = \int_0^t f(\tau)\,\mathrm{d}\tau$ in the base interval $[0,T]$.

$$\int_{nT+a}^{mT+b} f(t)\,\mathrm{d}t = (m-n)F(T) - F(a_0) + F(a_1) \quad (4)$$

The term $F(T)$ is the integral over one period of the waveform and can be cached for the evaluation of multiple exposures. For a constant exposure time, a whole parameter set for the DC offset and contrast can be calculated simultaneously, because the DC offset integrated over a constant interval is also constant, and the contrast is applied by a scalar multiplication. After calculation, these results can be scaled and clipped simulating sensitivity and full well capacity of the sensor, respectively.

Photo-diode model

One set of exposures corresponds to a time series signal recorded by a single pixel. By varying the timing offset a rolling shutter sensor can be simulated. Running multiple simulations with varying exposure times allows gathering the raw data necessary for High Dynamic Range (HDR) tone mapping.

The output of the photo-diode model is given in arbitrary units (au). It is currently proportional to the value of the charge accumulated in the floating diffusion, as the integral of the temporal overlap between the modulated light source and the exposure time of the photo-diode. It is thus numerically scaled by the value of the maximum exposure time used in this study, i.e. by 11 au, which is what physically happens when the charge is accumulated for longer exposure times. In other words, the maximum numerical value for a constant DC light source with maximum intensity of 1 exposing the photo-diode with the maximum exposure time of 11 ms yields a numerical value of 11 au.

Currently the sensitivity is implemented using a simple scaling factor. Later this can be expanded to include spectral properties and quantum efficiency. Further, a simple clipping algorithm does a zero-order approximation of a full-well capacity.

In a further refinement of the model this amount of charge will be compared to the physical full-well capacity, and hence moved into a model of the A/D-converter with appropriate lower and upper voltage bounds, which then gives digital numbers. Here, more complex full-well models are easily implemented (analytically, or as a look-up-table). This is left for future work.

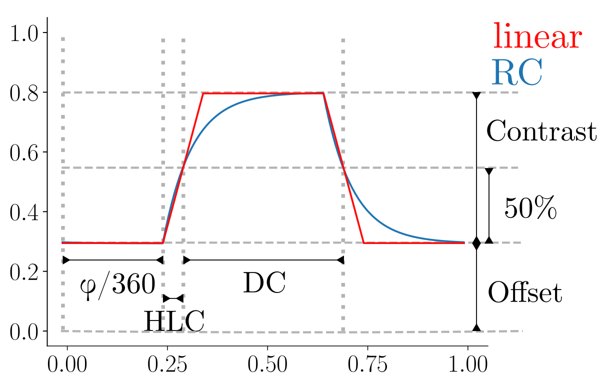

Figure 1. *PWM driven LED waveforms.*

Simulation validation study

As part of the provisional validation of the flicker simulator, a small scale validation study was performed. The primary goal of this study is to confirm that the output from the flicker simulator produces results in line with expected performance from real world sensors. A secondary goal of the validation study to measure flicker using the metrics proposed by the IEEE P2020 working group. The following section defines the validation study protocol.

Simulation study model parameters

Table 2 below shows the flicker and sensor parameters selected for the validation study.

For FDI calculations, a contrast detection threshold of 10% was selected. Similarly, for MMP, a δ value of 10% was also used. All in all, 24 configurations were simulated.

Table 2: Validation study parameters

Validation study model Parameters	
Parameter	**Description**
Frequency (Hz)	70, 89, 241, 415
Offset	0.25 au
Contrast	0.75 au
Phase offset (degrees) φ	0
PWM model	
Duty cycle (%)	10, 50, 90
Rise/Fall curve	Capacitance loading curve
Half load cycle HLC	0.001
Sensor model	
Exposure time (ms)	LFM mode: 11 ms. Non LFM mode: 5 ms

Results

Flicker Model Results

For the purposes of illustration, two exemplary model outputs are outlined below. Figure 3 and Figure 5 show sample time series generated by the flicker model. In Figure 3, the exposure time is relatively short, and the PWM duty cycle and frequency are quite low. In this example, in many cases, it can clearly be seen that the exposure times do not overlap with the PWM light pulse. The corresponding time series plot in Figure 4 shows the signal amplitude is low, and the level of flicker is quite high relative to the amplitude of the signal.

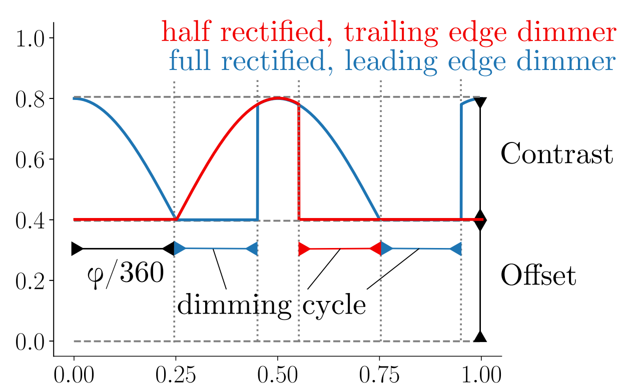

Figure 2. *Rectified AC driven LED waveforms.*

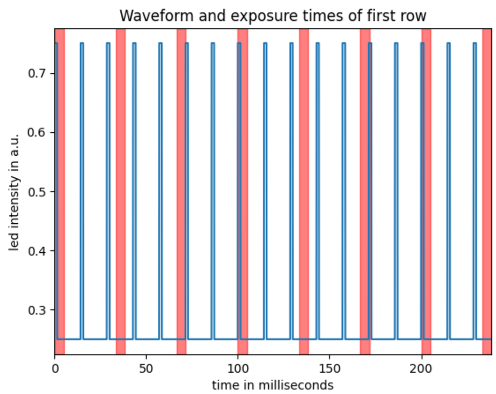

Figure 3. Model PWM output signal. The shaded band indicates the exposure period. Exposure time = 5 ms*, PWM frequency =* 70 Hz*, duty cycle = 10%*

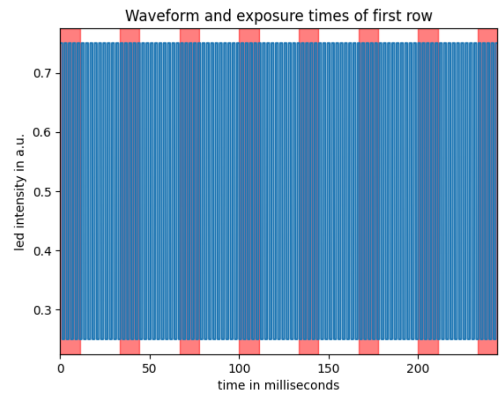

Figure 5. Model PWM output signal. The shaded band indicates the exposure time. Exposure time = 11 ms*, PWM frequency =* 415 Hz*, duty cycle = 50%*

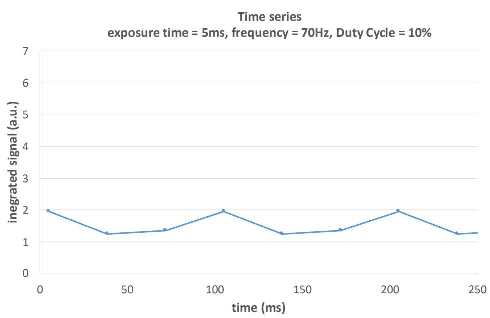

Figure 4. Model output integrated signal time series output. Exposure time = 5 ms*, PWM frequency =* 70 Hz*, duty cycle = 10%*

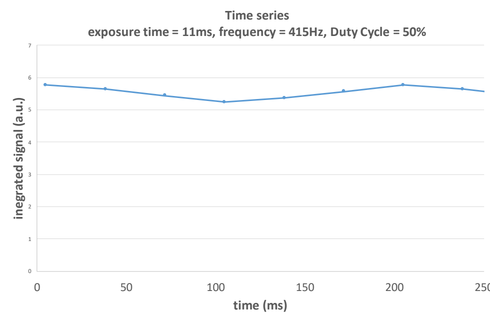

Figure 6. Model output integrated signal time series output. Exposure time = 11 ms*, PWM frequency =* 415 Hz*, duty cycle = 50%*

In contrast, in Figure 3, the exposure time is longer, and the PWM frequency is higher, as is the duty cycle. The variation in integrated signal will vary less in this use case, and the signal amplitude will also be higher. This is clearly shown in Fig. 6.

Any combination of the 24 sets of simulation parameters yields a slightly different model output, as a time series. Then, every simulation result was evaluated with the proposed flicker metrics.

Flicker KPI results

For each time series generated, FMI, FDI and MMP were calculated. The results for FMI are shown in Fig. 7 and Fig. 8.

FMI is higher for 5 ms exposure time, and for lower frequencies. This is in line with expectations, because there is less overlap between the sensor exposure time and the on cycle of the PWM light signal. Somewhat surprisingly, FMI was highest at 50% duty cycle. This observation can be explained by the fact that the integrated signal level at 50% duty cycle has higher amplitude than for the 10% duty cycle case (as shown in Figure 4 and Figure 6). At 90% duty cycle the likelihood of the integration period coinciding with the PWM-off phase is lower. Thus, the modulation in the integrated signal level is lower, because the PWM-on signal time is at least as long as the integration period for most integration periods.

FDI is lower for lower frequencies and duty cycles. FDI is also higher for the 11ms use case. This is in line with expectations. For short exposure time, low frequencies and low duty cycles, the likelihood that the exposure time coincides with the off period of the PWM cycle is much higher. This can be intuitively understood from visual inspection of the time series plots, as shown for example in Figure 4.

MMP results are summarized in Figure 11 and Figure 12. In the 5 ms use case, MMP is zero for all frequencies with 10% duty cycle, trends to zero for 50% duty cycle, but increases at higher frequencies for 90% duty cycle. In the 11 ms use case, MMP is 1.0 for all frequencies and duty cycles. This is not in line with expectations. MMP is a metric that describes a sensors ability to mitigate flicker. In principle, MMP should be higher for longer exposure times, higher frequencies and higher PWM periods. This is not reflected in the results, and is the topic of further analysis in the Discussion section.

Discussion

The primary aim of this study is to validate the flicker model is operating as predicted, and is representative of real world modulating signal and image sensor behaviour. This first implementation is a very much simplified model. It does not model the actual physics of light sources or take image sensors into account. The output is in arbitrary units, which are not directly matched to an actual image sensor or camera output. Also, a monochromatic response is assumed.

Given these limitations, the model in its current implemen-

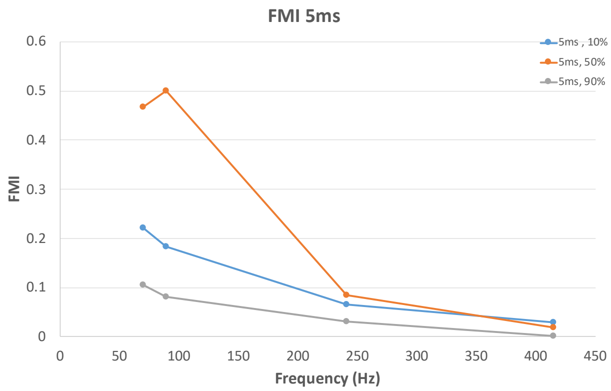

Figure 7. *FMI,* 5 ms *exposure time*

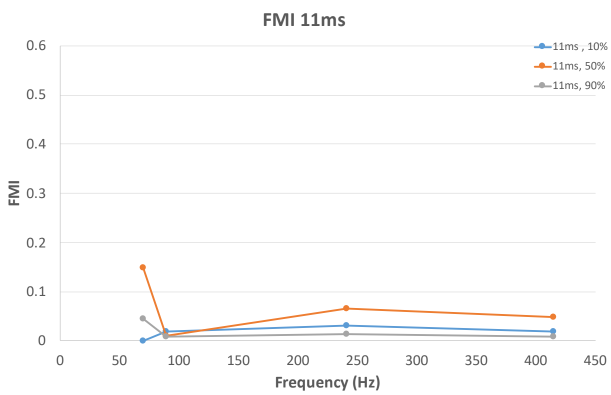

Figure 8. *FMI,* 11 ms *exposure time*

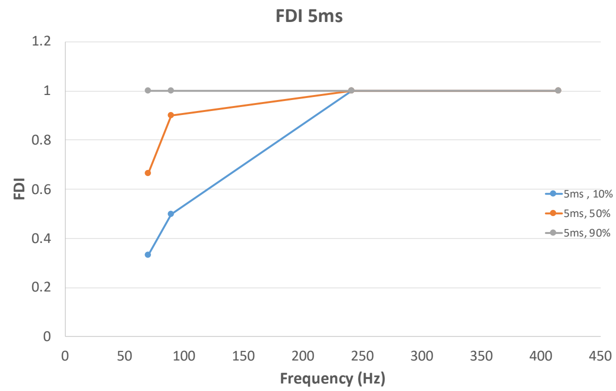

Figure 9. *FDI,* 5 ms *exposure time*

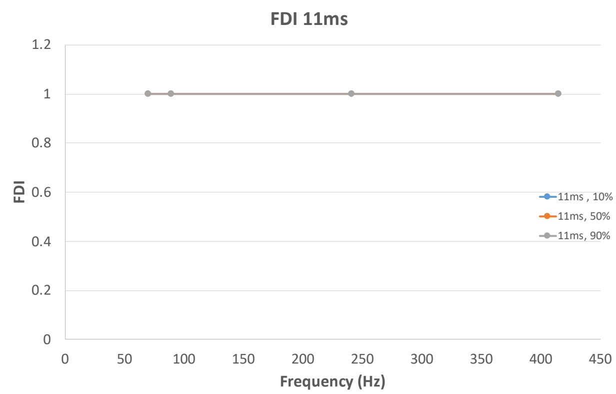

Figure 10. *FDI,* 11 ms *exposure time*

tation, is generating time series outputs in line with expectations. Low frequency signals with low duty cycles are producing signals with lower amplitude, and higher levels of modulation in the time series plots. Longer exposure times are producing time series of higher amplitude, with comparatively less flicker. Also, the waveform plots as shown in Figure 3 and Figure 5 provide an intuitive method for understanding the interaction between the sensor exposure time and the modulating light signal. Based on the results of this initial study, the model is generating operating correctly, within the scope of the current model limitations.

The number of test cases chosen for analysis was limited. This was a deliberate decision, as the frequencies, duty cycles and image sensor exposure times are quite typical of real world applications, and the expected camera output for these configurations is known. For example, it is well understood that to capture at least one pulse of a PWM driven light source, the exposure time has to be at least as long as the inverse of the PWM frequency (i.e. to capture at least one pulse for frequencies $\geq$ 90Hz, the exposure time should be at least 11 ms). In general, when a camera or system claims to have LED Flicker Mitigation (LFM), the primary mechanism of mitigating flicker is the extended exposure time. For this study, two exposure times were selected, one which meets the criteria for LFM, and one which does not. Based on the results of this pilot study, it can clearly be seen that longer exposure times are associated with superior flicker metrics. FMI, FDI and MMP are all higher in the 11 ms use case. While more analysis needs to be performed, the results from this study do indicate that FMI and FDI in particular can be useful metrics for quantifying image flicker.

MMP results, as measured in this study, are not in line with expectations. MMP is expected to measure the likelihood that a flickering light source will be within a tolerance level of an anticipated reference signal level. The reference level, in the case of this study, was originally assumed to match the signal level in the case where no flicker is present i.e. $X_{\text{ref,on}}$. This is not the case, as illustrated in Figure 13. Here, 0.75 au corresponds to the maximum amplitude of the signal level in this example ($X_{\text{ref,on}}$ for MMP), and 0.25 au corresponds to the minimum signal level ($X_{\text{ref,off}}$ for MMP). For an 11 ms exposure time, though, the signal level for a DC light source of amplitude 0.75 au ,would be $11\,\text{ms} \times 0.75\,\text{au} = 8.25\,\text{au}$. (cf. Sec. Photo-diode model). However, when integrating a PWM driven signal, assuming 70 Hz frequency and 10% duty cycle, the maximum signal level is actually $11\,\text{ms} \times 0.75\,\text{au} \times 0.1 + 11\,\text{ms} \times 0.25\,\text{au} \times 0.9 = 3.4\,\text{au}$. This is significantly lower than the anticipated $X_{\text{ref,on}}$ signal level. As a result, MMP will be zero, unless the duty cycle is relatively high. In other words, using $X_{\text{ref,on}}$ and $X_{\text{ref,off}}$ as input into MPP does not yield the expected result.

The results of this study have identified a critical problem with the MMP metric in its current definition. Despite the limitations and simplifications of this model, this result alone has demonstrated its value. The issues identified with MMP will have

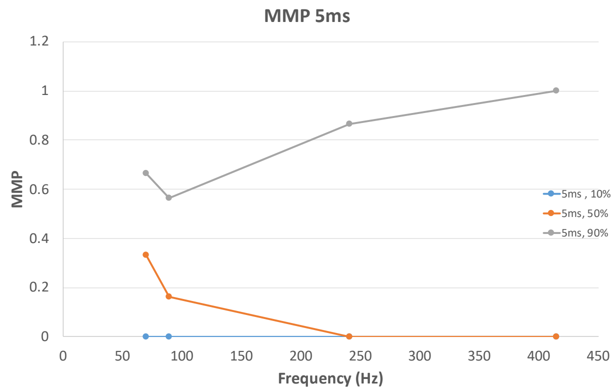

Figure 11. *MMP, 5ms exposure time*

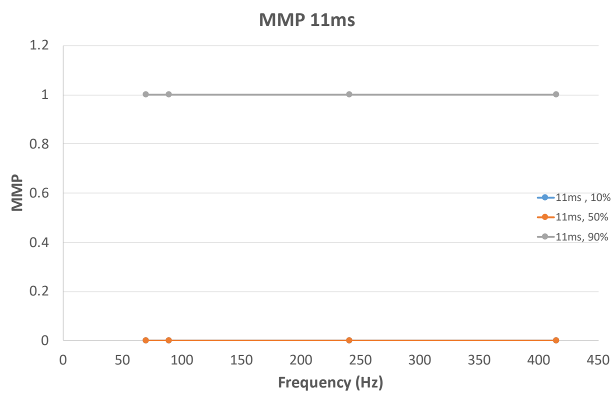

Figure 12. *MMP, 11ms exposure time*

to be addressed within the IEEE P2020 Working Group prior to standard publication. It is anticipated that this model will be heavily utilized for further metric validation studies.

Future work

In this paper, we present a simplified model of a modulated light source, and a simple pixel model. While not a physically accurate model, in it's current form, it is nevertheless sufficient for the purpose of assessing the proposed IEEE P2020 flicker metrics.

Future work aims to increase the accuracy of the model, by implementing a physics based light source and pixel model. Modelling a physically accurate light source will involve modelling spectral distribution of the light source. For this purpose, modelling the spectra of some standard illuminants (e.g. incandescent, fluorescent and standard LED spectra) would be representative of likely real world illumination conditions. The power output of the light source will also have to be modelled, using the measured spectrum of the light source.

Similarly, the pixel model will be developed into a physics based model. This will include modelling quantum efficiency, conversion gain, full well capacity, and similar properties. The initial pixel model has been based on a monochromatic pixel. Future models can incorporate various filter arrays common in automotive applications, including Bayer RGGB, RCCC, RCCG etc.

Another limitation of the current model is that it does not model HDR sensors. The majority of HDR sensors in automotive utilize a combination of multiple exposures, sensitivity adjustment and full well capacity extension to achieve increased dynamic range [6]. The current pixel model can be easily expanded to incorporate these dynamic range extension techniques. A HDR image merge algorithm, based on a configurable alpha blend method, will also be added.

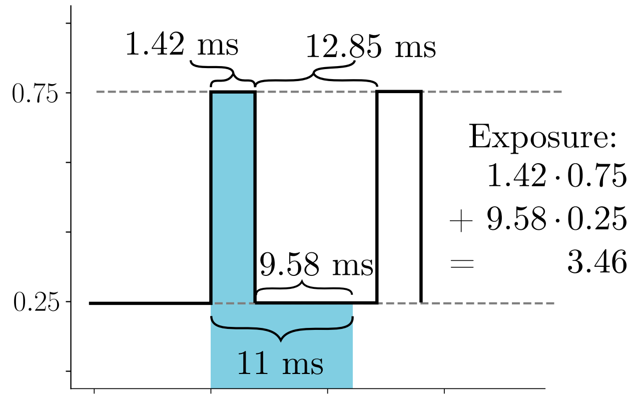

Figure 13. *Exposure example, 11ms exposure time,* 70 Hz *frequency, 10% duty cycle.*

The analytic-numerical approach has proven robust and fast, enabling the simulations in the first place, as the memory and processing requirements for highly resolved light pulse forms quickly become infeasible. It further enables an easy way forward to implement the aforementioned extensions of the model. For example, to model full-well capacity accurately the saturation point needs to be taken into account, which is a non-linear phenomenon. Because the bulk of the computation (i.e. the integral of the overlap of the lights' waveform and the exposure timing) is already done at this point a detailed model of this full-well saturation is a simple one-time function call, which can then be quite complex without impacting overall performance too much. Similar reasoning applies to spectral considerations, quantum efficiency or HDR modes.

The ultimate aim of this work is to generate a freely available, physically accurate flicker and pixel model, which can be used by engineers and developers, to model flicker, explore and validate test cases, and prototype solutions for real world flicker use cases.

Conclusion

In this paper, a flickering light source and sensor model have been presented. The model output has been validated, based on a small sample of representative frequencies, duty cycles and exposures. Further validation studies will be required, using more frequencies, duty cycles, phase offsets, ramp times, waveform shapes etc. Future work will also involve updating the model to be more representative of the actual physics of the flickering light sources and image sensors. However, even in its current limited form, the model has identified a critical issue with the MMP metric in its current definition. This is a very valuable initial result. The issues identified with MMP will have to be addressed before it can be incorporated into the IEEE P2020 Automotive Image Quality Standard.

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Author Biography

Christian Wittpahl received his BEng and MSc from the University of Applied Sciences, Düsseldorf, in 2017 and 2020 respectively. Currently, he is a researcher for automotive image quality at the same university, focusing on physically realistic image degradation. He implemented the flicker simulator on behalf of the IEEE P2020 Automotive Image Quality working group.

Alexander Braun received his diploma in physics with a focus on laser fluorescence spectroscopy from the University of Göttingen in 2001. His PhD research in quantum optics was carried out at the University of Hamburg, resulting in a Doctorate from the University of Siegen in 2007. He started working as an optical designer for camera-based ADAS with the company Kostal, and became a Professor of Physics at the University of Applied Sciences in Düsseldorf in 2013, where he now researches optical metrology and optical models for simulation in the context of autonomous driving. He's member of DPG, VDI, SPIE and IS&T, participating in norming efforts at IEEE (P2020) and VDI (FA 8.13), and currently serves on the advisory board for the AutoSens conference.

Brian Deegan received his Bachelor's Degree in Computer Engineering from the University of Limerick in 2004, an MSc In Biomedical Engineering from the University of Limerick in 2005 and PhD in Biomedical Engineering from the National University of Ireland, Galway in 2011. Since 2011 Brian has been working in Valeo Vision Systems as a Vision Research Engineer focusing on Image Quality. His main research focus is on high dynamic range imaging, LED flicker, topview harmonization algorithms, and the relationship between image quality and machine vision.