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LED flicker: Root cause, impact and measurement for automotive imaging applications

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Abstract

In recent years, the use of LED lighting has become widespread in the automotive environment, largely because of their high energy efficiency, reliability, and low maintenance costs. There has also been a concurrent increase in the use and complexity of automotive camera systems. To a large extent, LED lighting and automotive camera technology evolved separately and independently. As the use of both technologies has increased, it has become clear that LED lighting poses significant challenges for automotive imaging i.e. so-called "LED flicker". LED flicker is an artifact observed in digital imaging where an imaged light source appears to flicker, even though the light source appears constant to a human observer. This paper defines the root cause and manifestations of LED flicker. It defines the use cases where LED flicker occurs, and related consequences. It further defines a test methodology and metrics for evaluating an imaging systems susceptibility to LED flicker.

Introduction

In recent years, the use of Pulse Width Modulation (PWM) driven LED lighting has become widespread in the automotive environment. Vehicle designers have taken advantage of the flexibility of LED headlamps to devise innovative styling designs, which have now become a key brand differentiator. LED lighting is also increasingly used in road signage and advertising, because of their high energy efficiency, reliability, and low maintenance costs. There has also been a concurrent increase in the use of cameras in the automotive industry. Automotive cameras have evolved from simple backup cameras to advanced surround view systems, mirror replacement systems, and machine vision cameras that enable Advanced Driver Assistance Systems (ADAS) and autonomous driving. Automotive cameras themselves have also evolved at a rapid pace, from simple low resolution cameras to advanced, high resolution High Dynamic Range (HDR) cameras. To a very large extent, LED lighting and automotive camera technology evolved separately and independently. As the use of both technologies became widespread, it has become clear that the increasing ubiquity of PWM driven LED lighting is posing significant challenges for automotive imaging i.e. so-called "LED flicker". LED 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 colour), even though the light source appears constant to a human observer.

Root cause

LED flicker is, in essence, a temporal sampling problem. It occurs when a light source is being powered by a modulated signal. LED lights may pulse several hundred times a second with varying duty cycle (i.e. the fraction of one period when the light is active) in order to adjust their apparent brightness. At frequencies greater than 90Hz, the light will usually appear to be constant to most human observers [1, 2]. However, a camera imaging the light source may require a very short exposure time to capture a scene correctly, particularly in bright conditions. An illustrative example is shown in Figure 1. In frame N, the camera exposure time coincides with a pulse from the PWM driven LED traffic light. Therefore, for frame N, the red traffic light will be captured by the camera. However, in frame N+1, the camera exposure time and LED pulse do not coincide. In this case, the red light will not be captured. Over the course of consecutive video frames, the traffic light will appear to flicker on and off, depending on whether or not the cameras exposure time coincides with the LED light pulses.

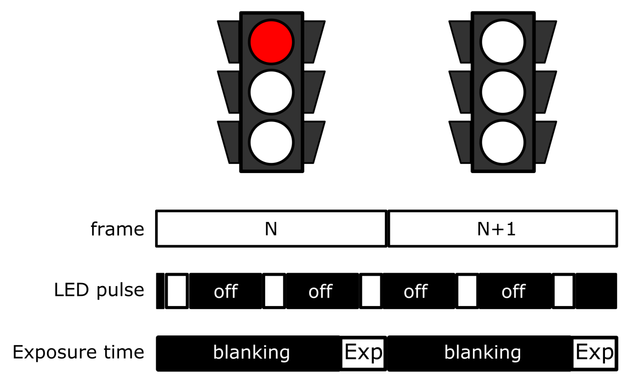

Figure 1. *LED flicker root cause. In frame N, the LED pulse and the camera exposure time coincide, and the traffic light is captured. In frame N+1, the LED pulse and exposure time do not coincide, and the traffic light appears off*

More specifically, a pulsed light source will flicker on/off if the exposure time of the camera is less than the reciprocal of the frequency of the light source i.e.

$$T_{exp} \leq \frac{1}{PWM_{freq}} * (1 - PWM_{dutycycle}) \quad (1)$$

where T_{exp} is the exposure time of the camera, PWM_{freq} is the frequency of the pulsed illumination, and $PWM_{duty\ cycle}$ is the duty cycle of the pulsed illumination, where 1.0 corresponds to 100% duty cycle. A real world example is shown in Figure 2.

A second manifestation of flicker occurs when the number of pulses captured varies from frame to frame. For example, if

Figure 2. *Example of flicker from directly imaged light source*

you consider two consecutive video image captures, in frame N, the camera exposure may capture one pulse from the light source, whereas in the second frame, the camera exposure may capture two pulses from the light source. Consequently, the brightness level in the captured image varies between exposures. This is illustrated in Figure 3:

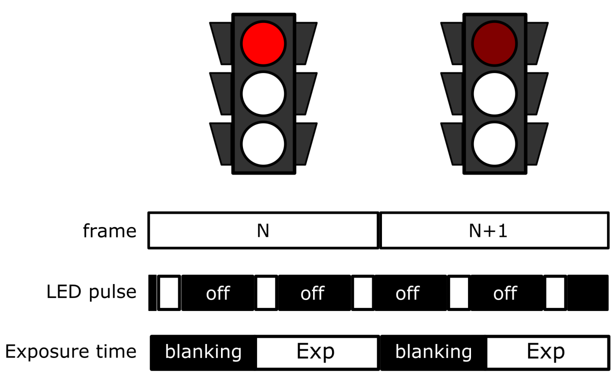

Figure 3. *In this example, the number of captured pulses varies between frame N and frame N+1. As a result, the brightness of the traffic light varies between frames*

This use case occurs when the exposure time of the camera is greater than or equal to the frequency of the pulsed illumination i.e.

$$T_{exp} \geq \frac{1}{PWM_{freq}} * (1 - PWM_{dutycycle}) \tag{2}$$

In this condition, the image light will never appear ”OFF”, but the luma/chroma will modulate. Also, the manifestation of the modulation varies, depending on the scene. In the case of directly imaged light sources, the luma/chroma of the light will modulate from frame to frame. The artifact is primarily temporal in nature. However, in the case where a scene is illuminated by a pulsed light source, the observed artifact depends on the characteristics of the image sensor. If the scene is imaged by a global shutter sensor, the brightness of the entire scene will vary between exposures. However, if a rolling shutter sensor is used, banding effects will be visible. These banding artifacts have both a spatial and temporal component. An example of this banding artifact is shown in Figure 4.

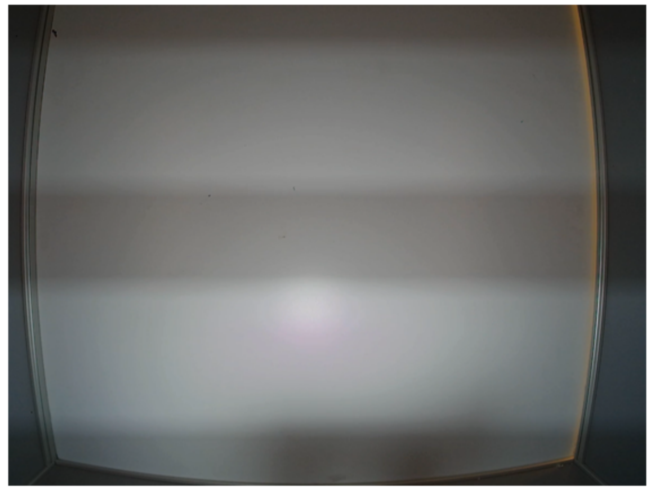

Figure 4. *Example of banding artifact. This image was captured with a rolling shutter sensor. In this example, the scene is illuminated by a diffuse LED light source, driven by a 75Hz, 10% duty cycle signal*

HDR imaging

There are also specific artifacts caused by HDR imaging of pulsed light sources. HDR imaging is quite common in automotive applications. This is because the dynamic range of many automotive scenes can be 120dB or more [3, 4]. This is beyond the dynamic range of standard image sensors. The majority of automotive HDR image sensors use one form or other of multi-image capture scheme. This is largely because multi-capture schemes typically offer the best overall trade-off between dynamic range extension and overall image quality, with minimal changes to the pixel and sensor design. Multi-capture HDR schemes also cause specific artifacts when imaging pulsed light sources. In very bright scenes (e.g. bright daylight), PWM flicker will likely appear the same as for a standard image sensor. This is illustrated in Figure 5. In this case, for frame N, all input captures may be shorter than the ”OFF” time of the pulsed light. However, in frame N+1, the LED light pulse coincides with the long exposure time, and is captured in the final output image.

In darker scenes, however, multi-capture schemes exhibit a different behaviour, as can be seen in Figure 6. In this example, in frame N, the L capture uses a significantly longer exposure time, to capture details in the dark. As a result, it captures multiple LED pulses, and may overexpose. However, the M capture misses the pulse, and so is under-exposed. When the input images are combined, it is often the case that the over-exposed image L is merged with the underexposed image M, and the combined output is medium grey combination with no detail. In frame N+1, the LED pulse is captured by both the L and M captures. In this case, the merged HDR output captures the image correctly.

A real-life example of this effect is shown in Figure 7. In frame N, the sign on the bus is overexposed in the long exposure

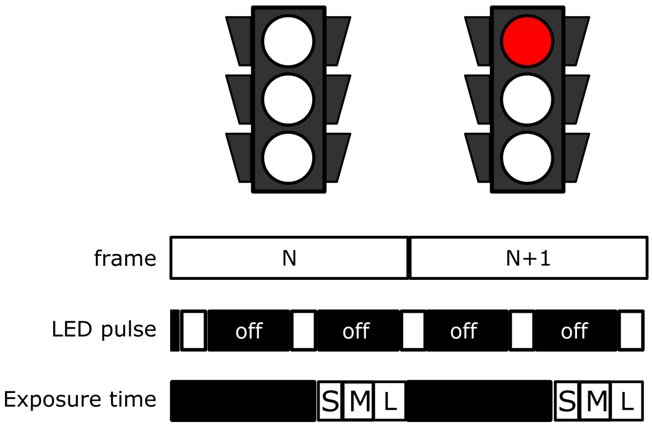

Figure 5. Illustrative example of multi-capture HDR scheme in bright scenes. L=long exposure time capture, M=medium exposure time capture, S=short exposure time capture. In this example, all three input images are shorter than the "OFF" period of the light pulse in frame N. In frame N+1, the LED pulse coincides with the long exposure, and so is included in the output HDR image. The result is that the traffic light pulses on and off

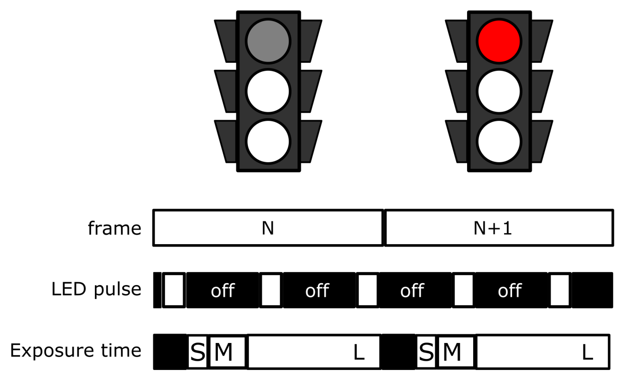

Figure 6. Illustrative example of multi-capture HDR scheme in dark scenes. L=long exposure time capture, M=medium exposure time capture, S=short exposure time capture. In this example, in frame N, the L capture uses a significantly longer exposure time, to capture details in the dark. As a result, it captures multiple LED pulses, and may overexpose. However, the M capture misses the pulse, and so is underexposed. When the input images are combined, it is often the case that the over-exposed image L is merged with the underexposed image M, and the combined output is medium grey combination with no detail. In frame N+1, the LED pulse is captured by both the L and M captures. In this case, the merged HDR output captures the image correctly

image, and underexposed in the short capture image. The merged HDR output is flat grey, with no detail. In frame N+1, the bus sign is captured by the short exposure capture, and is therefore reproduced correctly in the output image.

Impact of LED flicker

The impact and severity of flicker depends on the use case and application. For slow speed applications, including back-up camera systems or surround view systems, LED flicker of light

Figure 7. Example of HDR PWM flicker in lowlight scene. Two consecutive frames from a video sequence are shown. The sign is driven by a PWM signal. In frame N (top), the bus sign is captured only by the long exposure and missed by the short exposure. The combined output is a mid-grey artifact with no detail. In frame N+1 (bottom), the bus sign is captured by the short exposure, and is therefore reproduced correctly in the combined HDR output image

sources within the field of view will, in most cases, be mostly an annoyance or a distraction to the driver, because the driver will typically have enough time to assess the situation. However, there remains the possibility that the LED flicker will distract the driver sufficiently to cause an accident. There is a separate scenario that is also problematic for backup and surround view applications. If a vehicle has PWM driven LED reversing lights, and is backing up into a parking space, it is possible that banding effects, as seen in Figure 4, may occur. This can be potentially quite disturbing to the driver. For high speed viewing applications, such as CMS (i.e. rear view mirror replacement systems), PWM flicker has a greater potential to cause accidents. As an illustrative example, consider the scenario where a vehicle has a CMS system, and the driver of this vehicle is viewing a vehicle following behind. The trailing vehicle is equipped with LED headlamps. It is common for vehicle LED headlamps to be driven by PWM signals with different frequencies and duty cycles. As a result, one headlamp may flicker at a slow rate (e.g. $\leq$0.1Hz), whereas the other headlamp may flicker at a faster rate (e.g.$\approx$0.5Hz). In this scenario, it may easily appear to a driver that the trailing vehicle has engaged their turn signal indicators. The driver may incorrectly assume the trailing vehicle intends to change lane or make a turn. This misinterpretation of the scenario has obvious potentially hazardous consequences. Similarly, there have been anecdotal reports of drivers misinterpreting a trailing car for an emergency vehicle (e.g. a police car) with its warning lights on. This scenario can occur if the PWM driven lights flicker at a higher rate, e.g. $\geq$5Hz. It has been observed that drivers changed lanes or made way for a trailing vehicle, under the false assumption that it was an emergency vehicle. PWM flicker also has a potentially very significant impact on ADAS and autonomous driving applications. PWM LED lights are increasingly used for traffic signals and other traffic signs, including variable speed signs, road works signs etc. PWM flicker may cause misdetection or non-detection of traffic signs, again with potentially very hazardous implications.

LED flicker mitigation

LED flicker mitigation is a complex topic. There is currently no consensus within the automotive imaging industry as to what level of mitigation is required. As a general rule, a most applications would require that a light source should never appear to be ”OFF” when imaged by a camera. This can be achieved by ensuring the camera exposure time is greater than or equal to the period of the PWM light (i.e. as described in Equation 2). However, unless the exposure time of the camera is an exact integer multiple of the frequency of the PWM light source, the brightness of the light will vary over time (Figure 3). In real world applications, it is practically impossible to achieve this, because there PWM frequencies are not standardized. There are standards in place which define the minimum frequency that can be used for road signs [1] to avoid visible flicker (90Hz or greater). This means that in any given scene, there may be multiple LED lights within the camera FoV, all operating at different frequencies. Setting a minimum exposure time to PWM_{freq} also introduces other difficulties. For example, to prevent a light from appearing ”OFF” for frequencies greater than 90Hz, a minimum exposure time of 11.111ms is required. In bright daylight scenes, almost all standard image sensors will overexpose if the exposure time is this long. A number of sensor companies have developed new pixel architectures to allow for longer exposure times without saturating. A review of these designs is beyond the scope of this paper. It has been observed, however, that increasing exposure time to mitigate LED flicker exacerbates motion blur [3]. This can be especially problematic for ADAS algorithms. For example, motion blur can make traffic signs unreadable.

LED flicker measurement

There are currently no standards for LED flicker metrics and measurement procedures. This is being address as part of the IEEE P2020 working group on automotive image quality standards. It is critical that the laboratory test should be robust and accurately reflect a camera system’s performance in real world scenarios. This section reviews a proposal for a testing procedure and metrics for measuring LED flicker in a laborartory setting.

Test Setup

The proposed test setup is outlined in Figure8. A PWM driven light is placed in front of a camera under test. A uniformly illuminated target is present in the background, ideally 18% neutral grey, illuminated by a constant/non-modulating light source. The background may be a reflective target, as shown in Figure 10, or may alternatively be a backlit tranmissive target.

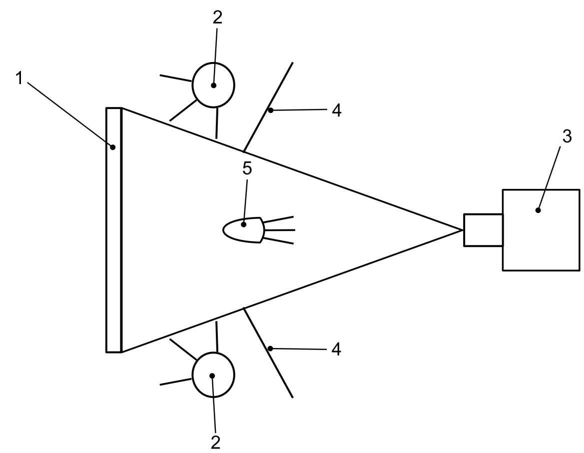

Figure 8. *Test setup for flickering within an area illuminated by a pulsed/modulated light source. 1 - uniform background, 2 - constant light source illuminating background (note: a backlit target is an acceptable alternative), 3 - camera under test, 4 - baffling to isolate background illumination from camera FoV, 5 - PWM driven light, directly in the FoV of the camera under test*

The modulated light source should have variable frequency (50Hz to at least 1kHz recommended) and duty cycle (5%-100%). The modulated light source may fill anywhere from 10% to 100% of the vertical field of view of the device. The light source should be uniform, and ideally should have the same colour temperature as the background illumination. The light source need not be in focus. The background illumination should be controllable, to simulate both daylight and lowlight conditions. This is required, because the manifestations of flicker vary depending on the exposure time and/or HDR scheme of the camera under test. During initial trials, lowlight conditions were simulated by setting the background illumination to 40lux. Daylight conditions may be simulated by setting the background illumination to 2000lux. For each frequency and duty cycle combination tested, the following sequence was used:

1. Two seconds - light on with 100% duty cycle
2. Two seconds - light off (reference ”OFF” level for light)
3. Sixty seconds - light driven by PWM signal

Ideally, the luminance of the light during the initial 2 second ”ON” period should match the luminance level during the 60 second PWM phase. This will require tuning of the voltage applied to the LED lights for each phase of the test.

LED flicker metrics

To assess LED flicker, two different metrics were used. The goal of the first metric is to determine whether or not the LED light appears ”OFF” at any stage during testing. The metric chosen was based on the Weber contrast metric, where:

$$\text{Flicker Dectection Index} = \frac{min(L_{PWM}) - L_{OFF}}{L_{OFF}} \quad (3)$$

where $\min(L_{PWM})$ is the minimum measured luma during the 60 second period where the light is driven by the PWM signal, and L_{OFF} is the measured luma during the 2 second ”OFF” period. In principle, if the light appears ”OFF”, then min(L_{PWM}) = L_{OFF} i.e. the minimum luma value during the PWM test period will be the same as the luma level during the baseline ”OFF” period. In practice, there is typically some hysteresis in camera automatic exposure/gain controls. Therefore, a tolerance of 10% was added i.e. if the Flicker Detection Index is less than 0.1, it is assumed that the light appears ”OFF”. As a general rule, a high Flicker Detection Index indicates good LED flicker mitigation performance.

A second metric, Percent Flicker, was also used, which was based on Michelson contrast:

$$\text{Percent Flicker} = \frac{max(L_{PWM}) - min(L_{PWM})}{max(L_{PWM}) + min(L_{PWM})} * 100 \qquad (4)$$

The purpose of the Percent Flicker metric is to measure the residual modulation in luma, in scenarios where the exposure time is greater than 1\PWM_{freq} (see Equation 2). As a general rule, a low Percent Flicker score indicates good LED flicker mitigation.

Test setup validation

The test setup was validated using an automotive HDR camera. The camera under test was configured to mitigate flicker for frequencies above 90Hz (i.e. the minimum exposure time was set to 11.111ms). The camera was placed in the test setup as per Figure 8. Figure 9 shows a still image captured by the camera within the test setup.

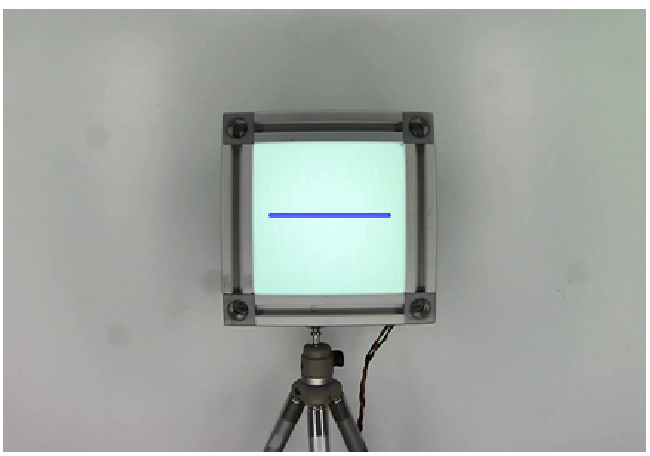

Figure 9. *Image captured during LED flicker bench testing. The blue box indicates the ROI chosen for measurement*

The average luma value (Y) was calculated within the ROI indicated by the blue rectangle (the ROI was 2 pixels high, 100 pixels wide). The shape of the ROI was chosen based on experience from development testing. The camera under test was a rolling shutter design. When flicker does occur, it manifests as bands rolling up or down through the image. If the ROI were square, it would include some pixels where the light was ”ON” and some where the light was ”OFF”. This would cause underestimation of min(L_{PWM}). Background illumunation was set to 2000lux, to simulate a relatively bright scene. For this evaluation, two test frequenies were used; 60Hz and 150Hz. A duty cycle of 20% was used for both tests. 60Hz was chosen because it is less than the minimum exposure time of the camera, therefore at some point the light would definitely appear ”OFF”. 150Hz was chosen because it is greater than the minimum exposure time of the camera. In this case, the light would never appear ”OFF”, but there will be some residual brightness modulation, which can be measured using Equation 4.

Results

Test results are shown in Figure 10 and Table 1. At 60Hz, Flicker Detection Index is less than 0.1, indicating the light appeared ”OFF” in the video. In contrast, Flicker Detection Index is 0.75 during the 150Hz, indicating the light always appears ”ON”. In this example the residual modulation is also quite low, as indicated by the Percent Flicker of 1%. The fact that the Flicker Detection Index is negative during the 60Hz test reflects the fact that there is hysteresis in the camera exposure control - the exposure and gain levels do not return to the exact same values after the light toggles on and off at the start of the test.

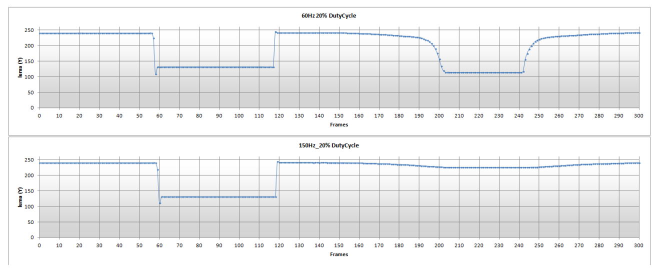

Figure 10. *Plot of luma (Y) for both 60Hz (top) and 150Hz (bottom). At 60Hz, it is clearly visible from the plot that the light appears ”OFF” approximately 40 frames. In contrast, the light appears more or less constant at 150Hz. There is, however, some residual modulation*

Flicker Detection Index and Percent Flicker measured for 60Hz and 200Hz

Frequency	Flicker Detection Index	Percent Flicker
60Hz	-0.14	36
150Hz	0.75	3

Figure 11 is an image taken during the 60Hz test. A dark band is visible in the middle of the light. The banding effect occurs because the sensor is a rolling shutter design - the dark band corresponds to the ”OFF” period of the PWM light. If the sensor were a global shutter design, the entire light would appear ”OFF”. In this example, the dark band rolls up through the image at a relatively slow rate. The height of the band, the rate of movement of the band and the direction of movement of the band all vary depending on the camera frame rate, PWM duty cycle and PWM frequency.

Conclusions and Future Work

This paper summarizes the root cause of LED flicker, it’s various manifestations, and potential impact for automotive applications. It also outlines a test setup, procedure and metrics for assessing LED flicker for a given camera system. This test setup has been shown to reliably indicate whether or not LED flicker will occur for a given camera, depending on background light level, PWM frequency and duty cycle. Future work will ex-

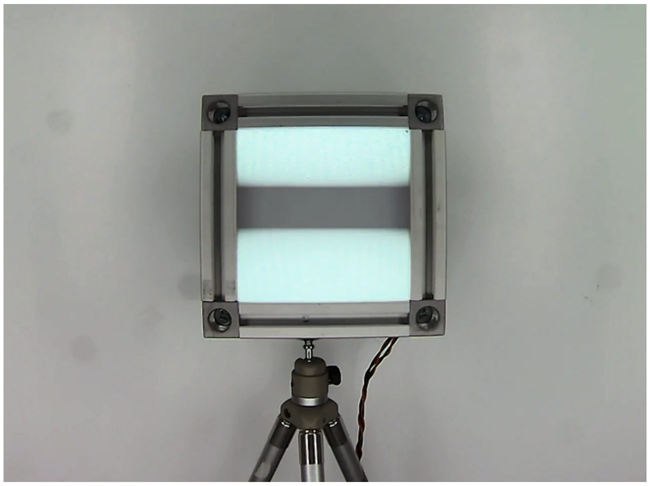

Figure 11. Image captured during 60Hz test. A dark band is visible in the middle of the light. The band is a rolling shutter effect

pand on the results presented in this paper. Further testing and analysis is required to validate the test setup and KPIs presented. Further work will also have to be performed to define KPIs for the banding effects as outlined in Figure 4. Further work will be required to validate the metrics used in this paper. It is entirely possible that frequency domain metrics may be more appropriate and provide further insights. Psychophysical studies to correlate objective metrics with subjective experience of flicker could also prove useful. Initial work has also focused on rolling shutter sensors. The impact on global shutter sensors will also have to be assessed. Also, KPIs and metrics will also have to be defined to assess the impact of LED flicker on colour reproduction. This will be particularly relevant for traffic sign recognition and similar algorithms. Ultimately, the results of these studies will be part of the IEEE P2020 Automotive Image Quality standard.

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Author Biography

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