Method for characterizing display washout performance

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Abstract
An approach was developed for high sensitivity characterization of the washout effect in display applications. The proposed measurement method and quantitative metric of washout are practical tools for the development of antiglare (AG) cover plates for display applications.

Author Keywords
Washout; displays; antiglare; cover plate; cover glass.

1. Introduction
Panel displays are widely used in various applications under different ambient light conditions, such as indoor with room light, outdoor under sunlight, in vehicles under direct sunlight [1-3]. To enhance display contrast and ease of content visibility, antiglare (AG) textures are normally applied to display cover plates to reduce specular reflections from light sources other than the displays [1-3]. One side effect of the use of an AG cover plate in a display, called "washout," is the visibility degradation of display contents under ambient illumination and manifests as a hazy reflection from the display internal and cover which decreases the overall contrast of the display content. This effect is particularly undesirable for a driver viewing displays in a vehicle under direct sunlight illumination [4].
For the purpose of the development of AG texture designs with suppressed washout effect, we developed a measurement method and relevant metric to quantitatively characterize the impact of washout effect on display image quality. In this method, the modulation transfer function (MTF) of an AG cover plate is measured under certain illumination conditions which imitate the use cases of a display with the AG cover plate under direct sunlight illumination. The introduced metric, called washout index (WI), is calculated by averaging the values of the measured MTF over a relevant spatial frequency range. The WI can reveal the degradation of the contrast of a display over a spatial frequency range due to the AG cover plate.

2. Measurement method, setup, and metric
MTF can reveal how an optical component reproduces the contrast of an image as a function of spatial frequency, and thus, it is related to display content visibility. In this method, the MTF of an AG surface is measured under certain illumination conditions which imitate two typical use cases of automotive displays under direct sunlight. The average value of MTF over a relevant spatial frequency range is used to calculate the metric of WI, quantitively evaluating the "washout" effect of an AG surface caused by sunlight and/or surrounding lights.
In general, MTF of an optical system is defined as the ratio of output image modulation function ($MF_{out}(f_n)$) to input image modulation function ($MF_{in}(f_n)$), which is written as

$$\boldsymbol{MTF(f) = \frac{MF_{out}(f_n)}{MF_{in}(f_n)}} \quad (1)$$

with

$$MF_{in/out}(f_n) = \frac{I_{in/out}(f_n)max - I_{in/out}(f_n)min}{I_{in/out}(f_n)max + I_{in/out}(f_n)min} \quad (2)$$

where f_n is image spatial frequency, $I_{in/out}(f_n)_{max}$ and $I_{in/out}(f_n)_{min}$ are the maximum and minimum intensities of input/output modulation image at spatial frequency f_n.

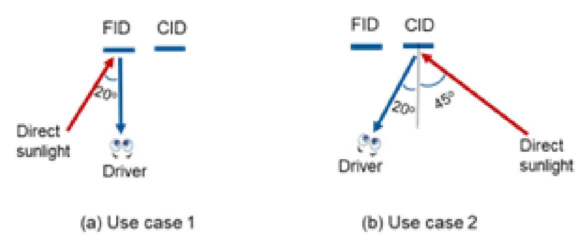


Figure 1. Illustrations of two typical use cases of a driver to view the displays in a car under direct sunlight. (a) the driver looks at front information display (FID) under direct sunlight illumination from driver front-door window. (b) the driver looks at center

information display (CID) under direct sunlight illumination from passage front-door window.

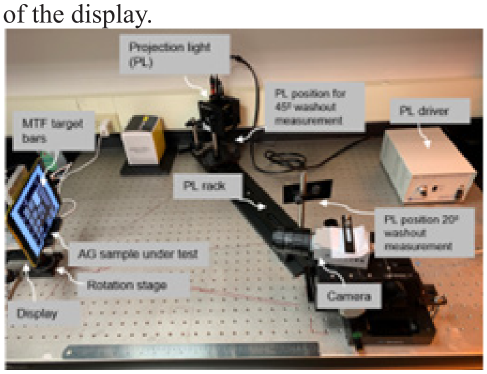
Figure 1 shows the two typical use cases of a driver to view the displays in a car under direct sunlight [4]. One (use case 1) involves the driver looking at front information display (FID) under direct sunlight illumination from driver's front-door window. Another one (use case 2) the driver looks at center information display (CID) under direct sunlight illumination from passenger's front-door window. These two use cases are selected in our washout measurement method. As shown in Figure 1(a), in use case 1, the viewer angle (VA) of the driver relative to the normal of FID is 0 degrees, and sunlight incident angle (SIA) relative to the normal of CID is 20 degrees. As shown 1(b), in the use case 2, the VA of the driver relative to the normal of ICD is 20 degrees, and the SIA relative to the normal of CID is 45 degrees. Considering typical direct sunlight conditions [4], the illuminance of sunlight of 45000 lux on the display is used in our measurement setup.

Figure 2 shows the washout experimental setup and its top view schematic. A high resolution (326ppi) display is used to display MTF target bars (USAF1951). An AG sample under test is proximately placed on the MTF target bars with the AG surface facing the camera. A high-resolution CCD camera (resolution: 2048(H) x 1536(V) 3.1MP color; pixel pitch: 3.2 µm x 3.2 µm) is used to capture the displayed images of MTF target bars with and without AG test sample and under different ambient light conditions. A projection light source emulates direct sunlight illumination for the study of washout effect.

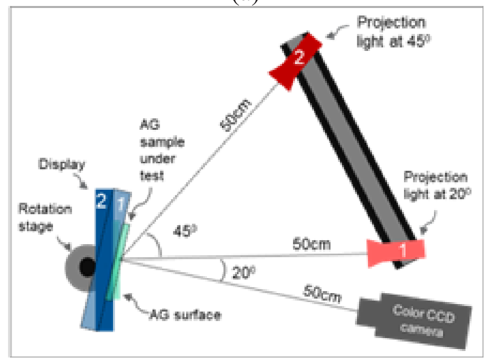
The washout index (WI) is defined as:

$$WI = 1 - \frac{1}{m}\sum_{n=1}^{n=m} \frac{MF_{out}(f_n)}{MF_{in}(f_n)} \qquad (3)$$

where MFin is the measured modulation function of the MTF target displayed by the display without sample under test in dark room, and MFout is the measured modulation function of the MTF target bars displayed by the display with the sample under test under lab room light (132 lux) and projection light illumination with 45000 lux on the display. The value of WI is in the range of 0 to 1. The higher the value of WI, the stronger the washout effect is. In our following measurements, five spatial frequencies (m=5) are used to calculate WI. To evenly weight the attributes of the contrast degradation at the measured spatial frequency range, the five frequencies are selected evenly between the display resolution and the lowest frequency of MTF bars in the FOV of the camera. The selected five spatial frequencies are f1=1.67 cycles/mm, f2=4.11 cycles/mm, f3=7.33 cycles/mm, f4=10.38 cycles/mm, and f5=13.08 cycles/mm, in which f5=13.08 cycles/mm is around the resolution of the display.



(a)



(b)

Figure 2. (a) photo of washout experimental setup. The experimental setup enables washout measurements for use cases 1 and 2. (b) Schematic (top view) of washout measurement setup.

3. Measurement results and discussions

Table 1 describes the example samples which are studied. Sample 1 is bare glass. The other samples have one surface with AG textures. In addition, sample 2 is measured before and after adding anti-reflection (AR) coating.

Table 1. Information of example samples to be studied.

Sample ID	Front surface treatment	Other metrics				
		Transmission[1] (%)	Transmission Haze[1] (%)	Sparkle @140PPI[2] (%)	Coupled DOI[3]	Coupled Rspec[3]
Sample 1	No	92				
Sample 2	AG	91.3	2.71	1.94	48.83	13.98
Sample 2 with AR coating	AG + AR	90.9	3.08	2.07	73.27	1.97
Sample 3	AG	91.2	6.02	1.62	94.8	15.3
Sample 4	AG	91.3	6.32	1.89	64.34	5.9

(1) measured by BYK Haze guard. (2) Measured by SMS-1000 with Lenovo Z450-4 display 140 ppi resolution. (3) measured by Rhopoint IQ 20/60 Gloss Haze DOI Meter.

Figure 3 shows MTF target bar images of the display and the display with an AG sample (Sample 3) under different ambient light conditions for use case 1 (top row) and use case 2 (bottom row). Figure 3(a) is the display without the AG cover glass under dark room conditions. Figures 3(b) and 3(c) are for the display with the AG cover glass under (b) room light and (c) room and projection lights, respectively. Figure 4(a) shows the MTF curves of the AG cover glass sample measured under room light (orange squares), and room and projection lights (blue squares) for use case 1 (VA=0 degree, SIA=20 degree). Figure 4(b) shows the MTF curves of the AG cover glass sample measured under room light (orange squares), and room and projection lights (blue squares) for use case 2 (VA=20 degree, SIA=45 degree). The spatial frequency of the display resolution is about 13 cycles/mm (see Figure 4). As shown in Figure 4, the small degradation of the MTF curve measured under room light condition can be resolved by this setup, indicating the sensitivity of the measurement setup is high. Room light only introduces smaller amounts of washout on the display, and the WIs of the use cases 1 and 2 are 0.025 and 0.055 respectively. With projection light (and room light), the WIs of use cases 1 and 2 are, respectively, 0.338 and 0.469, which clearly show that the project light (which emulates direct sunlight illumination) cause much more degradations of display image readability.

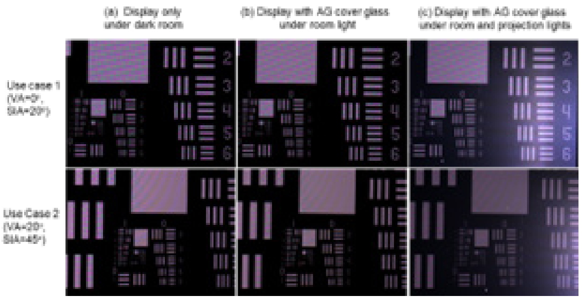
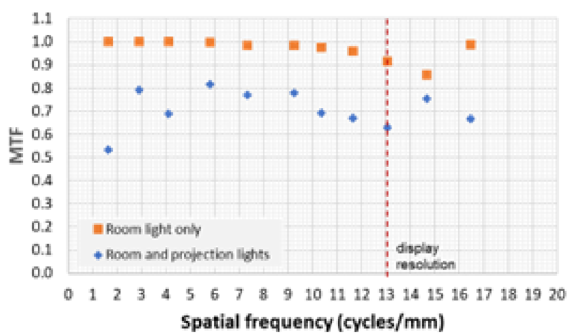
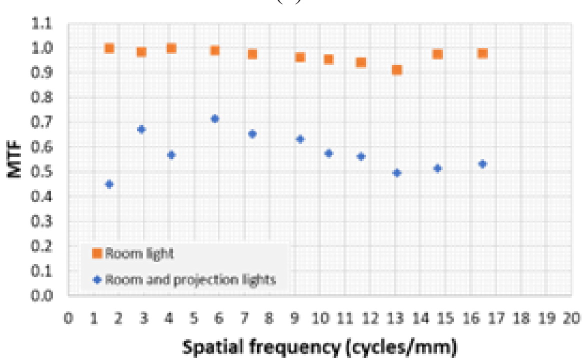


Figure 3. MTF target bar images of the display without and with an AG cover glass sample. (a) display without the AG cover glass under dark room; (b) display with the AG cover glass under room light; (c) display with the AG cover glass under room and projection lights. The top row is for the measurement of the use case 1 (VA=00 and SIA=200). The bottom row is for the measurement of the use case 2 (VA=200 and SIA=450).



(a)



(b)

Figure 4. (a) MTF curves of the AG cover glass sample measured under room light (orange squares), and room and projection lights (blue squares) for Case 1. (b) MTF curves of the AG cover glass sample measured under room light (orange squares), and room and projection lights (blue squares) for Case 2.

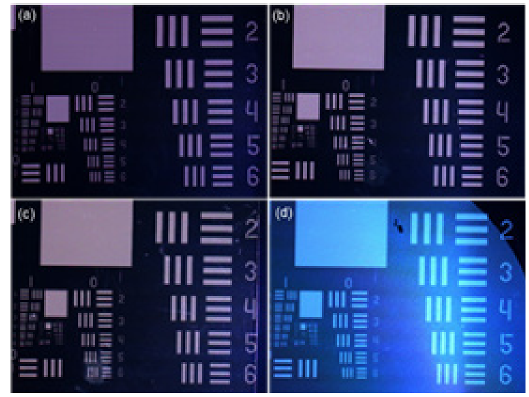
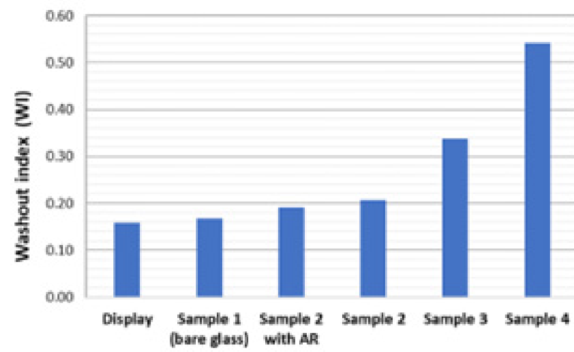
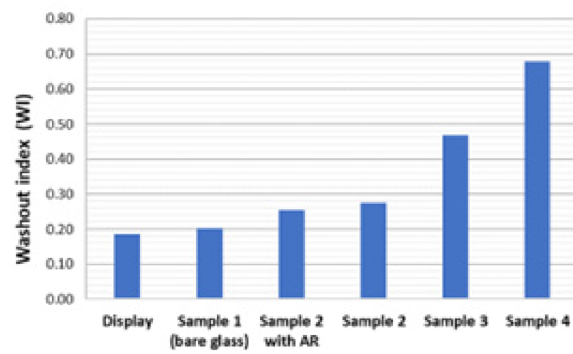


Figure 5. MTF bar images of the display with (a) sample 1, (b) sample 2 with AR coating, (c) sample 2, and (d) sample 4 for the measurement Case1 (VA=00 and SIA=200).



(a)



(b)

Figure 6. WIs of the display and the display with different AG samples. (a) Use case 1. (b) Use case 2.

Figure 5 show MTF bar images of the display with (a) sample 1, (b) sample 2 with AR coating, (c) sample 2, and (d) sample 4 for the measurement of use case 1. The WI measurement results for use cases 1 and 2 are summarized in Figure 6(a) and 6(b), respectively. The measurement results clearly reveal the impact of washout effect caused by different AG textures on display readability. As shown in figure 6, the diagnosis of the small WI difference between display with and without sample 1(bare glass) indicates that this method has very high measurement sensitivity. The WI measurement results of sample 2 before and after AR coating shows that AG surface with AR coating can help to suppress washout effect. Even without AG cover plate, the internal reflection of ambient light can still cause the degradation of display image.

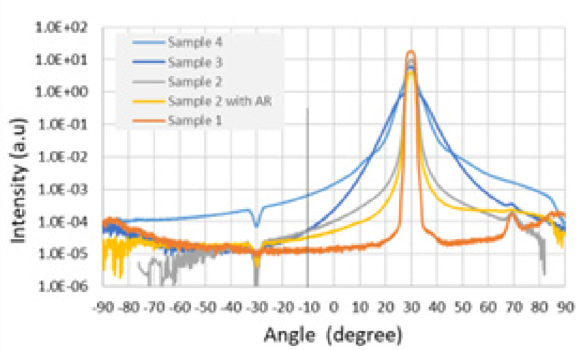


Figure 7. BRDF curves of the samples. The incident angle of the light (white) to the sample surface normal for the measurement is 10 degrees.

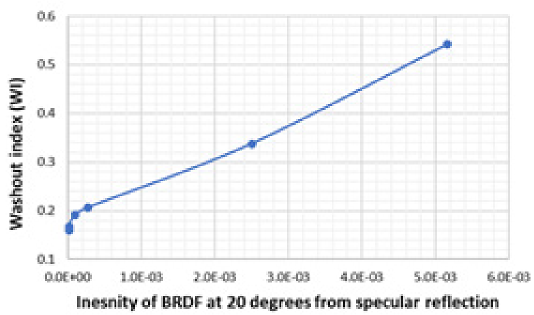


Figure 8. Washout index of sample under test versus the intensity of the sample BRDF at 20 degrees from specular reflection.

Figure 7 show the curves of the measured bidirectional reflectance distribution functions (BRDFs) [5] of the samples 1,3,4 and the sample 2 before and after AR coating. The equipment used to do BRDF measurements is REFLET 180S. The incident angle of the light (white) to the sample surface normal for the measurements is 10 degrees. Figure 8 show the curves of WI of the sample under test as a function of the intensity of the sample BRDF at 20 degrees from specular reflection (BRDF@20deg). Near-linear correlation (in range MI>0.2) between WI and BRDF@20deg indicates that the scattering of reflected projected light from cover glass surface is the major root cause of display washout in the cases we studied. The basis of the washout curve is because of the washout effect which is caused by display internal reflection.

4. Conclusion

We developed a measurement method and a relevant metric to quantitatively characterize the impact of the washout effect on display image quality. Utilizing MTF technique means this method exhibits a few desired features as follows. The developed metric, WI, is not sensitive to the display used in the measurement system to display MTF bars. The metric WI weights the degradation of display contrast at various spatial frequencies due to the AG cover plate. The method has high measurement sensitivity. The different root causes of washout can be easily separated by conducting washout measurements under different conditions. The method provides a useful tool for the development of AG cover plates for display applications.

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