WHITE PAPER

Methods for Measuring Small Defects in Automotive Curved Displays

Evaluating Approaches and System Specifications

RADIANT
VISION SYSTEMS

A Konica Minolta Company

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Introduction

Displays continue to acquire more real estate within the vehicle, with recent notable increases in size and resolution. With flat panel displays used in place of center stack controls, instrument cluster panels, and now mirrors, available integration space throughout the vehicle interior is severely restricted. With the advent of flexible display technologies such as flexible plastic LCD-TFT backplanes, OLED panels, and microLEDs, automotive interiors have reached a new era of freedom in design, where curved and freeform shapes break out of traditional flat-panel integrations. Innovations in display component flexibility allow manufacturers to match the curvature of existing surfaces, fitting displays seamlessly into the cockpit without overwhelming the interior, reducing functionality, or increasing driver distraction.

In direct view of the driver, displays used in place of instrument panels and center stacks offer more immediate and comprehensive information than their analog counterparts, with the added benefit of illumination for improved visibility in all lighting conditions. Studies suggest the positive effect of using curved displays in the driver's line of sight (namely, in the speedometer region). A concave display with a horizontal radius of as much as 1,000 mm (referred to as 1000R) has been shown to reduce visual fatigue[1]—presumably because this curve more closely matches the natural curvature of human vision. Horizontal display curvature can reduce the driver's eye movement, reduce distortion of elements at the display edges, and improve visual immersion. Brand perception is also important, with next-generation curved displays providing a sense of luxury as a competitive advantage for automakers.

Figure 1 - *Flexible display concepts that match the dimensionality of the A-pillar (top) and door frame (bottom) enable seamless, space-saving integration.*[2] *(Source: Flexenable)*

Figure 2 - *A curved instrument panel display by Bosch with 1500R (1,500 mm horizontal radius of curvature) at 12.3-inch diagonal size, manufactured for the Volkswagen Touareg, shown inside (left) and outside of the vehicle (right).*[3] *(Source: Bosch, 2018)*

Challenges of Curved Display Testing

Flat panel displays (FPDs) have provided the foundation for display test methods. Image-based (CCD or CMOS) photometric or colorimetric measurement systems and analysis software can easily evaluate the visual performance of flat displays in a single image to test luminance, color, contrast, uniformity, and other data across the entire display area at once. FPDs can also be measured effectively from a single perpendicular angle to simplify focus distance and limit view-angle effects, such as changes to brightness, color, contrast, and defect clarity when light is received at an angle and/or refracted through various substrates.

Measuring curved displays, however, requires new approaches that account for changes across the curve. A single perpendicular measurement angle, a single measurement image, and a single analysis function may be insufficient for ensuring the accuracy of data across the display, particularly as view-angle changes obscure the visual qualities of the display (causing variation in brightness, color, and contrast), or as defects fall outside of focus and are distorted at the edges of the display.

Because of these challenges, system specifications and approaches defined for traditional flat panel display testing must be reviewed and revised for curved displays to ensure that defects can be consistently and accurately identified. By evaluating data from various test methods and system specifications, analysis results can point to a recommended approach that achieves optimal accuracy and efficiency in measurement applications for curved displays.

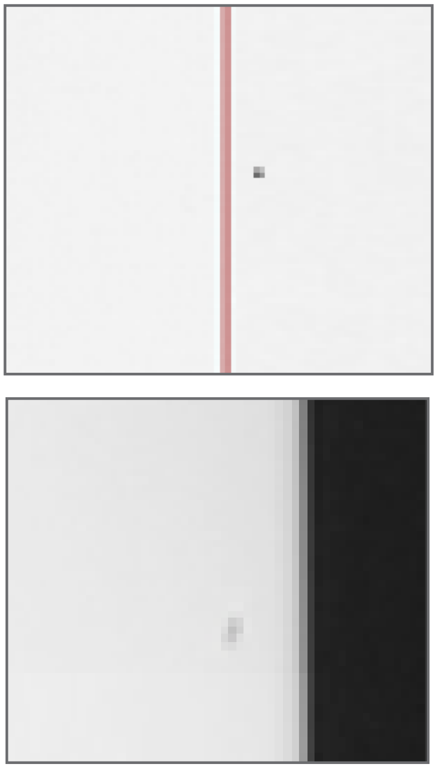

Figure 3 - *Comparison of pixel defects captured with an imaging system positioned perpendicular to the center of a curved display. Defects in the center of the display (top) appear higher contrast and more circular when imaged from this angle than defects at the edges of the display (bottom), which appear out-of-focus and distorted.*

Evaluating Test Methods

Engineers at Radiant Vision Systems applied imaging colorimeters and analysis software to evaluate system effectiveness for unique curved display test methods. The results of this evaluation demonstrate the benefits and disadvantages of each approach, and provide a recommended method (number of images and analyses, and types of image processing methods) and system specifications (sensor resolution and depth of field (DOF) determined by lens F-stop) for each measurement scenario.

Test Methods: Radiant engineers evaluated three test methods for curved displays—two single-image approaches and one multi-image approach—using the same range of system specifications in each case to compare efficiency, complexity, and accuracy. Three methods evaluated were:

Method 1: Single-Image/Single-Analysis
Method 2: Single-Image/Multi-Analysis
Method 3: Multi-Image

Equipment: The same dark lab environment was used to test a curved display with these specifications:

- 1500R (1,500 mm horizontal radius of curvature)
- 1920x1080 pixel resolution
- 23.6-inch diagonal size
- LED-backlit LCD

This display was measured using Radiant Vision Systems ProMetric® I Imaging Colorimeters using a 50mm lens, with image processing and analyses applied using Radiant's TrueTest™ Automated Visual Inspection Software. Three ProMetric imaging systems (2-, 8-, and 16-megapixel (MP) sensor resolution options) were applied for the purposes of determining a baseline imaging resolution required for each test. Three DOF settings (F-stops F/2.8, F/8, and F/13) were also evaluated for each imaging system to determine baseline focus settings required for each test.

This display was measured using Radiant Vision Systems ProMetric® I Imaging Colorimeters using a 50mm lens, with image processing and analyses applied using Radiant's TrueTest™ Automated Visual Inspection Software.

Tests Performed: The effectiveness of each set of system parameters for each test method was evaluated based on the results of three defect analyses:

1. **Horizontal Line Defects:** Three horizontal lines (three contiguous strings of dead pixels) at the top, center, and bottom of the display. Measurement accuracy was evaluated based on defect contrast. Defect contrast was determined by lowering a minimum contrast percentage threshold in analysis software until all three lines were detected (a high threshold indicated high-contrast defects that could be detected reliably while limiting false defects).

2. **Vertical Line Defects:** Three vertical lines (three contiguous strings of dead pixels) at the left, center, and right of the display. Measurement accuracy was evaluated based on defect contrast. Defect contrast was determined by lowering a minimum contrast percentage threshold in analysis software until all three lines were detected (a high threshold indicated high-contrast defects that could be detected reliably while limiting false defects).

3. **Pixel Defects:** Dead pixels in non-contiguous rows (one vertical and one horizontal) intersecting at the center of the display. Measurement accuracy was evaluated based on defect contrast and size. Defects were identified using a minimum contrast percentage threshold (a high threshold indicated high-contrast defects that could be detected reliably while limiting false defects) and sensor pixel size (number of sensor pixels occupied by the defect on the imaging system's sensor, where more sensor pixels per defect enabled more precise measurement).

Tests for large spatial defects warrant their own evaluation, but fall outside of the scope of this paper. Such defects include display contrast, uniformity, and mura defects (randomly occurring dark or light areas on the display). Comprehensive testing of mura defects of a variety of shapes, sizes, and locations—especially on the display edges—is needed to determine the optimal test method and equipment. This additional testing would help to guide both general display testing and regulated testing for qualities like Black Mura Gradient—as published by the German Flat Panel Display Forum (DFF)—in curved displays.

Image Processing. Image processing functions (Register Active Display Area, Moiré Removal, and Repair Dark Areas) were used to ensure accurate measurements for each test. Image processing was relatively consistent across test methods outlined in this paper, and is summarized below.

- **Register Active Display Area (RADA):** All measurements required an initial application of RADA to crop the measurement image to the active area of the display. In the single-image setup for Method 1 and Method 2, engineers were able to control the positioning of the display relative to the measurement system very precisely, and therefore limited cropping and alignment of the measurement image was needed. Aligning the camera to the center of the left and right halves of the display for multi-image testing in Method 3 increased the negative space around the display, making it necessary to crop more significantly to the display area, which was automatically performed by the analysis software.

- **Moiré Removal:** Moiré Removal was necessary in nearly every measurement to eliminate the aliasing effects of moiré from measurement images—except for images captured by imaging systems using a DOF setting of F/2.8. At this F-stop, image defocus resulted in little to no evidence of moiré. At higher DOF settings—especially for high-resolution imaging systems—Moiré Removal improved line defect detection and was critical for pixel defect detection. Aliasing effects of moiré at high resolutions easily obscures defects as small as individual pixels. The Moiré Removal function applied in analysis software automatically eliminated obstructive aliasing without loss of resolution, preserving pixel defect size and shape for accurate detection.

- **Repair Dark Areas:** Repair Dark Areas was necessary to eliminate dark bands on the lower edge of the display in all measurement images. These dark bands appeared in images as a result of the display's curvature (see Figure 4). A Repair Dark Areas function in the analysis software was applied to threshold out these dark areas, which may otherwise be falsely interpreted as horizontal line defects or rows of dead pixels. Dark areas were more evident at higher resolutions, where more photosensitive areas (sensor pixels) were applied. As such, using Repair Dark Areas was increasingly important at higher resolutions.

Figure 4 - *Close-up of a measurement image showing dark areas on the bottom edge of the display, which are visual effects caused by the horizontal display curvature.*

Method 1: Single-Image/Single-Analysis

In this method, the imaging system was positioned perpendicular to the display center. The system captured the entire curved display in a single image and applied a single software analysis function to the image for each test.

Expected benefits of this method:
- Enables holistic display evaluation
- Limits measurement time
- Limits equipment to one camera and software

Expected disadvantages of this method:
- Small defects may be distorted at the edges or obscured (low contrast) at the edges of the display as viewed perpendicular to the display center.
- This perspective also results in view angle effects at the edges that may affect measurement accuracy.

Method 1: Test Setup

In the test setup for single-image/single-analysis (see Figure 5), an imaging system (ProMetric I Imaging Colorimeter) is positioned at a defined distance[i] from the display. The system is aligned perpendicular to the display center using a Black Mura Gradient alignment image.

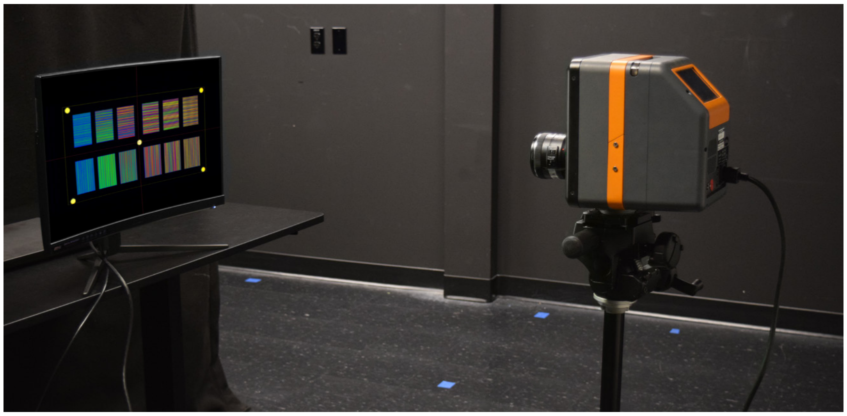

Figure 5 - *Test setup for Method 1.*

Method 1: Results of Testing

Horizontal Line Defects

Analysis data for horizontal lines in Method 1 suggest the positive effects of high imaging system resolution and DOF settings (see Table 1, next page).

Increasing DOF (F-stop) of the imaging system generally increased the accuracy of the Horizontal Line Defects analysis. Defect contrast improved as DOF was increased for each system, (peaking at F/8), with little variation between 8MP and 16MP resolution systems. Measuring perpendicular to the display center, the display's horizontal curvature primarily exhibited distortion at the extreme left and right edges of the image. Horizontal lines are minimally affected by focus changes along this curve, which could be the reason for less significant contrast variation at higher F-stops (i.e., the highest contrast is achieved as all areas of the display come into focus around F/8).

Across imaging system resolutions, a decrease in contrast at F/13 is likely the result of aperture settings at the imaging system position (distance), and does not indicate a significant loss in accuracy for defect detection. Further testing—for example, using a Modulation Transfer Function (MTF) test measurement to calculate image sharpness at this DOF setting—could help to diagnose this issue, which is only observed for horizontal and vertical line defects (not pixels) throughout the results in this paper.

Increasing resolution had the greatest impact on horizontal line defect contrast, maximizing contrast at 30% for 8MP systems at F/13, with slightly higher contrast possible at 35% for 16MP systems at F/8 (more than doubling contrast values from 2MP measurements). Increasing resolution also produced visibly higher contrast horizontal lines (see Figure 6).

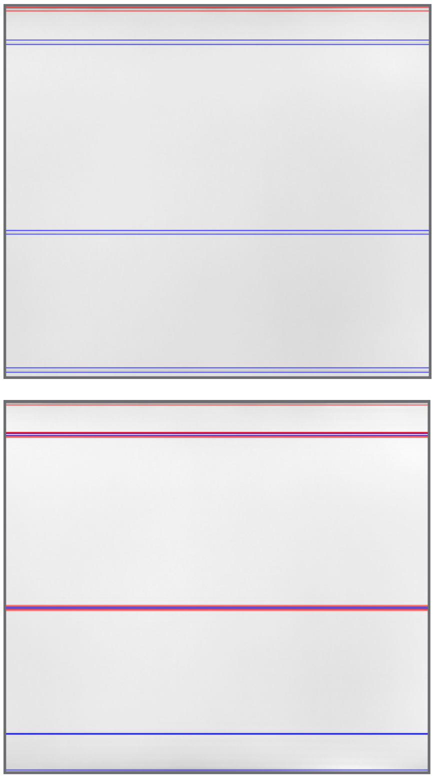

Figure 6 - *Horizontal Line Defects analysis performed by a 2MP imaging system (top) versus an 8MP imaging system (bottom). Horizontal lines are noticeably higher contrast using the 8MP imaging system.*

Horizontal Line Defects: Min. Contrast Threshold (%)		
		Whole Display
2MP	***F/2.8***	4.5
	F/8	11.5
	F/13	10.5
8MP	***F/2.8***	13.5
	F/8	29.5
	F/13	30
16MP	***F/2.8***	13.5
	F/8	35
	F/13	27

Table 1 - *Horizontal Line Defects analysis data for Method 1. Data gives the minimum contrast value of line defects.*

Vertical Line Defects

Compared to horizontal line defects, vertical line defects are more susceptible to variation due to focus changes across the horizontal curvature of the display when measuring perpendicular to the display center. Curvature at the edges of the display causes vertical lines at the edges to appear visibly low-contrast and out-of-focus in measurement images taken using low DOF settings (see Figure 7).

This effect is captured in the analysis data for vertical line defects (see Table 2). Increasing DOF settings for this analysis resulted in a much more significant increase in defect contrast (32.5% increase from F/2.8 to F/8 in 16MP systems) as compared to horizontal line defect analysis data (21.5% increase from F/2.8 to F/8 in 16MP systems).

Like the Horizontal Line Defects test results, analysis data for vertical lines in Method 1 suggest the positive effects of high imaging system resolution and DOF settings. Across resolutions, increasing DOF improved the accuracy of defect identification, with defect contrast maximized at F/8 for 8MP and 16MP systems.

Vertical Line Defects: Min. Contrast Threshold (%)		
		Whole Display
2MP	***F/2.8***	8.5
	F/8	17
	F/13	15
8MP	***F/2.8***	8.5
	F/8	32.5
	F/13	31.5
16MP	***F/2.8***	10.5
	F/8	43
	F/13	36

Table 2 - *Vertical Line Defects analysis data for Method 1. Data gives the minimum contrast value of line defects.*

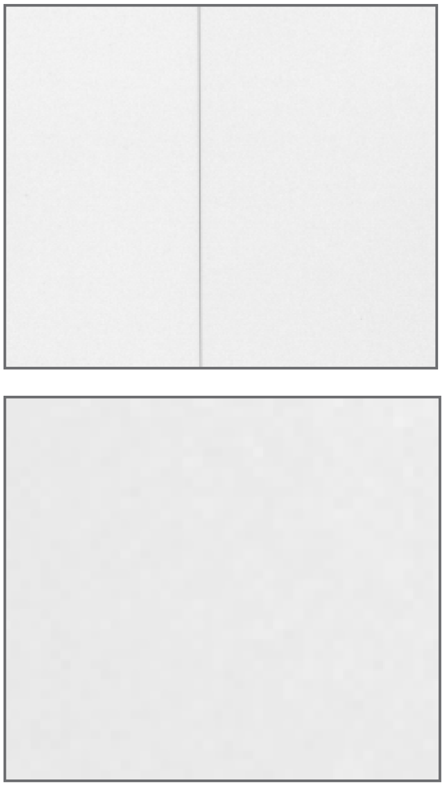

Figure 7 - *Measurement images from a 2MP imaging system at F/2.8, illustrating the effect of display curvature on defect focus in the center of the display (top) versus the edge (bottom).*

Increasing resolution yielded the greatest improvement in defect contrast for vertical lines, maximizing contrast at 32.5% for 8MP systems at F/8, with higher contrast possible at 43% for 16MP systems at F/8 (more than doubling values from 2MP measurements).

Pixel Defects

Like vertical lines, pixel defects are easily distorted and obscured at display edges when measured perpendicular to the display center. Pixel defects on the extreme left and right edges—which fell out of focus at low DOF settings—were missed due to low contrast (see Figure 8).

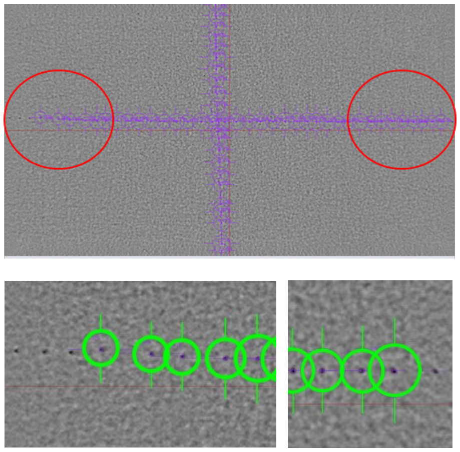

Figure 8 - *Pixel Defects analysis performed by a 2MP imaging system at F/2.8 (top). Close-up of left (bottom-left) and right (bottom-right) edges of the display where several pixel defects were missed at the edges. (Defect detectors highlighted for clarity.)*

Because defect contrast varies significantly from the center of the display to the display edges, precise minimum contrast thresholds are needed. At low F-stops (F/2.8 and F/8), a 1%-6% difference in contrast was recorded between pixel defects on the edges (lower contrast) and defects in the center (higher contrast) (see Table 8, page 18, for complete edge data). Setting minimum contrast thresholds for pixel defect detection relies on a sufficiently high minimum contrast, where the edge defect contrast percent (lower contrast limit) should be used as the minimum to reliably capture all defects.

However, the contrast minimum cannot be *too* low, or false defects can be introduced to the measurement. Because pixel defect contrast varies so dramatically from display center to display edge at lower F-stops, inaccurate thresholds may allow for errors in either region: more defects missed on the edges of the display if the minimum contrast is too high, or more false defects in the display center if the minimum contrast is too low. This wide contrast variation is best addressed by a single-image/multi-analysis (see Method 2) or multi-image (see Method 3) approach where minimum contrast can be set for each area (center or edges) where the defect appears.

For Method 1, increasing DOF for pixel defect analysis eliminated false defects like those in Figure 8 as edge defects were brought into focus and reached more uniform contrast with center defects. For example, increasing DOF of the imaging system from F/2.8 to F/13 increased the contrast of pixel defects at the edges of the display (from 2% to 3.5% in 2MP systems; from 3% to 11% in 8MP systems; from 5% to 15% in 16MP systems; see Table 8, page 18, for complete edge data) to match contrast values of defects at the center of the display.

Increasing resolution and DOF settings together enabled the most precise thresholding of pixel defects in Method 1, where a minimum defect contrast could be set as well as minimum sensor pixels per defect, to ensure accuracy and eliminate false defects. A 16MP imaging system at F/13 measured uniform defect contrast from the display center to the edges. Higher resolution also allowed more refined threshold setting for minimum number of sensor pixels per defect for greater accuracy (avg. minimum 6 sensor pixels per defect using the 8MP system; avg. minimum 7 sensor pixels using the 16MP system; see Table 3, next page). A combination of high resolution and DOF settings therefore enables the most precise threshold setting for pixel defect analysis in Method 1, with a baseline of 16MP resolution at F/13.

Pixel Defects: Min. Thresholds and Accuracy		
		Whole Display
2MP F/2.8	Min. Contrast Threshold	2%
	Min. Sensor Pixels	1
	False Defects	11
	Missed Defects	0
2MP F/8	Min. Contrast Threshold	3%
	Min. Sensor Pixels	5
	False Defects	0
	Missed Defects	0
2MP F/13	Min. Contrast Threshold	3%
	Min. Sensor Pixels	4
	False Defects	0
	Missed Defects	0
8MP F/2.8	Min. Contrast Threshold	4%
	Min. Sensor Pixels	5
	False Defects	8
	Missed Defects	1
8MP F/8	Min. Contrast Threshold	8%
	Min. Sensor Pixels	8
	False Defects	1
	Missed Defects	0
8MP F/13	Min. Contrast Threshold	11%
	Min. Sensor Pixels	5
	False Defects	0
	Missed Defects	0
16MP F/2.8	Min. Contrast Threshold	5%
	Min. Sensor Pixels	9
	False Defects	9
	Missed Defects	0
16MP F/8	Min. Contrast Threshold	15%
	Min. Sensor Pixels	8
	False Defects	1
	Missed Defects	0
16MP F/13	Min. Contrast Threshold	15%
	Min. Sensor Pixels	5
	False Defects	0
	Missed Defects	0

Table 3 - *Pixel Defect analysis data for Method 1. Data gives the minimum contrast value of pixel defects and minimum number of sensor pixels that define a pixel defect. Included are the number of false defects and missed pixel defects when the highest minimum contrast thresholds and sensor pixels were set for each analysis region.*

Increasing resolution and DOF settings together enabled the most precise thresholding of pixel defects in Method 1, where a minimum defect contrast could be set as well as minimum sensor pixels per defect, to ensure accuracy and eliminate false defects.

Method 1: Summary

As expected, using a single-image/single-analysis method to evaluate curved displays is affected most significantly by focus differences that cause distortion and low contrast of defects on the extreme left and right edges of the display. Increasing DOF improved measurement accuracy for this method significantly, with a jump in defect contrast between F/2.8 and F/8 settings for all defects across imaging system resolutions. A high DOF is recommended (in this case, a baseline of F/8) to ensure the most uniform contrast of defects from the center to the edges of the display, enabling more reliable defect detection and more precise contrast threshold-setting. Increasing resolution of the measurement system offers the most significant improvement to accuracy, especially where defects are smaller in size (i.e., pixel defects). If a system is limited to a lower DOF setting (F/2.8 or F/8), a higher imaging system resolution is recommended to enable more precise threshold-setting based on minimum sensor pixel size. Only by using the highest F-stop at high resolutions (F/13 for both 8MP and 16MP systems) can a single set of contrast thresholds be set to capture all defects and eliminate false defects reliably across the display. To optimize measurement accuracy for Method 1, the minimum system specifications recommended are 16MP at F/8.

Increasing DOF improved measurement accuracy for this method significantly, with a jump in defect contrast between F/2.8 and F/8 settings for all defects across imaging system resolutions.

Method 2: Single-Image/Multi-Analysis

In this method, the imaging system was positioned perpendicular to the display center at a defined distance.[ii] The system captured the entire curved display in a single image, but applied separate thresholds for defect detection to unique analysis regions of the display (left, center, right) using the multi-channel capability of the analysis software. The same expected benefits and disadvantages outlined for Method 1 apply to Method 2. In the course of Method 2 testing, a multi-analysis approach proved to be an additional benefit for greater accuracy in single-image testing.

Method 2: Test Setup

The test setup for single-image/multi-analysis (Method 2) replicates the Method 1 setup (see Figure 9 and Figure 10, next page). The same Black Mura Gradient alignment image is used to align the imaging system to the display center.

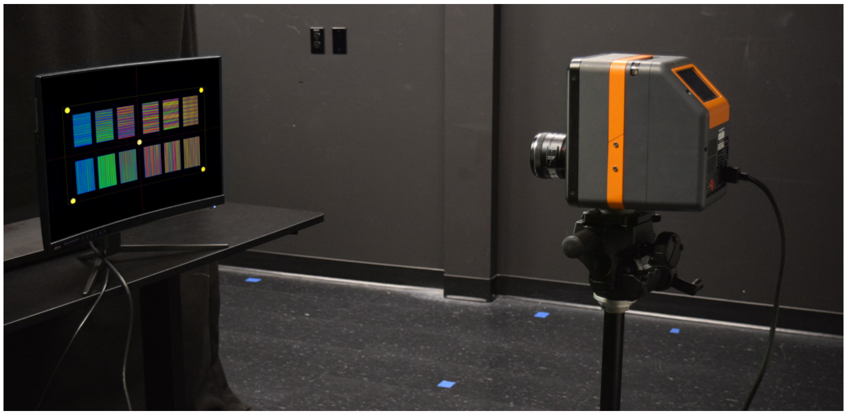

Figure 9 - *Test setup for Method 2.*

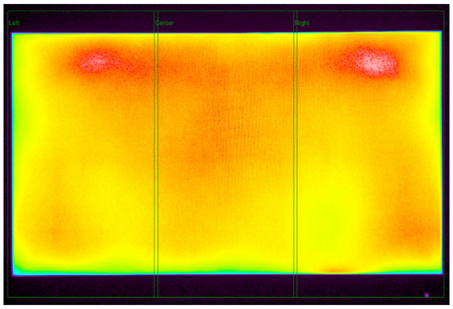

Figure 10 - *Differences in setup for Method 2 occurred in the analysis software. Three analysis channels were set (display left, center, and right) to analyze each section of the measurement image separately. Channels overlapped by 2 sensor pixels to ensure the entire display is analyzed.*

Method 2: Results of Testing

Horizontal Line Defects

Method 2 immediately proved beneficial for the Horizontal Line Defects test at low DOF settings. Even at F/2.8 using a 2MP imaging system, local contrast of defects at the center and the edge of the display, respectively, were much higher (10% at the center and 6.5% at the edge channels, versus 4.5% across all areas when analyzing the display in whole; see Table 4). This difference results when local contrast of defects is weighted solely by the luminance of the analysis area (channel) where the defect appears. Even if defect focus is very low across a curved display captured in single-image measurement, analysis channels can use local luminance values to detect defects using more precise thresholds at the edges and center independently.

Horizontal Line Defects: Min. Contrast Threshold (%)				
		Method 1	Method 2	
		Whole Display	Center Channel	Edge Channel
2MP	***F/2.8***	4.5	10	6.5
	F/8	11.5	12	12.5
	F/13	10.5	11	10.5
8MP	***F/2.8***	13.5	14.5	13
	F/8	29.5	31.5	28.5
	F/13	30	30	30
16MP	***F/2.8***	13.5	14.5	14
	F/8	35	39	36
	F/13	27	31.5	26.5

Table 4 - *Horizontal Line Defects analysis data for Method 2 compared to Method 1. Evaluating the display as a whole in Method 1 requires using the lowest contrast threshold to capture all defects, risking detection of false defects in the center. This issue is mitigated using Method 2.*

This data suggests that it is possible to use a measurement system with a smaller DOF to measure a curved display with improved accuracy, as long as the display is measured using separate analysis channels. Analyzing the display in different channels—each with its own relative contrast—allows a much higher minimum contrast threshold to be set for defects in each region of the display. This eliminates more false defects than relying on the lower minimum threshold settings that are required when analyzing the display as a whole.

This data suggests that it is possible to use a measurement system with a smaller DOF to measure a curved display with improved accuracy, as long as the display is measured using separate analysis channels.

Using Method 2, increased DOF improved the contrast of horizontal lines similarly to Method 1—there was a notable jump in defect contrast from F/2.8 to F/8 for all channels at all imaging system resolutions, suggesting a baseline DOF setting of F/8. Notably, the difference between edge and center defect contrast began to decrease at higher F-stops, with uniform contrast from edge to center at F/13 for 8MP systems (30% contrast for all measurements). This suggests that all defects from center to edge come into focus at a higher DOF. Therefore with Method 1, using a single minimum contrast threshold for the entire display appears to be a viable option for reliable defect detection, as long as the highest DOF setting is used.

Using Method 1, a single minimum contrast threshold for the entire display appears to be a viable option for reliable defect detection, as long as the highest DOF setting is used.

Increasing resolution had the greatest impact on measurement accuracy, with the highest contrast values measured at the display edges using 8MP and 16MP systems (30% contrast for 8MP at F/13; 36% contrast for 16MP at F/8).

Vertical Line Defects

As in Method 1, vertical line defects in Method 2 exhibited extremely different contrast values from the center to the edge of the display. Using a single-analysis method (Method 1), the highest DOF setting was required to detect vertical lines with the highest accuracy across the display, enabling defects on the edges to come into uniform focus with the center, eliminating the effects of the display's horizontal curvature.

Vertical Line Defects: Min. Contrast Threshold (%)				
		Method 1	Method 2	
		Whole Display	Center Channel	Edge Channel
2MP	***F/2.8***	8.5	15	8.5
	F/8	17	17.55	17
	F/13	15	16	15
8MP	***F/2.8***	8.5	25	8.5
	F/8	32.5	36.5	32
	F/13	31.5	33	30.5
16MP	***F/2.8***	10.5	29	11
	F/8	43	54	41.5
	F/13	36	39.5	35.5

Table 5 - *Vertical Line Defects analysis data for Method 2 as compared to Method 1. Evaluating the whole display in Method 1 requires using the lowest contrast threshold to capture all defects, risking detection of false defects in the center. This issue is mitigated using Method 2.*

Using a multi-channel analysis approach (Method 2), the relative contrast of vertical lines within the context of the independent center and edge channels is much higher (see Table 5). Again, this data suggests that even a measurement system with a low DOF setting can more accurately detect vertical line defects when a multi-channel analysis method is applied (setting a higher contrast threshold in the center channel without missing defects on the edge; setting a lower contrast threshold in the edge channel without including false defects at the center). The difference in vertical line defect contrast between center channel and edge channel was also significantly reduced for higher DOF settings (the smallest difference being 2.5% between the center and edge defects for 8MP systems at F/13). This suggests that focus differences between the center and edges of the display are reduced by using a higher DOF setting at all imaging system resolutions.

Because vertical line defects on the edge of the curved display are the lowest contrast, increasing DOF settings has a much greater impact in the edge channel than the center channel of the display. Again for Method 2, there is a significant jump in defect contrast from F/2.8 to F/8 across imaging system resolutions, with the highest minimum contrast percentage achieve by F/8 systems.

Increasing the system resolution also continues to have the greatest impact on measurement accuracy, with the highest contrast achieved for vertical line defects using a 16MP system at F/8.

Pixel Defects

Method 2 continues to prove beneficial for identifying pixel defects across the display, where setting unique contrast thresholds for independent analysis channels captures more defects and eliminates more false defects than a single-analysis approach (Method 1). Still, because of the small size of pixel defects (as compared to line defects), threshold settings must be much more precise to isolate pixel defects with reliable accuracy.

Because of the small size of pixel defects, threshold settings must be much more precise to isolate pixel defects with reliable accuracy.

Both low DOF and low resolution contribute to the number of missed defects and false defects during Pixel Defect analysis (see Table 8, page 18, for complete results). Only when using a high DOF setting (F/8 or F/13) is there a significant accuracy improvement, illustrated by fewer false defects and fewer missed defects—with 100% accuracy (zero false defects and zero missed defects) for all methods and all imaging system resolutions when F/13 is used.

Increasing resolution of the imaging system provided the most significant improvement to contrast of pixel defects in each channel, with the highest contrast percentage achieved using 16MP systems (15% for all defects across the display). The sensor pixel size of a defect is also a critical factor for accurate pixel defect detection. In addition to contrast thresholds, a greater number of sensor pixels are needed in the initial measurement image to precisely set thresholds for defect size based on the number of sensor pixels occupied by the defect. To increase sensor pixels per display pixel defect, a higher resolution imaging system is needed.

A combination of high resolution and high DOF are recommended for accurate pixel defect detection on curved displays, even using a the more accurate multi-channel analysis method. This enables greater precision in setting both minimum contrast thresholds (using higher DOF) and sensor pixel size thresholds (using higher resolution).

Method 2: Summary

When analyzing a single measurement image captured by a system aligned perpendicular to the center of a curved display, a multi-analysis method as outlined in Method 2 appears to be the optimal approach. This is especially true for line and pixel defects, where results from Method 1 limit the precision of contrast threshold-setting, because the contrast of defects deviates so much from the center to the edges of the display. Using Method 2, the contrast of defects relative to their analysis regions is higher—defects at the center of the display appear higher contrast relative to the center, and defects at the edges of the display appear higher contrast relative to the edges.

As summarized in Method 1, a higher DOF setting (a recommended minimum F-stop of F/8) allows a single set of contrast thresholds to be used to capture all defects and eliminate false defects reliably from both the center and edges of the display in a single image. By comparison, Method 2 allows a lower DOF (an F-stop as low as F/2.8 in 8MP and 16MP systems) to be used to capture line defects on the center and edges of the display with improved accuracy over Method 1. Therefore, when limited by the imaging system's F-stop, a multi-analysis approach is recommended.

Multi-channel analysis can improve the accuracy of results over single-analysis methods when DOF of the imaging system is limited.

Imaging system resolution still has the most significant impact on accurately and reliably identifying pixel defects. For pixel defect detection, a higher imaging system resolution is recommended (in this case, a baseline of 16MP). This enables precise threshold-setting based on minimum defect contrast as well as minimum sensor pixel size to capture all defects and eliminate false defects.

To optimize measurement accuracy for Method 2, the minimum system specifications recommended are 16MP at F/8. However, multi-channel analysis can improve the accuracy of results over single-analysis methods when DOF of the imaging system is limited.

Method 3: Multi-Image

In this method, the imaging system was rotated on its x-axis to capture the display in two images: one aligned to the center of the left half of the display, and one aligned to the center to the right half of the display. The imaging system was positioned at a defined distance[iii] from the center alignment position on each side of the display. Images at each rotation were analyzed separately (effectively evaluating each image as an entirely separate display).

Expected benefits of this method:

- Limits view-angle effects and imaging system focus changes
- Increases effective resolution of each measurement since only half of the display is measured at a time
- Enables testing a larger radius of curvature (and larger displays) at shorter distances, or in smaller measurement spaces, which may be more viable for production of large displays

Expected disadvantages of this method:

- Taking multiple images reduces the holistic measurement accuracy of the test
- The method may require additional equipment for rotation of the imaging system to each perpendicular view angle (robotics, actuator, or positioning tools)
- Rotation of the imaging system may limit measurement accuracy
- Rotation of the imaging system and multiple image capture extends measurement time

Method 3: Test Setup

In the test setup for the multi-image method (Method 3), the imaging system was aligned to two points on the horizontal axis of the display, measuring all three test images at each position. A virtual reality display test image (designed for alignment to VR displays as viewed through each eye lens) was used to align the camera to the center of the left and right halves of the curved display respectively (see Figure 11).

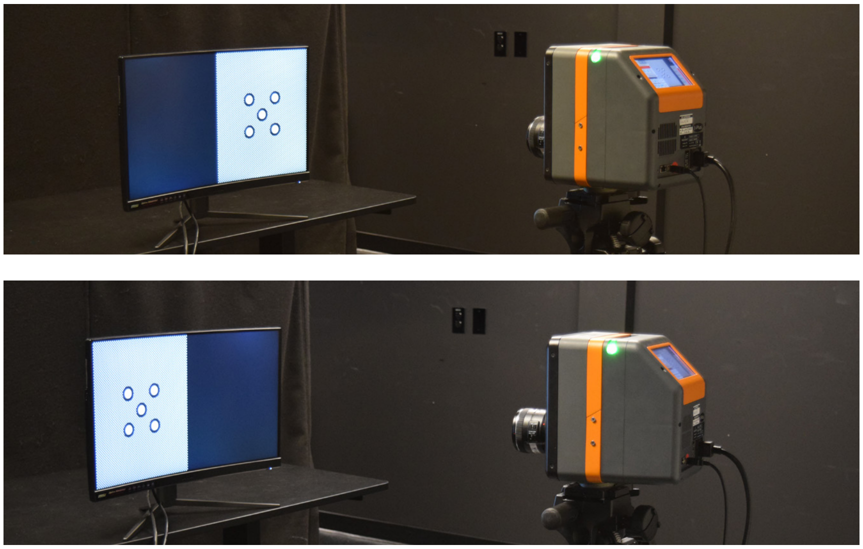

Figure 11 - *Test setup for Method 3.*

Method 3: Results of Testing

Horizontal Line Defects

Compared to Methods 1 and 2, the results of Method 3 demonstrate a considerable contrast improvement for horizontal line defects on the edges (typically lower contrast than center defects) even at the lowest DOF settings and system resolutions (see Table 6, next page). Using a 2MP system at F/2.8, contrast of the left-edge defect was improved 13.5% over Method 2 (multi-channel analysis) and 15.5% over Method 1 (single analysis of the whole display). These discrepancies from method to method appear to decrease as DOF settings are increased such that defects are captured in better focus across the display. However, the immediate impact of measuring left and right halves of the display as separate images (with the imaging system at a perpendicular alignment to the center of each half) is demonstrated by improved measurement results using any system specifications, with overall improvements in defect contrast across imaging system DOF and resolution as compared to previous methods.

The immediate impact of measuring left and right halves of the display as separate images is demonstrated by improved measurement results using any system specifications, with overall improvements in defect contrast across imaging system DOF and resolution as compared to previous methods.

Increasing DOF for multi-image measurement (Method 3) does not seem to have a significant impact in 2MP measurements, except on the right-image defect contrast values. As before, there is a jump in defect contrast from F/2.8 to F/8 settings for higher resolution systems, peaking at 35% defect contrast for 8MP systems at F/13 and 40% defect contrast for 16MP systems at F/8.

Increasing resolution continues to improve defect contrast overall (doubling defect contrast in left and right images from 2MP to 16MP systems at higher DOF settings).

While the best possible defect contrast is achieved across imaging systems using a multi-image approach (Method 3) for horizontal lines, it is evident that systems with higher resolution and DOF can improve defect clarity even further if required (with the greatest accuracy achieved using a 16MP system at F/8 or F/13). Increasing these parameters may be helpful where smaller or lower contrast defects need to be identified across the display.

Horizontal Line Defects: Min. Contrast Threshold (%)						
		Method 1	**Method 2**		**Method 3**	
		Whole Display	**Center Channel**	**Edge Channel**	**Left Image**	**Right Image**
2MP	***F/2.8***	4.5	10	6.5	20	10
	F/8	11.5	12	12.5	20	15
	F/13	10.5	11	10.5	20	20
8MP	***F/2.8***	13.5	14.5	13	20	10
	F/8	29.5	31.5	28.5	30	35
	F/13	30	30	30	35	35
16MP	***F/2.8***	13.5	14.5	14	15	15
	F/8	35	39	36	40	40
	F/13	27	31.5	26.5	40	40

Table 6 - *Horizontal Line Defects analysis data for Method 3 compared with data from Method 1 and Method 2.*

Vertical Line Defects

Vertical line contrast is less significantly improved using Method 3 over Method 1 and Method 2. For a 2MP system at F/2.8, contrast of the left-edge defect was improved 6.5% over both Method 2 and Method 1. For an 8MP system at F/2.8, contrast of the left-edge defect was improved 16.5% over both previous methods (see Table 7, next page).

Increasing DOF for multi-image measurement improves vertical line defect contrast across all system resolutions. As usual, there is a jump in defect contrast from F/2.8 and F/8 settings for higher-resolution systems, peaking at 45% defect contrast for 8MP systems at F/8, and 55% defect contrast for 16MP systems at F/8.

Increasing resolution continues to improve defect contrast overall (more than doubling defect contrast in left and right images from 2MP to 16MP systems at higher DOF settings).

As with horizontal lines, defect contrast is improved for vertical lines using a multi-image approach (Method 3). It is evident that systems with higher resolution and DOF can improve defect clarity further if required (with the greatest accuracy achieved using a 16MP system at F/13). Increasing these parameters may be helpful where smaller or lower contrast defects need to be identified across the display.

Vertical Line Defects: Min. Contrast Threshold (%)						
		Method 1	**Method 2**		**Method 3**	
		Whole Display	**Center Channel**	**Edge Channel**	**Left Image**	**Right Image**
2MP	***F/2.8***	8.5	15	8.5	15	10
	F/8	17	17.55	17	20	20
	F/13	15	16	15	20	20
8MP	***F/2.8***	8.5	25	8.5	25	15
	F/8	32.5	36.5	32	45	45
	F/13	31.5	33	30.5	45	40
16MP	***F/2.8***	10.5	29	11	25	15
	F/8	43	54	41.5	50	55
	F/13	36	39.5	35.5	55	55

Table 7 - *Vertical Line Defects analysis data for Method 3 compared with data from Method 1 and Method 2.*

Pixel Defects

Using a multi-image method has a notable effect on defect contrast for pixels that appear on the left and right edges of the display, compared to Method 1 and Method 2. Pixel defect contrast exhibits the greatest method-to-method improvement for systems with higher DOF settings and resolutions. For a 2MP system, average contrast of the left-edge defect was improved 1.67% over Method 2 and 2% over Method 1. For an 8MP system, average contrast of the left-edge defect was improved 3.17% over Method 2 and 2.83% over Method 1. For a 16MP system, average contrast of the left-edge defect was improved 4% over both Method 2 and Method 1 (see Table 8, next page).

Increasing DOF for multi-image measurement of pixel defects improves defect contrast across system resolutions. Once again, there was a jump in defect contrast from F/2.8 and F/8 settings for higher-resolution systems, peaking at a 13% defect contrast for 8MP systems at F/13 and a 17%-20% defect contrast for 16MP systems at F/13. There were also zero defects missed and zero false defects found using F/13 across imaging systems, suggesting that pixel defects are most accurately measured using a baseline DOF of F/13 regardless of resolution.

Pixel defect analysis data suggests that a higher DOF setting will provide the greatest accuracy for capturing all pixel defects and eliminating false defects. Increasing resolution improves contrast of pixel defects, with the highest contrast achieved by 16MP systems.

Increasing resolution more than quadrupled pixel defect contrast in left and right measurement images from 2MP to 16MP system measurements at higher DOF settings. Using 8MP and 16MP systems also provided benefits for thresholding on minimum sensor pixel size, with 10 pixels being the most consistent and accurate threshold for both 8MP and 16MP systems.

Overall, pixel defect analysis data suggests that a higher DOF setting will provide the greatest accuracy for capturing all pixel defects and eliminating false defects. Increasing resolution improves contrast of pixel defects, with the highest contrast achieved by 16MP systems. Also, as with line defect tests, pixel defect contrast was notably improved using a multi-image approach (Method 3). Using this method, the greatest accuracy was achieved using a 16MP system at F/13.

Pixel Defects: Min. Thresholds and Accuracy						
		Method 1	**Method 2**		**Method 3**	
		Whole Display	**Center Channel**	**Edge Channel**	**Left Image**	**Right Image**
2MP F/2.8	Min. Contrast Threshold	2%	3%	2%	3%	2%
	Min. Sensor Pixels	1	1	2	3	3
	False Defects	11	1	0	2	10
	Missed Defects	0	1	1	0	0
2MP F/8	Min. Contrast Threshold	3%	3.5%	3.5%	5.5%	5%
	Min. Sensor Pixels	5	1	2	5	5
	False Defects	0	1	0	1	0
	Missed Defects	0	0	0	0	0
2MP F/13	Min. Contrast Threshold	3%	3.5%	3.5%	5.5%	5.5%
	Min. Sensor Pixels	4	1	1	5	5
	False Defects	0	0	0	0	0
	Missed Defects	0	0	0	0	0
8MP F/2.8	Min. Contrast Threshold	4%	6%	3%	6.5%	5%
	Min. Sensor Pixels	5	9	5	8	9
	False Defects	8	1	0	1	3
	Missed Defects	1	0	0	0	0
8MP F/8	Min. Contrast Threshold	8%	10%	8%	12%	12%
	Min. Sensor Pixels	8	5	5	9	10
	False Defects	1	0	0	0	0
	Missed Defects	0	0	0	0	0
8MP F/13	Min. Contrast Threshold	11%	11%	11%	13%	13%
	Min. Sensor Pixels	5	5	5	9	10
	False Defects	0	0	0	0	0
	Missed Defects	0	0	0	0	0
16MP F/2.8	Min. Contrast Threshold	5%	11%	5%	10%	7%
	Min. Sensor Pixels	9	6	5	9	12
	False Defects	9	1	0	0	1
	Missed Defects	0	0	0	0	0
16MP F/8	Min. Contrast Threshold	15%	15%	15%	17%	15%
	Min. Sensor Pixels	8	9	7	10	10
	False Defects	1	0	0	0	1
	Missed Defects	0	0	0	0	0
16MP F/13	Min. Contrast Threshold	15%	15%	15%	20%	17%
	Min. Sensor Pixels	5	5	5	10	10
	False Defects	0	0	0	0	0
	Missed Defects	0	0	0	0	0

Table 8 - *Minimum contrast values and minimum sensor pixel size of pixel defects using Method 3 as compared with data from Method 1 and Method 2.*

Method 3: Summary

Data from Method 3 suggests that a more normalized measurement angle does in fact improve the accuracy of results for curved display testing across measurement system specifications. This is especially true for smaller defects, like lines and pixels, which are most significantly affected by the curvature of the display as captured from a given measurement angle. Even compared to a multi-channel analysis approach (Method 2), which enables independent thresholding per region, the highest defect contrast is achieved when the imaging system is aligned at the most normal orientation with the display surface (Method 3).

> *The highest defect contrast is achieved when the imaging system is aligned at the most normal orientation with the display surface.*

Across measurement methods, an imaging system with high resolution and DOF settings continues to optimize measurement accuracy. Overall, to optimize measurement accuracy for Method 3, the minimum system specifications recommended are 16MP at F/8.

Uniformity

Supplemental to the analysis of small defects throughout this paper, a Luminance Uniformity test was applied in the early stages of lab testing with mostly consistent results from method to method—suggesting that display curvature does not have a significant effect on measurement results for uniformity. Increasing DOF at each resolution appears to have virtually no effect on luminance uniformity percentage (see Table 9). As resolution is increased, there is a consistent decrease in overall uniformity measurements across methods, with the lowest luminance uniformity percentage achieved with the 16MP system. This is an expected result given the increased photosensitivity of the imaging system. By applying more sensor pixels to the measurement, the analysis captures a less uniform, but more accurate, result. To maximize the accuracy of uniformity measurements, regardless of measurement method, a high-resolution system is recommended (16MP using any DOF setting).

Uniformity: Luminance Uniformity (%)							
		Method 1	**Method 2**			**Method 3**	
		Whole Display	**Center Channel**	**Edge Channel (L, R)**		**Left Image**	**Right Image**
2MP	***F/2.8***	63.4	72.8	64.7	72.7	61.1	64.8
	F/8	63.6	72.8	64.7	73.8	60.8	65.2
	F/13	64.3	73.3	65.2	74	61.2	65.2
8MP	***F/2.8***	57.1	68	57.9	68.1	51.9	60.4
	F/8	56	69	58	69	51.5	58.5
	F/13	55.8	66.7	56.8	67.6	50.8	57.7
16MP	***F/2.8***	49.1	63	50.9	61.7	47.7	55.5
	F/8	49.4	63.8	50.7	62.6	48	55
	F/13	50.7	63.8	51.8	63.6	47.3	55

Table 9 - *Luminance Uniformity analysis data for all test methods. Left and right edge channel data in Method 2 illustrates a uniformity issue on the left edge (inherent to this particular display) that is affecting the overall luminance uniformity percentage of the display across measurements in Method 1 and Method 3.*

Conclusion

Although the shape of displays in the vehicle may be changing, expectations of display quality remain constant. Displays that break from the traditional flat panel design challenge traditional display test methods. However, a new approach to traditional display test components and applications may be all that is required to ensure curved displays can be objectively measured for visual quality.

As demonstrated through the test results provided in this paper, measurement accuracy for small defects across the display can be improved most significantly by employing a measurement system with high resolution and high DOF settings (with a recommended baseline of 16MP and F/8 for all measurement methods).

Capturing multiple images of the display to normalize the alignment of the measurement system to the display's changing curvature greatly improved the accuracy of defect analysis compared to single-image methods. A multi-image method should therefore be considered when display curvature is high, or in lab-based metrology applications for characterization or design where precision is paramount. For these situations, a multi-image method (Method 3) using a robust measurement system (high resolution and DOF settings) provides the ultimate accuracy.

In situations where time and equipment efficiency are paramount—such as in manufacturing quality control and production operations—the more complex process of acquiring multiple images may not be ideal. Measuring a single image, analysis results can be improved by applying multiple analysis regions (channels) to enable regional thresholding (Method 2), combined with a robust measurement system for a balance of accuracy and efficiency. After an initial setup of multi-channel analysis regions and defined contrast or sensor pixel thresholds, the measurement process for this method can be easily automated using software, allowing multiple displays to be measured against a consistent set of criteria in quick succession.

Using results and recommendations like those offered in this paper, an effective method for curved display testing can begin to be formalized. Bringing together similar research, standards bodies can ultimately define universal evaluation criteria, thereby allowing manufacturers to successfully incorporate new display form factors at a level of quality that is consistent with existing expectations.

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[i] Measurement distance was optimized to capture the measurement area of the display in maximum resolution based on each system's field of view. For Method 1, the 2MP system was positioned at 3.22 meters for all DOF settings; the 8MP system was positioned at 1.6 meters for all DOF settings; the 16MP system was positioned at 1.1 meters for F/2.8 and F/8, and 0.975 meters for F/13.

[ii] For Method 2, the 2MP system was positioned at 3.22 meters for all DOF settings; the 8MP system was positioned at 1.6 meters for all DOF settings; the 16MP system was positioned at 1.1 meters for F/2.8 and F/8, and 0.975 meters for F/13.

[iii] For Method 3, the 2MP system was positioned at 2.19 meters for all DOF settings; the 8MP system was positioned at 1.225 meters for all DOF settings; the 16MP system was positioned at 0.95 meters for all DOF settings.

Curved displays offer manufacturers new design flexibility for vehicle interiors, but also introduce challenges for display measurement. This paper presents the results of several lab tests measuring a 1500R LED-lit curved display using an imaging colorimeter and analysis software to evaluate the effectiveness of various methods and system specifications to optimize the accuracy of small defect detection (pixels and lines) in automotive curved displays.

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