

Switchable Privacy Displays with Liquid Crystals and Collimated Backlight: Techniques and Measurements

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Abstract

Switchable Privacy Displays (SPD) enhance a wide range of applications, such as codriver displays in cars. In "private" mode, the driver must not be distracted. SPDs are mainly based on liquid crystal effects and collimated backlights. Angular measurements of different SPDs have been performed to extract relevant parameters such as luminance and uniformity. Evaluations with 20 subjects recommend a luminance of <math>< 0.1 \text{ cd/m}^2</math> for the driver in private mode at night to avoid distraction.

Author Keywords

Liquid crystal; PDLC; LCD; switchable privacy; backlight; luminance; viewing angle; uniformity; switching ratio; evaluation.

1. Introduction

In addition to e-mobility and autonomous driving, another megatrend in the automotive industry is more and larger displays including a dedicated display for the codriver for e.g. video, games and information.

Figure 1 shows a codriver (CD) watching a movie on the codriver display (CDD) while driving. The driver (D) is not allowed to view any content while the car is manually driven, as distraction of the driver must be avoided for safety and legal reasons. When the car is parked, the CDD can be switched to public mode, which allows the driver to see the content, for example when deciding on a restaurant with the codriver on a restaurant. Such a display is an electronically switchable privacy display that provides a very convenient way of blocking distracting content and is therefore well suited for automotive applications. More details can be found in our recent article¹. Here we present additional optical measurement methods, the measurement results of several new switchable privacy displays (SPDs), and the results of extensive static and dynamic evaluations with human subjects.



Figure 1. Visualization of automotive switchable privacy: The image on the codriver display is blocked to the driver if distracting content is shown. Source: Continental.

Common definitions of (switchable) privacy displays are (visualized in Figure 3 top left), we use the first ones in this paper:

- Public mode: Display content is visible to everyone" with image quality; other names are share- and wide-angle mode.
- Private mode: Only viewers with perpendicular orientation to the display can read the content which is blocked for oblique angles. Other names are privacy-, narrow angle-, anti-spy- and anti-peek mode.

In addition to switchable privacy displays, fixed privacy solutions (using louvres on the display surface) are also well known, see Table 1 for a comparison. Beyond the automotive sector, there are many other applications for privacy displays where they have many advantages over fixed privacy, but at a higher cost:

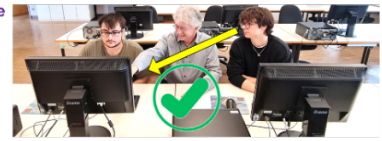
- Mobile devices in public places to avoid "shoulder surfing".
- ATMs: Private mode prevents shoulder surfing and camera skimming. Direct and secure pin entry on a touchscreen is possible. A mechanical pin pad may no longer be needed. Public mode: The display does not darken ("ATM in operation") from oblique angles as with fixed privacy.
- Other applications: E-learning and e-testing devices to prevent cheating (Figure 2), PIN-based facility/room access to prevent door code skimming, tablet devices for inventory control to prevent information leakage and hidden price calculations for sales staff in front of their customers.

Table 1. Comparison of fixed and switchable privacy.

(selected examples)	Fixed	Switchable
Technique	Louver film	Front film (all displays) or backlight (LCD only)
Mobile devices	Aftermarket (foils): Smartphone, laptop (detachable)	Integrated: Few laptops (e.g. HP Sure View)
Stationary	ATM (device appears OFF from oblique angle)	None so far
Automotive	e.g. Porsche Cayenne (no image visible for driver even when e.g. parked)	e.g. Mercedes Hyper-screen (blocks distracting content while driving)

Benefits of Switchable Privacy Displays:

Explaining software programming in public mode



Switching to private mode for exam in lab



Cheating is avoided by switchable privacy in private mode compared to standard displays



Figure 2. Benefits of switchable privacy in a software lab.

This paper presents the different approaches to implement switchable privacy in modern displays (§ 2) followed by optical measurements for privacy displays (§ 3) and evaluations with 20 subjects (§ 4) with a focus on automotive applications. Our methods can be used as a guideline for other applications (see Table 1).

2. Methods for Switchable Privacy Displays

Virtually all approaches to switchable privacy displays are based on liquid crystal technologies, for a review and comparison see Li². Most of the methods provide a black image in private mode for oblique observers, while a white image or logos are also possible³. An overview of the most commonly used technologies and their visualization is given in Table 2:

- I. **LCD with Dual Backlight**^{4,5} (BL): Each mode has its own LEDs and light guide (cost!). The collimated light of the “private” BL limits light emission to perpendicular angles.
- II. **LCD with PDLC**^{6,7}: Collimated (by a louver film) light passes through a layer of PDLC (or other LC types). Without voltage, this light is scattered in all directions (public). An electric field causes the LC molecules to align and light is emitted only in perpendicular direction (private).
- III. **LCD with Dual Pixel**^{8,9}: Each subpixel is divided into 2 parts: The IPS pixel is the “standard” subpixel while the Viewing Angle Control part blocks the backlight (0 V, public), while a voltage leads to white light at oblique angles (private).
- IV. **Front LC layer (all displays)**^{10,11}: A TN LC with alignment layers and two polarizers is mounted on top of the display and is therefore suitable for all technologies. The light from the display is emitted in all directions without a voltage (public). By applying a suitable voltage, the emission angle can be limited to mostly perpendicular (private).

Table 2. Techniques for switchable privacy displays.

(simplified)	Public	Private
I. LCD with Dual Backlight		
II. LCD with PDLC		
III. LCD with Dual Pixel		
IV. Front LC layer (all displays)		

The best solution for a given application depends on the requirements and cost. If white light is emitted at oblique angles in private mode as in III, automotive (night driving!) is not a suitable application compared to e.g. laptops. “Dual Pixel” (III) requires a completely new design of the LC glass whereas the addition of only a front layer (IV) is easier to integrate, also compared to backlight modifications (I, II). The optical performance (§ 3) is very important for the automotive use of SPDs.

3. Optical Measurements of Switchable Privacy

Optical measurements are required to quantitatively describe switchable privacy displays and to demonstrate that the privacy feature can block distracting content for the driver, while maintaining high image quality for the codriver. A typical geometry for an automotive grade 10.5 inch display is shown in Figure 3. The CDD is approximately 60 cm apart from the codriver, giving a 24° field of view (FoV). The driver’s viewing distance is typically in the range of 100 cm and therefore has a FoV of about 11° at an oblique angle of about 40° ...50°. These figures are highly dependent on the vehicle parameters and position of the CDD.

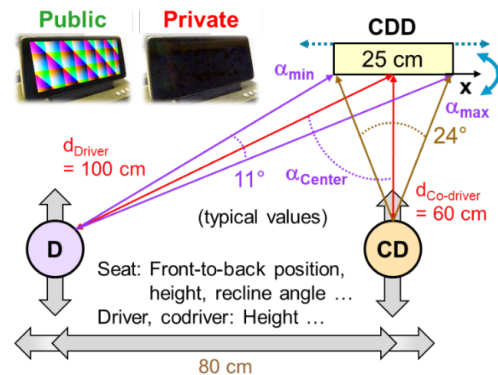


Figure 3. Typical geometry for driver (D) and codriver (CD) for codriver displays (CDD). The view is blocked for the driver in private and visible in public mode.

The angular characteristic of the white luminance of a CDD in public and private mode is the most fundamental quantity¹. Viewing angle characteristics are usually visualized as polar plots using false colors. However, it is more appropriate for the assessment of SPD performance to show results in (usually) horizontal direction only²⁻¹⁰ (2D charts). These plots can be extracted from polar plots, see for example Heber¹¹. They show the angular behavior better and different SPDs can be compared by normalization. In addition, driver and co-driver angular ranges, uniformity and thresholds are easier to understand in 2D plots.

Figure 4 shows the horizontal dependence (angle α) of the normalized white luminance (full screen test pattern) for two example LCDs (“1” and “2”) with very different characteristics. Public and private modes are combined in one graph and the typical angular ranges for driver and codriver are marked (see Figure 3). All SPD measurements are a superposition of the angular characteristics of the display and the (switchable) privacy technology. LCD “1” (solid lines) shows a relatively high luminance for the driver in public mode (green) and a very low luminance in private mode (red) (as intended). However, the luminance in private mode drops steeply towards the left and right edges of the display causing noticeable uniformity problems. LCD “2” (dashed lines) performs better, but the luminance for the driver in private mode may be too high for the driver at night to avoid distraction. Its luminance in public mode is also too low for good image quality, at ~15% of the perpendicular luminance.

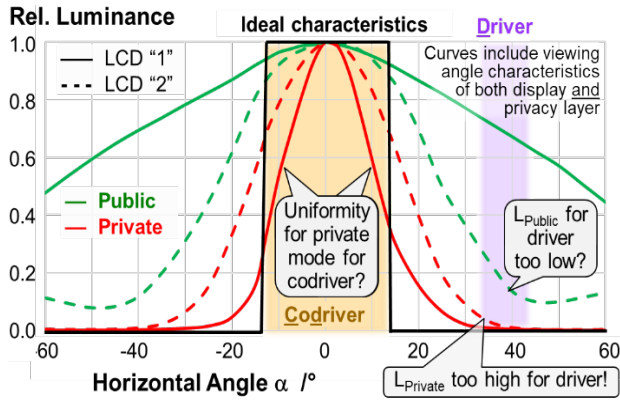


Figure 4. Measurement of two switchable privacy LCDs with very different characteristics: The relative luminance over horizontal observer angle is plotted for public (green) and private (red) mode (ideal: black) as well as the markings of the typical angular spans for driver and codriver.

The steep drop of the luminance perceived by the codriver in private mode for LCD “1” in Figure 4 indicates uniformity problems that may also occur in public mode for the driver. We have addressed this issue by using an imaging light measurement device (ILMD) and extracting line profiles¹². They resemble to one period of a sine wave for the codriver in private mode and half a period for the driver in public mode, see Figure 4. We used the contrast sensitivity function^{13,14} (CSF) to extract threshold value for noticeable non-uniformity. Our evaluations¹ show that a CSF of 5 is an acceptable compromise between noticeable uniformity problems and the performance/cost ratio of SPDs.

The angle measurements are used to calculate the Switching Ratio (SR) - a key private mode parameter that describes the 'blocking' performance for the driver, see Figure 5. The switching ratio $SR(\alpha)$ for the private mode is defined by

$$SR(\alpha) = 100\% \cdot \frac{L_{Driver}(\alpha)}{L_{Codriver}(0^\circ)} \quad (1)$$

As illustrated in Figure 5, the results of three LCDs are presented with comments on their performance as insets. Examples of OEM requirements are visualized by colored boxes. The horizontal dashed magenta line indicates the recommendation of $SR = 0.5\%$ set by the “Alliance for Automotive Innovation” (AAI, www.autosinnovate.org).

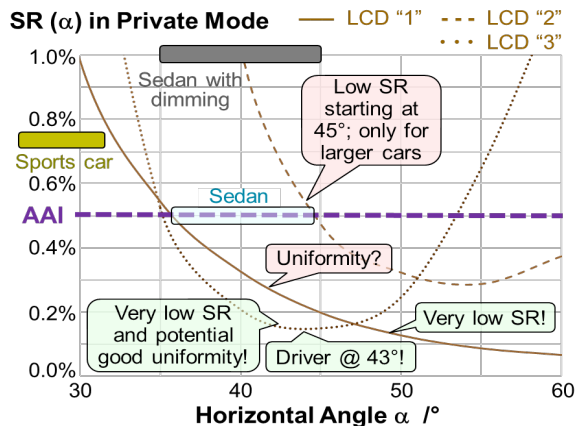


Figure 5. Switching ratio SR for private mode over the driver's observer angle α and selected proposals from different OEMs and AAI recommendation of 0.5%.

Figure 6 shows a strong change of white, expressed by the correlated color temperature (CCT), for LCD “4” from public to private mode. This may unacceptable in premium cars (first use of SPDs) for the codriver: 8,200 K in public mode reduce to 7,000 K in private mode. Also, white appears different for driver (7,800 K, @ 40°) and codriver in public mode.

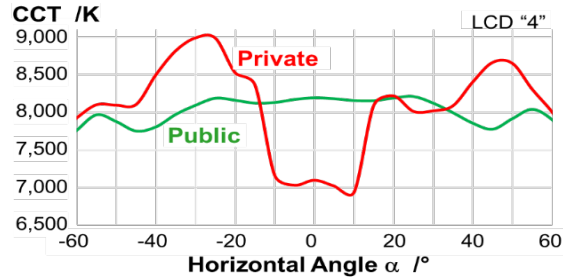


Figure 6. Angular dependency for the correlated color temperature in public and private mode for LCD “4”.

4. Evaluations of Switchable Privacy Displays

As optical measurements do not provide a metric for driver distraction, human subject evaluations are required. We have carried out many evaluations (Figure 7) with 20 subjects using a large number of different test patterns. The most critical case is night driving as there are no reflections from ambient light to reduce the readability. The evaluations were performed on three different privacy LCDs for both static (e.g. readability of numerals with different grey levels¹, identification of objects) and dynamic (video clips, animations) conditions with 20 subjects in each group. The objective is to evaluate a proposal for the maximum allowable luminance for the driver in private mode.

Four examples of "dynamic" tests are presented in Figure 8 using video clips (A to C) and black and white flashing of a full screen test pattern (D). The latter is performed with "eyes on the road", means that the subject does not look at the display and is asked about the effect of this blinking on their peripheral vision. Two luminance levels (0.6 and 1.2 cd/m² for white) were chosen to assess the effect of absolute luminance. The results are illustrated in Figure 9. It is evident from the figure that the readability of light content (B to D) is diminished by approximately 20% when the luminance is reduced from 1.2 to 0.6 cd/m². The luminance of the faces in clip A is ~10% of the very bright scenes. The results demonstrate that the correct answers are significantly reduced when the luminance is reduced from 0.12 to 0.06 cd/m². For the "standard" luminance of 50 cd/m², an SR of 0.1% would be required for a CDD according to equation (1).

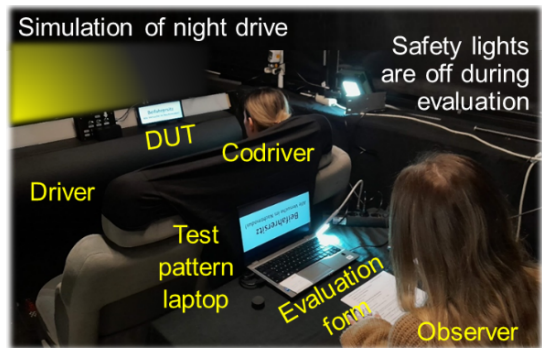


Figure 7. Set-up used for the evaluation in dark room with simulated headlight at night drive, details¹.

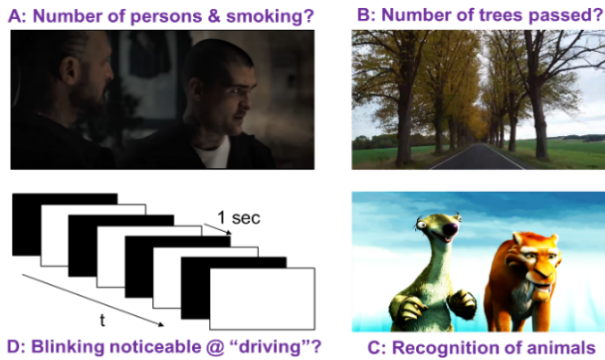


Figure 8. Examples of tests with dynamic content (e.g., video clips and “blinking”) and related questions.

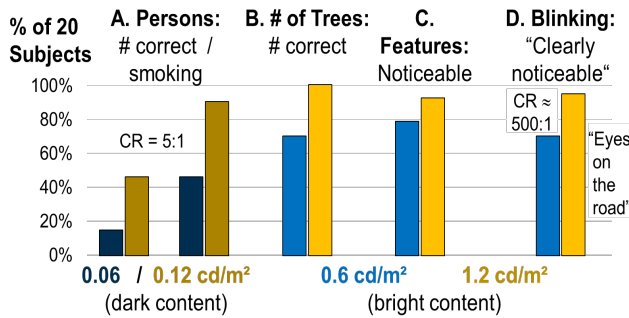


Figure 9. Results of dynamic tests (see Figure 8) for two privacy luminance levels (A: dark scene, left) with simulated night driving conditions (see Figure 7) and LCD “6”.

The objective of the evaluations with subjects is to determine a proposal for an acceptable (in terms of driver distraction) threshold luminance and a display luminance for the codriver via the switching ratio. The summary of our various evaluations is shown in Figure 10 as the percentage of “correct” or “readable” etc. responses over the luminance towards the driver in private mode during night driving. This summary includes static tests, such as the readability of figures¹, the recognition of the silhouette of people with a CR of 5:1 and dynamic tests (Figure 9). The results obtained indicate an acceptable luminance level of approximately 0.05 cd/m² (green area). Assuming an SR of 0.5%, we obtain a (white) luminance of 10 cd/m² for the codriver in private mode during night driving. A higher SR allows for a higher L_{Codriver}, thus improving the perceived image quality (eye adaptation).

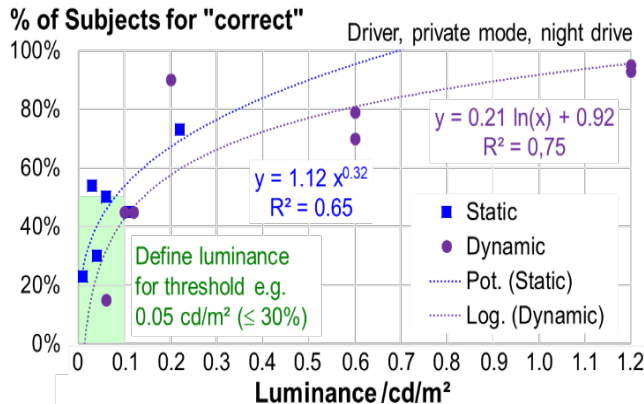


Figure 10. Percentage of “correct” answers vs. luminance for static and dynamic test patterns (driver, private, night).

5. Discussion, Summary and Impact

A number of switchable privacy displays have been measured and evaluated in order to determine their suitability for automotive applications. The most critical use case for driver distraction is night driving, where there are no reflections on the display. We carried out measurements and obtained the following results:

- Angle measurements: Luminance, SR, gamma and color.
- Safety: We propose a maximum luminance of only 0.05 cd/m² for the driver in private mode during night driving.
- Uniformity: Luminance and color especially in private mode.
- SPD technologies: Most approaches are only suitable for LCDs (backlight etc.), but OLED-compatible approaches are favorable due to the increasing use of OLEDs in cars.

Our findings help to design and implement switchable privacy displays. We focused on automotive applications but our methods, measurement results and evaluations can be transferred to other applications such as ATMs.

6. Acknowledgements

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7. References

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