

Turn Any Automotive Window into a Bright, Colorful Display



ABSTRACT

Advancements in smart glass window films and Texas Instruments (TI) DLP® projector technology are enabling automotive OEMs and ride hailing companies to turn any vehicle window into a bright, colorful display. Polymer-dispersed liquid crystal (PDLC) window films support two distinct states, a transparent state and a translucent state that can be used to display projected content. This paper will provide an overview of PDLC smart glass automotive window applications, an update on the key aspects of this technology, performance achieved to date, and cover projector design considerations when illuminating transparent films. A detailed description of a 1000 lumen (lm) Red Green Blue (RGB) projector optimized for illuminating transparent films are provided as an example.

Key Words: PDLC, smart glass, location-based advertisement, automotive, projector, DLP, DMD, and Gauzy.

Table of Contents

1 Introduction	2
2 PDLC Smart Films	3
2.1 Film Transparency and Translucency.....	4
2.2 PDLC Film Options.....	6
3 DLP Projector Design Considerations	6
3.1 Projector Design Challenges.....	8
3.2 Brightness Results.....	8
4 Conclusion	9
References	9

List of Figures

Figure 1-1. V2V Communication Back Window Display.....	2
Figure 1-2. Location-Based Advertisement Side Window Display.....	2
Figure 2-1. PDLC Film in the Off State (no applied voltage).....	3
Figure 2-2. PDLC Film in the On State (+48V applied).....	3
Figure 2-3. Two Different PDLC Morphologies. The More Consistent the Size and Distribution of the Liquid Crystal Droplets, the Better the Optical Performance.....	4
Figure 2-4. T-min is the Amount of Specular Transmission of Incident Light When in the Translucent State.....	5
Figure 2-5. T-total is Total Amount of Light (specular, diffused, and scattered) Transmitted When in the Translucent State.....	5
Figure 3-1. Illumination Diagram of Standard DLP Projector.....	6
Figure 3-2. Pupil Diagram of DLP5532-Q1 Projector at f/2.4 and f/1.8 Aperture Sizes.....	7
Figure 3-3. Image of 1,000 Lumen DLP5532-Q1 Projector.....	8

List of Tables

Table 2-1. Key Film Specs for the Transparent and Translucent Film States.....	6
Table 3-1. Optical Performance of the Projector, With 1,000 Lumens Directed Towards the Film.....	7
Table 3-2. PDLC Brightness Relationship With Image Size and Projector Lumens.....	8

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1 Introduction

New transparent display technologies are enabling car manufacturers and ride hailing companies to turn virtually any transparent surface into a bright colorful display. Front, side, and back windows as well as panoramic sunroofs can now be turned into interior or exterior facing displays. Target applications include location-based advertisement, vehicle to vehicle (V2V) and vehicle to pedestrian (V2P) communication, passenger, driver greeting, roof, infotainment, and driver assist displays. [Figure 1-1](#) and [Figure 1-2](#) show examples of V2V and location-based advertisement window displays.

From an advertisement perspective, it is becoming common to see taxis or ride hailing vehicles driving around major US cities with large rooftop mounted LED displays. Location-based-advertisement allows marketers to target customers when they are within a certain geographical area or distance from a retail location. Messaging can be tailored based on location, time of day, driving routes, and even weather. Ride hailing companies such as Uber and Lyft are running location-based-advertising services in several major US cities with the goal of increasing revenue and driver pay [1] [2]. Roof mounted LED advertisement displays produce large, bright images but have several disadvantages including reduced vehicle fuel efficiency due to drag, road noise, high power consumption, high cost, difficulty in removing the display when not in use, and arguably unappealing aesthetics.



Figure 1-1. V2V Communication Back Window Display



Figure 1-2. Location-Based Advertisement Side Window Display

As an alternative to rooftop mounted displays, technologies such as PDLC smart glass films that support transparent and translucent states are being evaluated for mobile advertisement. Instead of installing a roof mounted display, the existing back or rear side window of a vehicle can be used to display advertisement. When the PDLC film is in the translucent state and illuminated by a DLP projector, the film acts as a rear projection display. When the film is in the transparent state, the window provides clear, unobstructed visibility. After picking up passengers, ride hailing companies can turn off the advertisement by placing the window into its transparent state, providing passengers full visibility of their surroundings during the ride.

Window and cartop LED displays both face some amount of regulatory challenges and uncertainty. Regulations around mobile advertisement are not fully defined and dependent on the region, down to the municipality. In addition, there are also country specific regulatory requirements defining what can and can't be displayed on a vehicle window in terms of color, location, and dynamic vs static content. The ability to support both transparent and translucent states provides flexibility to adapt to the ever-evolving regulatory environment.

A significant design challenge with any window display technology is achieving brightness levels high enough to support daytime viewing. Supporting night time viewing is relatively easy but in order to maximize advertising revenue, daytime viewing should be supported. Supporting a large display area is another design challenge, with the larger the display area, the more projector lumens required. Doubling the display area requires 2x the projector lumens in order to maintain the same display brightness.

Display brightness measured in candelas per meter squared (cd/m^2) or Nits is a function of the film efficiency, screen gain, display size and projector illuminance. As shown in previous work on display brightness requirements, the luminance contrast ratio (LCR) should also be considered [3]. TI and Gauzy have collaborated to design, build and characterize a PDLC smart glass display system using a high-lumen projector co-designed and developed with TQ Optoelectronic. This document provides an update on Gauzy's PDLC technology, TI's high lumen DLP projector reference design built by TQ Optoelectronics, and discusses the characterization results of the high lumen projector / PDLC smart glass system.

2 PDLC Smart Films

PDLC films consist of liquid crystal droplets dispersed in a UV cured optical polymer-based matrix coated between two sheets of conductive transparent layers effectively forming a capacitor. The size, characteristics, and distribution of the droplets housing the liquid crystal molecules determine the optical properties of the PDLC film. In its default state, the liquid crystals in the droplets are randomly oriented (Figure 2-1) but when a voltage of sufficient strength is applied to the capacitor, the liquid crystals align themselves to the electric field (Figure 2-2).

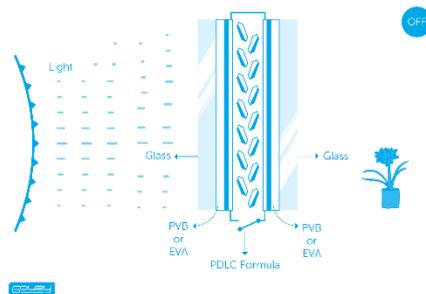


Figure 2-1. PDLC Film in the Off State (no applied voltage)

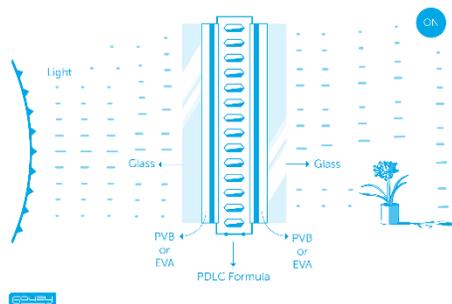


Figure 2-2. PDLC Film in the On State (+48V applied)

The PDLC capacitor is laminated between two pieces of glass with an adhesive interlayer of polyvinyl butyral (PVB), polyurethane (TPU), or ethylene vinyl acetate (EVA). When +48 V or greater is applied to the capacitor the film appears transparent. Power consumption of Gauzy's PDLC film when in the transparent state is minimal at 1-4 watts per square meter depending on film shape and busbar location.

Film optical scattering properties can be manipulated through refractive index variations in the PDLC film manufacturing process. Such manipulation occurs to the different components in the formulation ultimately affecting the morphology of the film. The morphology of a PDLC film is defined based on the quantity, quality, and distribution of the liquid crystal droplets and is what determines the optical performance in both the translucent and transparent states. Figure 2-3 shows the variation in morphology and therefore optical performance between two different PDLC film suppliers.

The size and distribution of Gauzy's droplets are distributed homogeneously to scatter light in the visible wavelength (400-700 nanometers), supporting a stable contrast ratio over a very wide viewing angle of up to 178°, making them optimized for projection screen applications.

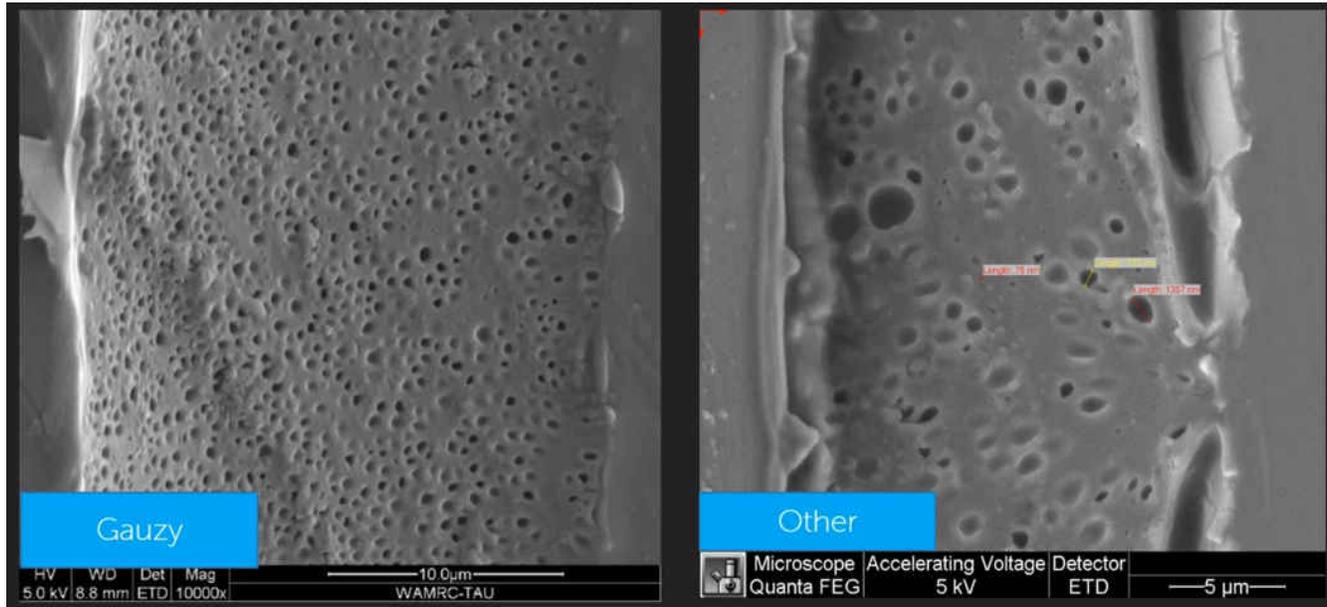


Figure 2-3. Two Different PDLC Morphologies. The More Consistent the Size and Distribution of the Liquid Crystal Droplets, the Better the Optical Performance.

Gauzy PDLC films are optimized at the chemistry level to withstand automotive specifications, including stability in transparency, opacity, and switching times within -20 - +90°C temperature range, as per the requirements of automotive testing standards (PV3929). Gauzy PDLC films are likewise stabilized for automotive lamination standards which includes lamination with PVB, and can be utilized in various stack configurations with ultra-thin or multi-axis curved glazing.

Current governmental regulations allow PDLC windows to be implemented in select areas of a vehicle's greenhouse glazing including panoramic sunroofs, or behind pillar b, the rear side passenger windows and backlights. As regulation begins to shift and the technology improves, additional vehicle window surfaces may be able to support PDLC smart glass displays.

2.1 Film Transparency and Translucency

When evaluating PDLC film performance in its transparent state, haze and transparency are the two key specifications determining film clarity. Haze is a measurement of light diffused or scattered more than 2.5° from the specular direction when passing through a transparent material. Transparency is the percentage of incident light that is allowed to pass through the film. Gauzy automotive grade PDLC films have an on-axis haze of ~ 2.5% and transmittance of ~ 80% providing excellent clarity when in the transparent state.

On-axis haze is defined as the haze level when viewing the film at an angle of incidence of zero (normal to the surface) and off axis haze is the haze level when viewing the film at an angle of incidence > 0°. Due to the structure of PDLC, there is an inherent off-axis haze that is higher than the on-axis haze and can impact overall transmittance and therefore clarity. Having the lowest overall haze is critical to ensuring a good viewing experience.

When evaluating PDLC film performance in its translucent or “off” state, T-min and T-total are the key specifications that describe a film’s performance. T-min is the percent of incident light normal to the surface of the film when in the translucent state that is transmitted maintaining its angle of incidence $\pm 2.5^\circ$. So, T-min is the percent of parallel light incident on the film that is passed through with minimal change in its angular orientation (see Figure 2-4). T-total is the total of all diffused, parallel, and scattered light that passes through a film in the translucent state (see Figure 2-5)

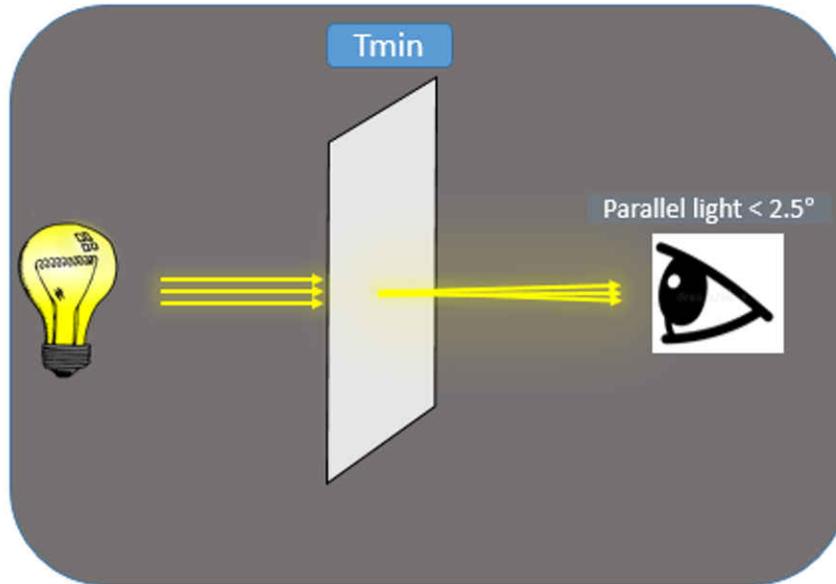


Figure 2-4. T-min is the Amount of Specular Transmission of Incident Light When in the Translucent State

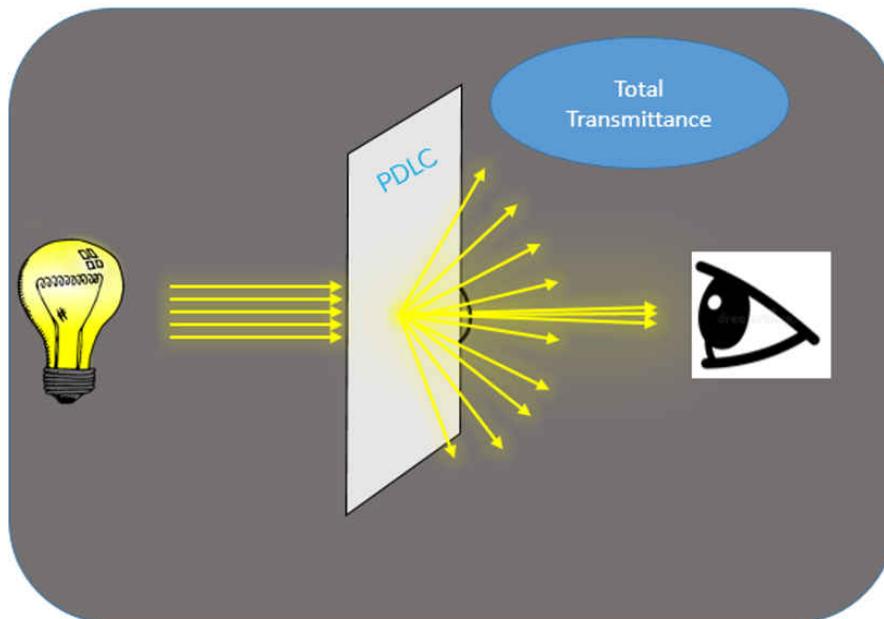


Figure 2-5. T-total is Total Amount of Light (specular, diffused, and scattered) Transmitted When in the Translucent State

Gauzy’s PDLC films have a T-min of ~4% and a T-total of ~ 60%. When a low T-min and a high T-total are combined, the result is a high-quality image with a wide viewing angle and low visual disturbance of the surrounding environment as all elements behind the translucent glass are hidden. Table 2-1 summarizes the key transparent and translucent specs.

Table 2-1. Key Film Specs for the Transparent and Translucent Film States

Film State	Key Specs	Value
Transparent	Transmittance	~ 80%
	Haze (on-axis)	~ 2.5%
Translucent	T-min	~ 4%
	T-total	~ 60%

2.2 PDLC Film Options

There are several PDLC film options to choose from in terms of colors and optical properties. Gray film surfaces may exhibit higher luminance contrast ratios as they reduce the amount of ambient light reflected off the surface or transmitted through the film, therefore increasing the relative brightness of the display imagery when compared to ambient. The gray level can be customized by combining a white PDLC film in a custom film stack including gray tinted glass or gray adhesive interlayers during lamination. Such customization supports both aesthetic flexibility and optical performance, including viewing angle, contrast requirements, and screen size. While a tinted or gray glazing increases the contrast ratio, it may impact the overall brightness of an image due to reflection or absorption of projector light. Utilizing DLP projectors with luminous flux greater than 1000 lm can mitigate this impact on brightness.

PDLC films are also available with IR solar control properties, which can reflect up to 78% of IR light, in turn reducing temperatures inside a vehicle by up to 15°C. [4] Pairing this with projection supports not only dynamic communication platforms, but more energy efficient vehicles that consume less fuel for cooling. Moreover, films are available with laser etched invisible segmentation which can be used for segmented solar and light control, or to create zones for location specific projections in one area while keeping some of the window transparent by powering selective zones.

3 DLP Projector Design Considerations

The Gauzy PDLC Smart Glass film technology must be paired with a projector that outputs a high amount of luminous flux to create a bright display at the surface of the film. DLP technology from TI enables a projector that offers high performance features for this application, such as high optical efficiency, high resolution, and constant performance across the automotive temperature range. At the core of DLP technology is the digital micromirror device (DMD), a two-dimensional array of millions of micromirrors that reflect the illumination source (LEDs or laser diodes). Each micromirror tilts in two states—on and off—using pulse width modulation (PWM) over the course of the video frame in order to create gray-scale pixel content in the final image. TI currently offers one DMD that is intended specifically for window display applications: DLP5532-Q1. This device has a larger micromirror array size and therefore can output higher optical power levels. A projector design from TQ Technology based on the DLP5532-Q1—illuminated by Luminus’s PTM-50X RGB LEDs—is considered for the purpose of this paper.

The PTM-50X series of RGB LEDs from Luminus is a great match for the DLP5532-Q1 DMD when targeting a bright window display application, enabled by specific projector design decisions. With any DMD-based projector, there is an inherent tradeoff between the total luminous flux throughput and the expected contrast of the projector. This relationship can be understood by referring to [Figure 3-1](#) and [Figure 3-2](#), which shows diagrams of the optical cones around the illumination of a standard DMD-based projector.

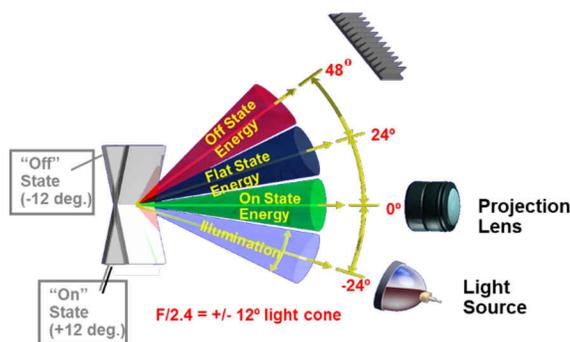

Figure 3-1. Illumination Diagram of Standard DLP Projector

Figure 3-2 is called a pupil diagram that looks at the different optical cones surrounding the DMD. The main thing to note is that a high contrast system has separation between the on-state cone and the surrounding cones.

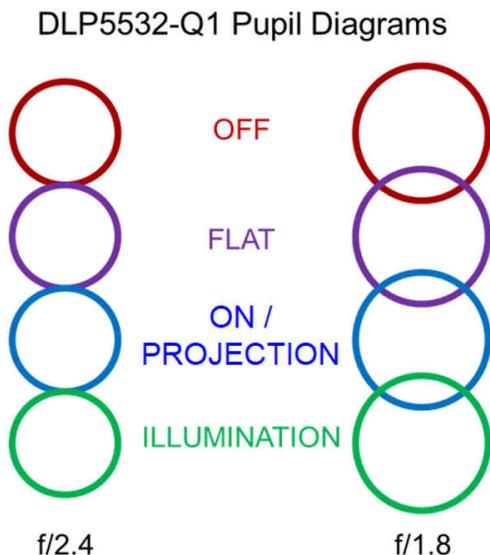


Figure 3-2. Pupil Diagram of DLP5532-Q1 Projector at f/2.4 and f/1.8 Aperture Sizes

For the DLP5532-Q1 device with an on/off tilt angle of $\pm 12^\circ$, a standard f/# for the projector apertures is f/2.4. This results in a pupil diagram where there is no overlap between the flat-state and on-state pupils. Flat-state refers to any light reflecting off flat surfaces such as the DMD coverglass. When pixels are tilted to the off-state position, the undesired flat-state light does not enter the projection lens pupil and thus leads to strong contrast performance.

However, the window display application is less sensitive to the contrast performance from the projector; rather the contrast of the final image is more impacted by the sunlight’s interaction with the screen material and the ambient environment. Therefore, for this application it can be recommended to expand the size of the aperture to f/1.8, as shown in Figure 3-2. This pupil expansion has a compounding effect for the DLP5532-Q1 and PTM-50X projector: the larger illumination cone is able to accept light from a larger LED. Since LEDs are often rated by their current density, a larger emission area is able to output more lumens. So, not only is there a higher throughput through the projector compared to a nominal f/2.4 projector, the LED itself will output more light as well. The tradeoff with f/1.8 aperture on a DLP5532-Q1 system is that there is now overlap between the on-state or projection lens pupil and flat-state light, which causes the contrast to decrease. As stated above, this tradeoff makes sense for vehicle window advertisement applications as the display is viewed at a distance.

Table 3-1 summarizes the optical performance of this DLP5532-Q1 and PTM-50X projector at f/1.8, showing that nearly 1,000 lumens are sent to the film. The projector optical efficiency is a measure of how much of the optical power from the LED is output from the projection lens to the first surface of the transparent window glass. The optical design of DMD-based projector is well-documented in the projector industry, and most display projector designs have similar transmission performance [5].

Table 3-1. Optical Performance of the Projector, With 1,000 Lumens Directed Towards the Film

Projector Configuration	Specification	Value
DMD: DLP5532-Q1 RGB LED: PTM-50X Projector aperture: f/1.8	Electrical Input Power to LEDs	75 W
	Optical Efficiency of Projector	24%
	Optical Output of Projector	1,000 lm
	Optical Efficacy	13.3 lm/ W
	Projector Contrast (FOFO)	600:1

3.1 Projector Design Challenges

With over 70 W of electrical power pumped into the LEDs, it's important to have a customized thermal solution to dissipate the heat in the LEDs and LED driver circuit board. Texas Instruments and TQ Technology have designed and built a projector capable of meeting the specifications listed in [Table 3-1](#). In order to manage the heat and provide robust performance across the automotive ambient temperature range, fans and heat sinks were added to this projector. As a result, the size of the projector is roughly 130 mm x 130 mm x 170 mm. [Figure 3-3](#) shows the high lumen DLP5532-Q1 projector.



Figure 3-3. Image of 1,000 Lumen DLP5532-Q1 Projector

Note that it is possible to optimize the size of the projector in any dimension depending on the mounting location and layout of the vehicle. Additionally, the height of this projector is mainly dictated by the projection lens (which is a function of the throw ratio) and the illumination orientation of the DMD. The DLP5532-Q1 DMD is a bottom-illuminated device, which means the illumination component must be perpendicular to the long edge of the DMD array. With different optical design architecture, it is possible to perhaps reduce the overall height. And in the future, side-illumination DMDs may be available, where the illumination can be rotated 90° relative to the DMD, which will reduce the height of the projector.

This design exercise has shown that a DLP projector can achieve high output optical power of nearly 1,000 lumens. Future optimizations to the projector may be able to increase the power and simultaneously optimize the thermal solution and therefore reduce the overall size.

3.2 Brightness Results

A PDLC film from Gauzy has been characterized when illuminated by 1,000 lumens DLP5532-Q1 projector using PTM-50X RGB LEDs. The size of the image can be adjusted to generate the appropriate brightness level, as screen brightness is inversely proportional to the area of the image size.

Table 3-2. PDLC Brightness Relationship With Image Size and Projector Lumens

Projector Luminous Flux	Screen Size (diagonal)	Screen Brightness
1,000 lm	12.2"	6,531 cd/m ²
1,000 lm	17.5"	3,132 cd/m ²
1,000 lm	35.0"	783 cd/m ²

While the display areas shown in [Table 3-2](#) are smaller than a cartop LED display, a 1,000-lumen projector nonetheless can support reasonably sized displays at high brightness levels supporting both daytime and nighttime viewing.

4 Conclusion

Location-based advertisement using vehicle window displays can provide incremental revenue streams to ride hailing and ride sharing companies. In order to maximize advertisement hours, daytime advertisement is desired requiring a high brightness display. Depending on display size and brightness targets, Gauzy's PDLC smart glass film technology combined with a high lumen automotive grade projector based on TI's DLP technology provides an alternative solution to cartop mounted LED displays.

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Note

A version of this paper was presented at the Vehicle Displays & Interfaces Conference in Detroit, Michigan on September 28th, 2021–September 29th, 2021. [Vehicle Display](#).

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