

Powering automotive displays to create interactive driving experiences



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Automotive displays are the primary conduits to present vehicle information to drivers and passengers. The number of vehicle displays is steadily increasing – by almost 65 percent between 2016 and 2021, according to Strategy Analytics – as is the quality of information displayed [1].

Technological advances in the personal electronics market are increasing consumer expectations for more interactive features and higher display aesthetics. Smartphone experiences will soon be seamless with automotive experiences.



Figure 1. The number of vehicle displays is expected to steadily increase by almost 65 percent in the next five years, including larger head unit screens in infotainment systems.

A functional display is no longer enough, as automakers try to differentiate themselves by meeting (and in many cases exceeding) consumer demand for aesthetically-pleasing interiors. At the other end of the spectrum, as vehicles become more autonomous, consumers spend less time driving and have more time for other activities. Thus, the infotainment functions of a vehicle will be even more important.

Studies have shown that consumers perceive beautiful objects as being more usable [2]. Automakers are enlisting designers and artists to

create more attractive environments, but mechanical and electrical engineers play a major role in these improvements as well. As technologies constantly change, it is advantageous for developers to understand the solutions available and how to apply them to automotive displays.

One factor affecting the human visual perception of displays is pixel density. Many consumers have probably experienced the evolution of dot-matrix printing to inkjet and then laser printing. When there are more dots in a given area, known as dot density, an image can appear smoother and more natural.

Similarly, those in the consumer display market are familiar with the transition from standard definition to high definition (HD) and then to ultra-HD (4K-UHD) for televisions.

We marvel at the improved picture quality and detail of the images and appreciate the realism and beauty of the objects. Accomplishing this effect requires consideration of both the viewing distance from the display and the pixel density. As the distance between the viewer and the display decreases, pixel density needs to increase in order to achieve the same viewing experience from a longer distance. This is one reason why the display on a smartphone has a higher pixel density than a computer display or television.

Inside a vehicle, a typical viewing distance of 70 cm (27.5 inches) will require a display with a pixel density of at least 300 pixels per inch (ppi) in order for occupants to see a quality image. For comparison, one of the most popular smartphones on the market has greater than 600 ppi for a typical viewing distance of 26 cm (10.2 inches). The need for larger and higher density displays is now leading to implementations of 1080p (2K) and 4K displays in vehicles.

Since displays can provide dynamic information and be interactive, they (along with simple lighting indicators and dials) are replacing traditional human-machine interfaces (HMIs) and mechanical gadgets such as buttons, sliders and wheels in vehicles. Plus, worldwide regulations for mandatory rearview cameras have helped accelerate the adoption of automotive displays in center stacks.

Multiple displays in the cluster, head unit and rear-seat entertainment systems – along with larger-size displays and higher pixel density – are presenting challenges for automotive infotainment and cluster developers, leading them to explore more efficient power supply solutions for displays.

Automotive display technologies

Liquid crystal display (LCD) panels are dependable and durable, and can support a wide range of screen sizes and resolutions, which understandably makes them the most widely used displays in automotive instrumentation, navigation and entertainment systems. There are two common LCD technology variants: passive matrix and active matrix using thin-film transistors (TFTs).

Passive matrix and segment displays are automotive displays that show a physically pre-defined row (or sections) of numbers, letters or graphics. Heating, ventilation and air conditioning (HVAC) or audio settings commonly use passive matrix displays.

Full-color, active matrix LCD (AMLCD) TFTs remain the incumbent technology for complex and dynamic graphical displays in automotive systems and will likely not change for the foreseeable future [3]. Most AMLCD panels use amorphous silica (a-Si) and are backed by a strong supply chain and almost 30 years of industry expertise.

Some panel manufacturers use low-temperature polysilicon (LTPS) technology to build LCD panels. LTPS panels provide better display quality by eliminating external components that can create signal connection issues, since the driver integrated circuit (IC) is mounted directly on the glass. Adoption of LTPS technology is expected to grow.

One key disadvantage of LCD displays is the need for an external light source such as a backlight. In the luxury vehicle segment, visual graphics have become the key differentiator for many automakers. Active matrix OLED (AMOLED) panels are lighter, sharper and support luxurious styling with their perfect hue of black without an external backlight. Plastic OLED (which uses plastic instead of a glass substrate) enables greater design freedom with curved or flexible displays, which work well in automotive environments.

Despite these advantages, the challenges of high-temperature reliability, long lifespan and low-cost requirements are limiting the number of automakers using OLEDs in the luxury market.

Key design requirements for automotive LCDs

Unlike other display applications, the automotive display market is highly customized and needs unique features to match a vehicle's brand value. Automotive displays typically need to support five years of vehicle production, in addition to supporting warranties and volume shipments for another few years. There are stringent test requirements for thermal operation, mechanical reliability (e.g., vibration and collision) and electromagnetic compatibility (EMC) (i.e., electromagnetic interference [EMI], electrostatic discharge [ESD] and load transients) in order to guarantee long-term reliability and safety.

The combination of limited space and functional safety concerns for vehicles creates unique design considerations for display system engineers. Let's take a moment to review some of the most challenging issues.

The essential features for automotive displays are:

- **High brightness.** It's critical that drivers can easily read displays in various ambient light conditions, ranging from broad daylight to complete darkness.
- **Wide viewing angles.** Center stack displays should be visible to both drivers and passengers, including those in the rear seat(s).
- **Wide temperature ranges.** Temperature ranges can typically span from -40°C to more than 105°C.
- **High image quality.** The migration of superior display technology from consumer electronics to the automotive market creates a need for

displays with high resolution, high contrast and high color-gamut characteristics.

- **Color depth.** Higher-resolution displays may need to upgrade from 18-bit red green blue (RGB) to 24-bit RGB to achieve a wider color gamut.
- **Long display lifetimes and sustained production support.** Displays must support design and production cycles of at least five years, extendable up to 10 years due to vehicle warranties. Ultimately, displays should last for the lifetime of the vehicle.

Additional features may include:

- **Quick response times and refresh rates.** Avoiding lags is critical for warning indicators and navigation functions like real-time maps and traffic updates.
- **Anti-glare and reduced reflection.** Displays must provide critical vehicle information to drivers without causing a distraction.
- **Low power consumption.** Low power consumption enables better fuel consumption and allows components to be placed in "hot spots." These are localized regions on the printed circuit board (PCB) that can be hotter due to uneven power dissipation across the board inside the cabin, either because they are placed in areas exposed to direct sunlight or are near other heat-producing systems.

Automotive display sizes and resolutions

Screen size and resolution are vital market drivers for in-vehicle displays. Automotive displays range from 1.5 inches to more than 12 inches. There is a growing trend toward larger display sizes (up to 20 inches), with the adoption of solid-state and digital clusters and the migration toward HD resolutions moving from wide video graphics array (VGA) (wide VGA [WVGA], 800 x 480) to 720p and 1080p.

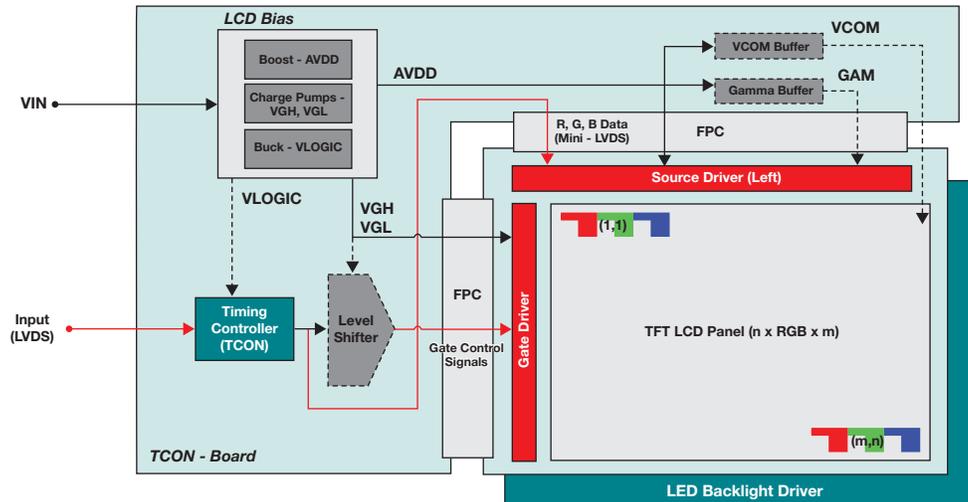


Figure 2. Block diagram of a TFT LCD subsystem.

In this paper, we will focus on displays larger than 6 inches.

As display sizes and resolutions increase, panel makers are moving away from a chip-on-glass solution toward an external PCB containing an LCD bias power-management IC (PMIC), gamma buffer, common voltage (VCOM) and/or a level shifter for better power efficiency. Large (free-form) displays formed by combining several “borderless” panels will require high-voltage level shifters to turn the embedded gate drivers on and off.

Understanding the key components of an automotive display

As shown in **Figure 2**, a typical TFT LCD module comprises a TFT panel, an LED backlight driver, a timing controller (TCON), source and gate drivers, an LCD bias supply, level shifters, VCOM, and gamma buffers.

TFT LCD panel

There are two different perspectives that can describe a TFT LCD: the cross-section perspective and the vertical perspective.

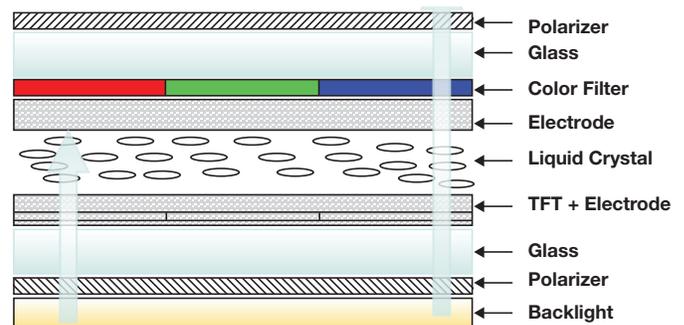


Figure 3. Cross-section of an LCD.

In the first perspective, the cross-section of the TFT LCD is a sandwich-like structure consisting of a polarizer, color filter, glass, liquid crystal and backlight. See **Figure 3**. Between the liquid crystal and glass are electrodes and thin-film-transistors (TFTs), usually made of indium-tin oxide (ITO). A drive signal applied to the cell electrode causes the liquid crystal to rotate. Depending on the orientation of the polarizer, the display is either a normally black display (no drive signal, opaque, like those used for televisions) or a normally white display (no drive signal, transparent, like those used for monitors).

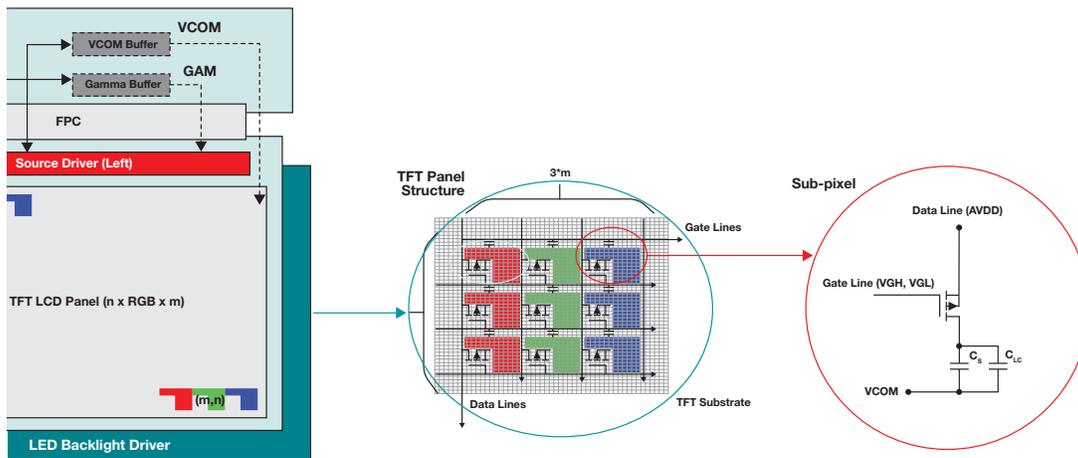


Figure 4. From panel to subpixel.

In the vertical perspective, looking at the panel with a magnifying glass reveals how the control circuit in a AMLCD can look like. The arrangement of the AMLCD addressing method enables it to address each pixel, or more precisely each subpixel. Three subpixels (one red, one green, and one blue) create one pixel, as shown in **Figure 4**. Another possibility that is known as passive matrix-driven LCD (PMLCD) is to address each pixel for more than one frame rate (1/fresh rate) such as 1/60 Hz.

Hereby the TFT, the switching element is not required. However this method is not more popular anymore as it has many disadvantages that correlate with the performance requirements for automotive displays.

The matrix contains columns (data lines) and rows (gate lines). The equivalent circuit of each subpixel is shown in the red circle in **Figure 4**, which consists of the liquid crystal, electrically seen as a capacitor in parallel to a storage capacitor, and in series to the transistor (the TFT) connected to the matrix. On top of it is the color filter.

As an example, an HD resolution of 1,920 x 720 pixels results in 1,920 pixels x three columns x 720 rows for a total of 4.14 million subpixels, and thus the same amount of TFTs.

When the TCON addresses a subpixel, a positive voltage (also called VGH) is applied on the corresponding gate and turns on the TFT. The

picture information is then put through in form of charging the capacitors ($C_{LC} + C_S$) up to the voltage of the data line (a fraction of AVDD). An additional storage capacitor in parallel to C_{LC} acts as a buffer and reduces the effect of C_{LC} leakage. The charge is kept for a frame period (normally 1/(60 Hz)). By applying a negative voltage on the gate line (also called VGL), the TFT will turn off again.

The mechanism to address all pixels within one frame period is done line by line, as illustrated in **Figure 5**.

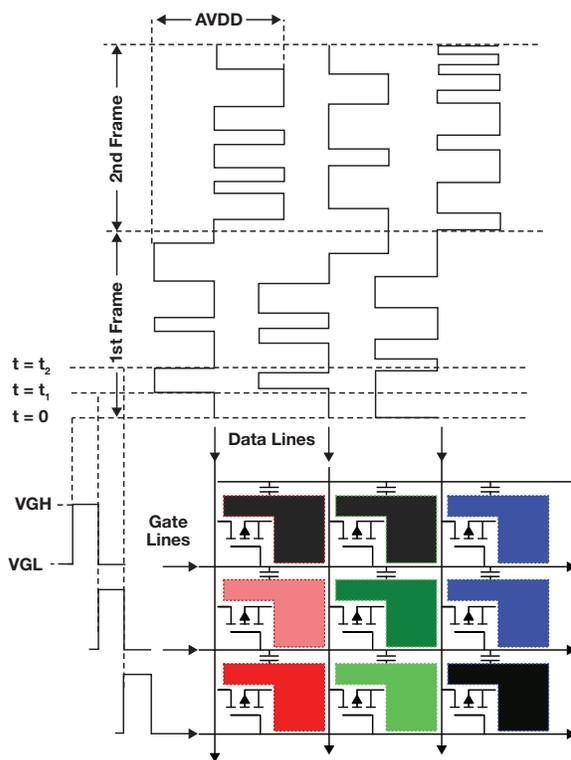


Figure 5. AMLCD addressing method.

TCON

The TCON is the logic part of the system, supplying control and image information to the source and the gate drivers. The picture information comes from the processor, which is interfaced either through flat panel display FPD-Link™, Embedded Display Port (eDP), High-Definition Multimedia Interface (HDMI), VGA or other type of video input port on the TCON board. For a low-resolution display, the link between the TCON and the source driver is typically in single-ended transistor-transistor logic (TTL) / complementary metal-oxide-semiconductor (CMOS) signaling, switching between 0 V and 3.3 V. Higher-resolution displays require higher switching frequencies, which can cause EMI. To reduce power consumption and noise, and to improve signal integrity, today's commonly used electrical signal interface standards are low-voltage differential signaling (LVDS), reduced swing differential signaling (RSDS) and current-mode logic (CML) FPD-Link II/III.

LCD bias

The location of the LCD bias supply depends on the panel technology. Chip-on-glass panels integrate the drivers for the LCD supply voltages directly on the glass. Such panels are typically used in small-size displays less than 6 inches. For LCD panels greater than 6 inches and those with higher resolutions, the LCD bias is located on an external PCB.

Another point to remember is the input voltage of the LCD bias supply. Typically, the input voltage ranges from 3.3 V for smaller displays and up to 12 V for larger screens like those for televisions. For automotive displays, the typical supply voltage is 5 V in order to ensure a reliable and robust lifetime for the supply rails, which is especially important for automotive panels. Protection features such as overvoltage detection, short-circuit (overcurrent) protection, adjustable fault detection (output voltage fault detection dependent on fault delay time)

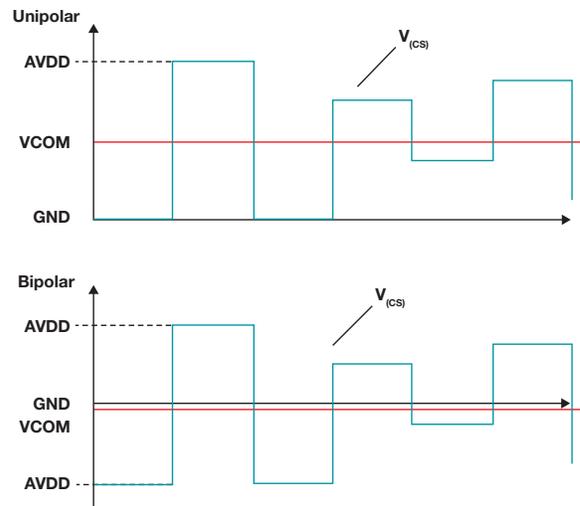


Figure 6. AVDD bipolar/unipolar.

and thermal shutdown are typically integrated into an LCD bias supply. The next lines will handle each rail that a typical LCD Bias Supply IC integrates. These are the source driving voltage ($AVDD$), the gate driving voltages (V_{GH} and V_{GL}), a logic voltage (V_{LOGIC}), the common backplane voltage (V_{COM}) and so on.

Source-driving voltage (AVDD)

$AVDD$ supplied by a boost converter is the maximum driving voltage across the liquid crystal, and typically also supplies the common voltage for the backplane V_{COM} (described three sections below). The $AVDD$ voltage is directly connected to the information representing the picture and therefore has very strict electrical requirements. Some of the criteria for $AVDD$ includes low voltage ripple, high immunity to line and load transients, and enough current capability to supply the source driver. Electrical disturbances need to be minimized or else the DC component on the liquid crystal will cause flickering.

There are two different ways to configure the source-driving voltage on the panel: bipolar or unipolar, as shown in **Figure 6**.

On panels with a bipolar $AVDD$ structure, V_{COM} is below ground to compensate for the parasitic

capacitances. On panels with a unipolar AVDD structure, VCOM needs to be adjusted to almost half of AVDD. The selection of source-driving voltage depends on the source-driver IC.

Gate-driving voltages (VGH and VGL)

VGH and VGL are the control voltages for the TFTs. These rails only control the time a pixel is turned on or off; therefore, the electrical performance is not as important as it is for the AVDD rail. In most applications, charge pumps generate these rails in different configurations.

One characteristic that plays a role and affects the performance of the display is that TFTs become inert in cold conditions. Low temperature slows down the turn-on and turn-off time of the transistors and thereby reduces data throughput. To compensate this effect some LCD Bias ICs integrate a temperature compensation function.

VLOGIC

VLOGIC is the supply rail for the TCON and is sometimes provided by the LCD bias supply. A buck converter or low-dropout regulator (LDO) generates the 3.3 V required by the TCON from the 5 V input voltage.

VCOM

Image sticking or image retention is the faint outline or “ghosting” of an image that remains on the screen even after the picture content changes. The bottom

of every subpixel needs to be referenced to VCOM in order to enable polarity inversion, therefore avoiding image sticking. A buffer provides this VCOM. It requires adjustment during the transition of the source-driving voltage (AVDD).

Image sticking is caused by the parasitic capacitance of the TFT sitting between the gate and the drain of the TFT, also called the Miller capacitance (C_{GD}). At the moment when the TFT turns off, C_{GD} and $C_{LC}||C_S$ are a capacitive voltage divider that leads to a voltage drop on the inductor capacitor (LC). The steeper the falling edge, the higher the residual DC component on the LC, which is perceived as image sticking. Thus, VCOM must compensate for this voltage drop and adjust the voltage to the center of the pixel voltage at the transition time, shown by the red line in **Figure 7**.

One method to prevent image sticking is to use gate voltage shaping (GVS), sometimes also called gate pulse modulation (GPM), which grinds the falling edge of the turn-off signal.

Another degrading effect on display performance is horizontal crosstalk, in which adjacent pixels falsely display the same grayscale. One reason for this may be the limited driving (peak) current capability of the VCOM buffer during the transition from on to off. If the driving current is limited, VCOM cannot regulate in time to achieve the nominal value before the next cycle.

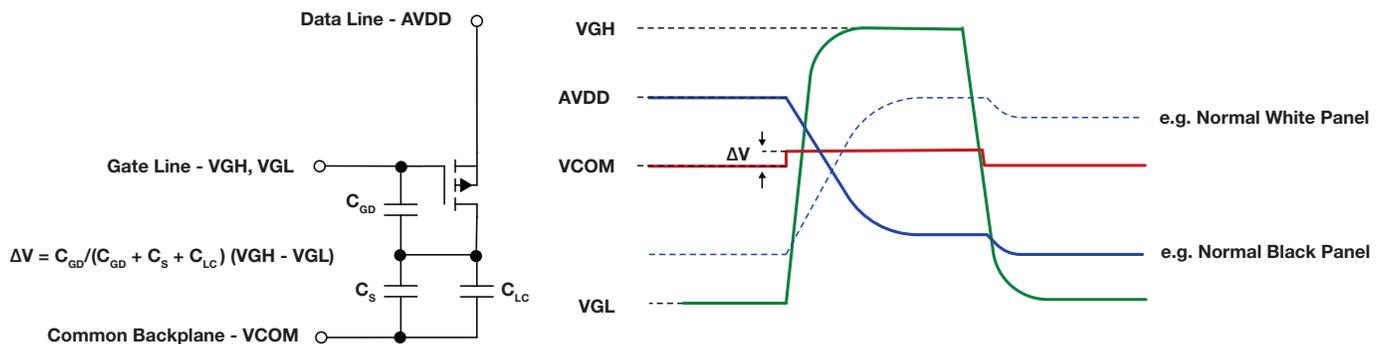


Figure 7. VCOM adjustment.

The key parameters for a VCOM buffer are output current capability, bandwidth and slew rate. VCOM must be adjusted for every panel during manufacturing, as the parasitic capacitances we've described above vary from panel to panel.

Level shifter

The level shifter transfers the gate signal with logic input/output (I/O) voltages coming from the TCON up to the levels to drive the on-glass transistors, VGH and VGL. VGH corresponds to a high signal and VGL to a low signal of the TCON logic outputs. The level shifter is basically an output buffer. GVS or charge sharing (CS) – a technique that reduces power consumption by recycling charge from one level shifter output channel to another – requires a higher amount of output and a higher level shifter logic density.

In most applications, the TCON provides a defined number of clock and control signals to the level shifter which generates as many output channels.

As we discussed earlier, displays are moving toward borderless or free-form panels. When combining multiple panels into one large display, it is essential to make this happen without borders or bezels. Gate-on-array (GOA) panels can offer slim bezels, as the gate driver is attached not next to the panel but in it (on the array). Such architectures require a level shifter on the TCON PCB. This level shifter can be integrated in the PMIC or be a stand-alone IC.

VGAM

The gamma correction voltage (VGAM) is the reference voltage for the source-driver digital-to-analog converters (DACs). Gamma correction is required to compensate for the encoding of images, due to the human eye's nonlinear perception of light. The source driver defines the number of different voltage steps that can be applied to the pixel. As an example, an 8-bit DAC responds to 256 steps of possible grayscale. The gamma will be corrected

by adjusting the voltage step relative to the gamma response (V/T curve) of the panel.

The gamma buffer can be integrated in the PMIC or be a stand-alone IC. The latter option enables dynamic calibration in the production line after the display is already mounted in the car. Production-line calibration also helps automakers ensure that they have highly accurate color matching between the display and dashboard to overcome manufacturing process variations.

Integration considerations

For the electrical requirements of an LCD, the industry offers solutions with many different levels of integration. Some solutions integrate bipolar or unipolar AVDD, VGH/VGL and VCOM, as well as an integrated LDO to supply VLOGIC.

Depending on the integration needs of the automotive display system, you can choose an all-integrated LCD bias solution or stand-alone ICs for LCD bias/level shifters/gamma/VCOM. For more information, see [TI's automotive display bias solutions](#).

Source driver

The source driver, also called a column driver or data driver, converts data from the TCON into the required voltage for the source of each TFT. The digital section applied by mini-LVDS (or TTL, RSDS) contains a shift register and a sample-and-hold register. The analog section, which converts the information to the corresponding voltage of the data line, consists of a DAC, multiplexer, output buffer, and sometimes a level shifter for large-size panels.

Some of the key parameters of a source driver are number of channels, operating voltage, gamma reference voltage, grayscale (8-bit, 10-bit), inversion method (frame, row, column, dot), output voltage, interface standard (mini-LVDS, TTL, RSDS) and package (TCP, chip-on-glass, chip-on-film [COF]).

Gate driver

The gate driver, also called a row driver or scan driver, converts the control signals from the TCON into the required voltage for the gate of each TFT. It contains a shift register, level shifter and output buffers. A start pulse (called STV) selects one data line of one source driver at a time. When the STV reaches the end of the gate driver, it will be transferred to the next gate driver, where it functions as a start pulse again.

Some of the key parameters of a gate driver are number of channels, operating voltage, two- or three-level driving, and package (TCP, chip-on-glass, COF).

What developers need to know about LED backlight drivers

Because it defines the user's experience, a critical part of any display is how visible the image is. For LCDs, an external light source is necessary in order to illuminate the image formed by the liquid crystals. This is typically implemented with LEDs located behind or on the edges of the LCD panel with a light guide. Human image perception factor is governed by the quality of the backlight driver – a feature-specified, performance-enhanced and cost-optimized device that drives the LEDs in a multitude of configurations, with the goal of providing a seamless viewing experience.

Automotive display backlighting methods

There are several ways to produce backlight. Most displays are edge-lit, which means that LEDs are placed along the edge of the panel with a diffuser film (or light guide) that enables an almost-even distribution of light across the panel. There are usually multiple strings of LEDs interlaced to get an even dispersion of light.

Another method of backlighting displays is the direct-lit backlight approach. In this implementation, LEDs are placed directly behind the glass. They can either be controlled globally or partitioned into smaller zones and controlled independently.

Let's cover the key considerations when picking an automotive backlight driver.

Power converter topology

In an automotive application, the primary source of power is the battery, with a typical steady state voltage of 13.5 V. Considering transients, the battery voltage can vary from as low as 4 V to higher than 40 V. The number of LEDs used to backlight the display will determine the output voltage that the driver needs. The ratio of input-to-output voltage will govern whether the driver will be used in a buck, boost or buck-boost/single-ended primary-inductor converter (SEPIC) topology. An LED backlight driver's DC/DC converter is not required to regulate a constant LED voltage over every battery transient condition. However, maintaining a constant LED current is required to maintain constant display brightness.

LED brightness control methods

There are different ways to control LED brightness. A pure analog approach involves linearly changing the current through the LEDs, as shown in **Figure 8**.

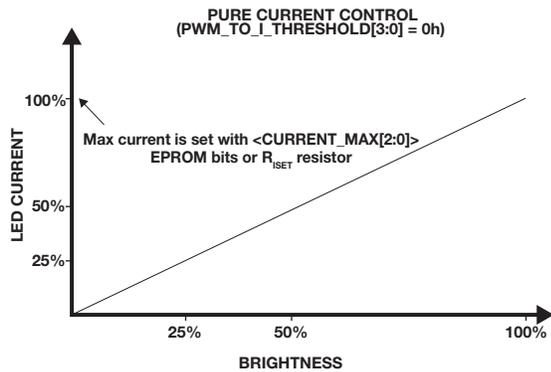


Figure 8. Analog current brightness control.

While current control is simple to manage and quite efficient from a power-delivery perspective, it does not provide the best resolution. At low brightness levels, it is difficult to provide very small values of current consistently. When current-controlled, the linearity of LEDs limits the minimum brightness. Plus, when controlled linearly, LEDs undergo a color temperature shift. These are highly undesirable factors of linear brightness control.

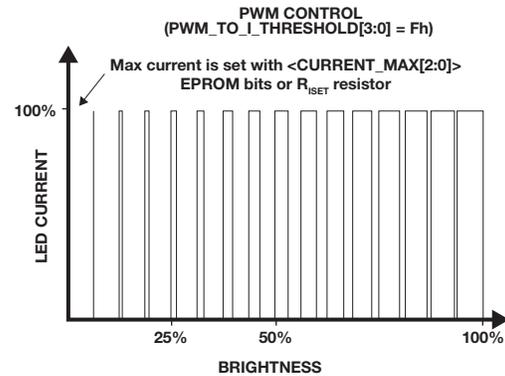


Figure 9. PWM brightness control.

Another common method of brightness control is pure digital pulse-width modulation (PWM), as shown in **Figure 9**. PWM control enables very low minimum brightness levels (well below 1 percent) to 100 percent. Since the current delivered to the LEDs is constant, even at low brightness, there is no shift in color temperature. However, due to its very nature, PWM signals suffer losses at high duty cycles. In the context of an LED driver, high brightness levels, which would have the highest use case, would be very power-inefficient and generate a lot of EMI noise.

A great combination of analog and PWM brightness control, called hybrid dimming, is found on several backlight drivers, like the [LP8860-Q1](#) and [LP8863-Q1](#) from Texas Instruments. Hybrid dimming combines the best benefits of both analog and PWM dimming. When enabled, incoming brightness is converted to a PWM signal, while the overall current is low. This helps avoid any color shifting and keeps noise level low and efficiency high. Upon reaching a certain threshold of brightness, the device transitions to current dimming, which is efficient and easy to manage.

Dimming ratio and dimming resolution

Dimming ratio is defined as the ratio of maximum brightness to minimum brightness. Typically, the limiting factors for the dimming ratio are the LED driver rise time and LED PWM period, as shown in **Figure 10**. Accordingly, before measuring brightness levels, a rule of thumb for estimating the dimming ratio is $T_{p_LEDPWM}/T_{r_LEDRISE}$. For example, with a 200 Hz PWM signal (5 ms) and a 200 ns rise time, the dimming ratio is 10,000-to-1.

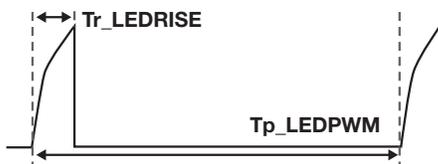


Figure 10. Dimming ratio is the ratio of maximum brightness to minimum brightness.

Dimming resolution is the number of brightness steps between 100 percent and 0 percent, as shown in **Figure 11**. For direct-PWM devices, the dimming resolution is limited by the host's ability to finely step the input PWM duty cycle. For sampled-PWM devices, the dimming resolution is limited by input PWM sampling or output PWM generation. For Inter-Integrated Circuit (I²C)- and Serial Peripheral Interface (SPI)-controlled applications, the dimming resolution is limited by the brightness register's bit width (typically 16 bits, or 65,535 steps).

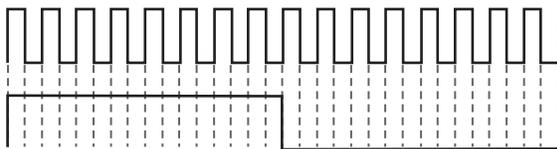


Figure 11. Dimming resolution is the number of brightness steps between 100 percent and 0 percent.

Automotive-friendly noise performance

A very important factor to consider for any power converter in an automotive design is its conducted, radiated and audible noise profiles. Such noise can lead to undesirable systemic effects. However, a well-defined driver and circuit can help reduce these effects. Let's review some features that allow for better operation.

A switching regulator creates both conducted and radiated noise as the gate-driver signal transitions. Slowly shifting the frequency at which the gate driver operates reduces the noise emitted at a given fixed frequency. This method of "spreading" the noise is called spread-spectrum operation. While the overall noise may remain equivalent, the peak levels are subdued, making for better EMI performance.

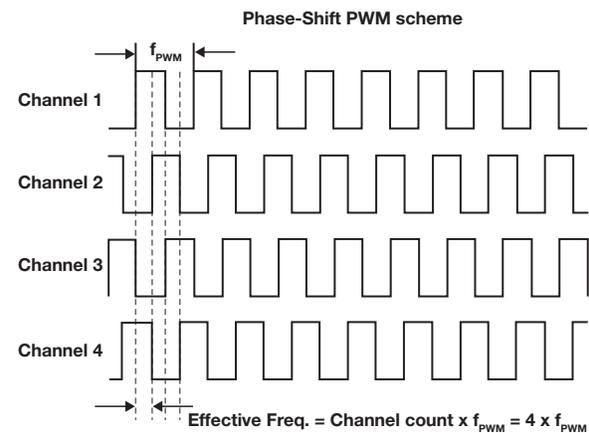


Figure 12. Phase-shifted PWM outputs.

Another major contributor of automotive noise is the synchronized switching of the PWM output from the current sinks. The solution is to offset the phase of the LED drivers so that the total phase shift is 360° (shift per phase = 360/number of channels), as shown in **Figure 12**.

Integrating this phase shift has a few benefits. It helps reduce the ripple magnitude of the boost output and increases the frequency of the boost ripple, which in turn also helps reduce the audible noise. Another major benefit is that phase-shifting the outputs significantly reduces the optical ripple in the LCD. This avoids the waterfall effect – an undesirable artifact caused by small differences between the refresh rate of a display, and the PWM frequency of its backlight driver. It often manifests as scrolling bright and dark bands over the image.

As you can imagine, there are many other salient requirements and features for selecting backlight drivers, many of which are application-specific. For more information, see ti.com/backlight.

Conclusion

Displays in a vehicle are becoming the key HMI for audio and media systems, HVAC controls, telematics, navigation – even social media networking. Consumers value functionality and features just as much as style and elegance. Designers must understand the primary market and technology trends in automotive displays and how they translate into design considerations for the basic building blocks of a typical automotive LCD display subsystem. This will determine the design and selection of critical power-supply components and auxiliary blocks.

TI offers highly integrated semiconductor solutions to drive automotive display panels (display bias PMIC with level shifter), power backlight (LED backlight drivers), and standalone gamma/VCOM ICs to improve image quality and enable real-time calibration for better styling. TI can power LCD display panels efficiently, whether they're using a-Si or LTPS technologies.

With over 35 years of automotive experience, continuous innovation in process and packaging technology, and a strong focus on quality, reliability and safety through our SafeTI™ initiative, TI offers a broad portfolio of more than 2,000 automotive-qualified analog, embedded processing and DLP® display products, along with more than 100 reference designs in the TI Designs library. For more information, see ti.com/infotainment.

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