

Electronics and LED Driver Reference Design for Augmented Reality Head-up Displays



Description

This reference design provides an electronics subsystem designed to drive an automotive augmented reality (AR) head-up display (HUD). TI DLP® technology enables bright, crisp, highly saturated HUDs that project critical driving information onto the windshield of the car, reducing driver distraction and increasing situational awareness. This design uses the DLP3030-Q1 chipset, which includes the DLP3030-Q1 0.3" DMD, the DLPC120-Q1 Automotive DMD controller, and the Piccolo™ TMS320F28023/F280023 microcontroller operating as an LED driver and illumination controller. This design enables a high brightness, wide field of view (FOV), AR display with low-power consumption.

Resources

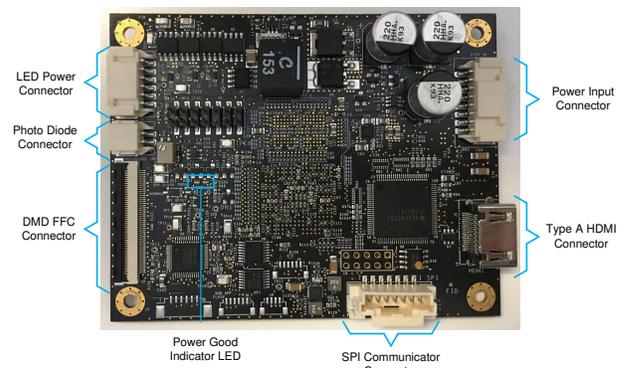
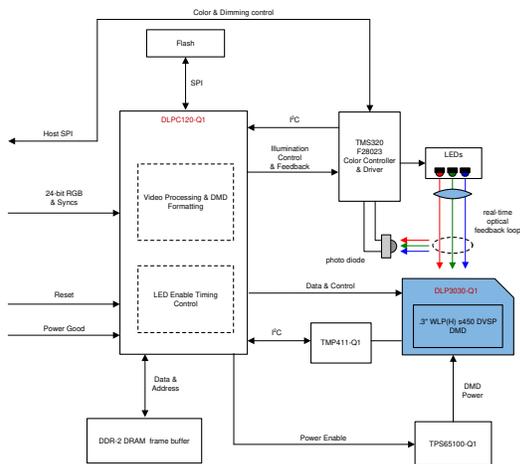
TIDA-080004	Design Folder
DLP3030-Q1	Product Folder
DLPC120-Q1	Product Folder
TMS320F28023	Product Folder
TMS320F280023	Product Folder

Features

- When paired with an optical system, this reference design can output up to 90 lumens with 7.1-W input power
- Over 5000:1 dimming ratio
- –40°C to 105°C operation
- Compact PCB layout
- 12-V input
- 3.3-A LED drive output
- Greater than 80-pixels-per-degree (ppd) HUD resolution at 10° FOV
- Reduced system cost
- Windows GUI for easy development

Applications

- Augmented Reality Head-Up Display
- Automotive Transparent Window Display



1 System Description

The design files included in this reference design are for the electronics portion of a HUD system. These include the DLP3030-Q1 based DMD PCB design and the DLPC120-Q1 based controller PCB design. Information for these electronics and designs can be found starting with [Section 3](#). However, it is useful to first describe parameters of a full HUD system as well as the tradeoffs associated. These system-level parameters determine the requirements for the PGU and electronics, so must be considered first, beginning in [Section 2.4](#).

The electronics included are designed to pair with [Osram CSL LEDs](#). The CSL LEDs have better etendue matching with the DLP3030-Q1 DMD than the previous Q8WP based design resulting in a much more efficient design. The use of CSL LEDs enable a smaller, lower cost picture generation unit (PGU) design by minimizing the size and cost of the LEDs, optical elements, heatsinks, and mechanical housing of the PGU. See [Section 2.4.2](#) for more information on LED selection.

1.1 Key System Specifications

Table 1-1. Key System Specifications

PARAMETER	SPECIFICATIONS
Input power source	12-V DC nominal, 6-V min to 18-V max
Power consumption	Power consumption depends on selected output brightness. Depending on DMD sequence, duty cycle, and other system parameters, power consumption for this chipset + LEDs is between 2 W to 7 W. For max brightness of 90 lumens, this system only consumes ~7.1 W of power.
Output	Red, Green, Blue LED drive
Temperature rating	The DLP3030-Q1 has an automotive temperature rating of –40°C to 105°C
Image resolution	864 × 480
Video input format	HDMI input deserialized into 24-bit parallel RGB
SPI interface bitrate	100 kHz
Dimming range supported	> 5000:1
Contrast	> 1500:1

2 System Overview

2.1 Block Diagrams

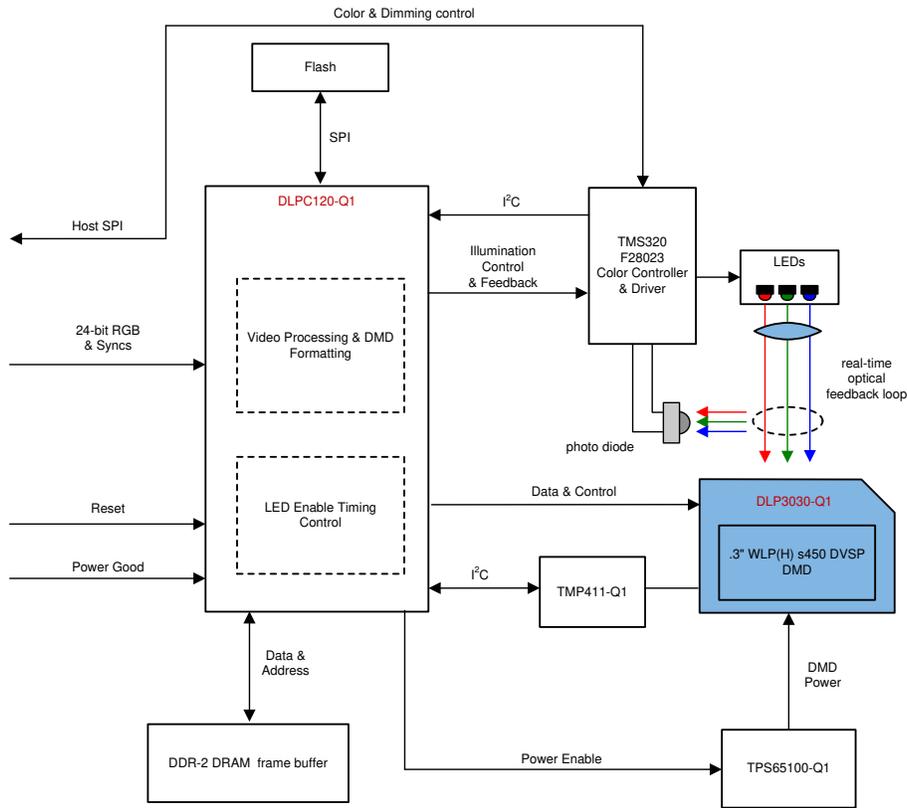


Figure 2-1. TIDA-080004 Block Diagram

Note

The [TMS320F280023](#) MCU is recommended for new designs. This product is from the latest generation of C2000™ real-time MCUs with enhanced features and performance at a lower cost structure.

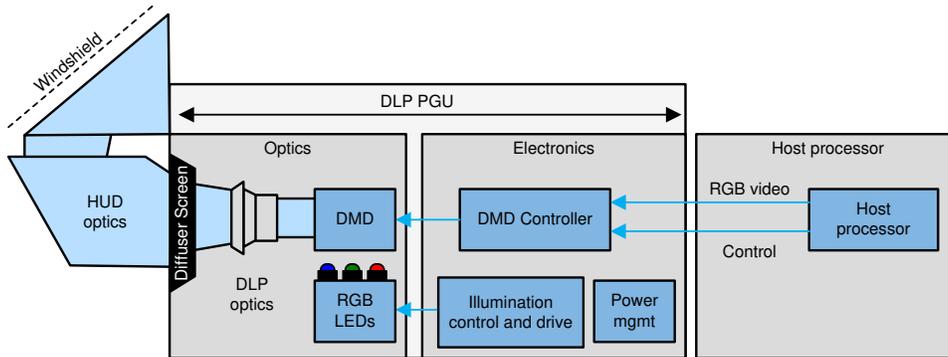


Figure 2-2. Head-up Display System Block Diagram

2.2 Design Considerations

Figure 2-1 shows the block diagram for the electronics for a HUD system. These are the electronics included in this reference design. While this reference design is primarily intended for use in a HUD system, it can also be used for any automotive transparent window display, such as a windshield cluster, a side window display, or a rear window display. Figure 2-2 shows a simple block diagram for a full HUD system. To use this reference design to design an entire HUD system, a host processor, LEDs, PGU optics, and HUD mirror optics will also be needed.

2.3 Highlighted Products

2.3.1 DLP3030-Q1

The DLP3030-Q1 Automotive DMD is primarily targeted for automotive HUD applications with very large FOV or AR capability requiring long focal distances. This chipset can be coupled with LEDs or lasers to create deep saturated colors with over 125% NTSC color gamut with support for 24-bit RGB video input. In addition, the chipset enables high brightness (15,000-cd/m² typical) HUD systems with wide dimming range, and fast switching speeds that do not vary with temperature. As used in the TI reference design, very high dimming range over 5000:1 can be achieved to meet the operating range of an automotive HUD system for bright daylight and dark night time driving conditions.

2.3.2 DLPC120-Q1

The DLPC120-Q1 DMD Display Controller for automotive applications is part of a chipset, compatible with one of two DMDs (i.e. DLP3000-Q1 or DLP3030-Q1). The core DLPC120-Q1 logic is responsible for accepting video input and formatting the data to display on the DMD while simultaneously controlling RGB LEDs in order to create a real-time image. The DLPC120-Q1 is also responsible for controlling the power-up and power-down events of the DMD, based on external system control or temperature input from the DMD. Combined with an external dimming circuit and microcontroller, the DLPC120-Q1 supports a wide dimming range > 5000:1 for HUD applications. Typically, the DLPC120-Q1 is a slave device in an I²C interface with a host processor.

2.3.3 TMS320F28023

The Piccolo F2802x family of microcontrollers provides the power of the C28x core coupled with highly integrated control peripherals in low pin-count devices. This family is code-compatible with previous C28x based code, and also provides a high level of analog integration. The internal comparators and high resolution PWM signals are both utilized to implement a very high speed LED driver. This microcontroller, when combined with the DLP3030-Q1 chipset, can support 1- μ s long LED pulses and 10-ns rise and fall times required by the 5000:1 dimming ratio.

Note

The [TMS320F280023](#) MCU is recommended for new designs. This product is from the latest generation of C2000™ real-time MCUs with enhanced features and performance at a lower cost structure. Refer to the [TMS320F2802x/TMS320F2803x to TMS320F28002x Migration Overview](#) application report for a list of differences between the two devices.

2.4 System Design Theory

This section describes the tradeoffs and design choices required for a HUD design. It is intended to give more background and understanding in the overall system for future application modifications.

AR HUDs require larger FOV, longer virtual image distances (VID), and larger eyebox sizes than traditional automotive HUDs. These large displays require much brighter PGUs. This reference design provides the hardware and software needed for a HUD design. Presented first is a high level discussion of design decisions. As an example, parameters in the following sections are chosen to meet the requirements of a HUD system:

- FOV: 10° × 5°
- Eyebox: 140 mm × 60 mm
- VID: 10 m
- Contrast: 1500:1
- Resolution: > 80 ppd
- Temperature rating: -40°C to 105°C

2.4.1 Head-up Display Parameter Design and Tradeoffs

2.4.1.1 Field of View and Eyebox

An AR HUD system has many design parameters. While all system parameters are important, there are two system parameters that are most responsible for determining PGU requirements in a HUD system: FOV and eyebox size. The following sections describe the high level tradeoffs associated with HUD FOV and eyebox size.

FOV in a HUD system is the solid angle of the displayed image, measured from the center of the eyebox. Typical FOV ranges from $4^\circ \times 2^\circ$ in a small, conventional HUD up to greater than $12^\circ \times 6^\circ$ in a large AR HUD. A larger FOV increases the size of the image seen by the driver. To achieve a larger eyebox, the HUD design must use a PGU with a higher luminous output to maintain the same brightness image. The DLP3030-Q1, combined with an LED based optical system, can output up to 90 lumens at room temperature and over 60 lumens across the entire automotive qualified operating temperature range (-40°C to 105°C).

Eyebox is the area at the viewing plane where the displayed image is visible to the driver. Typical eyebox sizes range from $100\text{ mm} \times 60\text{ mm}$ to much larger $140\text{ mm} \times 140\text{ mm}$. A larger eyebox allows the driver to move their head further from center and use different seat positions while maintaining visibility of the displayed image. A large vertical eyebox also allows drivers of different heights to accurately see the image without adjusting any internal HUD components like mirrors. Because a larger eyebox spreads the image light out more than a smaller eyebox, larger eyeboxes require a higher lumen PGU to achieve the same brightness image.

Figure 2-3 provides an estimated PGU brightness requirement to achieve 15,000 nits (cd/m^2) for given eyebox and FOV specifications. For an eyebox size of $140\text{ mm} \times 60\text{ mm}$ with a $10^\circ \times 5^\circ$ FOV, approximately 55 lumens are required from the PGU.

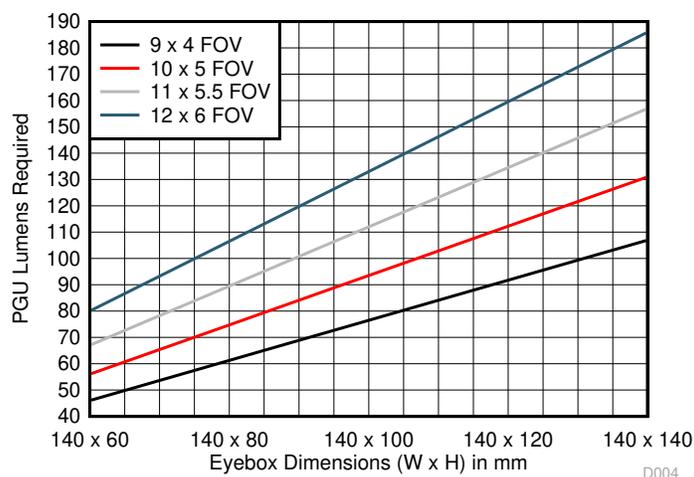


Figure 2-3. PGU Lumens vs Eyebox Dimensions and Field of View

2.4.1.2 Resolution

FOV also determines image resolution for a given DMD array size. Resolution of a HUD is typically measured in ppd. A person with 20/20 vision cannot notice resolution improvements in images above 60 ppd. The DLP3030-Q1 has a horizontal resolution of 864 pixels, which allows for a 14° wide FOV while maintaining a 60-ppd resolution. It is often useful to design for a slightly higher resolution display to allow for some image warping or other correction factors. For a 10° horizontal FOV, the DLP3030-Q1 provides 86-ppd resolution.

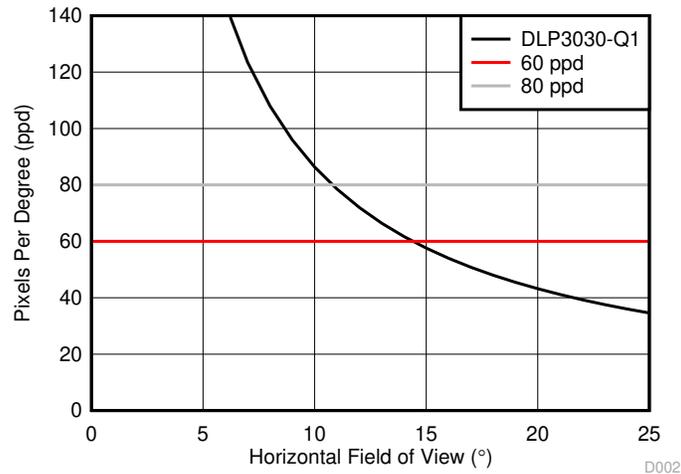


Figure 2-4. Resolution vs Field of View

2.4.1.3 Virtual Image Distance

VID is a very important system design parameter. It does not have a large effect on required brightness, but it drastically changes the solar loading of the imager. AR HUDs perform well with longer virtual image distances, 7.5 m and above. This allows the displayed image to conformally overlay information on the road and cars in front of the driver for a seamless image. These long virtual image distances collect and focus more sunlight back into the HUD system. This solar load can cause problems with absorptive display devices such as TFT panels, increasing the temperature beyond rated conditions. A DLP3030-Q1 based projection system uses a transmissive diffuser screen to create the displayed image. Sunlight collected and incident on this screen is both transmitted and dispersed, minimizing temperature rises of the screen and reducing light concentration on the optics behind the screen. This enables a DLP3030-Q1 based HUD design to support a VID > 15 m.

For more information on the effects of solar load and virtual image distance, please see [DLP® Technology: Solar loading in augmented reality head-up display systems](#) white paper.

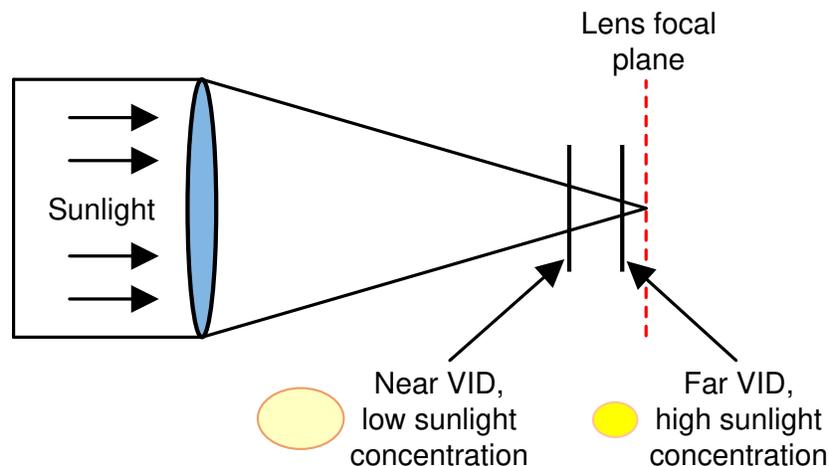


Figure 2-5. Increased Sunlight Concentration With a Longer Virtual Image Distance

The brightness, resolution, and long virtual image distances enabled by the DLP3030-Q1 DMD and chipset allows for HUD systems with bright images, large eyeboxes, and sharp displays.

2.4.2 Picture Generation Unit Design Decisions

After the number of required lumens has been determined from HUD eyebox and FOV parameters, as discussed in [Section 2.4.1](#), details about the PGU design can be considered. Two key factors that influence PGU lumens output are the LED part selection and the optical aperture $f/\#$ in the illumination path and projection lens.

For a DLP technology based PGU, high brightness projection LEDs are often required. While larger LEDs will output more lumens, it does not necessarily mean they are the best choice at a system level. It is important to choose the best LEDs for every application. The key considerations for LED choice include:

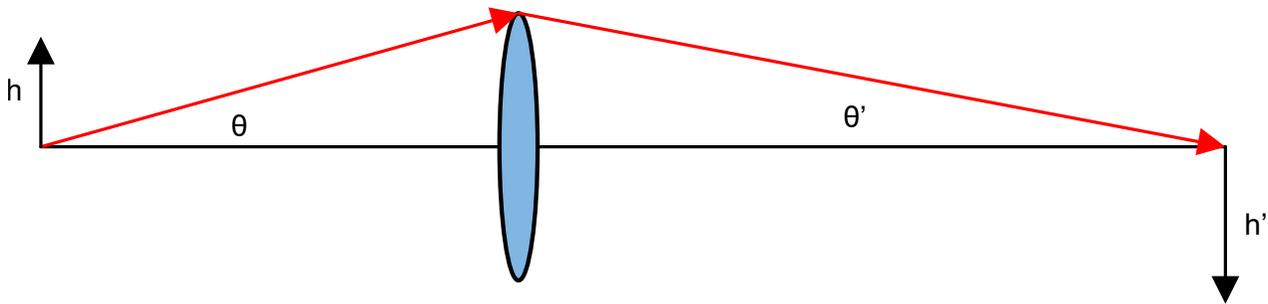
- Etendue efficiency match
- f/# tradeoff on brightness and contrast
- Thermal solution

2.4.2.1 Etendue Efficiency Match

The main way to increase lumens out of an LED is to increase the emission area. However, more lumens out of the LED do not necessarily produce more lumens out of a PGU. Due to the optical property of *Etendue*, there is a limit to how much of the emitting area matches to the collection angle of the DMD illumination path. As the LED die size increases, there is a point of diminishing returns where the luminous output of the LED cannot be captured (and reflected) by the DMD.

Etendue is defined by optical surfaces' area and emission/collection angle. When calculating the etendue match between two optical components, the *Abbe Sine Invariant* equation can be used.

$$h \times \sin(\theta) = h' \times \sin(\theta') \tag{1}$$



With the DLP3030-Q1 DMD, the area is fixed ($6.6 \times 3.7 \text{ mm}^2$), and the illumination angle is also fixed at a 12° tilt. Any incoming light that cannot be captured on this array area at a 12° cone is lost. (To optimize the optical design and take advantage 12° tilt, $f/2.4$ is typically used, however the $f/\#$ can be varied to optimize brightness and contrast. $f/2.4$ is assumed for the following calculations.) For more information, see [Section 2.4.2.2](#)

Analogous to the 12° illumination angle of a DMD, LEDs and their collimating lenses have a collection angle. In a traditional LED-illuminated DLP system, this collection angle is roughly 80° . With a fixed angle, the only remaining variable in [Equation 1](#) is the LED emission area. Refer to [Equation 2](#) and [Equation 3](#) for a calculation of the ideal LED array size.

$$h_{\text{LED}} \times \sin(80^\circ) = 3.699 \times \sin(12^\circ) \tag{2}$$

$$w_{\text{LED}} \times \sin(80^\circ) = 6.572 \times \sin(12^\circ) \tag{3}$$

[Equation 2](#) and [Equation 3](#) show that the best etendue match for the DLP3030 DMD is an LED with $w = 1.38 \text{ mm}$ and $h = 0.785 \text{ mm}$. Any device which is larger in either dimension will be over-sized and result in unused light.

In a system in which power efficiency is optimized, an LED is selected which is either a perfect etendue match or under-sized. This assures that all of the light which is captured by the collection lenses of the LEDs is within the illumination cone of the DMD and reflected into the projection path. An oversized LED wastes light, resulting in inefficiencies and adding unused power.

The two most popular LED parts for the 0.3" DLP3030-Q1 in a RGB display application are from Osram: [Q8WP](#) and [CSL series](#). From their data sheet, here are the dimensions of each part's array:

Table 2-1. LED Array Dimensions

	Width (mm)	Height (mm)
Q8WP	1.5	1.2

Table 2-1. LED Array Dimensions (continued)

	Width (mm)	Height (mm)
CSL	1	1

An *Etendue Diagram* can be used to visually show the match of each LED with a set DMD. In the diagram below, the etendue size of the DLP3030-Q1 DMD, Q8WP LED, and CSL LED is shown. The dimensions were calculated using the Abbe Sine Invariant equation.

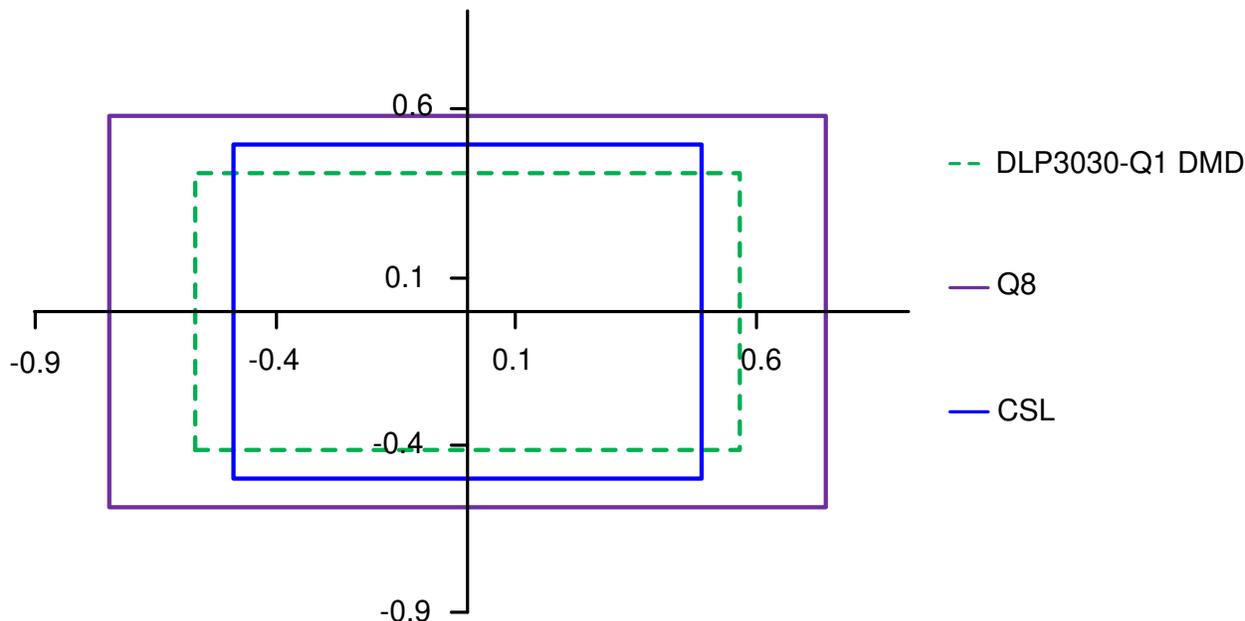


Figure 2-7. Etendue Diagram of 0.3" DMD With Different LEDs at f/2.4 Aperture

Figure 2-7 shows that while the Q8WP and CSL LEDs both have unused light outside the DMD, the CSL LED is much more efficient, with 85% etendue efficiency compared to the Q8WP's 65% efficiency. In order to increase this efficiency, the optics design can open up the aperture, or use a smaller *f*/#. The advantages and tradeoffs of changing the aperture are discussed in Section 2.4.2.2.

2.4.2.2 Aperture Size: Selecting *f*/# of Optics

The *f*/# of an optical system refers to the size of the aperture. For a DLP projector, there are apertures in the illumination and projection path, and typically the *f*/# of each one should match. The DLP3030-Q1 DMD has a tilt angle of $\pm 12^\circ$, which corresponds to *f*/2.4, as dictated by the following angle-*f*/# relationship:

$$f/\# = 1 / (2 \times \sin(\theta)) \tag{4}$$

However, an optical designer may prefer to open or close the aperture, by decreasing or increasing the *f*/# respectively. By opening the aperture, this allows more light to pass through and increases the brightness. However, this also allows light from the illumination- and flat-state pupils to leak into the off-state pupil, which raises the black level and degrades the contrast. Closing the aperture reducing the etendue match and allows less light through, but also increases the contrast by separating the pupils.

Figure 2-8 shows this tradeoff of contrast and brightness with a varying *f*/#. To support a HUD design with 1500:1 contrast, and aperture of *f*/2.6 should be used.

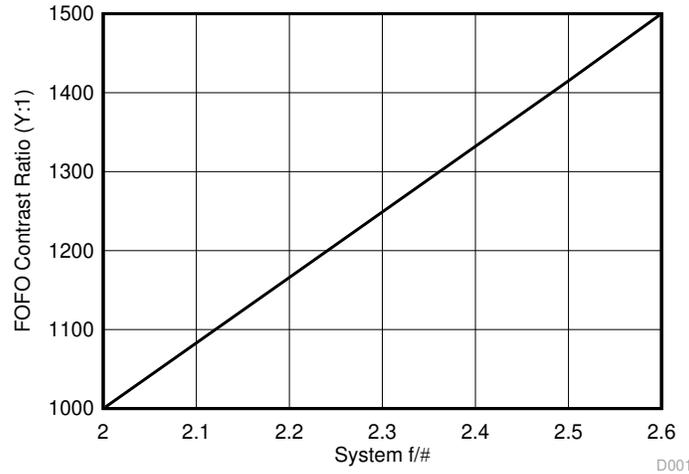


Figure 2-8. Picture Generation Unit Contrast and Brightness vs f/#

2.4.2.3 Thermal Design

In general, HUD systems have a low transmission percentage, due to only a small percentage of HUD lumens being reflected by the windshield to the driver’s eyebox. A lot of electrical power is required to overcome this low transmission and to generate enough brightness in day-time driving conditions. Higher LED power consumption requires robust thermal designs in order to dissipate the heat and keep the LED junction temperatures at reasonable levels.

Additionally, HUDs are typically enclosed inside the vehicle dashboard with minimal airflow. This exacerbates the issue with higher power consumption, since the heat is recycled and further increases the temperature of all components. LEDs are sensitive at higher temperatures, so this results in an power-to-brightness efficiency decrease as well.

Therefore, it’s important to select LEDs which are efficient in order to simplify the thermal solution and total HUD volume.

2.4.2.4 LED Selection Summary

Figure 2-9 shows that despite emitting more lumens, larger LEDs do not necessarily offer more system lumens. This example uses Osram’s Q8WP and CSL LEDs which are readily available for the automotive market today. For a PGU that requires 55 lumens, CSL LEDs with an f/2.6 aperture provide more than the required brightness at the best power efficiency.

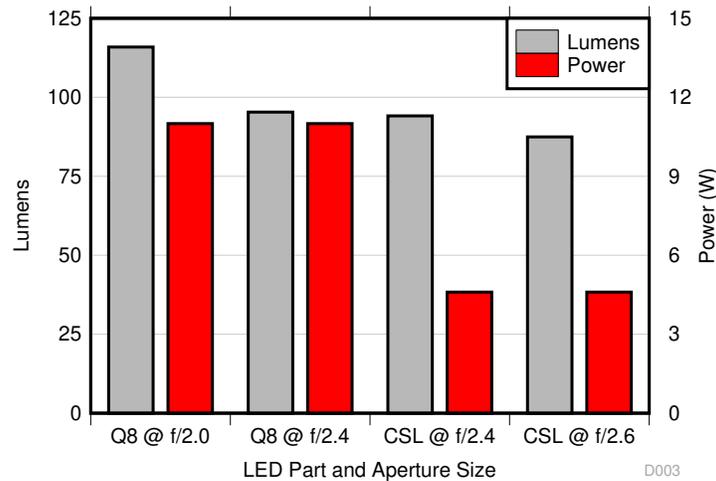


Figure 2-9. Brightness vs Power With Different LEDs and f/#

2.4.3 Design Summary

The design tradeoffs presented in this document can be used to determine hardware capability and requirements for a HUD design. The example HUD design specification from [Section 2.4](#) is:

- FOV: $10^\circ \times 5^\circ$
- Eyebox: 140 mm \times 60 mm
- VID: 10 m
- Contrast: 1500:1
- Resolution: > 80 ppd
- Temperature rating: -40°C to 105°C

[Figure 2-3](#) shows a HUD with this FOV and eyebox will require about 55 lumens output from the PGU. [Figure 2-9](#) shows that the CSL LEDs will output around 90 lumens at with f/2.6 optics. The CSL LEDs will provide enough brightness margin to account for LED efficiency roll-off at high temperatures while minimizing typical power consumption. [Figure 2-8](#) shows that with f/2.6 optics, a HUD design can realize a 1500:1 contrast ratio. Using the DLP3030-Q1 DMD with a horizontal FOV of 10° gives a resolution of 86 ppd. The DLP3030-Q1 chipset is fully automotive qualified with a temperature rating of -40°C to 105°C .

This example HUD design is well suited to use the DLP3030-Q1 chipset.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

The items listed in [Table 3-1](#) are required for electronics only operation. To operate a full PGU system, LEDs, LED cables, and an optical system are also required.

Table 3-1. Required System Components

ITEM NO.	ITEM	Part Number
1	DMD interface board	See the schematic files for TIDA-080004
2	Formatter controller board	See the schematic files for TIDA-080004
3	Total phase Cheetah USB to SPI adapter	Cheetah
4	3-in DMD ribbon cable (2×)	Parlex Flex Cable, 0.5mm, 3 inch 050R50-76B
7	Cheetah SPI interface cable	Custom
8	Power input cable	Custom
9	6-ft HDMI cable	Any

Table 3-2. Required Tools and Items

ITEM NO.	ITEM
1	12 V at 3-A power supply

3.1.2 Software

For required software, download the included software on the [TIDA-080004](#) design folder.

3.2 Testing and Results

In order to support the large dimming ratio of 5000:1 in an automotive HUD system, this design uses a specially designed LED driver and color control system to manage white point balancing across all temperatures and dimming ratios with minimal power consumption.

3.2.1 Test Setup

The hardware from this reference design was connected to an optical system to measure LED pulse times and total power consumption. This was the same optical system used in [DLP3030-Q1 Picture Generation Unit \(PGU\) EVM](#). The total power consumption is shown below in [Table 3-3](#). The shortest LED pulse time is shown below in [Figure 3-1](#).

3.2.2 Test Results

Power consumption is primarily determined by luminous output. Maximum brightness of 90 lumens requires about 7.1 W of power, but this is only needed on extremely sunny days. Nominal HUD brightness will be closer to 25 lumens, which only requires about 2.9 W of power.

Table 3-3. Typical Power Consumption vs Luminous Output

HUD Brightness	Calculated Luminous Output	Measured System Power (W)
Max Brightness	90 lumens	7.1
Medium Brightness	75 lumens	5.9
Low Brightness	25 lumens	2.9
Min Brightness	0.018 lumens	1.8

To support the lowest brightness ranges, around 1/5000th of max brightness, the LED driver must create very small, short pulses of light. The LED driver included in this design supports LED pulses below 1 μ s. [Figure 3-1](#) below shows a short pulse on the output of the photodiode signal, measured at TP6.

For more information on the LED driver and dimming functionality, please see the [Enabling the Next Generation of Automotive Head-Up Display Systems](#) application note.

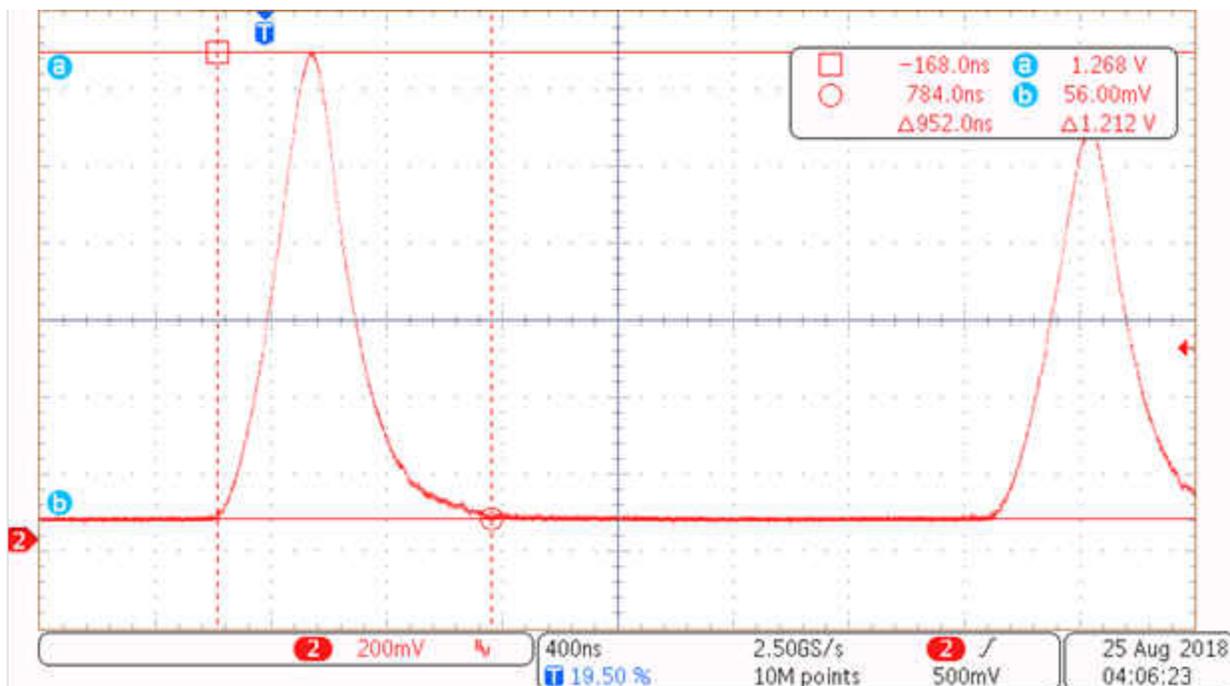


Figure 3-1. Shortest LED Pulse of 952 ns

4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-080004](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-080004](#).

4.3 PCB Layout Recommendations

Refer to DLPC120-Q1 data sheet for specific PCB layout and routing guidelines. For specific DMD PCB guidelines, use the following:

- V_{CC} should have at least one 2.2- μ F and four 0.1- μ F capacitors evenly distributed among the thirteen V_{CC} pins.
- A 0.1- μ F, X7R rated capacitor should be placed near every pin for the V_{REF} , V_{BIAS} , V_{RSET} , and V_{OFF} .

4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-080004](#).

4.4 Cadence Project

To download the Cadence Allegro® project files, see the design files at [TIDA-080004](#).

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-080004](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-080004](#).

5 Software Files

To download the software files, see the design files at [TIDA-080004](#).

6 Related Documentation

1. Texas Instruments, [DLP3030-Q1 0.3 WVGA S450 DMD](#) data sheet.
2. Texas Instruments, [DLPC120-Q1 Automotive DMD Controller](#) data sheet.
3. Texas Instruments, [TMS320F2802x Piccolo™ Microcontrollers](#) data sheet.
4. Texas Instruments, [TMS320F28002x Real-Time Microcontrollers](#) data sheet.

6.1 Trademarks

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7 Terminology

- AR – Augmented Reality
- DMD – Digital Micromirror Device
- FOV – Field of View
- HUD – Heads-up Display
- PGU – Picture Generation Unit
- ppd – Pixels per Degree
- VID – Virtual Image Distance

8 Revision History

Changes from Revision * (October 2018) to Revision A (May 2022)	Page
• Added TMS320F280023.....	1
• Added note to block diagram.....	3
• Added TMS320F280023 note.....	4
• Added TMS320F28002x data sheet hyperlink.....	13

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