Fundamentals to automotive LED driver circuits

TEXAS INSTRUMENTS

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LED circuits: simple to turn on, complex to design.

LEDs are current-driven devices that are substantially affected by changes in operating conditions, such as voltage and temperature. LEDs used in the automotive environment are subject to a wide range of operating conditions, and LEDs can commonly degrade or permanently fail before their expected lifetime. A proper circuit design can enhance LED longevity and performance.

In a car, LEDs are a popular choice for illumination from tail-lights in the rear to telltale status indicators in the cluster as shown in **Figure 1**. Their small size enables flexibility in styling and has the potential to last as long as the vehicle's lifespan. However, LEDs are susceptible to damage from unstable voltage, current and temperature conditions, especially in the rugged automotive environment. To optimize their efficiency and longevity, LED driver circuit design requires careful analysis.
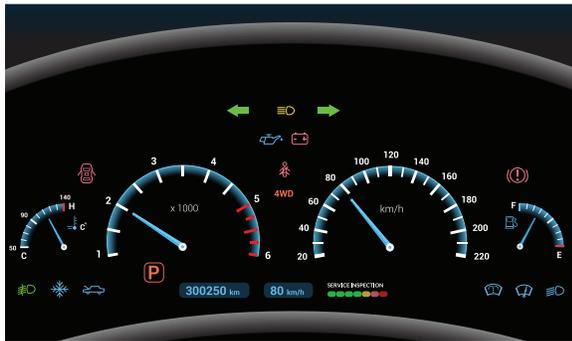
Figure 1. *Instrument cluster dashboard indicators.*

The electronic circuits used to drive LEDs implement transistors. One typical circuit topology used to drive LEDs is the linear topology, in which the transistor operates in the linear region. You then have the choice of implementing your driver circuits using discrete transistors or transistors integrated in a semiconductor integrated circuit (IC) with other LED-related functionality. In discrete implementations, bipolar junction transistors (BJTs), which are commodity devices, are popular. Although BJTs are trivial to design from a circuit viewpoint, substantial challenges exist when developing a total solution

that meets current accuracy, board size, thermal management and fault detection requirements across operating temperature range and input voltage conditions.

In addition, as the number of LEDs grows or project requirements become more complex, circuit design with discrete transistors becomes more complex. In contrast to designing with discrete components, using integrated solutions can simplify not only the circuit design, but also the design and test process. Additionally, the overall solution may be even cheaper. Thus, when designing circuits to drive LEDs in an automotive lighting application, it is important to consider LED priorities, compare circuit design options, and factor in system needs.

Key LED considerations

An LED is a P-type N-type (PN) junction diode that allows current flow in only one direction. Current starts to flow once the forward voltage (V_F) of an LED is reached. LED brightness is driven by the forward current (I_F); how much current an LED draws depends on the applied voltage. While I_F has a linear relationship to brightness, a minute change in the V_F of an LED can cause an exponential increase in the current draw of the LED; too much I_F will damage the LED.

Different color LEDs have different V_F and I_F requirements because of their different semiconductor compounds (**Figure 2**). You must take each LED's datasheet characteristics into consideration, especially when using different color

LEDs within the same design. For example, when designing with red-green-blue (RGB) lighting, a red LED has a V_F close to 2 V, whereas the V_F of blue and green LEDs is closer to 3 to 4 V. Since you're sourcing from the same voltage supply, you will need an appropriate current-limiting resistor for each color to prevent LED damage.
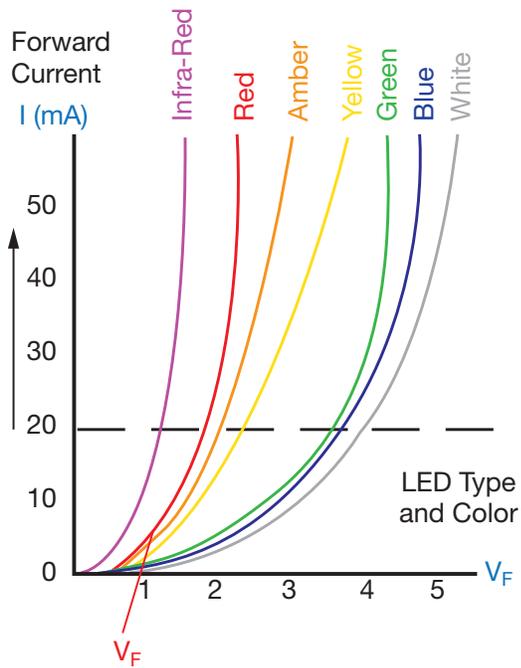

Figure 2. *LED V_F vs. I_F.*

Thermal and power efficiency

In addition to supply voltage and current, temperature and power efficiency also require careful analysis. While current flowing through an LED is converted to light, some energy is converted into heat at the PN junction. The junction temperature of an LED is affected by the ambient temperature (TA), the thermal resistance between the LED junction and ambient air ($R_{\theta JA}$), and the power dissipation (P_D). **Equation 1** expresses the P_D of an LED:

$$P_D = V_F \times I_F \qquad (1)$$

Using **Equation 1**, **Equation 2** then calculates the junction temperature (T_J) of an LED:

$$T_J = T_A + R_{\theta JA} \times P_D \qquad (2)$$

It is important to calculate the T_J not only under typical operating conditions, but also under the application's expected maximum T_A for worst-case-scenario considerations. As the T_J of an LED increases, its output efficiency diminishes. An LED's I_F and T_J should remain below their absolute maximum ratings as listed in the datasheet in order to prevent damage (**Figure 3**).
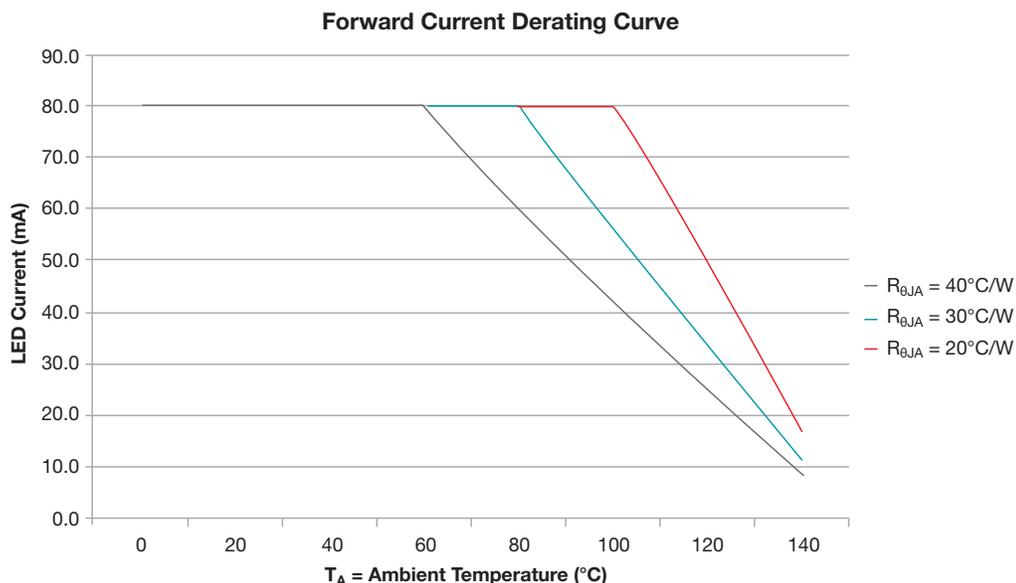

Figure 3. *Example LED current derating curve.*

In addition to the LEDs themselves, you must consider the power efficiency of resistors and driving components like BJTs and operational amplifiers (op amps), especially as the number of discrete components grows. Poor power efficiency from the driving circuit, the duration of LED on-time and/or a warm environment can all contribute to temperature increases that affect the output current of the driving BJTs and also lower the V_F drop of the LEDs. As the V_F drop decreases, the LED current draw increases; this results in higher P_D and temperature increases, which lead to the V_F decreasing further. This overheating cycle, called "thermal runaway," causes LEDs to operate beyond their maximum operating temperature, degrade, and eventually fail, as too much I_F is consumed.

Linear LED driving

It is possible to drive LEDs linearly with either discrete components or ICs. Of all options, the most basic way to control an LED is to connect it directly to the voltage supply (V_S). Adding an appropriate current-limiting resistor will stabilize the current and provide the correct voltage dropout to power the LED. **Equation 3** calculates the current-limiting series resistor (R_S) as:

$$R_S = \frac{V_S - V_F}{I_F} \qquad (3)$$

Since three LEDs are in series in **Figure 4**, the total V_F of the LEDs must be factored into the V_F calculation. (The LEDs' I_F remains the same.)

While this is the most basic LED driving circuit, it is the least practical in a real-life application. Power supplies, especially automotive batteries, are prone to fluctuations. A small change to the power supply causes the LED to consume more current and likely become damaged. Additionally, high PD through the resistor increases the heat, which may contribute to thermal runaway.
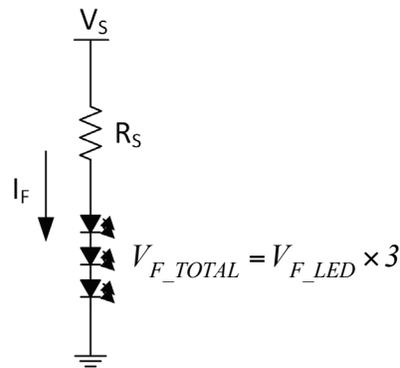

Figure 4. *Direct LED drive with R_S.*

Discrete constant-current LED drivers

Implementing a constant-current circuit will provide a more power-efficient and stable design. As the most common method to switch an LED on and off, a transistor provides a regulated supply of current. As shown in **Figure 5**, you can choose either a BJT or metal-oxide semiconductor field-effect transistor (MOSFET), depending on the voltage and current needs of the LED design. Transistors can handle higher power than a resistor, but they are still prone to changes in voltage and temperature. For instance, if the voltage across a BJT increases, then its current increases as well.
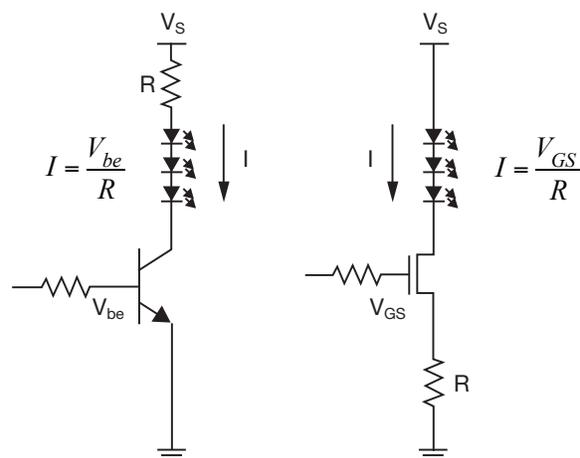

Figure 5. *Constant-current LED drive with transistors.*

To ensure further stability, you can modify these BJT or MOSFET circuits to provide stable current even with fluctuations in voltage. Figures 6 through 8 offer a few current-source circuit examples. In **Figure 6**, a Zener diode produces a stable output voltage to the base of the transistor. Current-limiting resistor R_Z provides appropriate current in order for the Zener diode to properly operate. The output voltage of the Zener diode remains constant regardless of fluctuations in the supply voltage. The voltage drop across emitter resistor R_E must match the voltage drop of the Zener diode, so the transistor adjusts the collector current; as a result, the current supplied to the LEDs is constant.

$$I = \frac{V_Z - V_{be}}{R_E}$$
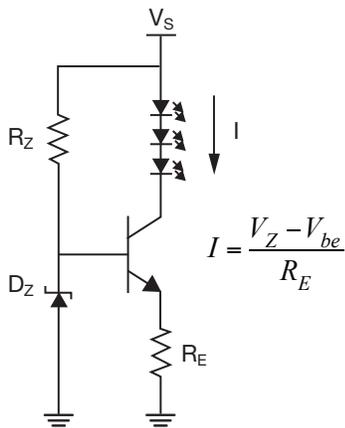
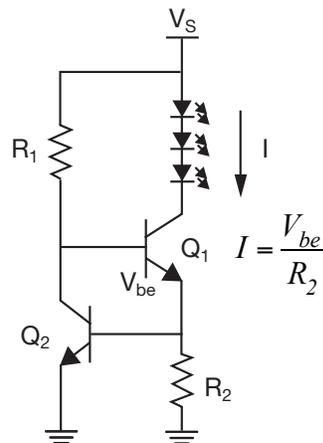**Figure 6.** *A current-source LED circuit with a Zener diode.*

In **Figure 7**, a feedback loop of an op amp adjusts its output so that its negative input matches its positive input. A Zener diode is used as the reference voltage. The voltage across sense resistor R_S must be proportional to the voltage across the Zener diode, so the op amp drives the transistor to the desired output. As long as the Zener diode remains in stable operation, the current flow through R_S and the LEDs is constant.


$$I = \frac{V_{REF}}{R_S}$$
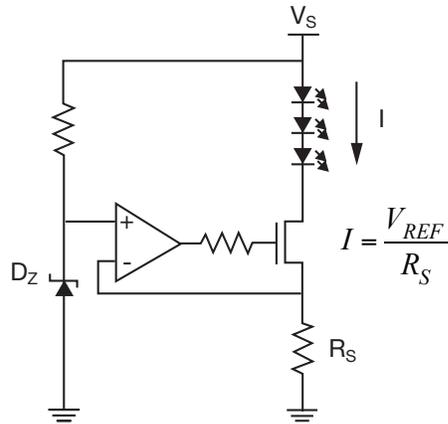
Figure 7. *A current-source LED circuit with an op amp.*

Figure 8 demonstrates another feedback loop accomplished with two transistors. The current flows through R_1, turning on transistor Q_1. Current then flows through R_2, which sets the current through the LEDs. As the current increases through R_2, the voltage drop against R_2 increases. Once its voltage drop reaches the base-to-emitter voltage (V_{be}) of transistor Q_2, Q_2 turns on. An enabled Q_2 starts pulling current through R_1, causing Q_1 to start turning off and effectively limiting the current to the LEDs.

This feedback loop ensures a constant supply of the appropriate current to the LEDs. BJTs are used in this example, but it is also possible to implement this circuit with MOSFETs.

$$I = \frac{V_{be}}{R_2}$$

**Figure 8.** *A current-source LED circuit with two transistors.*
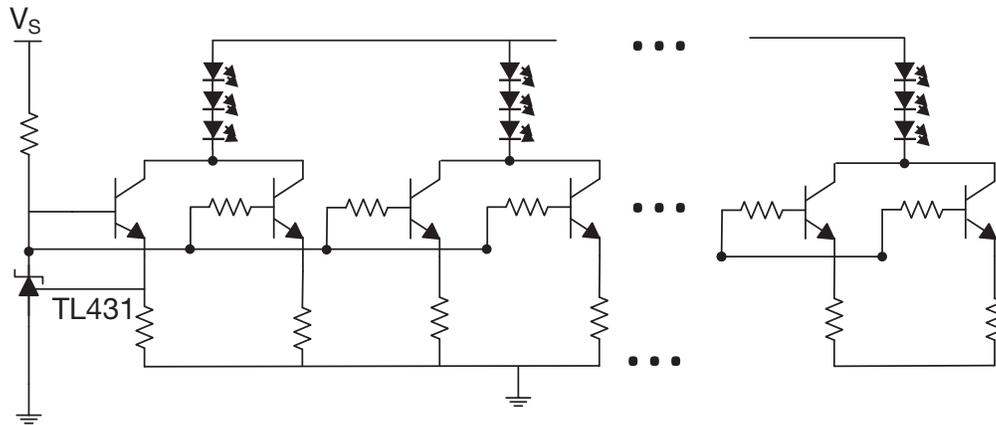
Figure 9. *Driving multiple LED strings with discrete components.*

Integrated constant-current LED drivers

Serving as fundamental building blocks, you can repeat these transistor-based LED circuits to drive any number of LED strings, as shown in **Figure 9**. Controlling even a handful of LEDs increases component count, limits board space and uses up general-purpose input/output (GPIO) pins. Additionally, these circuits do not account for brightness control and fault diagnostics, which are common requirements in LED applications; implementing requirements such as brightness control and fault diagnostics adds more discrete components and additional design analysis. In projects that have a high LED count and/or challenging requirements, discrete circuit design not only starts to become more crowded, but also more complex.

To simplify the design process, it's best to use dedicated ICs to drive the LEDs. Dozens of discrete components like those shown in Figure 9 can be simplified with an LED driver like the one shown in **Figure 10**. LED driver ICs are efficiently designed for the voltage, current and temperature challenges characteristic of LEDs, while reducing component count and board space. Additionally, LED driver ICs may integrate brightness control and diagnostics, such as over temperature protection. Again, it is

possible to implement brightness adjustment and diagnostic features with a combination of discrete circuitry, but LED driver ICs provide a simple yet reliable alternative.
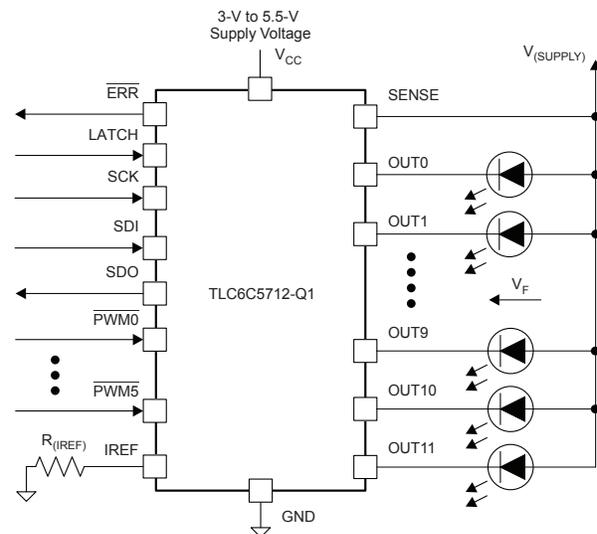
Figure 10. *The TLC6C5712-Q1 multichannel LED driver IC reduces component count.*

Common challenges in LED applications

For many applications, you must adjust the brightness of an LED. Since brightness is proportional to I_F, it is possible to use analog current dimming and pulse-width modulation (PWM) dimming to adjust brightness. **Figure 11** compares
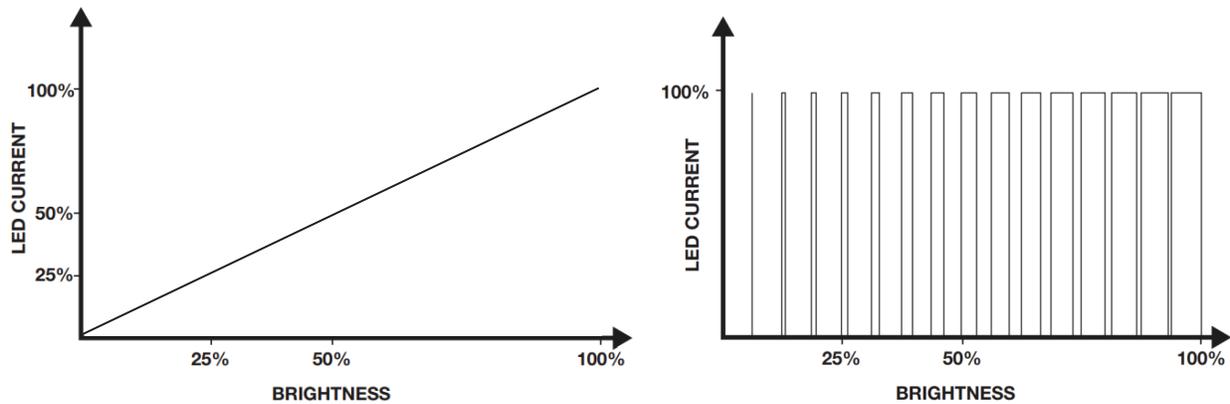
Figure 11. *Analog dimming vs. PWM dimming.*

the difference between these two brightness control methods. With analog dimming, the brightness is adjusted by the amplitude of a constant current flow; higher current proportionally results in higher brightness. However, the resolution of analog dimming is poor, especially at low brightness levels. Analog dimming is also not a good fit for color-dependent projects, such as RGB lighting or status indicators; variations in I_F can cause variations in color output.

On the other hand, PWM dimming supplies a constant I_F while switching the LEDs on and off. The time-averaged LED current is proportional to the duty cycle (the ratio of pulse length over the pulse period of the PWM); a higher average current results in a higher brightness. Since you can fine-tune the duty cycle to different brightness levels, PWM dimming provides a wider dimming ratio compared to analog dimming, but requires more design analysis. The PWM frequency must be faster than what the human eye can perceive, or else the LEDs will appear to be flickering.

Additionally, PWM dimming is prone to creating electromagnetic interference (EMI). An LED circuit with poor EMI performance may affect other applications, such as creating audible noise interference with the radio antenna. LED driver ICs can offer both analog and PWM dimming and may even have additional features to reduce EMI, like

programmable slew rate, or output channel phase-shift or group delay.

LED diagnostics and fault reporting

LED diagnostics – such as overheating, short circuit or open circuit – are a common design requirement, especially when driving multiple LEDs. Reducing the chance of LED failure, LED drivers provide a more precise, regulated output current compared to a discrete-based circuit, but they also integrate overtemperature protection to enhance the longevity of the LEDs and the device itself. LED drivers can also diagnose faults such as an LED open or short circuit.

Some applications may also call for follow-up action in response to a detected fault. For example, a rear light module has multiple strings of LEDs to drive tail lights and brake lights. If a broken LED fault is detected in one of the LED strings, then all LEDs can be turned off, not only to prevent further LED degradation but also to alert that the brightness level of the rear-light module is no longer within market regulation and must undergo maintenance.

In order to give a diagnostics alert to the driver, a smart high-side switch in the body control module (BCM) detects a fault from the rear-light module as shown in **Figure 12**. However, diagnosing an LED fault from the BCM can be challenging. Sometimes you can use the same BCM board design to

diagnose a traditional incandescent bulb-based system or an LED-based system; since LED load currents are significantly smaller compared to incandescent bulb loads, distinguishing between a valid LED load and an open load may be difficult if the current-sense diagnostics are not accurate. Compared to a single open LED string, having all LED strings off is more detectable for the BCM to diagnose an open load. One-fail-all-fail fault circuitry can be implemented to turn off all LEDs in the event of a broken LED. Automotive linear LED drivers have the option to enable a one-fail-all-fail response and can share a common fault bus across multiple ICs.
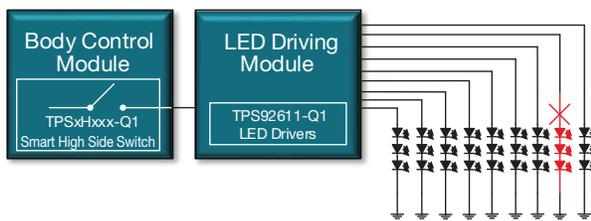
Figure 12. *The BCM diagnoses faults from the LED driving module.*

Integration and flexibility

For high LED count designs, a major challenge is GPIO pin availability. Besides driving multiple LED channels within a one-chip solution, many multichannel LED drivers have serial communication, such as Serial Peripheral Interface (SPI) or I²C, that enable channel brightness control and diagnostics. Serial communication allows the daisy-chaining of multiple multichannel devices, thus enabling the control of dozens or even hundreds of LEDs with only two to four wires from the microcontroller.

There are many LED drivers available to meet different project needs. A variety of channel options range from simple single-channel devices like the TPS92611-Q1, which is a robust alternative to a discrete BJT circuit, to multichannel devices for RGB lighting like the TLC6C5712-Q1 from Figure 10. Some systems, such as rear combination

lighting, exterior headlight, or display backlighting, can utilize application-specific devices that can help enable a one-chip automotive solution. Finally, while all devices offer better constant-current regulation and thermal protection over a discrete circuit, some also integrate a full suite of protection and diagnostic features.

Lighting up future designs

For many lighting applications, LED circuitry design can be complex due to the sensitive behavior of LEDs in regard to voltage, current and temperature. Design complexity increases in applications with high LED counts and/or challenging requirements, such as brightness control and diagnostic reporting. Through careful analysis, you could address these challenges with a discrete circuit implementation. However, when using a multitude of BJTs and other discrete devices within an LED system, the component count, board space and overall system cost add up; using numerous components also increases design and manufacturing risks. Considering the resources spent designing, debugging and assembling all discrete components, you can save both time and money with an integrated LED driver solution. LED driver ICs offer simple design, reliable performance and cost-competitiveness. TI offers a wide range of LED drivers to address any lighting design.

Additional resources

• Learn more about "Trends and topologies for automotive rear lighting systems."

• Evaluate the Comité International Spécial des Perturbations Radioélectriques (CISPR) 25 Class 5-compliant "Automotive dual stage (SEPIC + linear) static LED driver module reference design for rear lights."

• Watch a video on "How to estimate junction temperature" for linear LED circuits.

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