

Trends and Topologies for Automotive Rear Lighting Systems



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In the early 1900s, driving at night was precarious.

Lit by kerosene lamps, drivers announced their maneuvers with hand signals and shouts while employing guesswork to predict the actions of the other cars on the road.

With fewer cars moving at slower speeds and dodging the occasional horse and wagon, they got by alright, but we've come a long way:

- Advancements from kerosene lamps to Incandescent bulbs to light-emitting diodes (LEDs) and organic LEDs (OLEDs) have provided more reliable, efficient light sources.
- The number of light sources installed in a vehicle for specific light functions has also increased, from a single bulb to multiple pixelated designs.
- Variable lighting has allowed drivers to better communicate their intentions, making driving safer overall.
- Exterior lighting serves function and form for styling and personalization purposes.
- Electronic lighting control modules enable signaling functions as required by law, but also enable dynamic rather than static signal functions, including personalized welcome messages for drivers, such as a logo on the puddle light.
- As rear-lighting systems become more complex, engineers from the optical, mechanical, electrical and manufacturing disciplines all face new challenges when designing new systems.

As a result of modern rear-lighting solutions, the actions of other drivers are becoming more predictable in all environments and making driving safer.

In this white paper, we will focus on electrical challenges and investigate possible solutions to overcome them. These challenges include:

- Higher power demand.
- Thermal management.
- Electromagnetic interference (EMI) compatibility.
- Fault detection and protection.

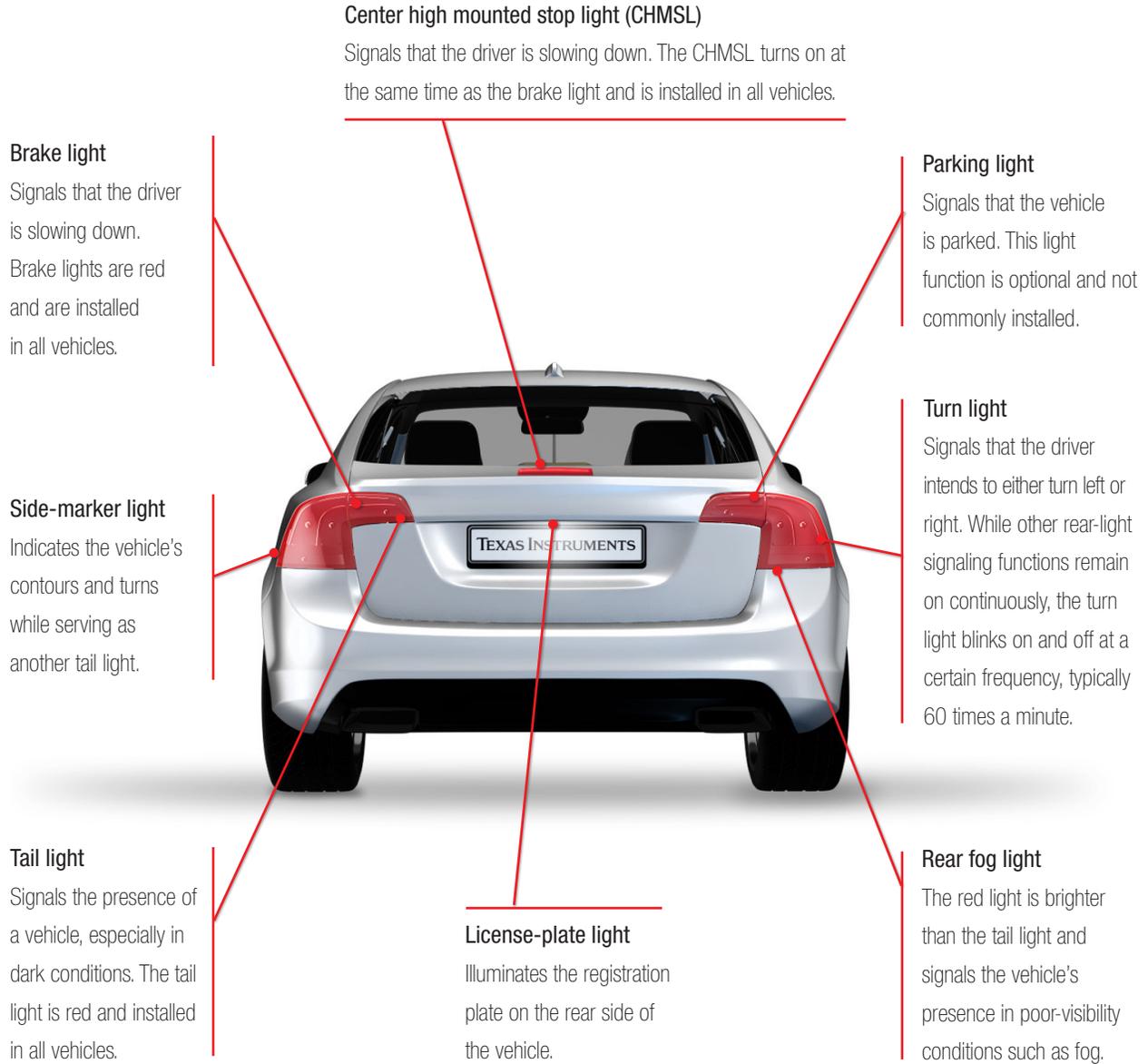


Figure 1. Components of a rear-lighting system.

Rear lighting on the road

Before discussing LEDs and the electrical topologies, let's first look at the different signaling functions legally mandated by regulatory agencies such as the U.S. National Highway Traffic Safety Administration and Europe's Economic Commission, as shown in **Figure 1**.

As illustrated in **Figure 1**, there are a variety of necessary rear-signaling functions for automobiles, all of which require a control module. **Figure 2** is a block diagram of a typical rear-light control module, showing all rear-light functions as well as the power supply, communication interface and LED-driver subsystems.

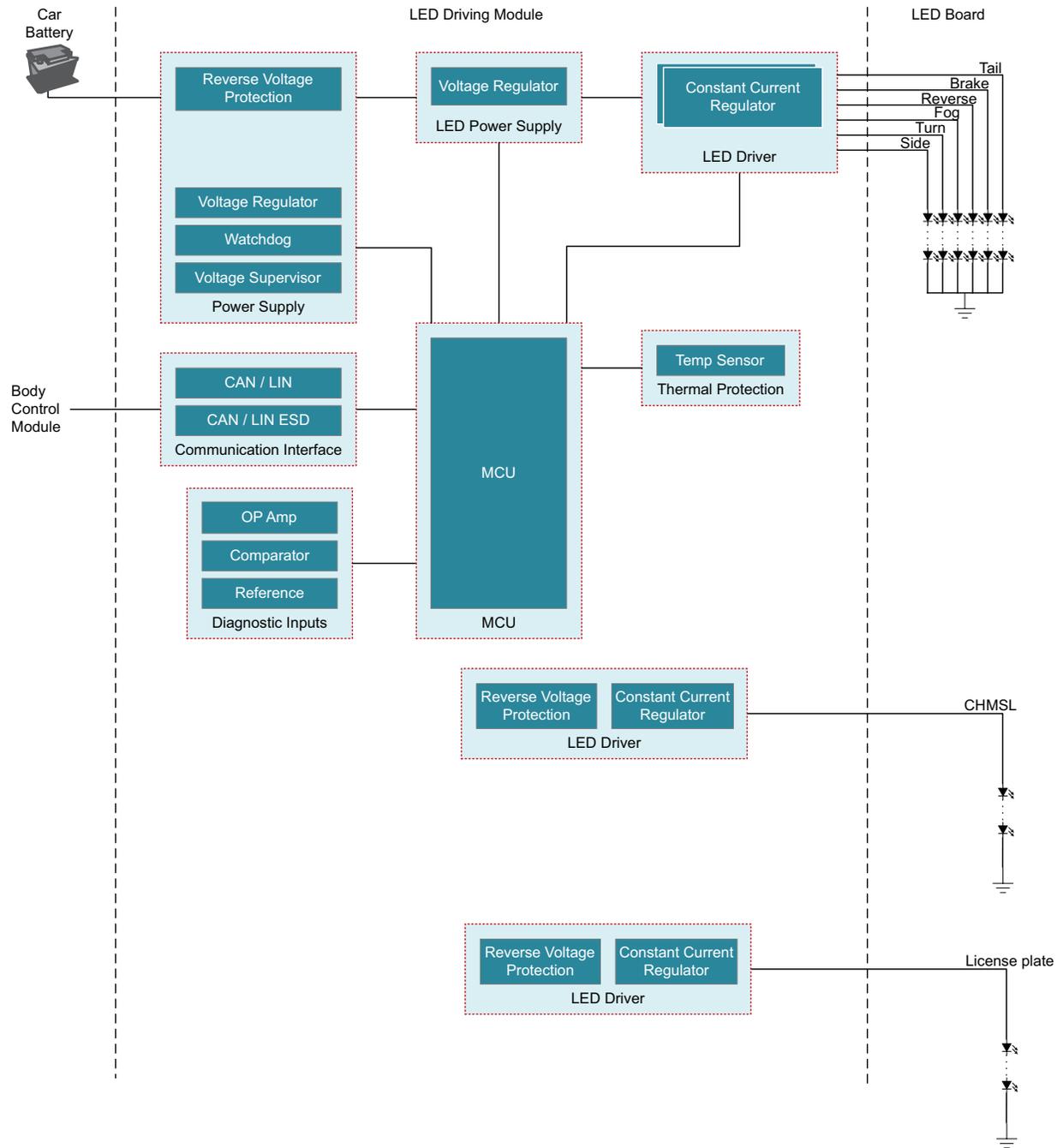


Figure 2. Block diagram of a rear light control module.

The basics of LED in rear lighting

An LED is a P-N junction diode that emits light when activated. Like any P-N junction diode, an LED is a unidirectional device with an exponential forward-current-forward-voltage (I-V) curve, as shown in **Figure 3**.

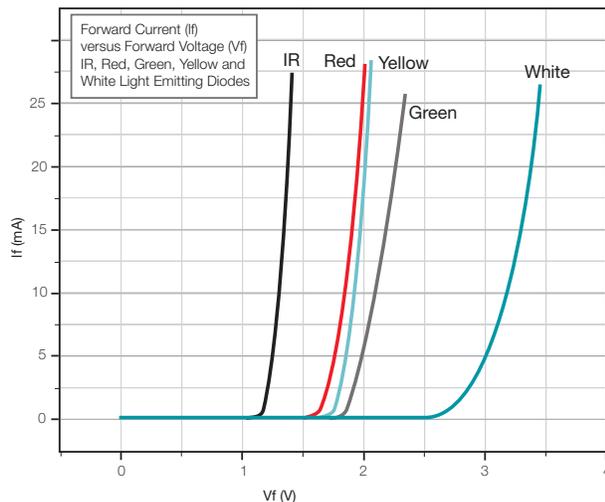


Figure 3. An LED's I-V curve. (Source: <http://lednique.com/current-voltage-relationships/iv-curves/>)

When a positive voltage is applied between the LED's anode and cathode terminals, current flows from anode to cathode, causing the LED to emit light. The voltage applied between anode and cathode is referred to as the LED forward voltage, which is usually measured at a nominal current condition. The higher the forward current through the LED, the brighter the LED light and the higher the LED forward voltage.

LEDs with different colors have different forward voltages. The forward voltage of most red and amber LEDs is around 2 V, while the forward voltage of white LEDs is around 3 V.

Benefits of LED lighting sources

A key benefit of LEDs compared to incandescent bulbs is that an LED is a more efficient light source. The efficiency of a light source is measured in lumens per watt, which indicates the amount of light emitted per unit of power consumed.

Typically, an LED source is six times more efficient than an incandescent bulb (**Figure 4**).

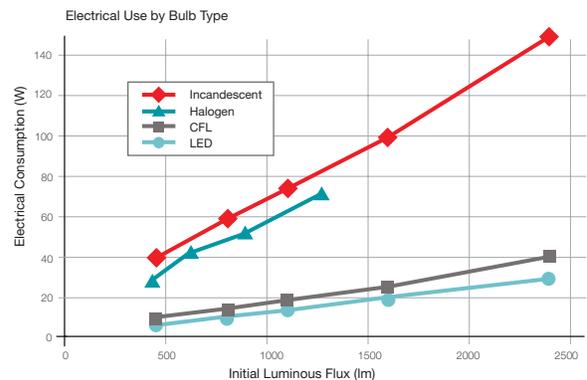


Figure 4. Efficiency of an LED light source vs. an incandescent bulb. (Source: https://commons.wikimedia.org/wiki/File:Electricity_use_by_lightbulb_type.svg)

Not only are LEDs more efficient than traditional incandescent light bulbs, but they also last nearly 42 times longer and enable easy adoption for different stylistic designs. Traditional incandescent lamps require replacement every couple of years; their lifetime is usually around 1,200 hours. The lifetime of LEDs extend to more than 50,000 hours, so an automotive LED lamp could last the vehicle's entire lifetime without needing replacement.

Transition from dot-type to surface-type

Traditional incandescent lamps have a fixed form factor because of their round housing. In contrast, LED lighting sources have small form factors, which means that automotive lamps no longer have to be the traditional round shape. By using multiple LEDs, the lamps can be designed with more flexibility to fit different physical design requirements; however, a visual effect of using LEDs in automotive rear lights is that the LEDs appear as dots.

Because both the LED light output and the direction of light are easily controllable, the latest automotive rear lamps use multiple optical methods to transition from dot-type lighting sources to surface-type lighting sources.

Using light guides and diffusers are the most common methods to accomplish this transition, but they decrease optical efficiency, necessitating an increase in LED brightness, either by using higher-brightness LEDs or more of them.

Design targets and challenges

While LEDs have many merits, there are also challenges in driving them to fit automotive specifications. A typical list of automotive LED driver requirements includes:

- A wide voltage range, with 9- to 16-V, 24-V and 40-V scenarios.
- An operating ambient temperature range of -40°C to 85°C .
- Animating a lamp feature.
- LED fault diagnostics.
- Electromagnetic compatibility (EMC).

Automotive wide-voltage ranges

An LED driver design must be able to operate within the wide-voltage range of automotive 12-V batteries. The International Organization for Standardization (ISO) 7637 and ISO 16750 standards present the most common requirements in the automotive industry for 12-V battery voltage transients that LED drivers must withstand.

An automotive car battery typically ranges from 9 to 16 V in normal operation. In this range, the light output must meet the required regulatory requirements under all temperature conditions. More recently, certain lamp functions such as turn indicator is operated when the automotive battery is at 6 V, which is the typical voltage during start-stop. Note that the starting voltage profile for start-stop may vary with battery condition as well as temperature. It is usually not necessary for the rear lamp to remain functional when the supply voltage is below 6 V. On the higher side, the battery voltage could surge to 24 V for one minute at room temperature in jump-start scenarios.

Lamp functions must be able to withstand any damage and recover when the voltage returns to normal.

During load dump, the battery is disconnected while the alternator is generating charging current, with other loads remaining on the alternator circuit. In this scenario, the supply voltage can shoot as high as 36 V for 400 ms in the case of suppressed alternator scenarios. In the event of a load dump, LED drivers must be able to recover when the voltage returns to normal.

Thermal considerations

Automotive applications need to withstand a wide temperature range. Automotive lamp circuitry needs to work at up to an 85°C ambient temperature. This maximum temperature includes the temperature rise in the housing caused by self-heating within an enclosed lamp.

High ambient temperatures present two challenges in LED rear lamps: controlling the junction temperature of the LED and the LED driver.

An LED's lifetime will drop significantly if its junction temperature exceeds its upper limit. If the LED driver is a constant-current driver, **Equation 1** gives an approximate estimation of the temperature rise on the LED's junction temperature, based on the ambient temperature, thermal resistance and amount of power dissipation:

$$T_{\text{JUNCTION}} = T_{\text{AMBIENT}} + \theta_{ja}P \quad (1)$$

where θ_{ja} is the package thermal resistance and P is the power dissipated.

Thermal considerations should also address LED drivers. Since constant-current drivers used in rear lamps are mostly linear LED driver integrated circuits (ICs), **Equation 2** estimates the power dissipated in an LED driver IC using the voltage drop across the driver times the total current:

$$P = \Delta V * I \quad (2)$$

where ΔV is the voltage across the LED driver and I is the LED-forward current.

When the input voltage is at a normal maximum operating voltage, such as 16 V, and the output LED voltage is minimal, such as two LEDs with 1.9-V forward voltages each, the maximum ambient temperature would be 85°C. A typical linear LED driver would need a maximum 2 W of power dissipation over the device in order to fit automotive applications. Using **Equations 1** and **2**, you can estimate the maximum LED current using the θ_{ja} .

Linear LED drivers such as [TPS92630-Q1](#) or [TPS92638-Q1](#) from Texas Instruments meet these power dissipation requirements.

Animation trends

Animation in rear lights enables style flexibility as well as personalization such as a welcome message. As new lamp designs adopt complex animation, rear-lamp designs are transitioning from controlling strings of LEDs to driving LED pixels independently, which can be accomplished using a device such as [TPS929120-Q1](#). **Figure 5** displays the transition from string LED control to independent pixel control.

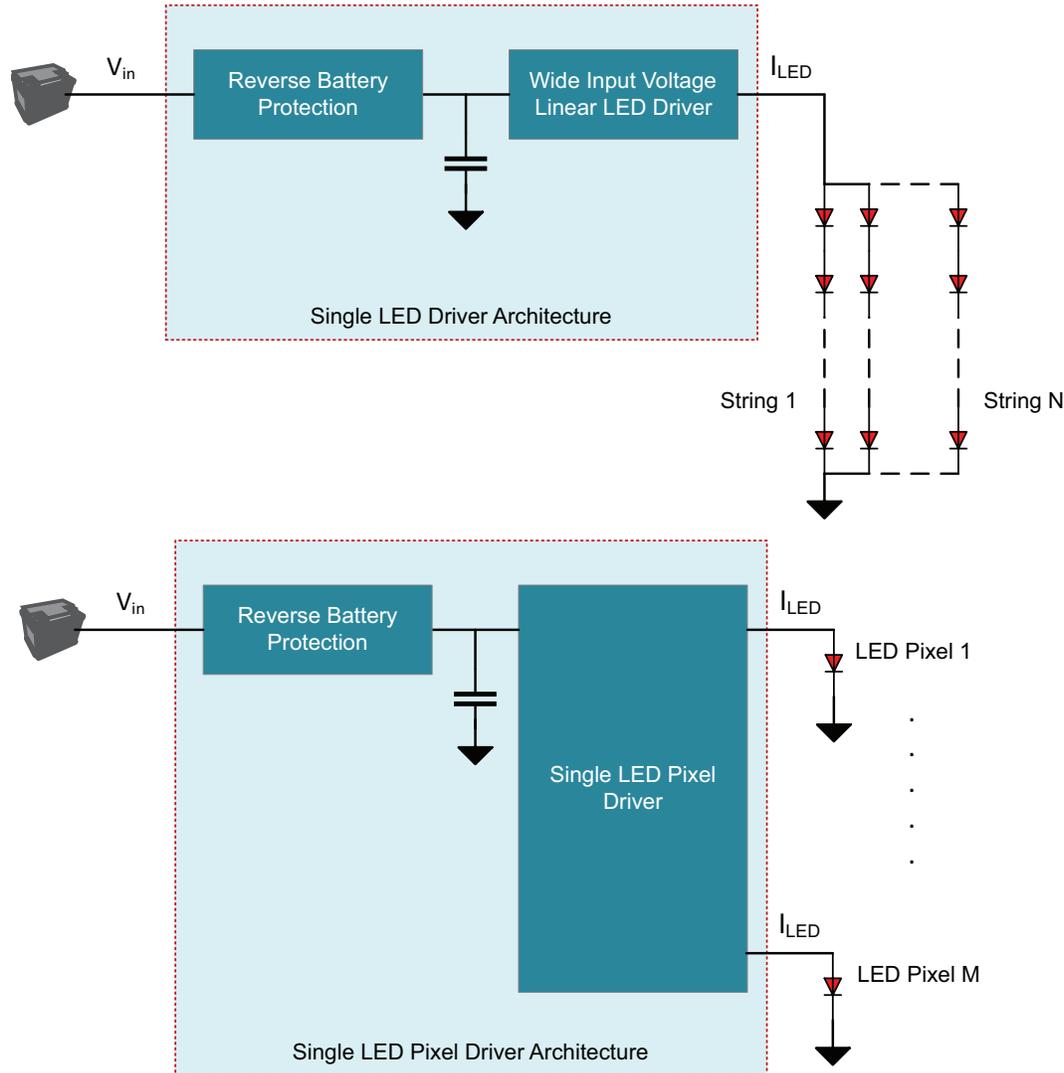


Figure 5. Controlling strings of LEDs with one LED driver vs. controlling each LED independently.

LED fault diagnostics

It is mandatory that an automotive lamp fulfill its lighting-output regulations during its lifetime. However, LEDs are also subject to failure. Although the lifetime expectation of an LED is much longer than the maximum operation hours of a vehicle, LEDs are still vulnerable to random failures. As many as 80% of random LED failures are open-circuit failures, while less than 20% are short-circuit failures.

It's easy to detect a traditional incandescent bulb-based lamp failure because a failed bulb will completely turn off. But because an LED-based lamp uses multiple LEDs in multiple strings, a single LED open-circuit fault or short circuit may not be easily detectable because the rest of the LEDs will continue operating.

While detecting an LED open circuit in a single string of LEDs is relatively straightforward, detecting a single LED short circuit may not be as easy to identify. Consider a string of three LEDs. A simple LED driver will not be able to distinguish a three-LED string from a two-LED string when a single LED short circuit occurs. Detecting such faults is imperative in an animated turn indicator because regulations require that the first 200 ms of light output meet a certain brightness level. If one LED short-circuits, the lamp will not be able to meet the brightness requirements, therefore, sophisticated fault-detection techniques are required to achieve one-fail-all-fail. In other words, a single LED failure turns off the entire lamp.

EMC

Many vehicles today reuse the rear window defogger as an antenna, while others use a separate antenna over the roof. In order to avoid interfering with the antenna, EMC requirements are exceptionally stringent for automotive rear lamps. Thus, LED drivers must have low emissions and high immunity. Using linear LED drivers in rear lights simplifies rear lighting designs for EMC. The rear-lamp system is often tested against emission standards such as Comité International Spécial des Perturbations Radioélectriques (CISPR) 25 and immunity standards such as the ISO 11452-5 bulk current injection standard.

LED driver topologies

Rear light LED driver topologies are either single or dual stage. The single-stage topology shown in **Figure 7** uses a single linear LED driver, while the dual-stage topology shown in **Figure 8** uses a voltage regulator followed by an LED driver.

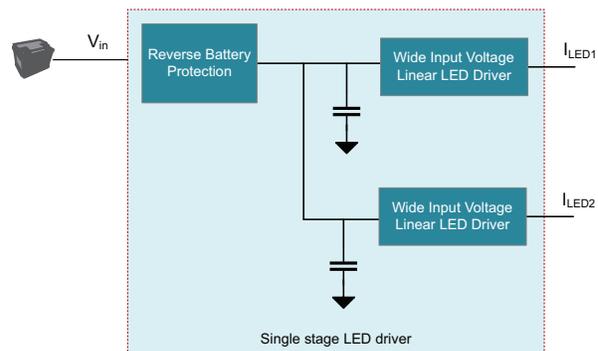


Figure 7. Single-stage LED driver.

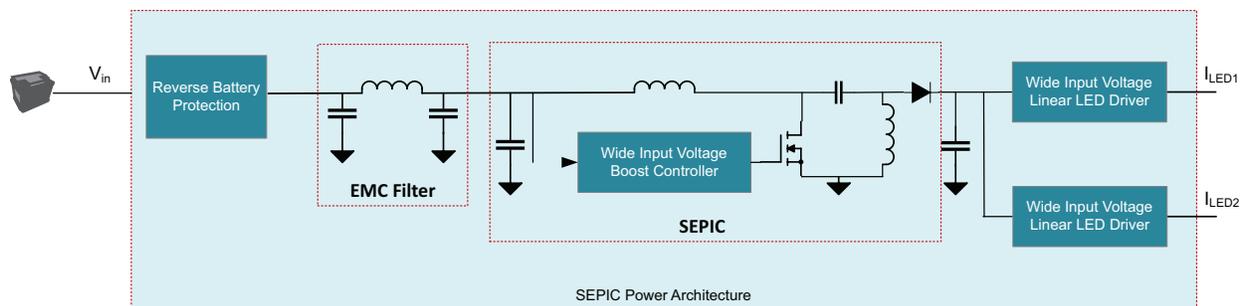


Figure 8. Dual-stage LED driver.

One possible circuit topology for a linear LED driver is a discrete circuit with a resistor and a transistor, as shown in **Figure 9**. **Equation 3** calculates the current in the LED as:

$$I_{LED} = \frac{V_{in} - V_f(LED)}{R} \quad (3)$$

While this circuit is simple to implement, it has many weaknesses. The LED current is not constant, given variations in the LED's I-V characteristics and temperature. Plus, the circuit does not have diagnostics. Finally, managing thermals in the circuit requires the implementation of parallel resistors and transistors to divide the power dissipation among the components and thus prevent a single component from failing due to excessive heat.

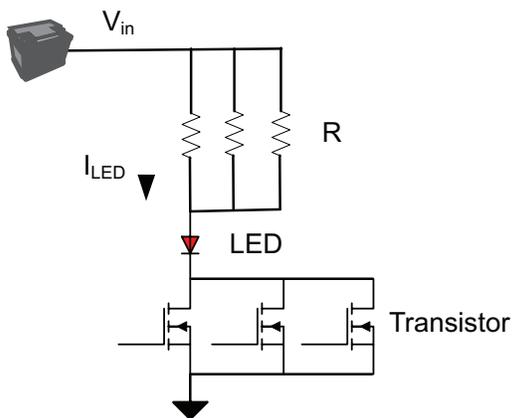


Figure 9. Discrete LED driver.

In contrast to discrete LED drivers, LED driver ICs offer many advantages. Driver ICs not only generate a constant current regardless of the input voltage, but also implement diagnostics inside to achieve one-fail-all-fail. Driver ICs also implement thermal foldback features that reduce the current in the LEDs if the temperature of the LED exceeds certain limit. Reducing current in the LEDs reduces the power dissipation, which decelerates the rise

in junction temperature (see **Equation 1**), thus preventing damage to the LED.

While rear lights commonly use linear LED drivers, high-current applications sometimes use a single-stage switching LED driver. In such an implementation, EMC challenges increase, requiring innovative techniques such as spread spectrum to reduce emissions.

Dimming the light

For scenarios that require dimming of the tail light and brake light, LED designers use two methods: analog dimming and digital dimming. Analog dimming reduces the current in the LED, which in turn decreases the light output, resulting in dimming. Digital dimming (also called pulse-width modulation [PWM] dimming) employs PWM to modulate the current between the LED driver output current and zero current. Thus, the average light output reduces, which once again results in a dimmed output.

Analog dimming is used as a dimming method and a way to improve design homogeneity by calibrating the current in each LED to achieve uniform luminosity. However, because LEDs are dimmed at a nominal current, reducing the driving current increases the luminosity differences between LEDs, leading to homogeneity concerns. Current accuracy at low currents is crucial for homogeneity designs. Most analog dimming ratios are limited to below 20-to-1.

For digital dimming, PWM is precise even at low duty cycles. The luminosity mismatches are almost negligible; thus, it is suitable for high-precision dimming. Digital dimming requires a PWM generator, either discretely with a 555 timer or through microcontrollers. In animated lamps, digital dimming is more common, since it is easy to control with firmware.

Rear lighting in the future

Automotive rear lighting systems have evolved significantly to accommodate for greater signaling, stylization and personalization needs in the marketplace. These changes have led to more complex systems that require an LED driver and present a range of electrical design challenges to engineers, including:

- Higher power demand.
- Thermal management.
- EMI compatibility.
- Fault detection and protection.

Lights out?

As the automotive industry moves toward greater autonomy, some may ask: will autonomous vehicles need exterior lighting? It's an interesting question.

If a car is independently operating through radar, LIDAR, cameras and vehicle-to-everything (V2X) technology without human intervention, one might assume lighting is just a drain on the battery.

But as discussed in this white paper, lighting appeals to aesthetics as well as serving signaling functions. Consumers have grown accustomed to the stylistic design of lighting and future customization will increase the appeal. Also, in the near future, automotive lighting will be crucial for signaling in traffic mixed with automated and traditional vehicles as well as pedestrians.

My estimation is that rear lighting is here to stay.

Related websites

- [Exterior rear light interactive block diagram](#)
- [TI's automotive LED driver solutions](#)
- [DLP® Products automotive chipsets](#)

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