LED DRIVERS FOR AUTOMOTIVE APPLICATIONS

Design Guide

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Introduction

LEDs are taking the automotive industry by storm due to significant advantages over traditional technologies and their diverse range of automotive applications (*Figure 1*).

Front-light modules tend to be high power (more than 100W), utilizing high-efficiency, switching-based drivers. Rear lights and other exterior lights tend to be lower power, sometimes low enough to allow the use of simple linear drivers. The superior clarity of white light in LED headlights improves driver reaction time. Adaptive front-lighting systems (AFS), enabled by LED matrixes, produce fast, complex light pattern changes that improve visibility for drivers in poor light conditions. At night, in response to the beams of an incoming car, AFS can automatically adjust the light pattern, preventing oncoming drivers from being blinded by harsh lighting.

The LED illumination rise-time is twice as fast as incandescent sources, allowing LED-based brake lights to illuminate quicker providing advanced warning to drivers and increasing road safety. Finally, LEDs consume less power than their incandescent counterparts leading to substantial advantages in fuel consumption. In this design guide, we will discuss LED controllers, the electronics that operate LEDs, and the important role they play in preserving and enhancing the inherent LED qualities of clarity, speed, and efficiency.

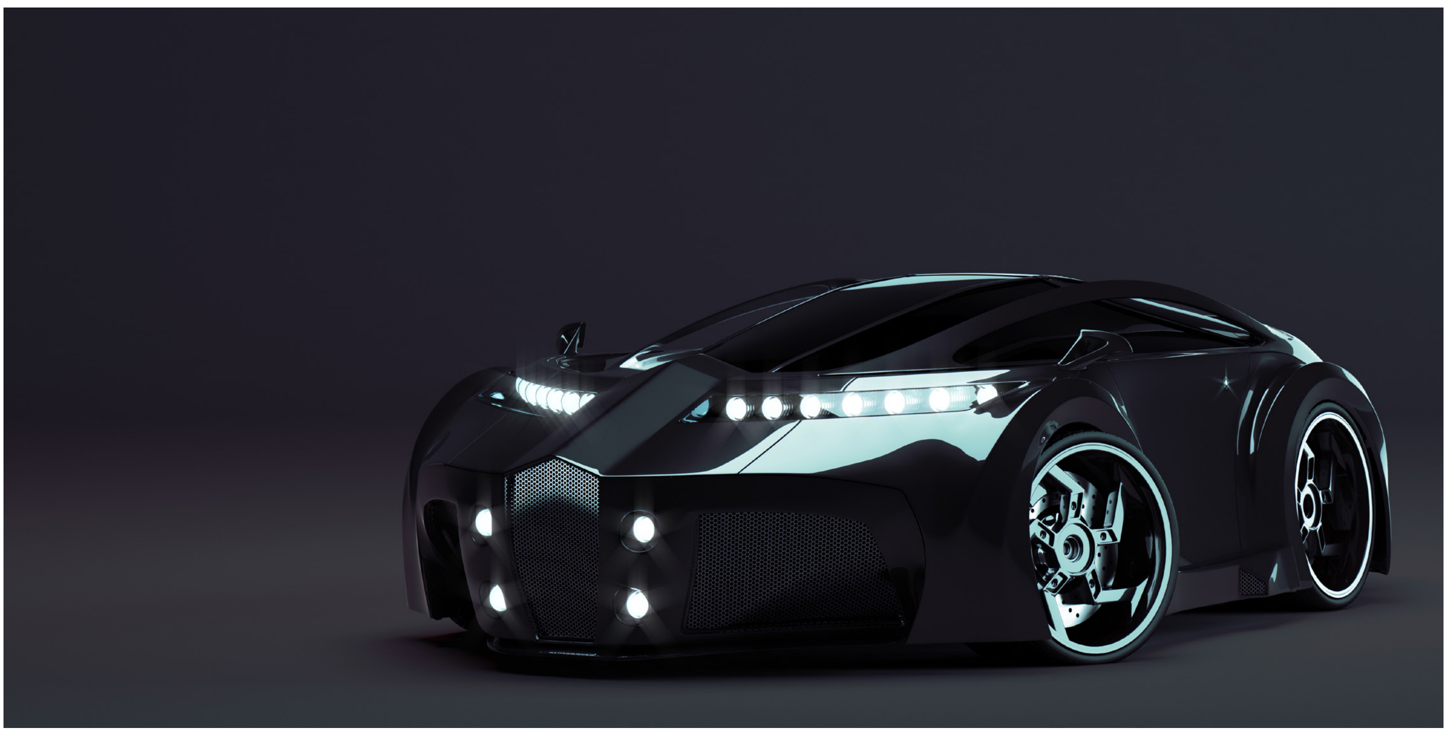

Figure 1. LED-Lighted Modern Car

Powering Automotive LEDs

LEDs have many automotive applications and are used in diverse configurations from a single LED to a string or matrix of LEDs. High-brightness (HB) LEDs require constant current for optimal performance. The current correlates with junction temperature and hence color. Accordingly, HB LEDs must be driven with current, not voltage. The power source can range from a 12V car battery up to a 60V boost converter to accommodate a long LED string. Vehicles that employ start/stop technology experience large battery voltage dips when the engine starts, causing the battery voltage to droop well below the typical 12V, sometimes even 6V or lower.

The Challenges

The proliferation of LED modules in automobiles places new requirements on system hardware including: reduced component size to fit additional electronics in the same space, improved energy efficiency to perform within the same or lower thermal budget, supporting connected and flexible architectures that enable multiple configurations, as well as accurate control to preserve LED light characteristics.

In the following sections, we will discuss five case studies that address the challenges for the following applications:

1. High-power front-end lights
2. Low/mid-power front-end lights
3. Infrared (IR) cameras for driver monitoring systems (DMS)
4. Rear lights and other exterior lights

Challenge 1 - High-Power Front-End Lights

Case Study I: Achieve Superior Automotive Front Lighting with a High-Power Buck LED Controller

High-power LEDs are becoming very popular in automotive front-lighting design (*Figure 2*) thanks to superior lighting characteristics and efficiency. The electronics that support LEDs must in turn be fast, efficient, and accurate for controlling light intensity, direction, and focus. They must support a wide input voltage range and must operate outside the car radio's AM frequency band to avoid electromagnetic interference (EMI). They must also support complex light patterns required in LED matrixes for AFS. This case study reviews a typical LED power management solution and presents a novel buck controller IC that enables a fast, efficient, and accurate LED lighting solution.

Figure 2. LED-Powered Car Headlight

Dimming

Dimming is a ubiquitous function in many automotive applications and an important safety feature for LED headlights. The human eye can barely detect light dimming from 100% to 50%. Dimming must go down to 1% or less to be clearly discernable. With this in mind, it is not surprising that dimming is specified by a ratio of 1000:1 or higher. Given that the human eye, under proper conditions, can sense a single photon, there is practically no limit to this function.

Since current must be kept constant to preserve color, the best dimming strategy for LEDs is PWM (pulse-width modulation), where the light intensity is modulated by time-slicing the current rather than by changing the amplitude. The PWM frequency must be kept above 200Hz to prevent the LED from flickering.

With PWM dimming, the limit to the minimum LED "on/off" time is the time it takes to ramp up/down the current in the switching regulator inductor. This may add up to tens of microseconds of response time, which is too slow for LED headlight cluster applications that require fast, complex dimming patterns. Dimming in this case can only be performed by individually switching on/off each LED in a string by means of dedicated MOSFET switches (SW_{1-K} in *Figure 3*). The challenge for the current control loop is to be fast enough to quickly recover from the output voltage transient due to switching in and out of the diodes.

LED Controller Characteristics

To be most effective, the LED controller must accommodate a wide input voltage range and have a fast-transient response as discussed earlier. A high, well-controlled switching frequency, outside the AM frequency band, is required to reduce radio frequency interference and meet EMI standards. Finally, high efficiency reduces heat generation, improving the LED light system's reliability.

The Headlight System

Sophisticated headlight systems utilize a boost converter as a front-end to manage both the variabilities of the input voltage (dump or cold-crank) and the EMI emissions. The boost converter delivers a well-regulated and sufficiently high output voltage (Figure 3). Dedicated buck converters, working from this stable input supply, can then handle the complexities of controlling the lamp's intensity and position by allowing each buck converter to control a single function, such as high beam, low beam, fog, daytime running lights (DRL), position, etc. Individual diodes are switched in and out by the switch matrix manager, allowing pixel-level adaptive lighting.

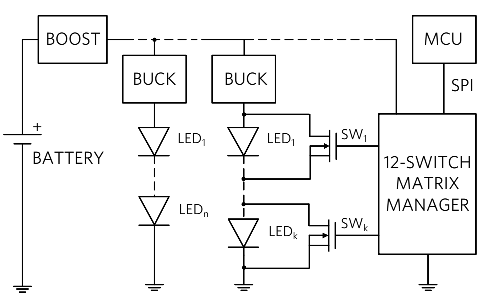

Figure 3. Advanced LED Lighting System

In this application, each buck converter's main control loop sets the current in its LED string, with two secondary loops that implement the overvoltage and overcurrent protection.

Typical High-Power Buck LED Driver Solution

A typical buck LED driver solution is shown in *Figure 4*. It uses a p-channel, high-side MOSFET, with relatively high $R_{DS(ON)}$ compared to an n-channel transistor, and a nonsynchronous architecture that relies on the Schottky diode D for current recirculation. Both are sure signs of an inefficient implementation.

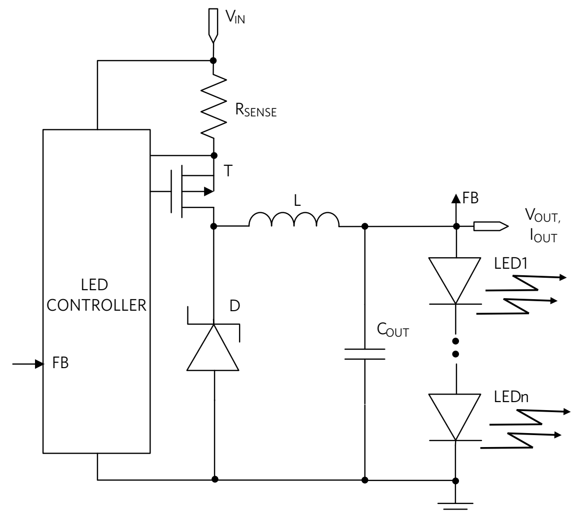

Figure 4. Typical Nonsynchronous Buck Led Driver

Typical Transient Response

Figure 5 shows another shortcoming of a typical solution in its transient response. In this test, in a string of 12 LEDs, the number of powered-up diodes has instantly risen from eight to twelve. The resulting output voltage step produces a current and voltage fluctuation that takes tens of microseconds to extinguish. A high-ratio PWM dimming circuit will sample this current for only a few initial microseconds where the amplitude is dipping, resulting in incorrect dimming brightness and color.

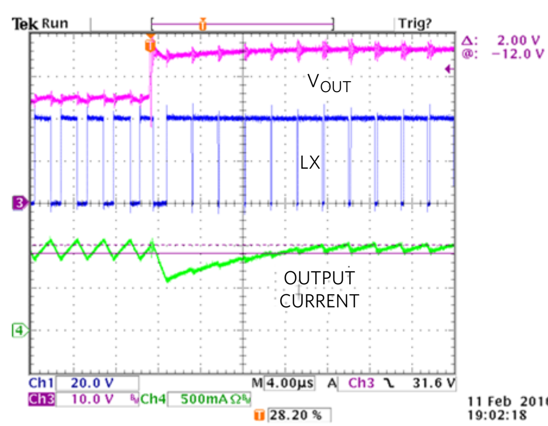

Figure 5. Typical Transient Response with Hysteretic Buck

Synchronous High-Power Buck LED Driver Solution

An ideal solution should meet the requirements of a wide input voltage range, fast transient response, high and well-controlled switching frequency, all while enabling high efficiency with synchronous rectification. The **MAX20078** LED controller enables such a solution (*Figure 6*).

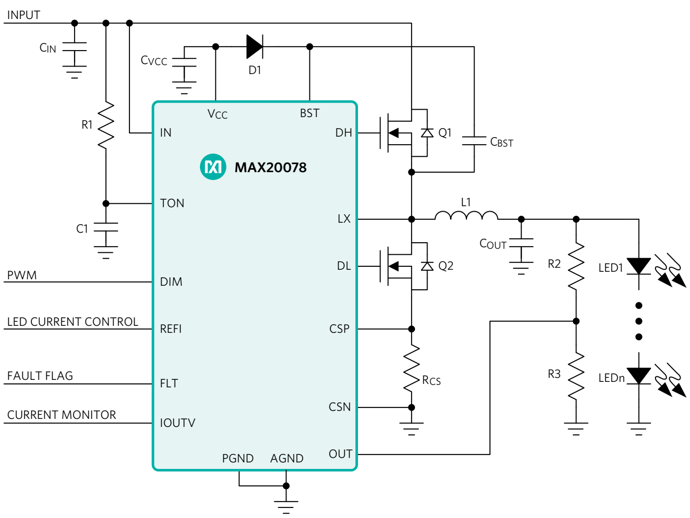

Figure 6. Synchronous High-Power Buck LED Driver

The MAX20078 LED controller uses a proprietary average current-mode-control scheme to regulate the inductor current while maintaining a nearly constant switching frequency. It operates over a wide 4.5V to 65V input range at switching frequencies up to 1MHz and includes both analog and PWM dimming. It is available in a space-saving (3mm x 3mm) 16-pin TQFN (regular or SW) or a 16-pin TSSOP package.

High Efficiency

Figure 7 shows the MAX20078-based LED driver's efficiency versus supply voltage. Two 107mΩ synchronous rectification MOSFET transistors provide high efficiency over a wide range of supply voltages.

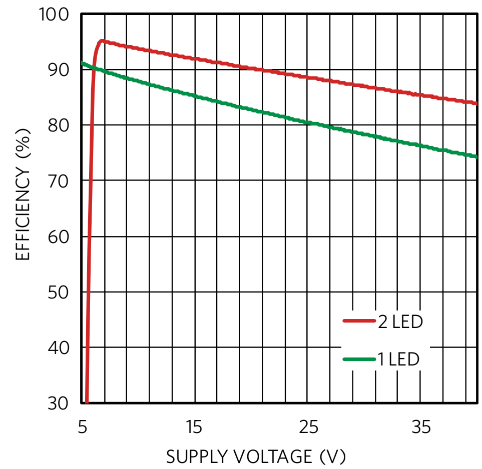

Figure 7. MAX20078 Solution Efficiency vs. Supply Voltage

Accurate Light Intensity Control

The proprietary architecture of the MAX20078 yields a transient response that is virtually error-free compared to that shown in Figure 5. In *Figure 8*, the increase in the number of diodes from eight to twelve does not produce any appreciable fluctuation in the output voltage or current.

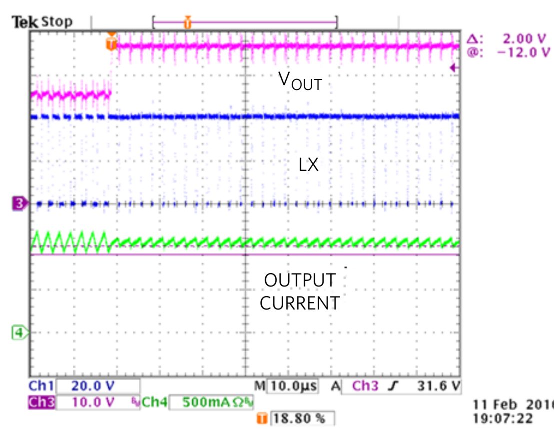

Figure 8. MAX20078 Transient Response

High Frequency of Operation

The on-time of the MAX20078 can be programmed for switching frequencies ranging from 100kHz up to 1MHz. Its on-time varies in proportion to both input voltage and output voltage, resulting in a switching frequency that is virtually constant. A high and well-controlled switching frequency, outside the AM frequency band, is easily set with the MAX20078. Radio frequency interference is reduced while the spread-spectrum feature meets EMI standards.

12-Matrix Switch Manager

The 12-matrix switch manager can be implemented by the **MAX20092**. The IC features a serial peripheral interface (SPI) for serial communication. The MAX20092 is a slave device that uses the SPI to communicate with an external microcontroller (µC), which is the master device. Each of the 12 switches can be independently programmed to bypass the LEDs across each of the switches in the string. Each switch can be turned fully on, fully off, or dimmed with or without fade-transition mode. The PWM frequency is set by an internal oscillator or set to an external clock source. The IC features open-LED protection as well as open- and short-LED fault reporting through the SPI. With open trace protection, if the trace, located between the MOSFET drain or the source, is disconnected from the LED, a fault will trigger. The MAX20092 is available in a 32-pin (5mm x 5mm) side-wettable TQFN (SWTQFN) package with a thermally enhanced exposed pad.

The boost converter in ***Figure 3*** is implemented with **MAX16990**/**MAX16992**, 36V, 2.5MHz automotive boost/ SEPIC controllers.

Conclusion

We have reviewed the many challenges in powering complex LED lighting systems and the requirements for optimal LED system performance. We showed how the MAX20078 meets those challenges using a novel LED controller architecture that provides accurate average current control, high-frequency operation outside the AM radio band, good transient response for high-ratio dimming accuracy, and high efficiency for minimum power consumption. Individual diodes are switched in and out by the MAX20092 switch matrix manager, allowing pixel-level adaptive lighting. These features in turn enable superior automotive exterior lighting, which is more efficient, supports complex light patterns and more accurately controls light intensity, direction, and focus.

Case Study II: Improve Matrix Lighting with the Next Generation of LED Buck Controllers

Modern automotive matrix lighting (***Figure 9***) often utilizes strings and matrices of LEDs, requiring an increasing number of integrated circuits to control them. New designs must usually pack more electronics in the same or smaller space.

To meet time-to-market constraints and provide for efficient use of design resources, it is imperative that LED modules designed for a given complex light pattern be easily reconfigured for a new pattern.

The space challenge clearly points to more integration of the LED controller building blocks, while the reconfiguration for fast time-to-market points to the ability to communicate with the LED controller IC.

In this case study, we will show how to pack more functionality in a smaller PCB space while adding flexibility to automotive matrix lighting.

Figure 9. Automotive LED Headlight

Typical Highly Integrated Solution

Integrating two controllers into a single IC is a good first step in the direction of up-integration. ***Figure 10*** shows a typical dual-channel automotive lighting implementation which uses nonsynchronous rectification. Unfortunately, in high-current applications, the use of nonsynchronous rectification, and the selection of p-channel transistors and Schottky diodes, leads to significant power inefficiencies.

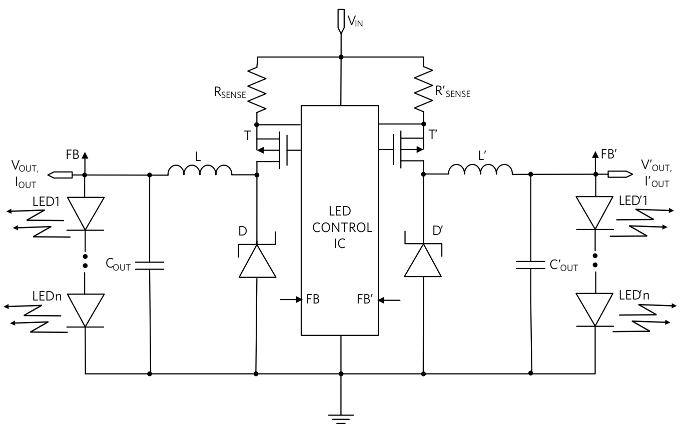

Figure 10. Typical Dual Controller Nonsynchronous Rectification Solution

In one possible nonsynchronous implementation, n-channel transistors can be used on the high-side instead of p-channel transistors in an attempt to recover some efficiency. However, this solution requires huge n-channel MOSFETs to compensate for the lossy Schottky diodes on the low side. The dual controller may also be housed in a bulky TSSOP package, further adding to the solution footprint. ***Figure 11*** shows that a typical n-channel, nonsynchronous rectification solution occupies a board area of 264mm².

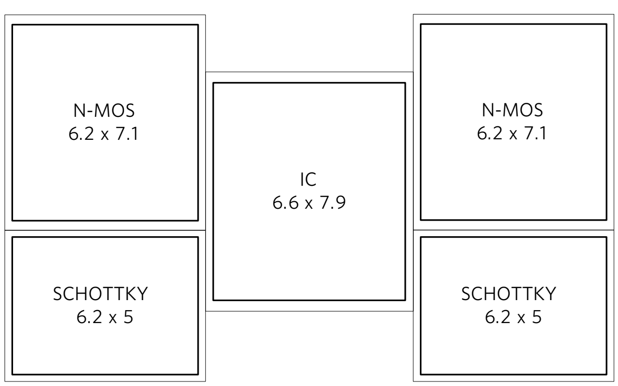

Figure 11. Nonsynchronous Rectification Solution Footprint (264mm²)

The Synchronous Rectification Advantage

As an example, for a 48V input and 12V output, the buck converter works with a duty cycle of about 25%. This means that the high-side transistor (T in ***Figure 10***) conducts only 25% of the time. The external rectifier diode (D) conducts the remaining 75% of the time, which accounts for most of the power dissipation. On the other hand, if we utilize a synchronous architecture, the diode is replaced with a low-side MOSFET acting as a synchronous rectifier. We can trade off the high drop across the diode with the low drop across the MOSFET transistor's on-resistance, $R_{DS(ON)}$. The MOSFET conduction loss can easily be one order of magnitude smaller than the Schottky power loss at full load. Clearly, the logical way to minimize power dissipation is to use synchronous rectification.

A Synchronous High-Power Dual-Buck LED Driver Solution

The synchronous, all n-channel, buck LED controller with SPI interface in ***Figure 12***, integrates two channels in a single IC, reducing the solution footprint and the BOM. Two out-of-phase channels smooth out the input current, spreading out its energy, resulting in lower RMS current and lower EMI emissions. With a lower RMS current, smaller and less expensive input capacitors can be used. A high, well-controlled switching frequency, outside the AM frequency band, reduces radio frequency interference and meets EMI standards. Fast transient response prevents output voltage and current fluctuations, consequent to instantaneous variation of the diode string length in high-ratio dimming applications. The device is ideal for matrix lighting and LED driver module (LDM) platforms.

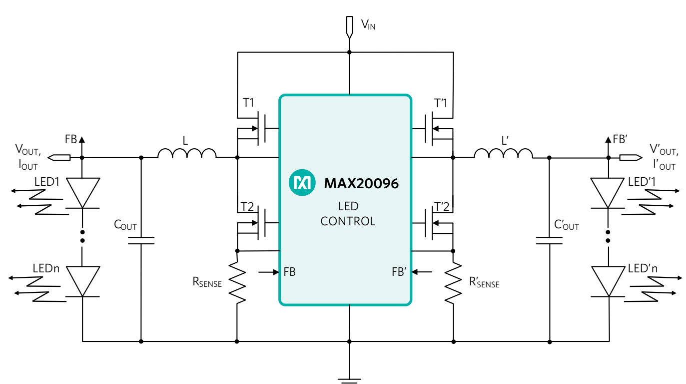

Figure 12. Synchronous High-Power Dual-Buck LED Controller

The utilization of an advanced silicon process allows the entire dual controller function to be housed in a small package. Elimination of the Schottky diode greatly reduces power losses in high current applications, while allowing the use of smaller discrete MOSFETs (*Figure 13*).

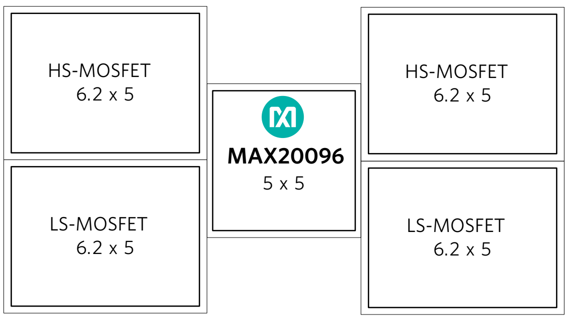

Figure 13. Synchronous Rectification Solution Footprint (149mm²)

With synchronous rectification, the net solution size goes down from 264mm² to 149mm², a 43% reduction. Further system integration can be obtained by using dual MOSFET devices (HS- and LS-MOSFET integrated in a single package).

High Efficiency

Figure 14 shows the efficiency of the LED driver. Two synchronous rectification MOSFET transistors (HS 107mΩ, LS 58mΩ), in a small LFPACK56 package, provide high efficiency over a wide range of load currents.

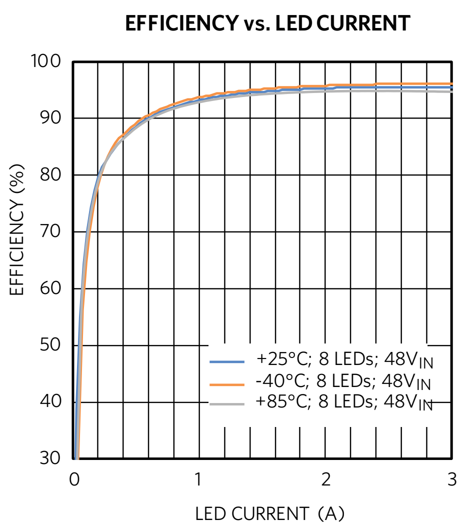

Figure 14. LED Driver Solution Efficiency vs. Load Current

Serial Peripheral Interface

The SPI interface allows flexibility and reuse of the LED lighting module since it is compatible with standard microcontrollers (µCs) from a variety of manufacturers. Dimming of the LED lights can be performed through SPI. Fault conditions, output currents/voltages on both channels and junction temperature can be read back through the SPI interface. In fail-safe mode, if SPI communication is cut, the device can still operate in analog mode.

Conclusion

In this case study, we showed how to pack more functionality in a smaller PCB space while adding flexibility to the next generation of LED controllers for automotive matrix lighting. The **MAX20096** synchronous, n-channel, buck LED controller integrates two out-of-phase channels in a single IC reducing the BOM and PCB space occupancy. It also enables higher flexibility and reuse via its SPI interface. The simpler **MAX20097** addresses applications that do not require SPI communication.

Challenge 2 - Low/Mid-Power Front-End Lights

Case Study: Flexible LED Boost Controller Simplifies Low/Mid-Power Headlight Design

In low/mid-power headlight systems, headlight functions like high beam and low beam are performed by simpler, single-function controller ICs.

A low/mid-power headlight system architecture that can accommodate a series of LEDs uses a boost converter. In the boost controller IC of *Figure 15*, one of the three feedback loops (CURRENT LOOP) ensures tight control of the output current. The other two feedback loops perform overvoltage protection (OVP LOOP) and overcurrent protection (OCP LOOP) for a string of 12 diodes, which creates 42V across the string (3.5V per LED).

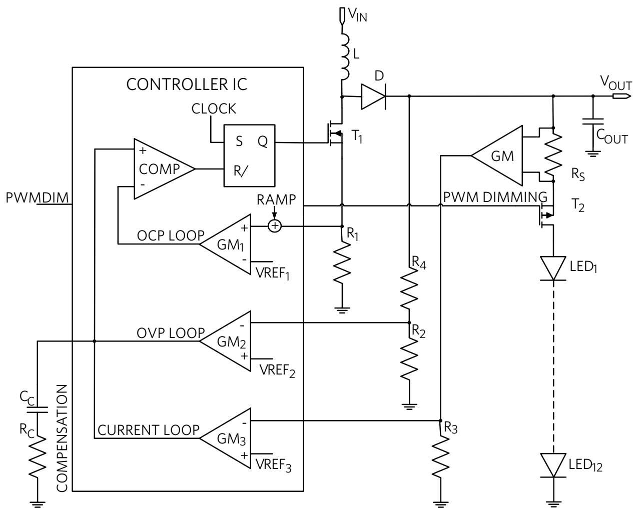

Figure 15. Typical Boost LED Control System

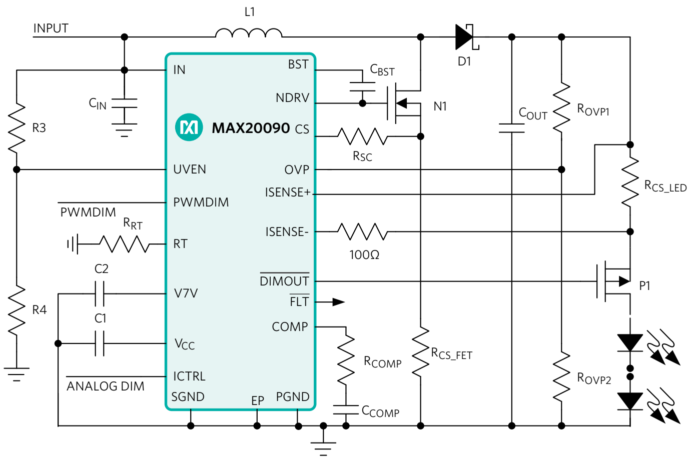

Figure 16. MAX20090 Boost LED System

In addition to current and voltage control, the IC must be equipped with all the features previously described (dimming, spread spectrum, etc.). High-side current sensing (via the resistors R_3 and R_S) is required to protect the LED system in case of shorts from the output to the ground or battery input.

Flexible LED Controller Architecture

Ideally, an LED controller should have a flexible architecture that supports multiple configurations that implement different features. We have discussed the boost configuration, but we should also consider the buck-boost configuration. A buck-boost mode configuration is necessary if the diode string is short, for example two or three LEDs (7V or 10.5V), against a battery voltage that can vary from less than 6V (cold crank) up to 16V. If the concern is input-to-output isolation, then a SEPIC (discontinuous output current) or a Chuck (continuous output current) converter may be the right solution. A single controller that supports many architectures has clear advantages of economies of scale and ease of reuse.

The **MAX20090** (*Figure 16*) is the most flexible controller for driving LEDs, allowing boost, high-side buck, SEPIC mode, or buck-boost mode configurations. The device is a single-channel HB LED controller for automotive front-lighting applications such as high beam, low beam, DRLs, turn-signal indicators, and fog lights. The HB LED controller can accept a 5V to 65V input voltage and drives a string of LEDs with a 65V maximum output voltage. The PWM input provides LED dimming ratios of up to 1000:1 and the ICTRL input provides additional analog-dimming capability.

Low EMI and Low Noise

A 200kHz to 2.2MHz programmable switching frequency allows the MAX20090 to operate well outside the AM radio frequency band, avoiding interference with the automotive radio signal. Built-in spread-spectrum modulation also improves electromagnetic compatibility performance. Spread-spectrum dithering is added to the oscillator to alleviate EMI problems in the LED controller. The boost converter oscillator (RT pin in F*igure 16*) is synchronized to the positive-going edge of the PWM dimming pulse (PWMDIM). This means that the NDRV pulse goes high at the same time as the positive-going pulse on PWMDIM (see Figure 16). Synchronizing the RT oscillator to the PWMDIM pulse guarantees that the switching-frequency variation over a period of a PWMDIM pulse is the same from one PWMDIM pulse to the next. This prevents flickering during PWM dimming when spread spectrum is added to the RT oscillator.

Conclusion

We have discussed the automotive headlight environment including its various functions, concerns, and corresponding LED controller configurations. The MAX20090 LED controller supports a high number of architectures for automotive exterior lighting and greatly simplifies their design. The flexible design options use boost, high-side buck, SEPIC mode, or buck-boost mode configurations, providing clear advantages in economies of scale and ease of reuse. In addition, high switching frequency allows operation above the AM radio frequency band while built-in spread-spectrum modulation reduces electromagnetic interference.

Challenge 3 - IR Camera for Driver Monitoring Systems (DMS)

Case Study: IR Camera for DMS

Infrared (IR) cameras, utilizing an IR-LED diode in combination with a CMOS sensor, help recognize hazardous microsleep that affects motorists. The advantage of using infrared is its invisibility to the human eye and its ability to operate day and night. Image analysis, processes information to determine if the driver is fatigued or distracted. With a typical forward voltage of 2.8V and a forward current of 1A, the electronics that drives the LED is directly connected to the battery.

As an example, the **MAX20050** buck LED driver is an ideal solution (*Figure 17*). The fully synchronous, 2A step-down converter integrates two low $R_{DS(ON)}$ 0.14Ω (typ) MOSFETs, assuring high efficiencies up to 95%. With its 4.5V to 65V input supply range, the MAX20050 can easily withstand battery load dump, making it ideal as a front-end buck converter in DMS applications. It helps feed the IR circuitry that checks on the driver's state-of-alert. This high level of integration yields minimum PCB area occupation.

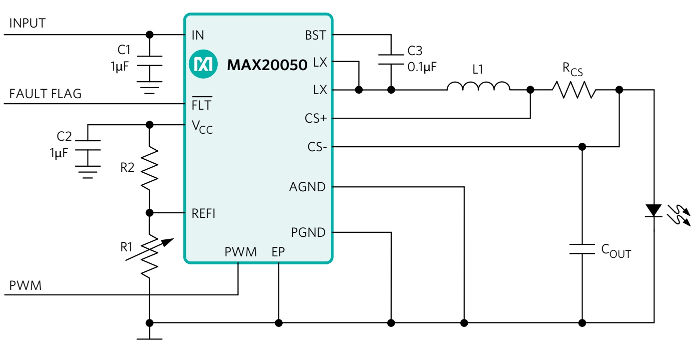

Figure 17. IR-LED Driver Solution

The **MAX20050**/**MAX20052** utilize internal loop compensation to minimize component count, while the **MAX20051**/**MAX20053** use external compensation for full flexibility. The MAX20050/MAX20051 have an internal switching frequency of 400kHz, while the MAX20052/MAX20053 have an internal switching frequency of 2.1MHz.

For higher power, the MAX20078 synchronous buck LED controller can be utilized. For higher voltage applications, the MAX20090 high-voltage HB LED controller is an excellent choice.

Challenge 4 - Rear Lights and Other Exterior Lights

Case Study: Powering Rear Lights and Other Exterior Lights

Rear lights and other exterior lights like stop lights, door-handle lights, etc., require less power and are handled by simple single-function ICs. Here, the MAX20090 can be utilized as a boost LED controller or for long strings that require voltages above the minimum battery voltage or as a front-end boost voltage regulator. The MAX20050 buck converter can drive short strings of diodes connected directly to the battery. Alternatively, it can drive long strings of diodes with the help of a front-end boost converter.

For noise-sensitive applications, a linear LED driver can be utilized. The **MAX16823** three-channel LED driver (*Figure 18*) operates from a 5.5V to 40V input voltage range and delivers up to 100mA per channel to one or more strings of HB LEDs. Each channel's current is programmable using an external current-sense resistor in series with the LEDs. Three DIM inputs allow a wide range of independent pulsed dimming in addition to providing the on and off control of the outputs. Wave-shaping circuitry reduces EMI while providing fast turn-on and turn-off times.

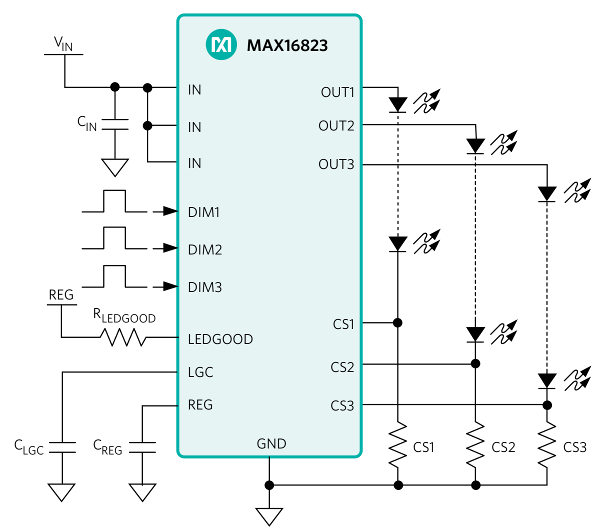

Figure 18. Linear Driver for Low Noise

Summary

Table 1 is a summary of automotive LED driver applications and proposed product solutions. See the **Product Selector Table** to compare product specifications.

Table 1. Automotive LED Drivers

Application	Function	Product
High-Power Front-End Lights	36V, 2.5MHz Automotive Boost/SEPIC Controllers	MAX16990/MAX16992
	Synchronous High-Power Buck LED Controller	MAX20078
	Synchronous High-Power Dual-Buck LED Controller	MAX20096/MAX20097
	12-Switch Matrix Manager for LED Lighting	MAX20092
Low/Mid-Power Front-End Lights	High-Voltage High-Brightness Boost LED Controller	MAX20090
	2A Synchronous Buck LED Drivers with Integrated MOSFETs	MAX20050/MAX20051/ MAX20052/MAX20053
IR Camera for DMS	2A Synchronous-Buck LED Drivers with Integrated MOSFETs	MAX20050/MAX20051/ MAX20052/MAX20053
	Synchronous High-Power Buck LED Controller	MAX20078
	High-Voltage High-Brightness Boost LED Controller	MAX20090
Rear Lights and Other	High-Voltage High-Brightness Boost LED Controller	MAX20090
	2A Synchronous Buck LED Drivers with Integrated MOSFETs	MAX20050/MAX20051/ MAX20052/MAX20053
	High-Voltage, 3-Channel Linear High-Brightness LED Driver with Open LED Detection	MAX16823

The block diagram in *Figure 19* shows Maxim's LED drivers by application.

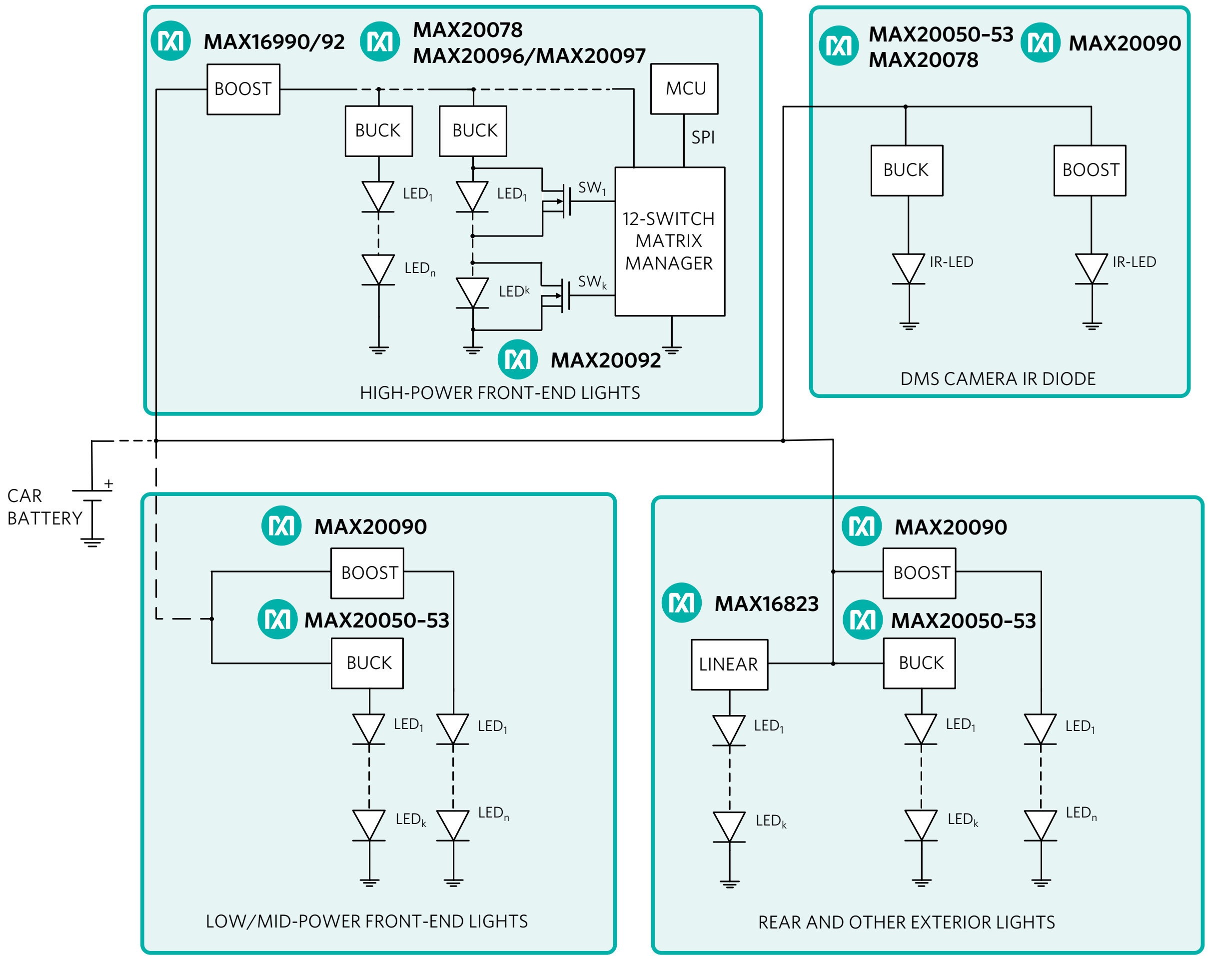

Figure 19. LED Drivers by Application

The proliferation of LED modules in automobiles places new requirements on system hardware including: reduced component size to fit additional electronics in the same space, improved energy efficiency to perform within the same or lower thermal budget, connected and flexible architectures supporting multiple configurations, and accurate control preserving the LED light characteristics.

In this design guide, we discussed five case studies that address the challenges in high-power and low/mid-power front-end lights, IR cameras used in DMS as well as rear and exterior lights. In each case, we proposed the best solution based on the application at hand.

Product Selector Table

LED Drivers for Automotive Applications

Part No.	Max. No. of LEDs	LED Channels	LED Configuration	I_{LED} per Channel (max) (A)	V_{IN} (min) (V)	V_{IN} (max) (V)	I_{CC} (max) (mA)	LED String Voltage (max) (V)	Oper. Freq (kHz)	Package-Pins
MAX16803	10	1	Series	0.35	6.5	40	3	38.6	—	TQFN-16
MAX16815	10	1	Series	0.1	6.5	40	2	38.6	—	SOIC-8, TDFN-EP-6
MAX16822A	15	1	Series	0.5	6.5	65	1.5	63	2000	SOIC(N)-8
MAX16823	10	3	Series-Parallel	0.1	5.5	40	3	39.1	—	TQFN-16, TSSOP-16
MAX16824	9	3	Series-Parallel	0.15	6.5	28	10	38.6	—	TSSOP-16
MAX16832	15	1	Series	1	6.5	65	1.5	63	2000	SOIC-8
MAX16833	15	1	Series	10	5	65	2.5	65	1000	TSSOP-16
MAX16834	40	1	Series	10	4.75	28	6	250	1000	QFND-20, TQFN-20, TSSOP-20
MAX16839	10	1	Series	0.1	5	40	10	39.1	—	SOIC-8, TDFN-EP-6
MAX20050	15	1	Series	2	4.5	65	10	60	400	TDFN-12
MAX20051	15	1	Series	2	4.5	65	10	60	400	TSSOP-CU-14, TSSOP-14
MAX20052	15	1	Series	2	4.5	65	10	60	2100	TDFN-12
MAX20053	15	1	Series	2	4.5	65	10	60	2100	TSSOP-CU-14, TSSOP-14
MAX20078	15	1	Series	30	4.5	65	50	60	100, 250, 262, 300, 500, 700, 750, 1000	TQFN-CU-16, TQFN-16, TSSOP-CU-16
MAX20090	15	1	Series	3	5	65	5	60	250, 262, 300, 500, 750, 1000, 1200, 1500, 2000, 2100	TQFN-CU-20, TQFN-20, TSSOP-CU-20
MAX20092	12	12	Series-Parallel	1.5	4.5	5.5	1.3	56	—	TQFN-CU-32
MAX20096	30	2	Series	30	4.5	65	10	60	100, 250, 262, 300, 500, 700, 750, 1000	TQFN-CU-32
MAX20097	30	2	Series	30	4.5	65	10	60	100, 250, 262, 300, 500, 700, 750, 1000	TSSOP-CU-28

Note:
1. All parts operate at -40°C to +125°C temperature range.

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