by **Keith Szolusha** | Linear Technology Corporation

SELECTING OPTIMUM DRIVERS FOR MAXIMIZING SOLID-STATE LED LIGHTING PERFORMANCE

Automobile manufacturers are increasingly taking advantage of the latest technologies in solid-state LED lighting to enhance the aesthetics and performance of their 2007–2008 model vehicles by using these lighter, smaller and more reliable devices for interior and exterior illumination. However, to maximize the benefits of LED lighting, the drivers must be optimal. In this article, the author discusses various automotive LED applications and their optimum driver requirements.

High-power LEDs promise a growing number of advantages, including lower long-term cost and longer life, over both incandescent light bulbs for interior lighting, and halogen or HID lamps used in headlights and brake lights. The nature of driving an LED or string of LEDs directly from a typical car battery requires a dc-dc converter to accurately regulate a constant LED current for uniform light intensity and color integrity. The converter must also protect the LEDs from the vagaries of the car battery bus. The dc-dc converter should be optimized for the number and type of LEDs in a string and for the functionality of each application such as headlights, taillights, signal lights, interior reading lights, instrument-panel backlights or LCD GPS monitor display lighting.

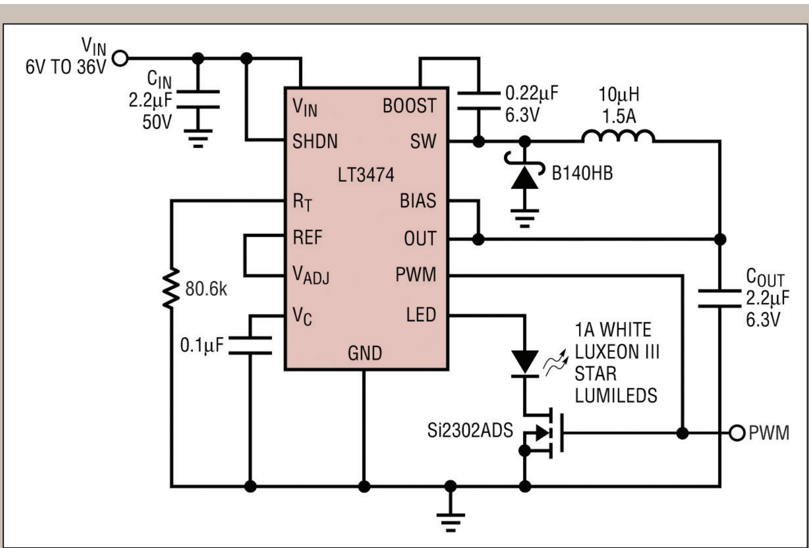

Figure 1. High voltage step-down 1A LED driver LT3474 with 250:1 PWM dimming.

Deciding which dc-dc converter IC and topology to use for each automotive LED application depends on the following factors:

Topology: The relation of LED voltage to battery voltage range dictates a buck, boost or buck-boost topology that must be able to maintain control of the constant LED current over the full battery voltage range.

Dimming: Large-ratio LED dimming must preserve chromatic characteristics across brightness levels and avoid visible-to-the-eye ripple or oscillations.

Efficiency: Highly efficient operation of the dc-dc converter and low power consumption are crucial requirements in driving high brightness (HB) LEDs since power losses drain the battery during non-operation and are dissipated as heat during operation in a thermally stressed automotive environment.

DRIVING A SINGLE LED

In-cabin white dome and reading lights may use just a single 3 W LED that produces 75 lumens to 100 lumens. This LED, such as a Luxeon III star from Lumileds (www.lumileds.com) has a typical forward voltage in the range of 3 V to 4.5 V with 1 A to 1.5 A of maximum current. The simplest LED driver design uses a step-down (buck) regulator to drive this LED from the full voltage range of the car battery. Figure 1 shows an example of a single-LED interior lighting circuit with dimming. The typical operating voltage range of the car battery is between 9 V to 16 V. A drained battery may drop down to 9 V before the car is started and the alternator charges it back up to 14.4 V while the motor is running. With some spikes and some overshoot, this typical dc battery voltage can be as high as 16 V. A normal, charged car battery rests at 12 V when the motor is not operating.

During cold-crank conditions, a car battery may drop down as low as 4 V. Critical electronics must work at these low voltages, but not necessarily the interior lighting. High voltage transients are also

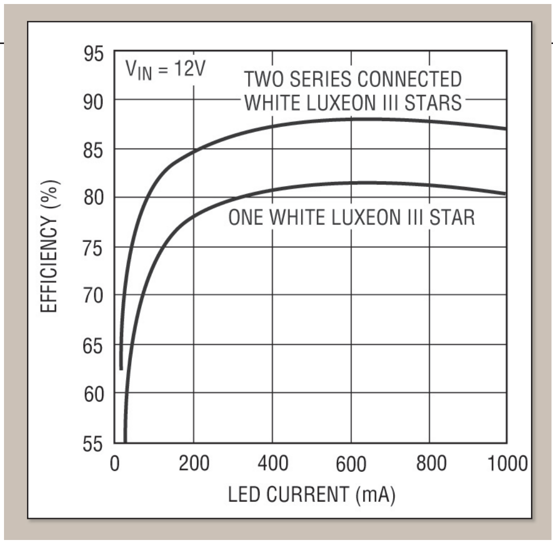

Figure 2. LT3474 buck drives single or multiple LEDs with high efficiency.

very common in car batteries. The long cables from the battery to different locations around the chassis and the electronically noisy automobile environment ensure that high-voltage spikes are ever-present. Typical transients of 36 V are necessary to consider when choosing a switching regulator for automotive design. Higher voltage spikes may be filtered with simple transient voltage suppressors or RC filters, in most cases. The converter IC used in Figure 1 is a high-voltage, high-current buck LED converter with a wide PWM dimming ratio that can drive one or more LEDs up to 1 A. It has several features that make it suitable for driving LEDs in an automobile environment. It is a dedicated LED driver with an on-board high-voltage npn power switch and an internal current sense resistor to minimize board space, reduce component count and simplify design while maintaining high efficiency.

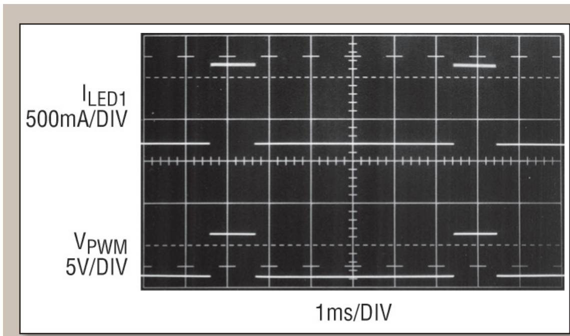

Figure 3. PWM dimming LED current waveform of circuit in Fig. 1.

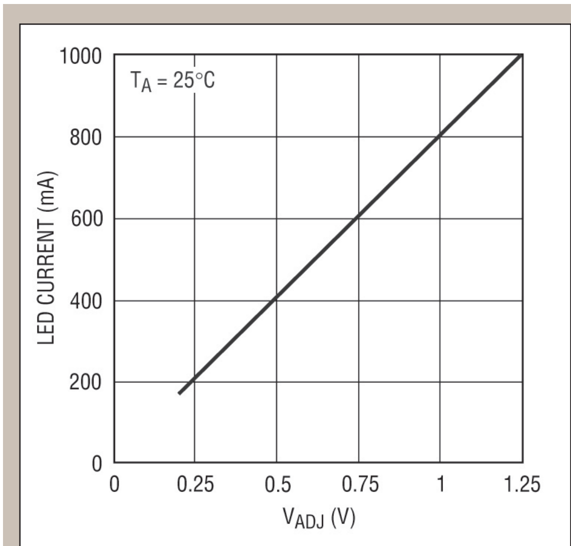

Figure 4. LED current vs. V_{ADJ} pin voltage.

The wide 4 V to 36 V operating input voltage range allows the LED driver converter to operate directly from the battery under all conditions while maintaining constant LED current regulation.

A low-voltage internal current sense resistor eliminates the need for a costly external op-amp to provide a low-voltage reference in the current sense resistor path. The buck regulator design and the adjustable high-frequency range of the LT3474 allow extremely low-ripple output current even with very small, low-cost ceramic output capacitors. X5R, X7R or equivalent ceramic capacitors are recommended for all of the converters discussed in this article.

Efficiency for the single LT3474 LED buck regulator is greater than 80% at $12V_{IN}$ for LED currents above 200 mA, as shown in Figure 2. As the LED current and brightness of the LED is reduced using analog control of the V_{ADJ} pin, efficiency appears to drop off, but power consumption remains very low. Tailored for automotive and battery-powered applications, this LED driver consumes less than 2 μA (typically 10 nA) when placed in shutdown. Shutdown can also be used as an LED on/off button function from a physical pushbutton or microcontroller IC.

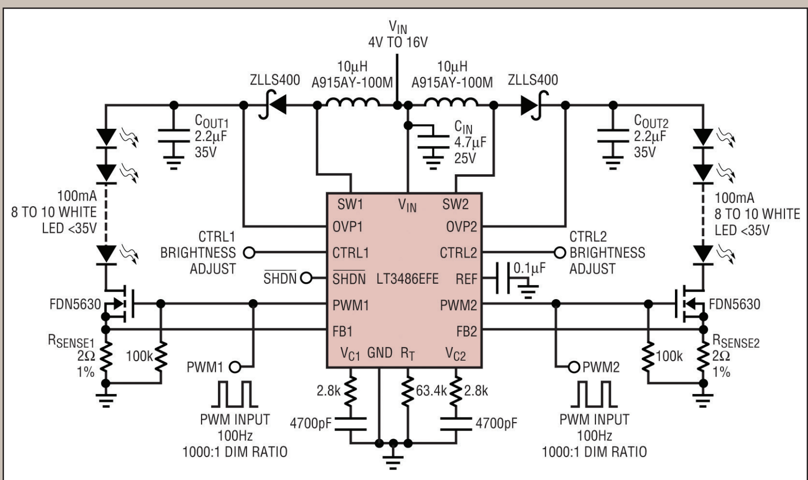

Figure 5. LT3486 drives 20 white LEDs at 100 mA in a GPS LCD monitor.

PWM DIMMING AND BRIGHTNESS CONTROL

LED brightness can be controlled on the LT3474 in Figure 1 with an analog voltage input to the V_{ADJ} pin or a digital PWM signal to the gate of the PWM dimming MOSFET and the PWM pin. Analog brightness control reduces the constant LED current from 1A to a lower value by reducing the internal sense resistor voltage. Although this is a simple way to decrease the brightness of the LED, the accuracy of the LED current is reduced at lower currents and the chromaticity of the LED changes. The graph in Figure 4 displays typical LED current as a function of V_{ADJ} pin voltage. The accuracy is typically 2% at 1 A, but only 3.5% at 200 mA. The dimming ratio has a practical limitation around 10:1.

Another method of reducing the brightness of the LED is digital PWM dimming. The PWM MOSFET in series with the LED creates the waveform shown in Figure 3 when a single white LED is dimmed at 1 A constant current. When the LED and PWM MOSFET are on during PWM on-time, the current is a well-regulated 1 A. During PWM off-time, the current is zero. This maintains the chromaticity and true color characteristics of any LED while reducing its brightness. Because the PWM function is inside the IC, the response to PWM is very fast in returning the LED to its programmed LED current. It has a 40 µs minimum dimming on-time, which gives a 250:1 digital PWM dimming ratio, more than sufficient for interior lighting.

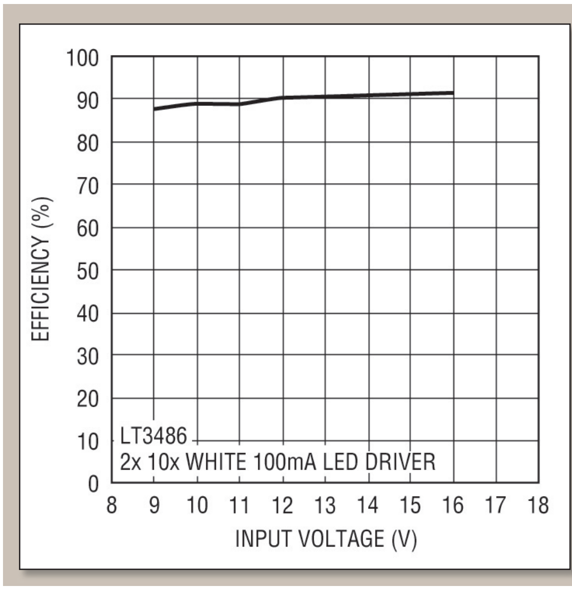

Figure 6. Efficiency for the LT3486 driver with 2 x 10 white LED strings is 90% over the operating range of the battery.

LCD MONITOR DISPLAYS WITH LED STRINGS

GPS navigation and in-cabin entertainment displays are increasingly popular in luxury vehicles and mainstream consumer models. These LCD displays require constant and bright strings of LEDs for use in daylight conditions and wide dimming ratios for nighttime operation. Strings of LEDs pose a different challenge than the single LED dome light. The multiple strings of 6-10 LEDs in these displays are usually lower current

For nighttime viewing of the extremely bright displays that are also used during daylight hours, a 1000:1 dimming ratio is useful.

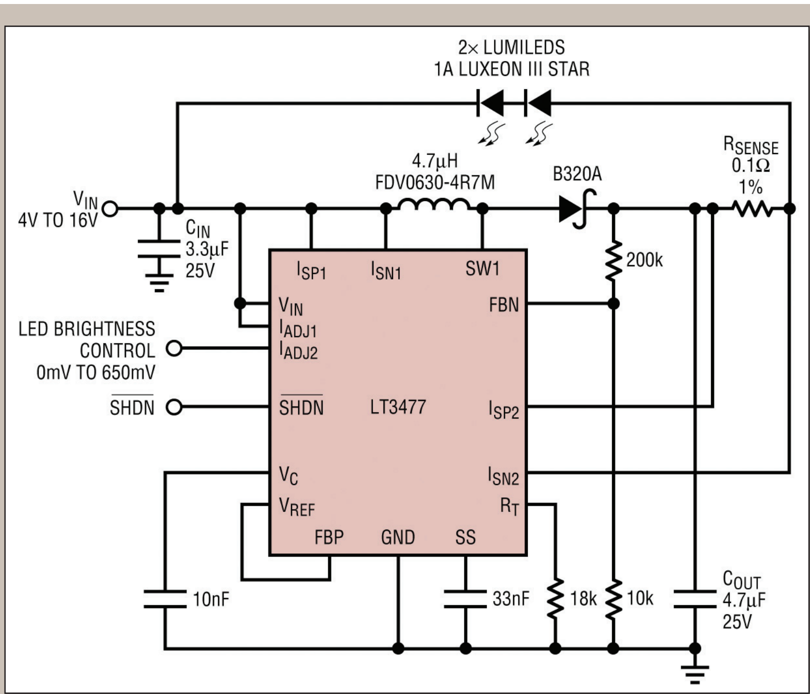

Figure 7. Buck-boost drives brake and signal 1A LED strings with 80% efficiency.

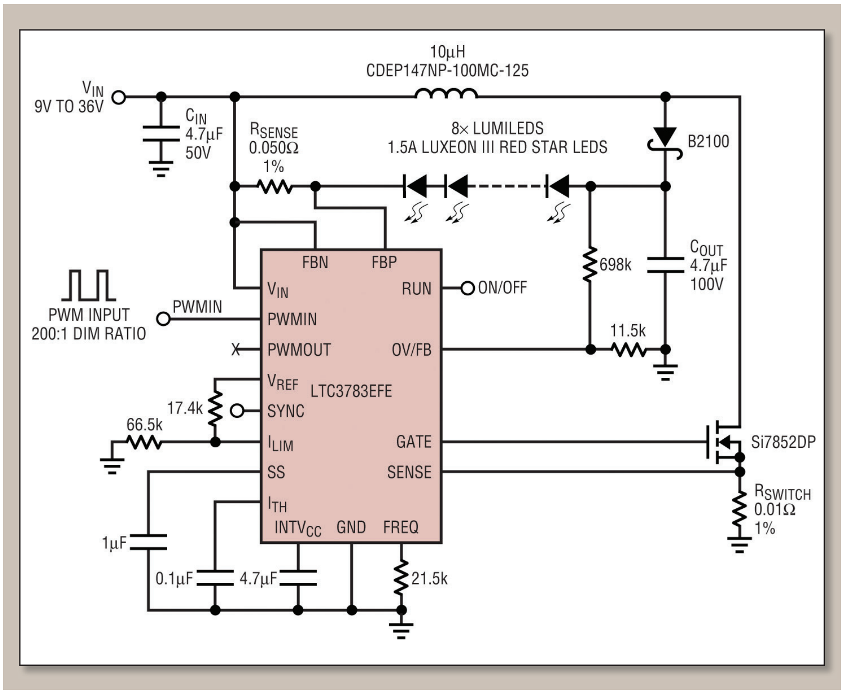

Figure 8. Brake light LED driver for 8 x 1.5 A red LEDs.

(<150 mA) for smaller LEDs, but stack up to a higher voltage than the car battery (>20 V). A high-power boost dc-dc LED driver with high efficiency and high PWM dimming capability is necessary for these monitors.

The LT3486 dual output boost LED driver application in Figure 5 drives two strings of LEDs with a constant current of 100 mA for up to 36 V of LED forward voltage. The boost converter LED driver provides high efficiency with a low voltage sense resistor in series with the LEDs and PWM dimming MOSFET. The full range of battery voltage, 9 V to 16 V, is below the operating forward voltage of the LED strings.

The advantage of using two LED drivers with two 10-LED strings, instead of a single 20-LED string, is that the maximum switch voltage remains that of a single 10-LED string (42 V maximum switch voltage, 36 V maximum output voltage). Efficiency, as shown in Figure 6, is approximately 90% over the operating range of the battery. If the battery voltage drops down to 4 V, the boost LED driver will still operate, but possibly in a current-limited state, depending on the programmed LED current and number of LEDs in the strings. Not only is the operating efficiency high, but the converter shutdown current consumption is less than 1 µA (typically 100 nA), merely sipping from the car battery when it is off. The LED current is set by selecting the external sense resistor value based on a very low 200 mV sense resistor voltage for maximum efficiency. The LED current can be adjusted separately on either string with an analog signal on the CTRL pin for a 10:1 accurate dimming ratio or with a PWM signal for very high dimming ratio.

For nighttime viewing of the extremely bright displays that are also used during daylight hours, a 1000:1 dimming ratio is very useful. The LT3486 has a PWM dimming ratio of 1000:1 with its unique internal PWM dimming architecture . An ultrafast PWM response time returns the LED current to 100 mA from 0 mA in less than 10 µs for true-color PWM dimming. Using two such drivers for four strings of R-G-G-B in top-end displays provides 1000:1 dimming and maintains the true-color of the display during dim nighttime operation.

SIGNAL, TAIL AND HEADLIGHTING

Exterior signal, tail and headlights require the highest power dc-dc LED drivers because they have the brightest and most numerous LEDs. Although extremely bright LED headlights are not yet as common due to thermal and regulatory constraints, red and amber brake and signal lighting are increasingly common based on their excellent aesthetic properties and durability. Driving high-power strings of amber and red LEDs poses similar challenges for interior and trim lighting, but on a different scale. Typically, high dimming ratios are not necessary, but simple on/off and high/low brightness functions are useful. The high power LED string voltage usually crosses over the full voltage range of the car battery, creating the need for an LED driver with both step-up and step-down (buck-boost) capability. Such a buck-boost LED driver shown in Figure 7 drives two high power LEDs at 1 A. The LEDs do not need to be ground-referred and are connected between what would typically be the converter output and the battery input. The LT3477 has two unique, floating 100 mV current-sense input pins that are connected to a non-ground-referred current sense resistor in series with the string of LEDs. Accurate LED current regulation is

provided at up to 1 A over the operating voltage range of the car battery and below. Its shutdown pin is used for on/off function of the lights and for reducing the input current to 1 µA (typically 100 nA) when not in use. The I_{ADJ} pin is used for dimming for brake and taillight applications such as the rear signal or brake lights. True color PWM dimming is not necessary for these applications.

Automotive taillights use more red LEDs at higher currents, up to 1.5 A. A string of 6–10 LEDs is fairly common for different lights, producing a total of up to 140 lumens per LED and around 1000 or more lumens per string. These lights not only need to provide very high current, but high voltage as well. These lights are driven directly from the car battery with no possibility of failing from high battery voltage transients. Being far from the battery, these lights are subject to wide-ranging input voltages.

The LTC3783, high-power LED driver powers 6–10 3 W red LEDs in a buck-boost topology as shown in Figure 8. The external switching MOSFET and switching current sense resistor provide maximum design flexibility for high power and high-voltage LED driver designs. The 9 V to 36 V input and up-to-25 V LED string output at 1.5 A require a 100 V switch rating and greater than 8 A peak switch current capability if the battery drops below 9 V. The constant 1.5 A battery current is well-regulated over the entire car battery voltage range. For brake and taillight dimming, the LED current can be reduced to up to 200:1 dimming ratio with a PWM signal tied directly to the PWM pin of the driver at 100 Hz. At 1 kHz, this dimming ratio is reduced to 20:1, sufficient for taillight applications. An adjustment to the ILIM pin can also reduce the LED current.

High efficiency is most important in the highest power applications of the vehicle. With up to 36 W output in this application, the 93% efficiency reduces the draw on the battery during braking, especially when the car is not running. The RUN pin, used for on/off control of the brake lights, reduces the LED current to 20 µA. The flexibility of the LTC3783 high-power LED driver enables it to turn into a high-power boost regulator to drive an even higher voltage string of LEDs of up to 60 W by connecting the string of LEDs to GND as opposed to V_{IN} and turning the topology into a boost converter. This requires that the LED string voltage is greater than the battery voltage maximum of 36 V, and that LED disconnect is provided via a PWM pin while the light is turned off. High lumen headlight applications using bright white LEDs will soon adopt this high-power LED driving boost topology.

CONCLUSION

There are many different automotive LED applications that require a dedicated high power, yet simple and efficient LED driver. Wide input voltage range, low current consumption during off-time, high PWM and analog dimming ratios, and excellent LED current regulation are often required in different combinations depending on the application.

ABOUT THE AUTHOR

Keith Szolusha is an applications engineer with Linear Technology Corp., Milpitas, Calif. He holds a BSEE '97 and MSEE '98 from MIT, Cambridge, Mass.