BESPOKE POWER

LEDs vs Incandescent Bulbs in Automotive Lighting

BPWP-001

Overview

Thomas Edison invented the incandescent bulbs in 1880, which has been the mainstay of the lighting world for over 100 years. They are thermal devices that are very close to a perfect black body radiator. The black body temperature is the standard by which we define white light. You have probably seen numbers like 3000K, 4100K, or 5000K stamped on fluorescent lamps. This is the CCT (**C**orrelated **C**olor **T**emperature) of the lamp expressed in Kelvin.

LEDs (**L**ight **E**mitting **D**iode) have been around for about 60 years. Initially their light output was only usable in indicator applications. In the last 20 years LED output has been increased to a level of being truly usable light source for illumination. It should also be noted that LEDs are the first alternative light source to incandescent bulbs that does not use mercury as a key component.

Definitions

It's worthwhile to go over some of the key metrics for light sources.

CCT

Color temperature (CCT) is measured in Kelvin (named for Lord Kelvin, a British mathematician) and comes from the Planckian locus (Max Planck, a German physicist). It's ironic that warm colors such as red, orange, and yellow have a lower color temperature than cool colors such as violet and blue. The Planckian locus is the black line in the middle of the chart in figure 1. White light is any point on that curve.

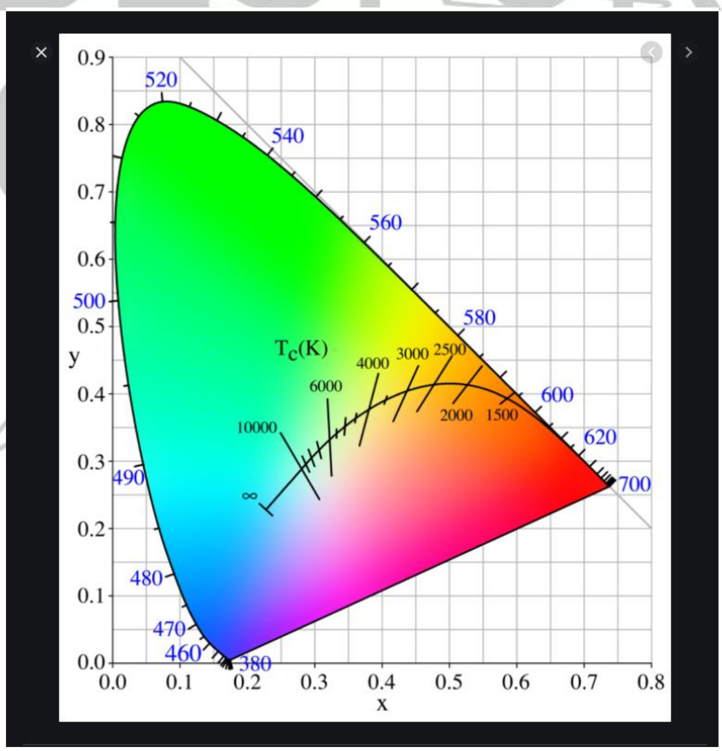

Figure 1. CIE 1931

Efficacy

Efficacy and efficiency are terms often used interchangeably but in fact have different meanings. Both terms are used when evaluating the input and output of a system. When the input and output power for a system is measured in the same units, usually Watts, the ratio of output power to input power

$$\frac{Pout\ (W)}{Pin\ (W)}$$

is a unit-less number usually expressed as percentage between 0% & 100%. Efficacy also compares the input and output of a system but uses different units. For lighting, the input units are usually Watts, and the output usually lumens.

$$\frac{Light_{out}(lumens)}{Power_{in}(Watts)}$$

It is possible to measure light output in radiant power rather than lumens but lumens are more tangible for human use. Keep in mind that lumens measure the total light output, not light intensity (measured in lux (lumens/m^2)). Lumens are photopically adjusted for the color response of the human eye which reads different colors in a non-linear way. So 1 lumen of red will appear as bright as 1 lumen of green even though your eye is much more sensitive to green.

An incandescent bulb typically puts out a range of 15 – 25 lumens/Watt while LEDs are 150 – 200 lumens/Watt. By comparison, the radiant power from a 100W incandescent bulb is 2-3 Watts which gives a pitifully low efficiency of 2-3%. LEDs have 10 times better efficiency, but 20% - 30% is still rather low. The power not radiated ends up as heat.

Advantages & Disadvantages

The efficacy of LEDs is 10X better in output than incandescent bulbs, yet incandescent bulbs do have many advantages:

1. Low Cost – 100 years of manufacturing experience has produced a highly optimized cost of production.
2. Insensitive to temperature – Automotive applications see temperature extremes of -40°F - 120°F. Since the tungsten filament temperature of the bulbs is ~5000°F, the ambient temperature does not really affect it.
3. Lumen Maintenance – This measures how much the lumen output changes over the service life of the bulb. Incandescent bulbs put out nearly 100% until they reach end of life. No other light source is better.
4. No Polarity – 12V power can be applied in either direction with no damage or change in performance.
5. Soft Turn-on – It takes a noticeable amount of time to fully heat up the tungsten filament. This results in a soft turn on and turn off.

Comparison Chart

	Incandescent	LED
Cost	Low	Medium
Lumen Maintenance	Excellent	Good
Ambient Temperature	Excellent	Good
Service Life	Low	High
Shock & Vibration	Medium	Excellent
Color Temperature	Warm	Can be Selected
Polarity	AC or DC	DC Only
Voltage Tolerance	Highly Sensitive	Low Sensitivity
Inrush Current	High	None
Turn-on/Turn-off time	Slow	Fast

Table 1. LED vs Incandescent

Vehicle Compatibility

LED lighting is becoming more standard for cars, and compatibility issues are non-existent in those applications. The long service life for LEDs allows for manufacturers to make less provision for easy replacement. The need for quick change standard sockets becomes obsolete.

Aftermarket suppliers make a variety of LED bulbs that are compatible with older vehicle connectors, allowing a relatively easy conversion to LEDs. However, some older systems cannot function correctly without the characteristics of the older bulbs. The most notable is the turn signal flasher. 60 years ago, the turn signal flasher was a thermally activated device that depended on the current of the bulb to heat up and switch on & off. If one bulb was burned out, often the turn signal did not flash at all. In the 1990s, turn signal flashers became electronic and more sophisticated by adding a “bulb out” function. This function caused the flasher to operate at double the rate if the current dropped low indicating a bulb out. Since LEDs draw such low current, neither of these flasher types will operate properly with LED bulbs. The aftermarket addressed this problem by adding balancing or ballast resistor loads connected in parallel with the new LED bulbs. They emulate the high current draw of the incandescent bulbs. Adding balancing resistors is very poor solution to the problem; it adds heat back into the system and nullifies one of the advantages of LEDs. The best solution is to replace the turn signal flasher with one designed for LED bulbs.

Service Life

On the surface, LEDs appear to have a great advantage regarding longevity. LEDs have a rated life of 50,000 hours while typical incandescent bulbs are rated for 2,000 operating hours. A turn signal, stop bulb, or headlight/taillight bulbs does not operate 100% of the time that the vehicle is driven. If the bulbs operate for 1/3 of the driven miles (which seems rather high), then the bulbs should be good for 6,000 hours of the vehicle, which is still much less than 50,000 hours. If you were driving on the highway @ 60MPH for 6,000 hours, you would accumulate 360,000 miles on your car. Even if that is overestimated by 50%, 180,000 miles is still nearly the life expectancy of the vehicle. Therefore, incandescent bulbs don't look so bad from a service life point of view. This also means that vehicle manufacturers don't have to provide an easy way to replace LED bulbs since they will last the life of the vehicle.

It's worthy to discuss how manufacturers rate the life of incandescent bulbs. Rated life is based on actual operating results, not a calculation. A group of bulbs is placed on a test rack under controlled conditions. The rated life is the time when half of the bulbs fail. This is not exactly an average of the operating hours. Some bulbs may fail very soon and some last much longer. The ultimate failure mode is well known in incandescent bulbs. Since the filament is heated to just below the melting point of tungsten (3422° C), the failure mechanism is tungsten evaporation. So the filament thins over time because the tungsten evaporates and re-condenses on the bulb wall. In principle, if all the bulbs were identically made, they would fail at the same time. In practice, this does not happen due to manufacturing variations and defects. Early failures are generally attributed to manufacturing defects. This doesn't affect the life rating much because they aren't averaging the operating hours.

Operating Voltage Effects on Service Life

Operating voltage affects both LED and incandescent bulbs but much more so for incandescent bulbs. Higher voltage of LED bulbs translates into higher heat of the LED die. If the LED has a good driver which accurately regulates the current, then the increased voltage has no effect. If there is a simple resistive current limiter, the current could rise 30% or more. If the voltage rise is short enough, there is no significant effect for the LED. LED life is dependent on die temperature.

The life effects are much more severe for the incandescent bulb. Tungsten evaporation causes failure, and this is highly dependent on temperature. A 5% overvoltage will half the life of an incandescent bulb while operating 5% under voltage will more than double the life. At a high enough over-voltage, they will fail almost instantly because you have reached the melting point of the tungsten filament.

Electrical Characteristics

Electrical characteristics vary greatly between LEDs and incandescent bulbs. It is common knowledge that the power consumption of LEDs is much lower for a given lumen output. It should be noted that the lumen intensity and illumination pattern are regulated by government standards (FMVSS).

In the context of this paper, an LED bulb will refer to an assembly of components which includes one or more LEDs, a current limiting device or circuit, and a base for making electrical and mechanical connections. We will compare the following characteristics: operating voltage, operating currents,

Operating Voltage vs Current

The voltage vs current graphs are very different for LEDs and incandescent bulbs. Generally performance on the vehicle is only specified at nominal operating conditions. Vehicle operating voltage is static in normal operating conditions. However, vehicles like all-electrical distribution systems, experience transient conditions due to changing loads, faults, transient operating conditions (i.e. engine start), etc. LEDs and incandescent bulbs behave very differently in these cases.

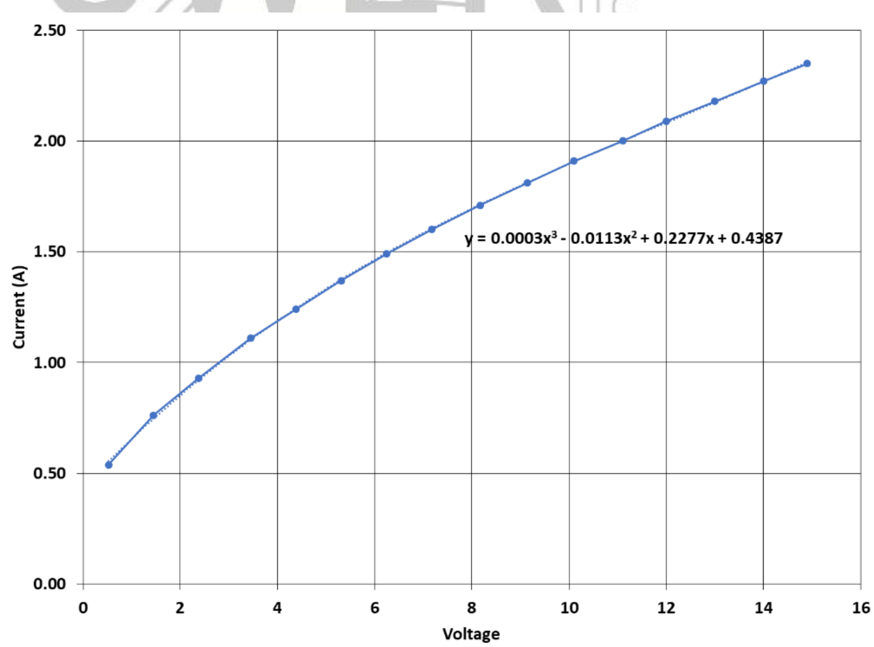

Figure 2. 1157 Bulb Voltage vs Current Graph

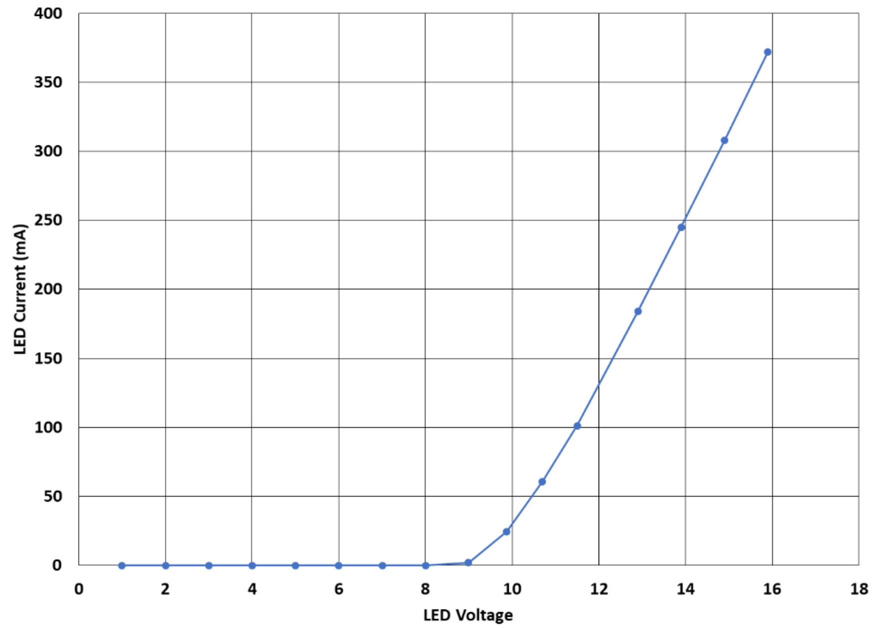

Figure 3. Typical LED Bulb Voltage vs Current Graph

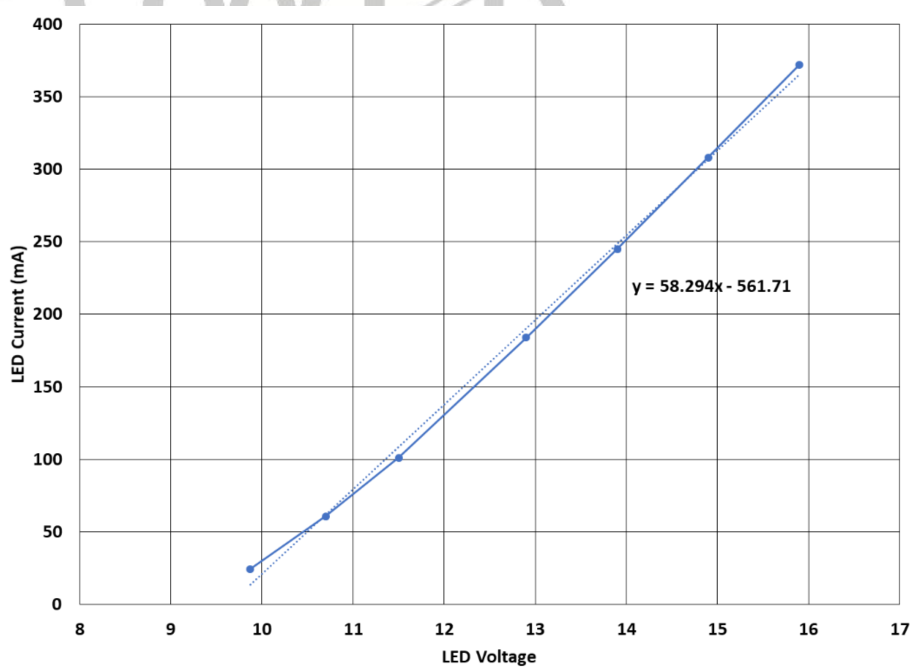

Figure 4. LED Active Region

A comparison for Fig. 1 and Fig. 2 show the full range of input voltage from 0V – 16V. Nominal performance is rated between 12V – 15V which is the regulated voltage range of the vehicle. You can see that the current draw for the LED bulbs is ~ 1/10 of the incandescent bulb, what we'd expect to see. However, beyond that range the two graphs look very different. The incandescent bulb draws current at every voltage point and the current does not rise linearly with applied voltage. In fact, the 3rd order polynomial shown in Fig. 2 is a reasonable curve fit for the VI curve. This behavior results from the changing filament resistance of the tungsten filament. Its resistance increases as a function of the temperature, a function of filament power. Since the temperature changes, so does the CCT of the incandescent bulb. This phenomenon is unique to incandescent bulbs. Neither LEDs nor any arc discharge lamps change CCT with changing power.

The LED VI curve show no appreciable current until reaching ~9V. LEDs have a threshold voltage that must be exceeded before current is increased. LEDs (the actual LED device, not the assembly) behave very much like voltage sources where their operating voltage is not greatly affected by operating current. There is a certain amount of equivalent series resistance called dynamic resistance or incremental resistance. This is inherent to the LED. Generally the dynamic resistance is much too small to control the LED brightness by controlling the applied voltage. A current limiting device (called a driver or ballast) is required. The current limiting device can be as simple as a high value series resistor or as complex as multi-component current regulator. We see that the current rises linearly with voltage above 9V. This tells us that the current limiting device is a simple resistor (most common and cheapest).

It's important to know the behavior of any bulb on the vehicle beyond nominal conditions to assure performance and/or withstand capability in transient conditions. During engine start, battery voltage can dip under 8V in very cold conditions. Also during load dump conditions, voltage as high as 100V can be seen for up to 0.4s. OEMs (**O**riginal **E**quipment **M**anufacturers) must meet all applicable standards as of the date of manufacture of the vehicle. Aftermarket products do not have to comply with industry standards, although good ones are diligent about testing their product according to industry standards.

Inrush Current & Optical Turn-on/turnoff

Inrush current and optical response time vary between LEDs and incandescent bulbs. Inrush current is the peak instantaneous current in the bulb at the instant that rated voltage is applied. Optical response time is the time that the bulb requires to reach full rated optical output. For figures 5-8, the green scope trace shows current while the yellow scope trace shows optical output.

Figures 5 & 6 measure the inrush current and optical response time of the LED bulb. The LED bulb current has no overshoot current and instantly goes to its steady state current of 300mA. The optical response follows the current instantly settling to the steady state value. The optical turn off time in figure 6 also instantly settles to full off state. The abrupt turn-on/turn-off time of the LEDs is very noticeable to the human eye. The human eye is a good integrator for rapidly flashing light sources.

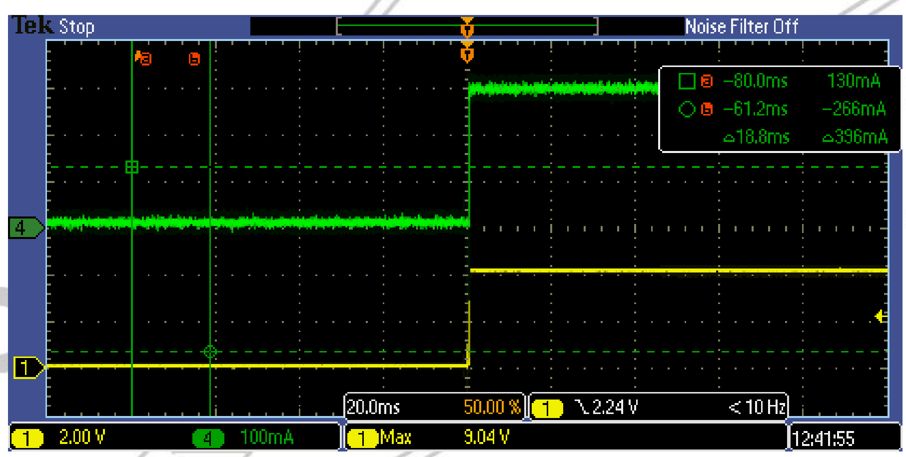

Figure 5. LED Turn on Current and Optical Output

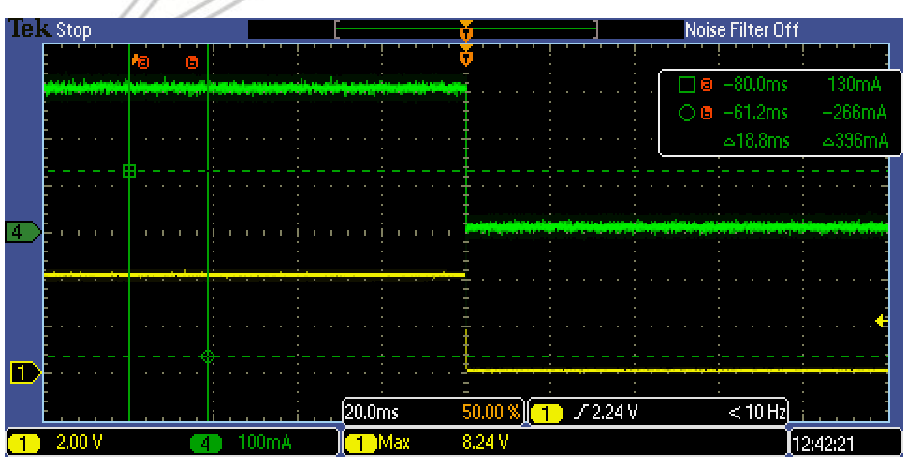

Figure 6. LED Turn off Current and Optical Output

Figures 7 & 8 measure the inrush current and optical response time of the incandescent bulb. The incandescent bulb current has significant overshoot current reaching 19.7A (~ 9X the steady state current). The current settles in a ~100ms to the steady state current of 2.23A. The optical response time is ~300ms which is very noticeable and very gradual (often called “soft” turn-on since its optically pleasing). The optical turn off time in figure 8 is ~ 200ms due to the thermal time constant of the tungsten filament. Unlike the LED bulb the optical rise and fall times are not symmetrical.

Figure 7. Incandescent Bulb Turn on Current and Optical Output

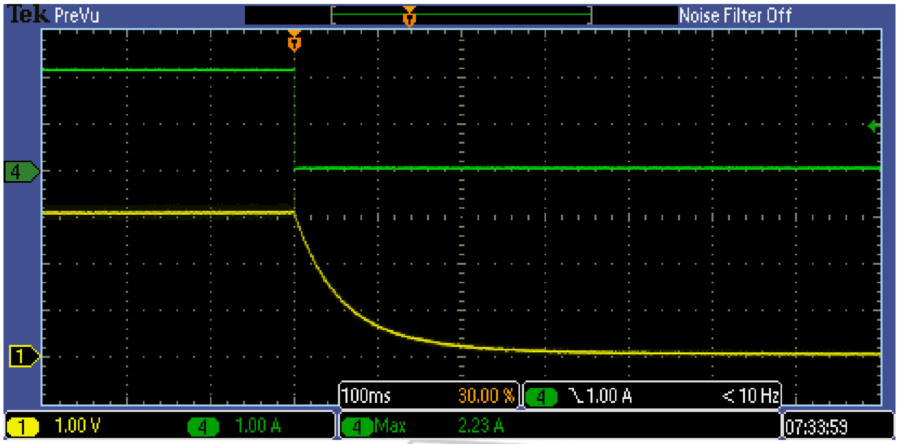

Figure 8. Incandescent Bulb Turn off Current and Optical Output

Summary

There is nothing inherently good or bad about either LEDs or incandescent bulbs. Both have their advantage and disadvantages. The choice comes down to parameters that one wishes to optimize. Incandescent bulbs are becoming regulated out of existence in general lighting applications due to energy consumption and carbon emissions. That argument is meaningless while driving around in your 2 ton carbon blaster. Incandescent bulbs have served the automotive industry well for over 100 years. There is no good technical reason to update older vehicles except for personal preference. On a good day, your gasoline engine is 15% efficient so the reduced load on the lighting system is insignificant. However, electric vehicles benefit from a reduced electric load since it represents battery run time. There is significant effort that goes into managing loads in battery operated systems of all kinds, including phones, laptops, and other portable equipment.