April 2015

Efficient Pulse Width Modulation LED Headlight Driver

Brendan Scott Cavanagh
Worcester Polytechnic Institute

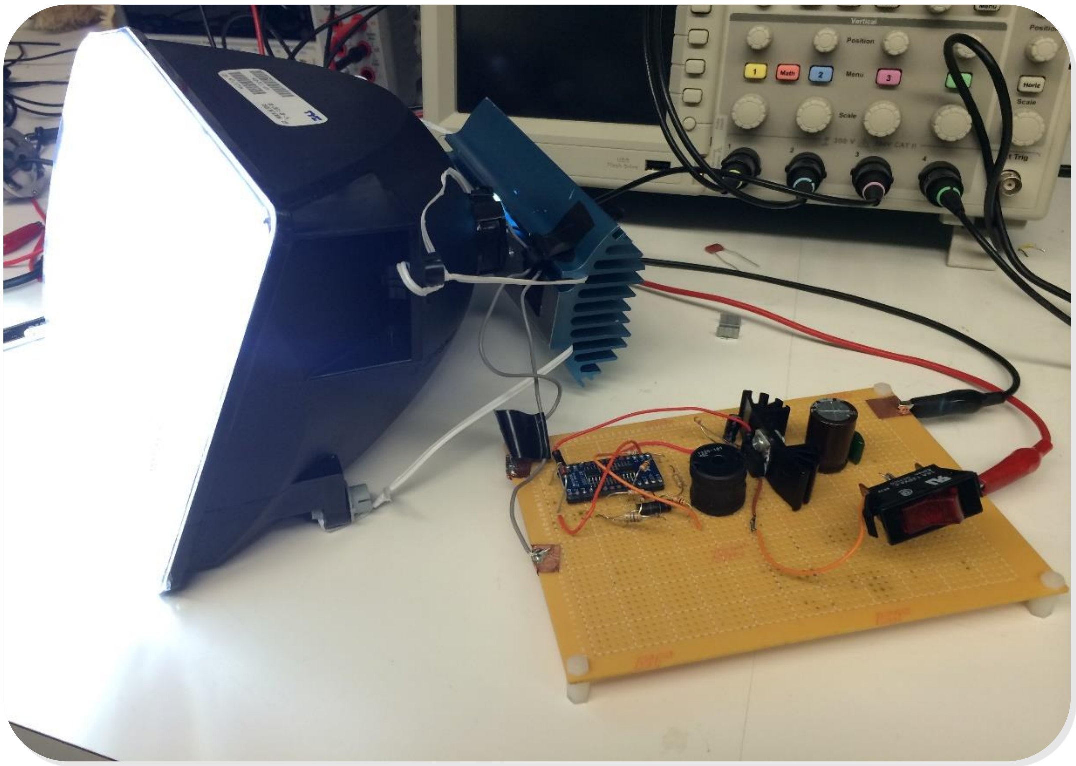
Matthew Aaron Janiga
Worcester Polytechnic Institute

Nathaniel Keahi Goodale
Worcester Polytechnic Institute

Repository Citation

Cavanagh, B. S., Janiga, M. A., & Goodale, N. K. (2015). *Efficient Pulse Width Modulation LED Headlight Driver*. Retrieved from https://digitalcommons.wpi.edu/mqp-all/1221

Efficient Pulse Width Modulation LED Headlight Driver



A Major Qualifying Project
submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
degree of Bachelor of Science

by
Brendan Cavanagh
Nathaniel Keahi Goodale
Matthew Janiga

Date:
April 30, 2015

Stephen Bitar
John McNeill
NECAMSID/Analog Labs
Worcester Polytechnic Institute

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

PROBLEM STATEMENT

Automotive headlight technology has lagged behind other technological adoptions used in vehicles. Most automotive headlights are essentially the same as they have been for the past five decades, utilizing incandescent halogen bulbs. This technology converts almost 90% of its energy into heat rather than light, and has a shorter life time compared to the alternatives available today. LED headlights are emerging in the marketplace on high end vehicles and aftermarket conversion kits. However, incandescent bulbs hold the majority of market share since they are made in large quantities, cheap and quick to manufacture, and offer satisfactory lighting characteristics. LED headlight technology is attractive since it boasts higher efficiency, resulting in higher MPG, extends the range of electric vehicles, longer lifespan than traditional bulbs, and provides more effective luminescence. These headlamps require a proper LED driving circuit, ease of installation, provide sufficient light to illuminate the road, maintain price comparable with that of traditional incandescent halogen bulbs. Unlike typical bulbs, LEDs do not radiate significant amounts of heat, leading to potential ice accumulation on the headlight cover glass. This paper concentrates on the use of pulse-width modulation for increased lumen output with greatly reduced power consumption.

ABSTRACT

LED headlights can provide better luminescence and less power consumption when compared to traditional halogen headlights. The adoption of LEDs in automobiles has been slow as the technology is more expensive than halogen bulbs, more complex to integrate, and younger. As such, an efficient, simplistic, and easy to use illumination driver was developed to spur on the widespread adoption of LED use in automobile lighting. The circuit developed is

capable of providing the necessary illumination for a fraction of the energy input required by traditional lighting.

ACKNOWLEDGMENTS

We would like to thank Professor Bitar, our main advisor, for all the help and guidance he provided throughout the year. His help was instrumental in the development of this project as and the successful completion of the circuit. We would also like to thank our co-advisor Professor McNeill as well as our sponsor NECAMSID. A special thanks to Bob and Bill from the ECE shop for their willingness to provide us with materials and help us fashion components.

CHAPTER I: INTRODUCTION

The desire for energy efficiency has spurred on a new drive in industry to produce products that consume as few resources as possible to operate. Traditional lighting techniques such as halogen bulbs have been the focus of some of these efficiency improvements. Almost 90% of the energy consumed by a halogen bulb is converted into heat rather than visible light (autoevolution, 2014). In the home, U.S. power companies have started to phase out incandescent lights in favor of CFLs (Compact Florescent Lights) and LED lighting (Light Emitting Diodes). Not only has the home seen pushes for improved lighting efficiency but so hasn't the automotive industry. As gas prices increase and the consumers' desire for greater MPG increases with it, automakers have taken to improving the efficiency of their illumination systems. By switching to LED lighting for a car's headlights, interior lights, running lights, indicators, etc. auto manufacturers can reduce energy consumption and advertise a higher MPG as well as boast environmentally friendly improvements. Currently, the integration of LED bulbs into headlights is typically seen only in electric vehicles and high end cars. However, recently announced cars such as 2015 Ford F150 will be the first pickup truck to offer a full forward LED illumination system. Currently, halogen bulbs and Xenon HID’s have the majority of market share, but as LED technology and ease of integration improve they will begin to take a greater portion of the market.

LEDs are far more efficient than traditional bulbs at generating light. Unlike halogen/incandescent bulbs, most of the energy is converted directly into light rather than waste heat. One reason LED headlights can be vastly more efficiency is by using pulse width modulation (PWM) to control the amount of light emitted. PWM works by turning the LED on and off at a frequency faster than the eye can see. PWM uses something called a duty cycle. Duty cycle determines what percentage of the time the power should be off. A 50% duty cycle would mean 50% of the time the power is on and 50% of the time the power is off. If an LED were driven with a constant voltage and then switched to a 50% duty cycle PWM driver, its efficiency would double. This is because 50% of the time the LED would technically be off. However, the frequency is such that the human eye cannot perceive this flickering. This is how a computer monitor operates, the screen is actually refreshing 60 times per second but we would never be able to notice it with the naked eye. By finding the correct frequency and duty cycle, the brightness and increased power efficiency can be achieved. Another aspect traditional halogen bulbs suffer in is dimming applications. When dimming a traditional bulb, an adjustable resistor is put in series with the bulb to vary the voltage over the bulb, this in turn adjusts the amount of light emitted. Thus dimming a traditional bulb does not reduce the expended energy. However, dimming an LED works as intended, a more dim light will use less power and PWM can be used to do this.

The team’s focus on automobile headlights is due to the unique nature of cars versus a stationary object plugged into an outlet. Cars consume electrical energy from the battery which consumes gasoline from the tank. Anything that drains more power from the battery will cause more gasoline consumption to allow the car to charge itself. Headlights are massive consumers of this energy from the battery. Halogen headlights draw upward of 50 watts per bulb. This power draw can be dramatically reduced by using LED bulbs which only take around 15W per bulb. Another advantage to LED bulbs is their longevity, as they last tens of thousands of hours compared to the average of only one thousand hours for halogen headlights.

Tesla, Toyota, and Audi are leaders in the field of integrating LED headlights, being some of the early adopters of the technology. LEDs were first adopted by Audi in a high profile manor because of their form factor and unique look. As LEDs are small, and arrays can be used to generate the required light, they can be made in various shapes and sizes. This appealed to the auto manufacturers as it allowed them to mold custom light housings into their vehicles. The LEDs also proved to be brighter and easier to mold into the desired light pattern for headlights than halogen bulbs used in the past. Along with the advantages of light brightness and design manipulation qualities of LEDs, Tesla and Toyota integrated LEDs to save on battery power. Now this battery could be preserved thus increasing MPG and extending the range of the vehicle or allowing additional features. Tesla and Audi are of course high end automakers, however we have seen slow adoption of LEDs into a more reasonable line of automobiles. Most hybrid or electric vehicles use LEDs as electrical power consumption is even more important than before. They are also being installed by end users in order to give them the lumen output they want or improve their cars efficiency.

There are several manufactures that are currently producing high power LED drivers that are able to power LEDs for headlights in vehicles. Allegro, TI, Rohm, and LT all produce these chips. However, with the exception of Allegro, the chips are far more complicated than they need to be, with multiple uses and setup configurations possible with each chip. This over complexity and feature recycling leads to inefficiency, higher price, more failure points, and more a complex understanding required. The aim of this project team was to develop a simple high power LED driver for headlights using pulse width modulation. If an easy to understand, effective, cheap, but extremely efficient driver could be developed, it might help ease the integration of LED's into all applications, specifically headlights.

CHAPTER II: BACKGROUND

As of 2014 the market for light emitting diode (LED) lighting in both the automotive and household industries is rapidly growing to incorporate increasingly efficient and effective products and techniques. In 2011 the LED market as a whole grew by 10%, while the use of LED's in the lighting sector grew by an astonishing 44% (LEDs Magazine, 2011). With this it is clear there is demand for practical, energy efficient, LED lighting options within the automotive industry. According to some, there is an expected compound annual growth rate (CAGR) of 34% for LED headlights alone, as the automotive industry reaches towards converting all front-end lighting to either Xenon high intensity discharge lamps (HID) or LEDs in a motion to reduce costs and increase MPG (miles per gallon) (LEDs Magazine, 2011). The automotive industry is going through a transitional period where manufacturers are slowly incorporating LED headlights into cars by creating headlight hybrids. The low beam of the car is reserved for the LEDs as they are more reliable, longer lasting, and more energy efficient. Whereas the high beams are implemented with halogen lamps or Xenon HIDs for increased brightness and distance. Currently, LEDs are produced by several major manufacturers like General Electric (GE), Philips, Osram Sylvania, and Cree.

Current Market and Manufacturers

In 2012, the global market for LED lighting was estimated to be around $4.8 billion and is projected to grow to $48 billion by 2019(LEDs Magazine, 2011). With LEDs holding an ever-increasing market share in the lighting industry, major manufactures and small startups have started to capitalize on this growth. GE produces various types of lighting and has been producing consumer-level LEDs for a while. Their applications are seen within most industries where lighting is needed. Specifically, GE’s line of premium NIGHTHAWK™ LED headlights have become a staple in many aftermarket headlight installations. As will be discussed later, these headlights claim to produce light that is closely matched with the color spectrum of average daylight. Meanwhile, a company by the name of Hella is now responsible for producing all LED headlights that are standard on Audi’s A8, A6 and A3, Cadillac’s Escalade, the Mercedes E-Class and a DAF truck (LEDs Magazine, 2011).

Companies like Philips produce LED headlights but have focused primarily on their home and office lighting applications. Philips’ Xenon HID headlights and standard halogen lamps are there most popular headlight as these two styles currently hold the largest market share. As of right now, the majority of LED headlights are used on luxury cars that try to get ahead of the current market and into the next trend. This is likely because right now, LED headlight technology and implementation is in its infancy compared to standard halogen bulb technology or even the growing Xenon market. Major companies like Philips and GE can produce great LEDs, based on electrical principles, but they may not make the best headlights which rely on light reflection and diffraction technology. As such, several smaller companies like NewBrights and several start-ups have come into the market to buy LEDs from major manufacturers and implement them in new ways using these lighting techniques. However, LED lighting in general has gotten a strong footing as the Toyota Prius, a car reliant on electricity and efficiency, has chosen LEDs for many of its lighting applications. Additionally, the first pick-up truck with LED headlights will be the 2015 Ford F-150, it will be using one LED bulb for both high and low beams (Williams, 2014).

The market is currently dominated by halogen lamps as they have become the cheapest to implement, have a long life, and offer good lighting characteristics in balance with the driver and oncoming traffic. As this lamp technology has been around for so long and production costs have become very low, automotive manufacturers have preferred this style of light. However, their power efficiency is a big drawback, leading some manufacturers to look for more energy efficient solutions to increase their MPG. This led to a successful introduction of Xenon HIDs, which claimed higher energy efficiency and a brighter light which can then be used by manufacturers in car safety advertising. Traditional halogen bulbs can produce roughly 1400 lumens and 30 mcd/m2 (millicandela per meter squared) whereas Xenon lights are advertised at 3000 lumens and 90 mcd/m2 (autoevolution, 2014). Xenon lights are estimated to have almost doubled the lifetime of traditional lamps. The specific technologies and power consumption factors will be discussed later in this paper.

Most recently, LED headlights have entered the market of automotive lighting applications. The main advantage is clear, they are the most energy efficient solution so far. As this will lead to an increase in MPG, auto manufacturers have LEDs on the horizon as a potential big evolution within the automotive industry. With current LED technology, the lumens produced are roughly equivalent to that of Xenon HIDs. So why hasn't the LED been adopted as the main source of lighting for cars? Currently, the technology is new, developing in efficiency, and not yet produced in large enough quantities to offer better value. This drives the cost upwards to a point it is still more expensive than halogen or Xenon. There are also not enough manufacturers or variations in the LED headlights offered so implementation into new car models is expensive, time consuming, and could even require a physical redesign (autoevolution, 2014).

Headlight Lighting Technology Comparison

By the 1920's electrical lights commonly appeared on automobiles to enable the driver to better view the road and for other drivers to better see the vehicle. Today there are three main types of bulbs used in automobiles: incandescent tungsten-halogen bulbs, high-intensity discharge lamps, and LEDs. Incandescent tungsten-halogen are the most common bulbs used in automobiles and are the simplest way of producing the necessary light, emitting about 800-1000 lumens (lm). This type of bulb is preferred because they are simplistic, cheap to make, and are easy to replace when the bulbs burn out. However, this type of bulb is not very efficient, with approximately 90% of the consumed energy being converted into heat and not visible light (autoevolution, 2014). A HID lamp emits light by creating an arc of electricity spanning across a quartz-glass tube with a metallic salt compound. This tube reacts with the electricity to create plasma, emitting light in the process at 2900-3200 lm. These bulbs are more efficient than incandescent tungsten-halogen bulbs and have a higher average lifespan as well (Table 1). Xenon lights work in much the same way but use Xenon gas instead of metallic salts. One of the drawbacks of both HID and Xenon technology is the high amount of heat produced by the bulbs. LED headlights must be arranged in an array, as one diode is insufficient to produce enough light. These bulbs, unlike the others discussed, convert the majority of energy directly into light and not heat. This leads to a drastic increase in efficiency. Many automakers have opted to use LED technology in taillights because of their quick illumination time, beating out incandescent lamps by 400-500 milliseconds to give the trailing driver more time to react (autoevolution, 2014).

The technology that produces the least amount of light is the incandescent tungsten-halogen bulb, producing about 800-1000 lm. HID's and Xenon bulbs are the brightest at about 2900-3200 lm. This brightness is comparable with that of LED technology. Currently, the limiting factors of luminescence include headlight housing design and power constraints. Headlight housings can be complex, as LED is a new technology to car headlights and kinks still need to be worked out. Power available to the LEDs is limited, as well as the maximum temperature range they can safely operate.

The lifespan of these different lighting technologies is also very important to take into consideration when choosing the right bulb to install in a vehicle. The consumer does not want to be changing the headlight bulb in their vehicle very often, no matter how cheap or easy it is to replace. Halogen bulbs have a lifespan of roughly 1000 hours, while HIDs/Xenon lamps last approximately 2500 hours, and some LED headlights have claims of up to 15,000 hours of operation (autoevolution, 2014).

Cost is an important factor when choosing a bulb technology to implement in the design of an automobile. As with other older technology, the halogen bulb is the cheapest to implement, produce and install. This is because it has been in use for a long period of time and is a very simple system to build and implement. With HIDs, LEDs, and Xenon lights, cost becomes a factor. These technologies are much more complex, require more expensive parts, and a more involved manufacturing process.

One of the main advantages of LED headlights it that they are small. This allows a greater manipulation of design and placement. LEDs possess a well-established efficiency advantage over the other lighting technologies, with nearly all of the input energy going directly to photon production, with very little being converted into heat. LEDs possess the longest operating-life of any of the technologies discussed previously. However, LEDs have a higher production cost and tend to produce less light when exposed to higher temperatures. One problem that designers face when implementing LEDs is that they tend to produce heat at their base that can affect adjacent components; a thermal regulatory system must be taken into account in the design process.

Current Considerations and Drawbacks of LED Lighting

The main attraction of utilizing LED technology is the energy saving potential offered by the technology as they convert roughly 80% of energy into light. As previously discussed, LEDs have a much longer operating life than that of other bulb varieties, upwards of 15,000 hours of operation for a car headlamp and upwards of 100,000 hours of operation for other fixtures. This helps to mitigate the upfront cost of purchasing the more expensive LEDs. With the longer lifespan and little toxic chemicals that go into LEDs, they are a much more ecologically friendly choice. See Figure I and Table 1 to view ecological effects related to the life cycle of the bulb and equivalency comparisons. With their small size, many design configurations are possible. LED systems also have the ability to be easily dimmed, unlike florescent systems.

However, there are disadvantages with using LED lighting technology. LED lights are much more expensive than more traditional methods of lighting. This can put people off from buying LED lights as the upfront investment is too expensive. This is especially true of people/companies that have adopted florescent lighting because there is less energy saving difference to incentivize the adoption of LED lighting systems. There is a temperature dependence for the LEDs, without an adequate heat sink, the ambient temperature of the environment combined with the heat produced by operation can be enough to result in failure of the system. This is especially important to take into consideration when planning for use in the automotive setting. When utilizing LEDs for light, it is also necessary to consider the voltage threshold and the current ratings of the diodes in question. A specific voltage must be maintained for optimal light emission, and below the current threshold so as to not damage the diode and maintain its efficiency.

Type of Bulb	Lifespan	Equivalent replacement bulbs to equal LED
Halogen	~1,000 hours	15
HID/Xenon	~2,500 hours	6
LED	>15,000 hours	1

Table 1 : Bulb lifespans (autoevolution, 2014)

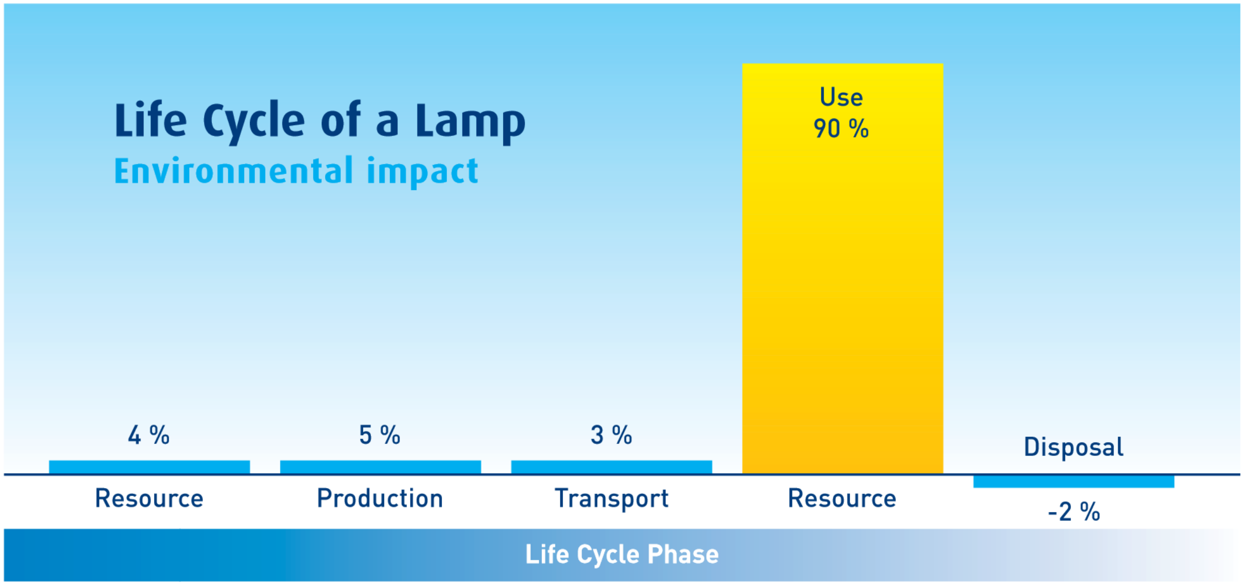


Figure I : Bulb phase environmental impact (Lighting European Lamp Companies Federation, 2009)

There are several different types of LEDs that are used for colorful aesthetics: Red-Green-Blue (RGB), Red-Green-Blue-Amber (RGBA), and Red-Green-Blue-White (RGBW). These systems combine different LED colors to recreate any color and hue by varying the intensity of the different colors. This is most commonly done with RGB combinations, but as a color LED has a very limited wavelength spectrum that is emitted, some colors do not come out as well as others. This issue has been mitigated by adding a fourth color to the array, amber, to create a RGBA light system. The amber helps to fill in missing wavelengths, leading to more realistic color reproduction. Another system was created to allow white LEDs to be used independently, the RGBW system. This allows for the regular RGB color combinations as well as the ability to mix in white light to any of the color combinations or as a standalone.

White LEDs can lead to color distortion when compared with natural light. Many white LEDs produce a cool blue light that does not bring out the brighter colors of objects. The temperature of the light can be described as “warm white”, “natural white”, or “cool white”. This temperature of light is measured in a Kelvin Color Temperature scale, ranging from 1,000K for red to 10,000K for blue sky. This can be seen in Figure II. The difference hues of light in an office environment can be seen in Figure III.

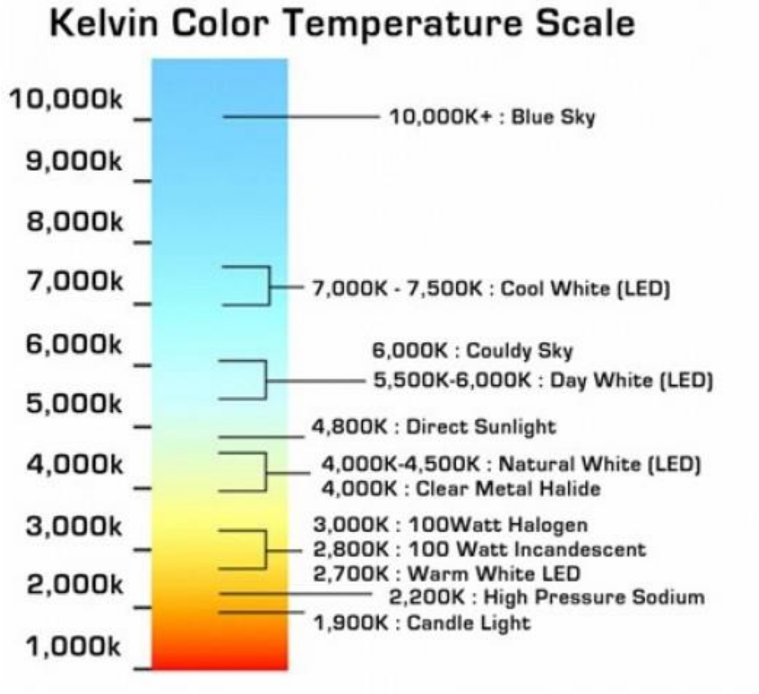


Figure II : Kelvin color temperature scale (HubPages, 2011)

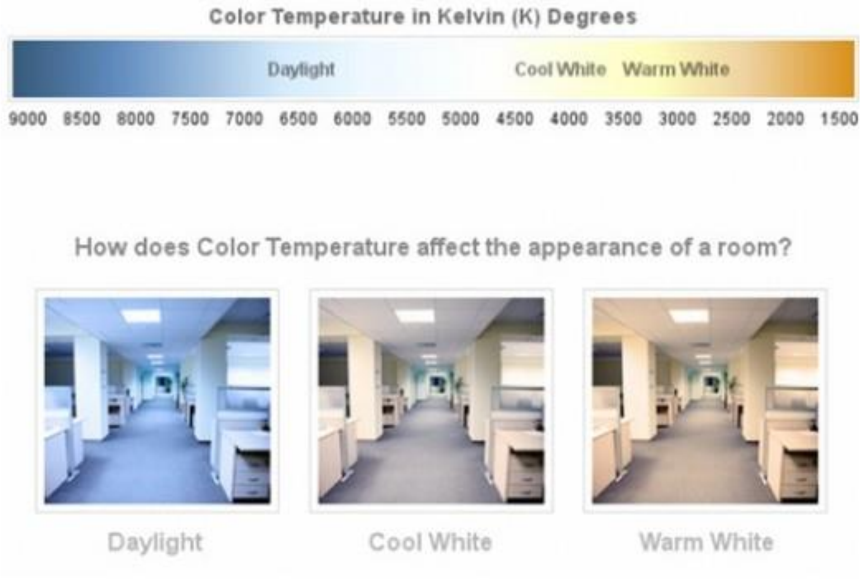


Figure III : Office environment color temperatures (HubPages, 2011)

Ecological Impact of Different Bulb Types

Halogen/Incandescent

Halogen bulbs create an immense amount of heat when operating. This requires that the housing of the bulb itself be able to retain enough heat for the system to function properly (250^{O}C) but also displace enough heat so that the system does not melt. If the bulb is too cool, the system will break down and eventually fail.

These bulbs are relatively easy to manufacture. They only require glass, a tungsten filament, and a halogen gas. This leads to a cleaner manufacturing process. The tungsten infused coil of the filament is made by winding a wire to create better light emission characteristics. The glass is first formed to fit over the filament and then attached to the housing. Then the mount is made by running the tungsten wires through a quartz rod to fix the system in place. The bulb is then sealed by pumping an inert gas such as nitrogen or argon into the housing to flush out any other gases. While this is happening the bulb is being heated and hermetically sealed. A small amount of halogen gas is placed inside each bulb. The bulb is then permanently sealed after the electrodes are attached securely to the base (MadeHow, 2014).

HID/Xenon

Xenon use less energy than that of traditional halogen lamps, resulting in less fuel consumption. The components of an HID are as follows: a mixture of noble (Xenon) gasses or metal halide salts, two electrodes, inner quartz housing, and outer quartz housing. There are three things that affect quality and performance of these bulbs: the purity of the noble gas or metal halide salts affects color and consistency, the arc electrode that seals the halogen gas mixture from leaking out, and the quality of the quartz can affect the amount of UV light emitted as some is filtered out (HID Extra, 2014).

LED

Diodes are made with very thin layers of semiconductor material, and impurities in these materials are used to create a specific electron density. The semiconductor material that is used to manufacture LEDs is gallium arsenide, gallium phosphide, or gallium arsenide phosphide. The different levels of impurities in these semiconductors allow for different colors of light to be produced from the diode. Note: These are impurities, not imperfections and are the intentional result of doping the material for a desired result. The doping consists of adding zinc or nitrogen, and more rarely silicon, germanium, or tellurium. The LEDs are covered in a transparent plastic, it is this plastic that determines the light refraction pattern emitted and if tinted, can alter the color of the light (MadeHow, 2014).

Corollaries

From this information, we can see that the materials and manufacturing that goes into these bulbs does not stand out as more or less environmentally harmful than others. However, if taken strictly from a manufacturing perspective the halogen bulbs would be the most environmentally friendly as they are the simplest to make. When taking HID/Xenon into account, the manufacturing process is much more involved but not directly harmful to the environment. As for LEDs, they have the most complex and precise characteristics of these technologies and require the use of semiconductor materials. However, these materials are used in small quantities. When taking into account usage, replacement rate, and disposal, LED technology leads the way in being environmentally friendly. Please refer back to Figure I. This shows that most of the energy and environmental degradation that results from a bulb in its lifetime is because of its use. This totals to about 90% of a bulbs environmental impact. With this in mind, LED technology leads the way in being environmentally responsible because it uses the least amount of electricity.

Power Comparison of Bulb Types

Halogen headlights consume about 55 watts of electricity to produce approximately 1,400 lumens per bulb. This is equal to 52.45 lumens/watt (autoevolution, 2014). When compared with HID/Xenon and LED technology, the energy usage is dramatically different. For HID/Xenon, the bulb produces 85.71 lumens/watt for each bulb. This is a significant amount more light emitted, with far less power usage. LEDs produce 88 lumens/watt for each light fixture (GTR Lighting, 2014). This is only slightly more than that of HID/Xenon; however at the 3,000 lumen intensity it is possible to blind other drivers on the road with the excessive amount of light. It is also important to remember that every extra watt of power that goes into using the headlights is coming from the fuel tank, thus more power being used lowers the fuel economy. These power ratings are for each bulb, and with a bulb on each side of a car the power usage must be doubled. Thusly, halogens use 110 watts, HID/Xenon use a total of 70 watts, and LEDs use 50 watts. Table 2 shows concise power comparisons between bulb technologies. This saved energy in an electric vehicle can be used to extend the range and reduce the frequency of charging, especially if all lighting in the car were to be LED.

LED headlights produce a clearer and more forward facing cone of light where it is needed by the driver. HID/Xenon lights produce a brighter and wider beam of light compared with the LEDs. When compared side by side, the LED lamps appear brighter and less “blue” in color, as they offer a whiter light. Halogen lights fall far behind HID/Xenon lamps and LED lamps. According to a MotorTrend side-by-side comparison, the Halogen lights offered inferior illumination of the road. When the authors of this article switched back to halogen they claimed it was as if there was a safety hazard from not having enough illumination of the roadway. Figure IV shows the lighting characteristics of halogen bulbs versus HID.

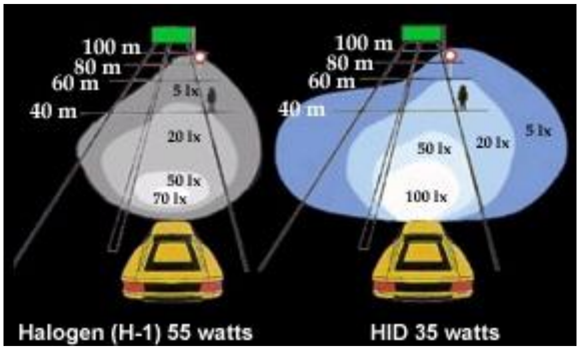


Figure IV : Light level at varying distances from source (Speedster Source, 2014)

	Lumens	Watts	Lumens/Watt
Halogen	1400	55	52.45
HID/Xenon	3000	35	85.71
LED	2200/2600	28	88

Table 2 : Bulb type lumens and power usage

External Automotive Lighting

Lighting on the exterior of automobiles has been developing over the last century, beginning with the first headlamp bulbs in 1908 (Wordenweber, 2007, p.96). A major development for exterior lighting occurred in 1960 when the first halogen light source was introduced in European vehicles (1979 in the US). Only twenty years ago the replaceable headlamp was introduced. Already consumers have an assortment of choices varying beyond incandescent, HID bulbs, and most recently light emitting diodes.

Modern vehicles have a number of components that make up headlamps. It is standard that these encasings sit between a height of 500 and 1200mm from the road's surface (Wordenweber, 2007, p.97). Inside the headlight unit are multiple bulbs which include the low beams, position, indicator, main beams, fog lights and running lights. The purpose of the low beams, also known as dipped beams, is to allow for a wide field of vision without hindering oncoming drivers (Wordenweber, 2007, p.99). Because of this, the dipped beams are designed with a light cut-off angle of 15 degrees with respect to the right curb. This means that above this angle from the curb, the amount of light diminishes rapidly. Additionally, these beams are angled slightly towards the ground so that light is directed downwards by 1%. This has the effect of allowing low beams to project only about 60m into the opposing lane while allowing the driver up to 120m of visibility in his or her own lane. High beams, or main beams are implemented into the headlight unit for the best possible range in low to no traffic driving situations (Wordenweber, 2007, p.100). Since these beams are not intended for use around other motorists, the direction of light does not need to be directed downwards. Rather the light is projected with a +- 10 degrees angle. Fog lights are angled even more than low beams tilting the light downwards by 2%. This allows for best visibility up to 35m in front of the car. The +- 35% horizontal beam width also adds to this close range visibility. Indicator, position, and daytime running lights are not used for the operator's benefit but rather for other motorists to increase visibility and reduce uncertainty.

The headlamps used in the automotive industry utilize either reflection or projection technology. Reflection technology is recognizable due to the reflectors behind the lens making it more distinguishable. This type of system works based on the shape of this reflector and patterns on the cover lens (Wordenweber, 2007, p. 101). These features are used to bend and manipulate the light in the desired direction for best optical performance. In a projection system, light from a source is passed through an elliptical reflector that is in the lens' focal plane (Wordenweber, 2007, p. 102). A shield covers this reflector and is used to shape the light and produce the desired cut-off. LED lighting systems can utilize either of these two designs. This offers the possibility of dynamic lighting and the ability to change light positions and intensities smoothly (Wordenweber, 2007, p. 110). Nonetheless, as LED lighting in vehicles is still emerging, designers have to take into consideration limitations such as current draw, the need for drive circuits, and different methods for heat dissipation.

The first LEDs appeared as brake light strips in the 1990s (Wordenweber, 2007, p. 111). These were in conjunction with the normal two taillight designs still seen today but incorporated single red LED strips on spoilers of vehicles. These initial packaged chips could only utilize a 20mA drive current without additional heat sinking. Similar to headlamps, the rear lamps of an automobile have several different bulbs. These include the rear position lamp, rear lights, brake lights, rear turn indicator, reversing light, central high mount stop lamp, license plate lights, and a rear reflex (Wordenweber, 2007, p. 160). The rear position lamp is the constant red light emitting from the tail lights when the headlights are on. These lights become brighter when the brake lights are activated and signal to other drivers that the vehicle is slowing down. The rear turn indicator also signals to other drivers that the vehicle is about to make a turn, and the reversing light indicates the vehicle will be or is already backing up. The central high mount stop lamp functions with the brake lights to also indicate that a vehicle is stopping. The rear reflex is not a bulb but rather a reflector that refracts light from a following driver's headlamps.

Interior Automotive Lighting

The interior of automobile lighting is following the trending technology of exterior lighting. That is, it is moving toward new sources of light, including LED (Wordenweber, 2007, p. 185). Only a few years ago car manufacturers started to incorporate more lighting features than the typical single overhead dome. Most standard and lower grade models still only have this one dome light. As cars are becoming more sophisticated, so is their interior lighting and the industry is working to create both aesthetic and useful lamp positions. The image below demonstrates different examples of light placements in a modern vehicle.

Figure V : Automobile light placement

Unlike exterior lighting, interior vehicle lighting is unregulated. It is important for designers to consider aspects such as overall brightness, glare and contrast levels, and comfort of specific color schemes while taking into account how the interior light will affect the driver's view out of the vehicle (Wordenweber, 2007, p. 188). The color of interior lighting in vehicles has a mental effect on the human brain. Colors associated with warm temperatures flaunts a technical ambience while cooler temperatures create a home-like environment. Much of the current lighting involves entering and exiting features such as sensors that control lights. These lights may turn on when a door is opened or shut off after a door is closed (Wordenweber, 2007, p. 196).

LED Notification Applications

Currently, LEDs are being used for various types of notifications and status indicators. For example, the iPhone has the ability to use the LED meant for the camera flash as a notification for something like a text message. Other smartphones have a front facing LED that will light up and stay lit with different colors to indicate different things. These type of concepts can and have been translated into the automotive industry, not necessarily with LEDs though. Things like a “check engine” light or a low gas light have, for a while, utilized a simply binary on or off light to indicate its status. However, there is room for a new form of check engine light that would be simple, cheap, smaller, and require less resources. A single LED that can change color to signify different things and then rotate between these notifications if there is more than one. This would reduce circuitry and therefore price. It would also integrate well with the current automotive trend of everything being digital, touchscreen, or luminescent versus physical indications.

Architectural Applications

Philips and Cree are two companies that are leading the architectural industry for LED retrofitting homes, businesses, and urban environments. Philips has an UrbanScape^{TM} product line of LED street lights resembling traditional street lamps with more efficiency. An overhead lamp can house up to 96 LEDs (Phillips, 2014) that can provide 20,000 lumens or equivalently an HID bulb rated at 400W. Philips has a wide variety of LED lights that come in an assortment of shapes and sizes depending on the application. Philips does produce LED A-type bulbs which are typically used in homes. Additionally, they are producing LED bulbs with the same shape as typical fluorescent tubes (T8 lamps). They advertise these LED lamps as "InstaFit" as they fit in the place of fluorescent tubes. This is convenient for businesses and other commercial applications that want to retrofit their lighting systems in a simple way (Philips, 2014).

Cree is also producing a number of LED lights with a wide range of applications such as Philips. Cree has a number of A-type bulbs that are tailored to residential consumers. An example of one of these bulbs is their A19 series bulb capable of outputting 1,100 lumens of light with a 25,000 hour lifetime. The bulbs in the A19 line have power ratings of 6, 9, and 13.5W which are equivalent to 40, 60, and 75W traditional bulbs. The energy savings as well as increased service life are making LEDs more practical for almost all applications. LEDs are becoming more common as they are dimmable, more efficient (85% less energy), and can go several years without replacement (Cree, 2014).

Car Electrical System

The major components of an automotive electrical system include the battery, starter, alternator, and electrical connections. When the ignition key is turned, the 12V battery provides power to the starter which begins spinning the flywheel. This wheel is what starts the motion of the pistons in the engine. The alternator is a crucial feature of the electrical system as it keeps the system running and the battery charged while the car is operating. Figure VI below shows visually how this intricate process works.

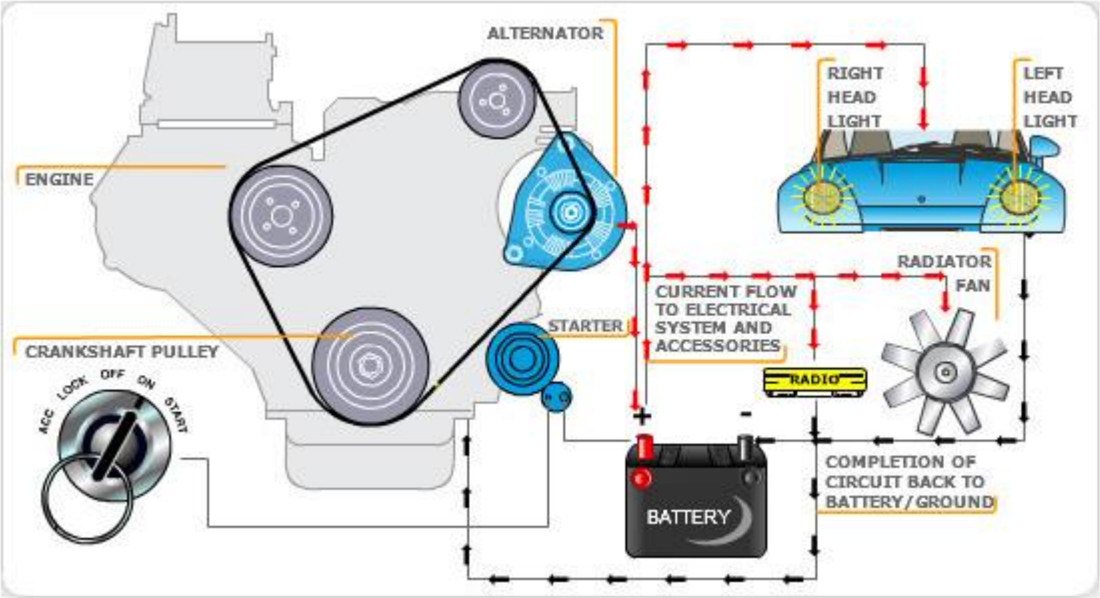


Figure VI : Automobile power system (Firestone, 2014)

This power system for a vehicle is distributed to the various electrical components inside through the use of a wire harness. The wire harness consists of a network of wires and connectors to power lights and electronics throughout the car and is traditionally a 12V DC system (Oba, 2013, p.1). A major concern for these long lengths of cables is weight, especially with new state of the art cars demanding more electrical terminations for components. A typical wiring harness in a car can weigh as much as 30 kg and can have an impact on fuel efficiency.

LED Headlights

LED headlights are emerging in the automotive industry for a variety of reasons. One of the biggest appeals of LED lighting systems is the extended lifetime. When implemented properly, LEDs should last longer than the lifetime of the vehicle. Other benefits include increased efficiency, an increase in style, and compactness (Dross, 2005, p.1). However, differences between LEDs and standard bulbs such as incandescent, halogen, and xenon make the circuit design procedure much different. Average bulbs typically project between 300 and 400lm of light and good bulbs can produce up to 900lm (Dross, 2005, p.2). The standard designs using reflection and projection technology as described earlier are used to direct the beam of the bulb. These traditional lighting systems only use one bulb so much of the luminous flux is lost directing the beam down towards the road. This reduces efficiency to as low as 30-50%. Although a single LED can only output around 100lm, the angle at which it produces light is much smaller allowing more efficient design. Since they emit a fraction of light compared to omnidirectional bulbs, a system of six or more LEDs is typically implemented. Multiple LEDs can be used in a system to illuminate a field of view for the driver without needing to reduce the angle of light such as with standard bulbs. This allows LED systems to reach efficiency levels of up to 80% (Dross, 2005, p.2).

The first automotive LED applications utilized the T-1 ¾ package and were mostly used in tail lights because current could only reach about 20mA before further heat sinking was required. By the end of the 1990s newer packages were able to output up to 50mA before additional heat sinking was required (Wordenweber, 2007, p. 111). Technological advances are increasing the power capabilities of LEDs and cooling systems need to keep up. Lower junction temperatures are desirable as an increase in temperature results in reduced light production and electrical stress that reduces lifetime of the diodes (Lin, 2012, p.1435).

Typical LED headlight circuit designs utilize either linear or switching regulating devices in order to brighten or dim the lamps. It is common to use a DC/DC converter to achieve this switching (ROHM Semiconductor, 2014). LEDs may either be connected in a single series string or multiple strings connected in parallel (Thomas & Pforr, 2009). Connecting smaller strings in parallel allows for a higher current draw than wiring the same number of LEDs in series but also presents the issue of individual LED parameters and the precision of fabrication. Figure VII below shows how a small difference in forward voltage of two LEDs can affect the current draw through a branch of the circuit.

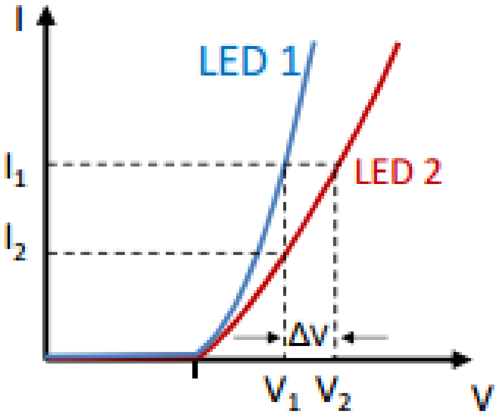


Figure VII : LED VI characteristics (Thomas & Pforr, 2009)

One way to avoid these mismatched parameters is called voltage binning. During production, LEDs can be sorted more precisely by grouping them with other parts that exhibit nearly the same forward voltages. However, this is inconvenient and rarely used as it slows down the production process and thus increases costs. Another way to obtain equal current draw through each branch involves adding a resistor in series to each string of LEDs (Thomas & Pforr, 2009). Unfortunately, this is not practical for high power applications either as a large voltage drop must be applied across these resistors to make current deviations smaller. Rather than use resistors, each branch may utilize a transistor as a current source. This allows for a more balanced current draw while reducing power dissipation but also increasing circuit intricacy. An example schematic is shown below in Figure VIII.

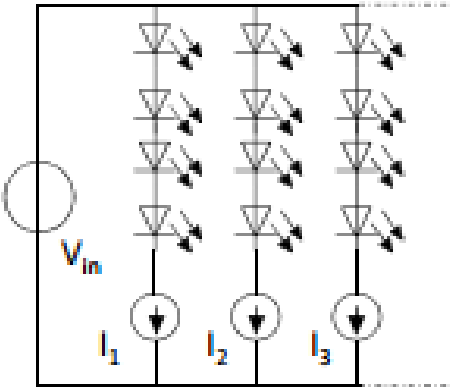


Figure VIII : Example LED array (Thomas & Pforr, 2009)

Another design involves the use of a sinusoidal voltage source and capacitors in series rather than transistors. Voltage drops across the capacitors reduce the magnitude of current deviations through the separate branches. Now that the waveform is AC, more parallel connections are needed in order to allow current to flow in both directions. An example circuit is show below in Figure IX.

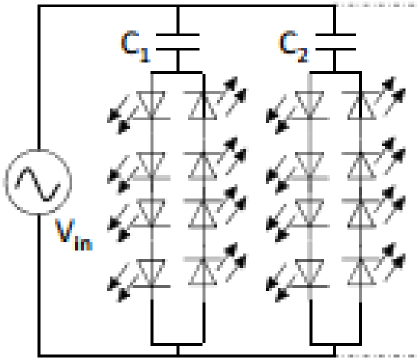


Figure IX : AC voltage LED array (Thomas & Pforr, 2009)

High Power LEDs

Manufacturers are continuing to develop LEDs capable of outputting higher luminosity. Several companies including Philips, Cree, and Luxeon are producing high brightness LEDs that are capable of being driven at several amps. These LEDs are also reaching higher efficiencies, capable of outputting up to 130lm/W (LuxeonStarLEDs, 2014). A particular LED that could be implemented in an automotive head lighting system is the Cree Xlamp XP-L (Cree, 2014). Cree produces a line of these LEDs in several colors including multiple hues of white. This line is attractive as a single LED can be driven at up to 3A to produce a luminous flux of up 1000lm (Cree, 2014). Figure X below shows the voltage and current characteristics for the XP-L LED. At the maximum drive current of 3A, the forward voltage is around 3.35V resulting in a power consumption of about 10W. Referring back to Table 2, a typical halogen bulb consumes 55W and produces only about 400 more lumens.

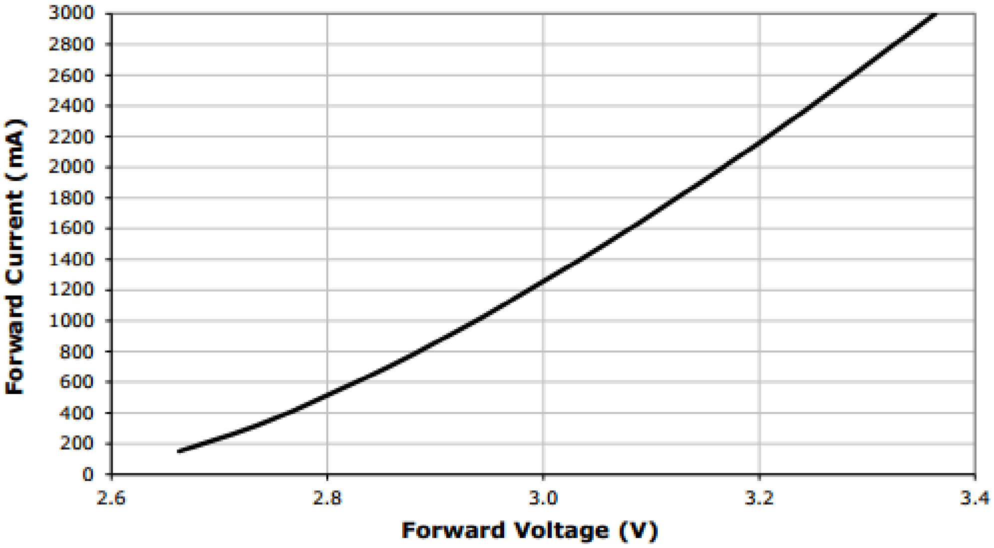


Figure X : XP-L LED typical forward voltage and current (CREE)

An advantage of using a high power LED is the freedom of choosing a desired luminous flux by biasing the current. The datasheet for the XP-L states that a cool white LED will output 620, 776, and 1034lm for respective drive currents of 1.5, 2.0, and 3.0A. This allows for an endless possibility of designs. For example, a dipped beam can contain two of these surface mount LEDs in series with a total current draw of 2A. This in turn would produce an output of over 1500lm. The new forward voltage across each diode would be approximately 3.15V resulting in a total of 12.6W dissipated. Furthermore, each XP-L can be purchased online for about $6 each at low quantities. Because of this, high power LEDs will be strongly considered for this project.

LED Driver Circuits

In order to maximize efficiency, the LEDs in a lighting system need to be pulse width modulated. This requires a DC to DC converter to regulate current draw as well as voltage. DC to DC converters fall into three categories: buck, boost, buck and boost. A buck converter is also known as a step down converter since it drives a load at a lower voltage potential than the input voltage (Buck Regulators Make Diving High Brightness LEDs Easy, 2011). These converters can reach efficiencies of up 90% or higher with most loss occurring when the active component is operating. A functional block diagram of Diodes Incorporated AP1509 buck converter is show in Figure XI followed by an example application in Figure XII (Diodes Incorporated, 2010).

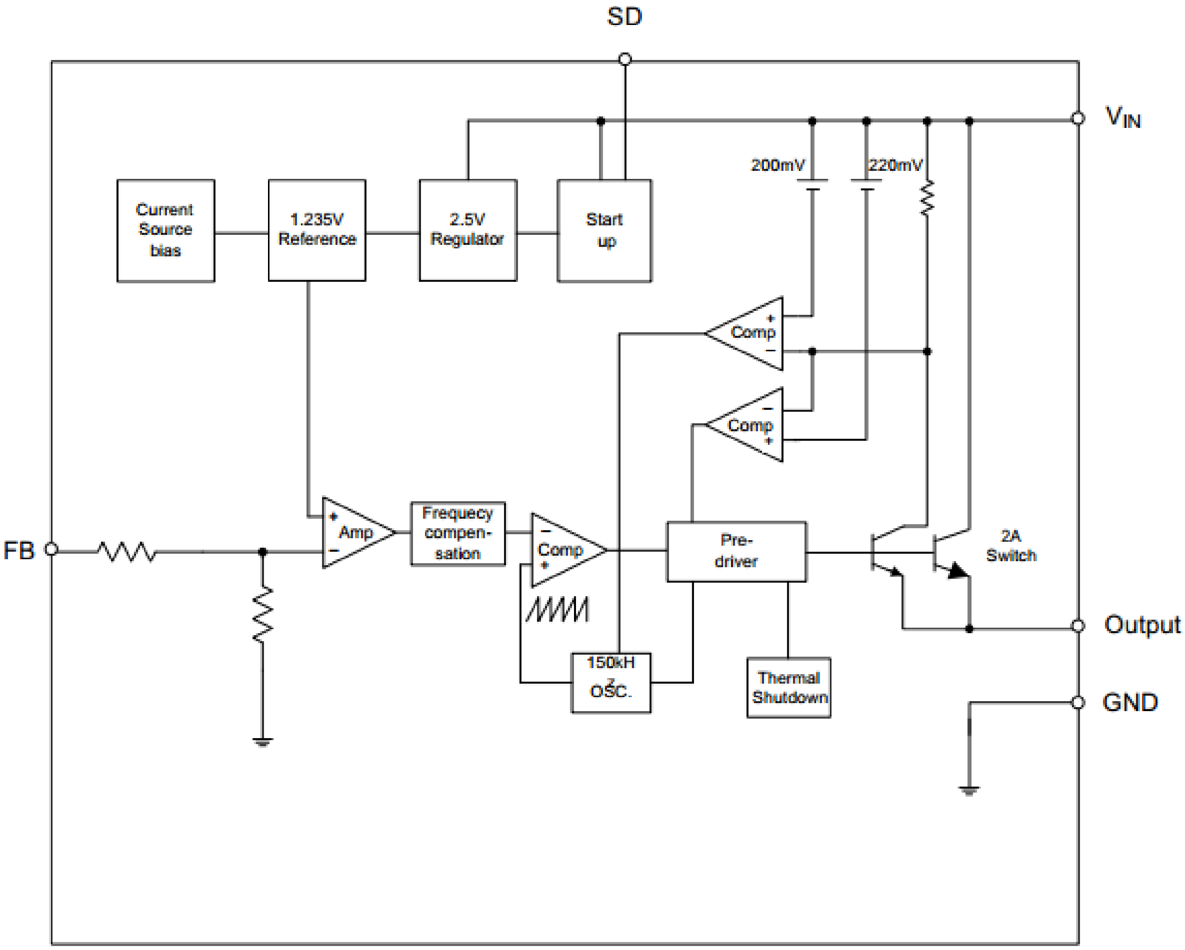
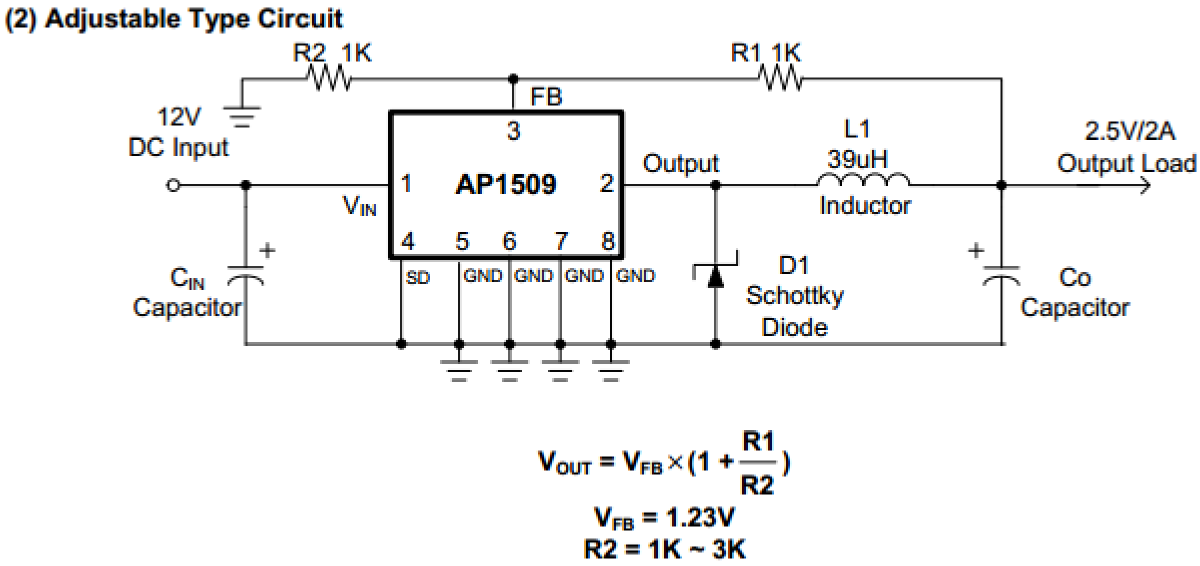


Figure XI : Buck converter (Diodes Incorporated, 2010)



$$V_{OUT} = V_{FB} \times (1 + \frac{R1}{R2})$$

$$V_{FB} = 1.23V$$

$$R2 = 1K \sim 3K$$

Figure XII : Buck converter adjustable application (Diodes Incorporated, 2010)

These two figures from the AP1509 data sheet illustrate a possible automotive LED driver. A 12V car battery can be connected to Vin and R1 and R2 can be picked accordingly to set the output voltage. The internal circuitry of the IC includes three comparators and an oscillator to switch between on and off states.

Conversely, a boost converter is used when a higher voltage is needed to drive a load than what is supplied by the source.

Department of Transportation Headlight Requirements

All innovations in headlight technology must be sure to comply with all Department of Transportation (DOT) rules and regulations. These regulations safeguard against headlights that, among other things, could be deemed too bright or pointing at an angle such that the oncoming driver's vision is reasonably impaired. Though headlight rules such as what time and in what conditions headlights must be on can vary by state, there is an overall set of regulations for the specificities and technicalities of all automotive lighting manufacturing. This is the Federal Motor Vehicle Safety Standard 108 (FMVSS 108) and it's produced by the United States Department of Transportation's National Highway Traffic Safety Administration (NHTSA) in conjunction with the Society of Automotive Engineers (SAE) and regulation SAEJ1383. These two standards, covering all automotive lighting, are over 200 pages and is what all automotive lighting manufacturers must comply with when developing their products.

A sample of some requirements is presented and consists of the following. Note that certain exclusions and exceptions apply. Any lower beam or high beam headlamps must be manufactured to produce a form of "white" light, must be of the same height, and symmetrical about the vertical centerline as far apart from each other as is practical. Regulations state that the wiring harness must be such that only the light sources intended for meeting lower beam or upper beam photometrics are energized when the selector switch designates it. The light must be considered steady and burning except if used in signaling purposes. Specific angle of incidence, light dispersion, intensity, heat requirements, etc. are all different depending on which type of headlamp is considered (United States Department of Transportation National Highway Traffic Safety Administration, 2004). The chart for upper beams follows in Figure XIII.

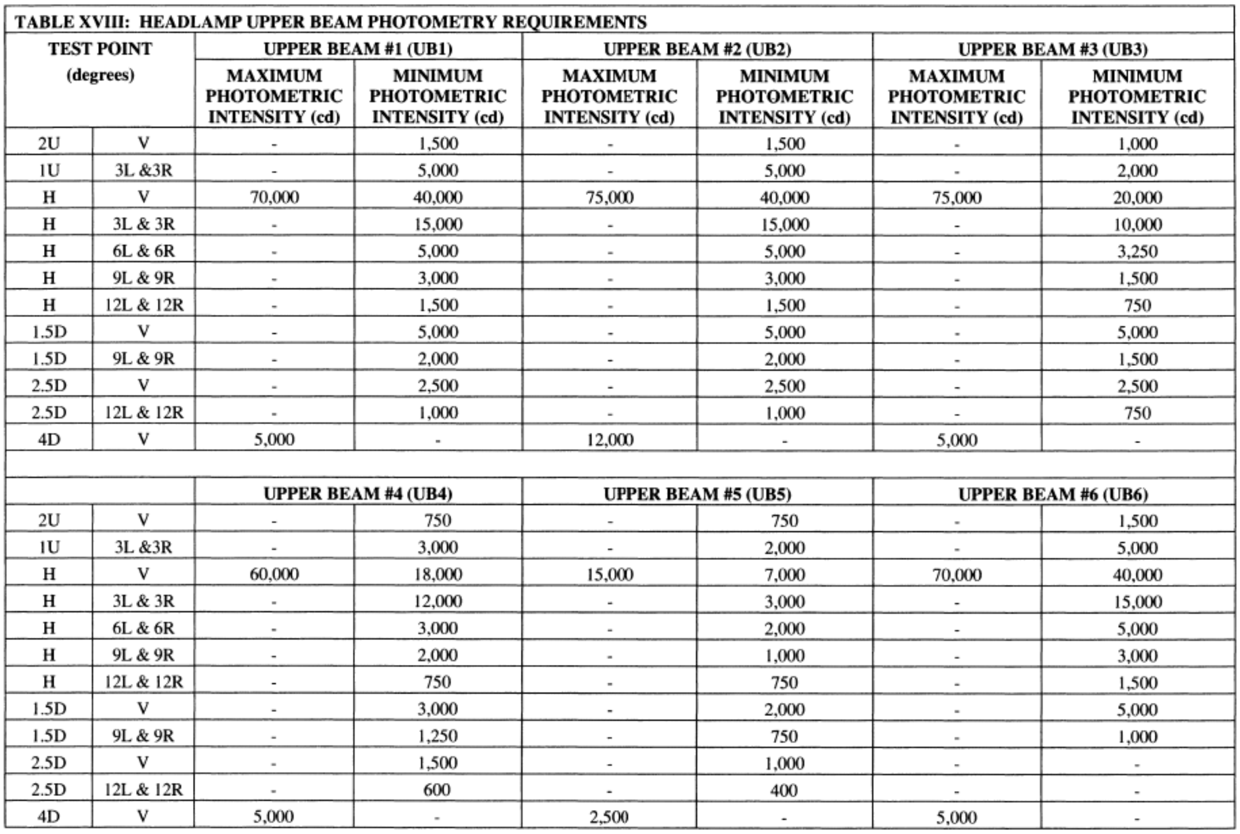


TABLE XVIII: HEADLAMP UPPER BEAM PHOTOMETRY REQUIREMENTS

TEST POINT (degrees)		UPPER BEAM #1 (UB1)		UPPER BEAM #2 (UB2)		UPPER BEAM #3 (UB3)	
		MAXIMUM PHOTOMETRIC INTENSITY (cd)	MINIMUM PHOTOMETRIC INTENSITY (cd)	MAXIMUM PHOTOMETRIC INTENSITY (cd)	MINIMUM PHOTOMETRIC INTENSITY (cd)	MAXIMUM PHOTOMETRIC INTENSITY (cd)	MINIMUM PHOTOMETRIC INTENSITY (cd)
2U	V	-	1,500	-	1,500	-	1,000
1U	3L &3R	-	5,000	-	5,000	-	2,000
H	V	70,000	40,000	75,000	40,000	75,000	20,000
H	3L & 3R	-	15,000	-	15,000	-	10,000
H	6L & 6R	-	5,000	-	5,000	-	3,250
H	9L & 9R	-	3,000	-	3,000	-	1,500
H	12L & 12R	-	1,500	-	1,500	-	750
1.5D	V	-	5,000	-	5,000	-	5,000
1.5D	9L & 9R	-	2,000	-	2,000	-	1,500
2.5D	V	-	2,500	-	2,500	-	2,500
2.5D	12L & 12R	-	1,000	-	1,000	-	750
4D	V	5,000	-	12,000	-	5,000	-
		UPPER BEAM #4 (UB4)		UPPER BEAM #5 (UB5)		UPPER BEAM #6 (UB6)	
2U	V	-	750	-	750	-	1,500
1U	3L &3R	-	3,000	-	2,000	-	5,000
H	V	60,000	18,000	15,000	7,000	70,000	40,000
H	3L & 3R	-	12,000	-	3,000	-	15,000
H	6L & 6R	-	3,000	-	2,000	-	5,000
H	9L & 9R	-	2,000	-	1,000	-	3,000
H	12L & 12R	-	750	-	750	-	1,500
1.5D	V	-	3,000	-	2,000	-	5,000
1.5D	9L & 9R	-	1,250	-	750	-	1,000
2.5D	V	-	1,500	-	1,000	-	-
2.5D	12L & 12R	-	600	-	400	-	-
4D	V	5,000	-	2,500	-	5,000	-

Figure XIII : Headlamp upper beam specifications (USDoTNHTSA, 2004)

For lower beams SAE provides a table seen in Table 3 as rough guidelines to what is acceptable.

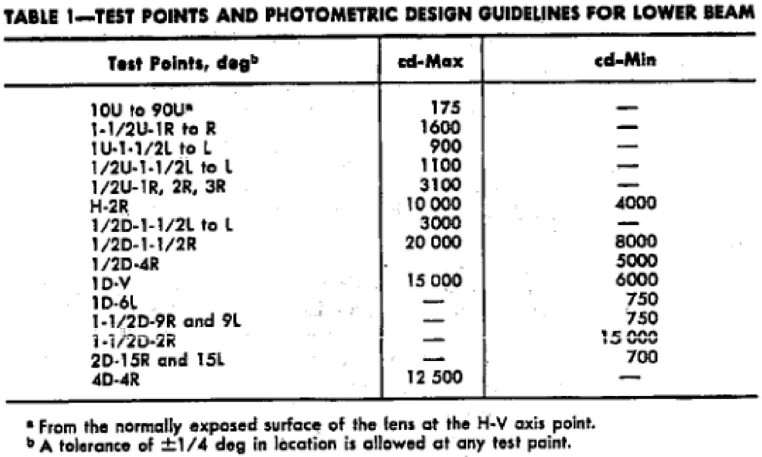


TABLE 1—TEST POINTS AND PHOTOMETRIC DESIGN GUIDELINES FOR LOWER BEAM

Test Points, deg[b]	cd-Max	cd-Min
10U to 90U[a]	175	—
1-1/2U-1R to R	1600	—
1U-1-1/2L to L	900	—
1/2U-1-1/2L to L	1100	—
1/2U-1R, 2R, 3R	3100	—
H-2R	10 000	4000
1/2D-1-1/2L to L	3000	—
1/2D-1-1/2R	20 000	8000
1/2D-4R		5000
1D-V	15 000	6000
1D-6L	—	750
1-1/2D-9R and 9L	—	750
1-1/2D-2R	—	15 000
2D-15R and 15L	—	700
4D-4R	12 500	—

[a] From the normally exposed surface of the lens at the H-V axis point.
[b] A tolerance of ±1/4 deg in location is allowed at any test point.

Table 3 : Headlamp lower beam specifications (Society of Automotive Engineers, 2010)

A general rule most states abide by, found in California’s DOT requirements for lighting angles states that the emitted light may be no higher than 2 ½ in. below the bulb height at 25 feet from the car. Certain manufacturers suggest varying changes to this formula, Toyota reduces this distance to 10 feet, Chrysler 33ft, and most of these are done because headlights and their housings differs as well as to accommodate larger tolerances as heavy weights in the rear can increase the vertical angle of the headlights to the road. Figure XIV is taken from SAE J1383 and provides insights into the vertical and horizontal angle of headlight requirements.

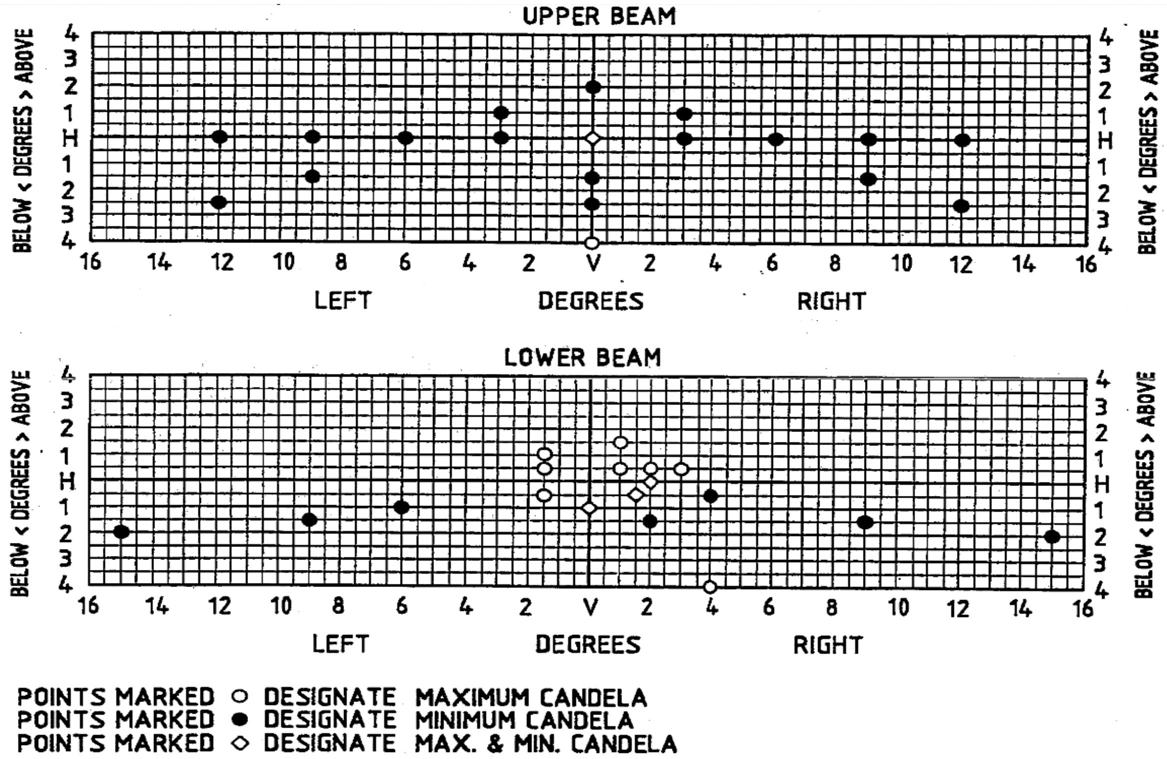


Figure XIV : Vertical & horizontal headlamp angles (Society of Automotive Engineers, 2010)

Headlight Heat Considerations

Traditional headlamps will produce radiated heat when active. This is because in order to produce light, the filaments and gas within the bulb must be energized thus producing their luminescence but with a side effect of heat. One very common reason traditional headlamps are often considered inefficient is their large percentage of energy conversion into heat. Almost 90% of the energy used to light these halogen bulbs is converted into heat rather than light (autoevolution, 2014). However, this can actually be an asset in certain geographies. For example, in the United States' northeast, conditions can become such that snow, ice, and sleet may accumulate on the housing and lens of the headlight. This heat produced from the bulb will radiate within the housing, thus heating up the lens. Of course, this will in turn act to melt snow and ice as well as keep it from forming on the headlights. Without effective headlight wipers, which have long since been removed as an option on most cars, this can create a situation where headlights could become ineffective and obstructed. As DOT states, it is the drivers responsibility and legal obligation to be sure there are no obstructions of emitted light from their headlights. Without this heat emission, it could cause a seriously dangerous and illegal situation for some drivers.

To this effect NHTSA and SAE have included in their regulations a thermal profile of the tests they simulate with headlights. In order for a headlight to pass certification it must succeed in the thermal cycling that can be found in Figure XV.

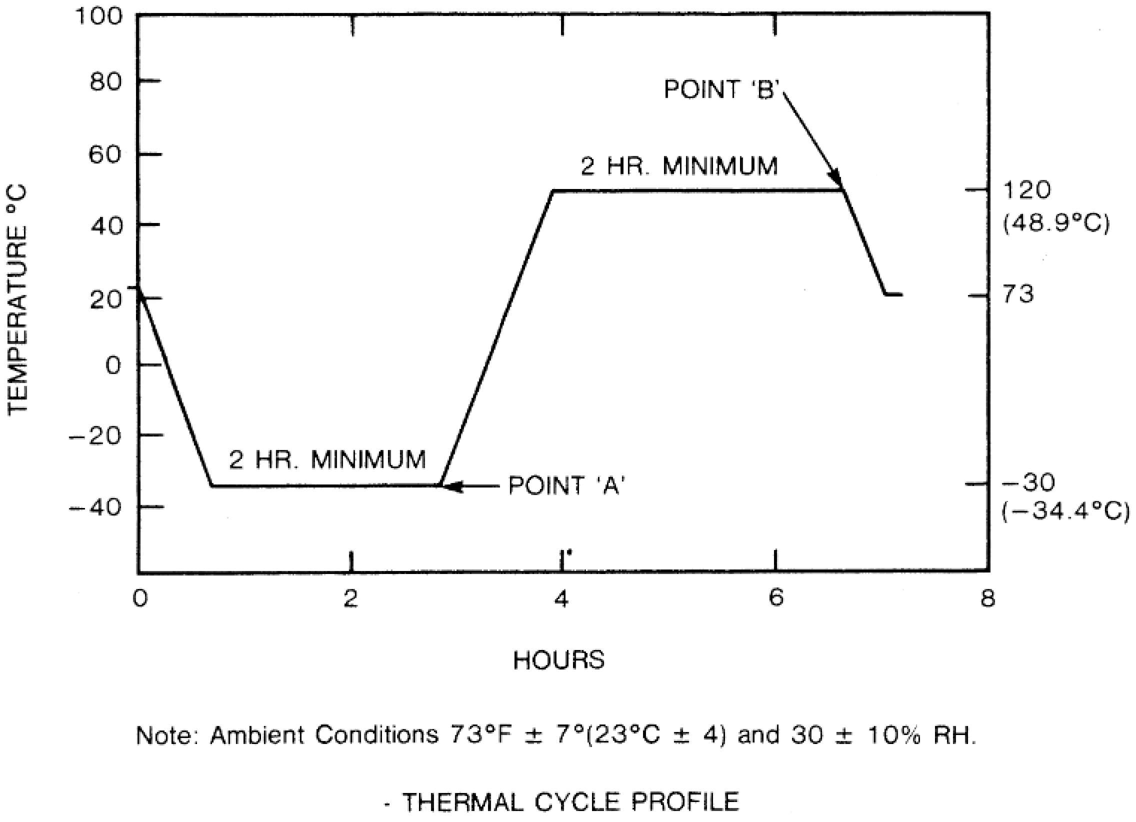


Figure XV : Thermal cycle testing (Society of Automotive Engineers, 2010)

This figure is simply meant to show the ranges of temperature that these regulatory organizations might expect a typical headlight to undergo. LED headlights would be subjected to these same stresses and the same snow and ice conditions any other type of headlight would. This presents an issue where LED headlights are not producing as much heat as halogen bulbs, thus unable to melt snow or ice. It also presents an opportunity of how to capture the available heat and utilize it. In a similar vein, it has been observed that LED traffic lights, if placed in northern climates, can become encrusted in ice thus inhibiting its proper signaling results. This problem has been held responsible for several car related fatalities and accidents (Ramde, 2010). Some cities have had to send public workers around to all traffic lights to melt the ice, a procedure far more costly than the traditional traffic lights' inefficiency (Winstrom, 2014). LED headlights face similar issues, if less severe due to the ambient engine heat. This issue has been recognized and there are currently solutions to mitigate these effects. One such solution is exterior spray nozzles located beneath the lens. These operate much like the spray nozzles to help wash your windscreen. When sprayed, the ice will melt much quicker and will also provide a film on the lens that snow and ice has a hard time attaching to. Some headlights even utilize a heated housing which intentionally cycles heat within itself to warm up the lens much like halogen bulbs naturally do. Aftermarket products like Rain-X™ act to create a surface snow cannot stay on and so help to prevent icing over. As LED headlights are still new to the market, different solutions, techniques, and work-arounds to produce or capture heat in hopes of preventing this issue are in development. The next section describes these in more detail.

LED Headlight Heat Dissipation Design

LED HEADLIGHT SUPPLEMENT:

LED headlamps use either reflection or projection technology like other typical systems (ElectronicsWeekly, 2013). Reflection systems are more common as they are cheaper to implement. When using LEDs for headlamps, their light is directed back towards the reflector. This allows for increased efficiency as all of the light can be reflected. Incandescent and HID bulbs cannot reflect all of their emitted light as they produce light in all directions. Figure XVI shows how the reflector and a pair of LEDs can be used to create both dipped and main beams.

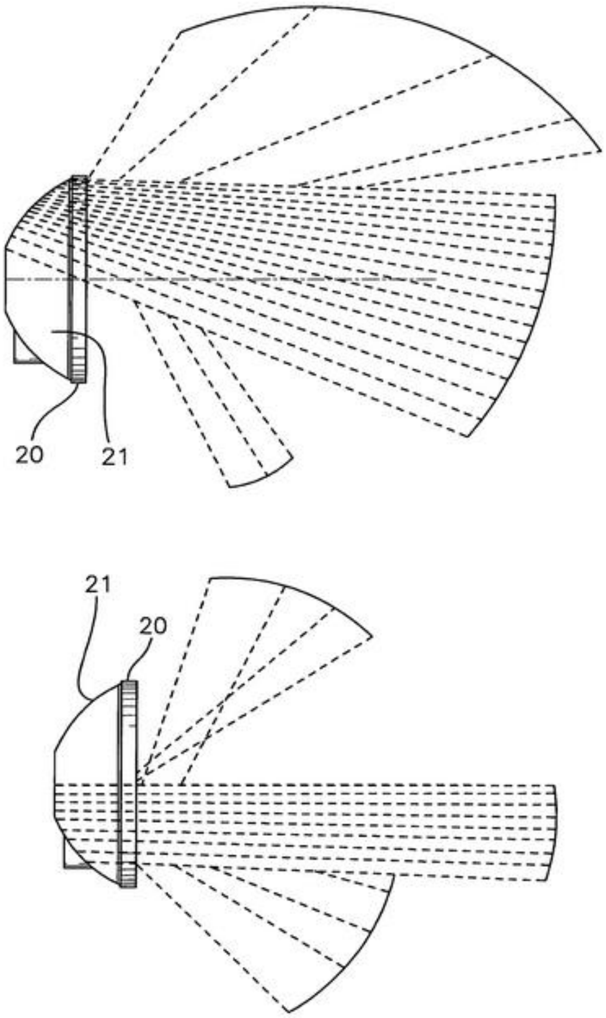


Figure XVI : LED Lamp reflection for high and low beams (Koester, 2010)

This diagram came from a patent for an LED reflector lamp and has uses for automotive lights, work lights, emergency vehicles and more (Koester, 2010). The design consists of a bulb containing two LEDs. In the top part of the figure, the LED on the bottom is off and the LED on the top half of the bulb emits light back into the top half of the reflector. This beam of light is directed down towards the road and functions as the dipped beams. Conversely, the bottom figure shows the beam of light produced for the main beams. This occurs when the top LED is off and the bottom LED is illuminated. Of course, the geometric shape of the reflector is calculated in order to produce the desired beams of light. An image of this lamp can be seen in

Figure XVII where “11” is the top LED.

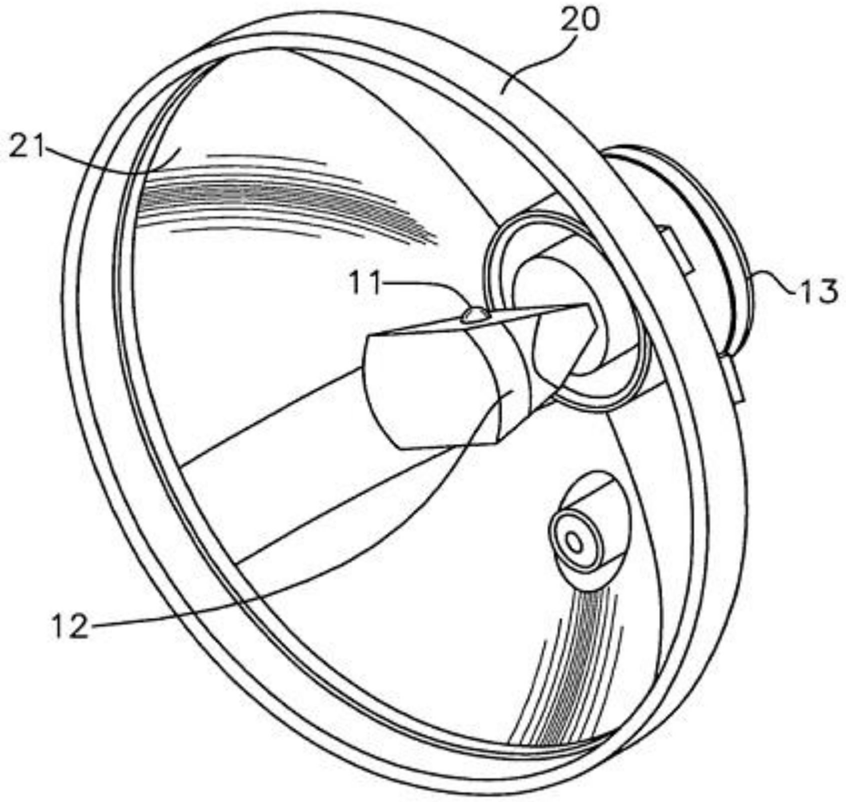


Figure XVII : Lamp diagram (Koester, 2010)

END SUPPLEMENT

One of the major concerns when implementing LED headlamps is freezing of the cover glass. In temperatures below freezing, ice may form on this headlight glass and alter the projected beam. This can be dangerous for drivers as it results in reduced visibility. Before the implementation of LEDs this was not a concern as incandescent, halogen, and HID bulbs are all thermal heat sources. The heat produced by these sources all comes from the bulb which keeps the glass covering warm. LEDs produce heat at their junctions and for head light applications need to be heatsinked. Some designers, for example Audi, are building heatsink systems that can defrost the headlamps (Audi, 2013). These work by heatsinking the LEDs at their junctions and utilizing a fan to move the heat towards the glass. Other systems may keep the glass warm by using heating lines or film. This is evident in a patent for an LED headlamp with a heated cover. This design applied a semi-transparent thermally conductive material between the LED driver circuit and the cover. This thermally conductive material allows for the transfer of heat from the LED driver circuit and LED junctions toward the plastic bulb cover through direct contact.

Another type of design to move heat away from LED junctions involves heat pipes. Heat pipes are an attractive cooling method for LED headlamps as they can keep junction temperatures at a specified temperature (60 degrees in one study) (Lin, 2012). Again this is beneficial as LED lifetime is extended by avoiding electrical overstress. It is additionally important to keep this temperature constant as an increase in temperature has an immediate effect on output brightness (Rice, 2004). In these types of systems, the LED and pipe are thermally coupled. The heat pipe is made of a thermally conductive material filled with either water or a refrigerant. Figure XVIII below shows a heat pipe.

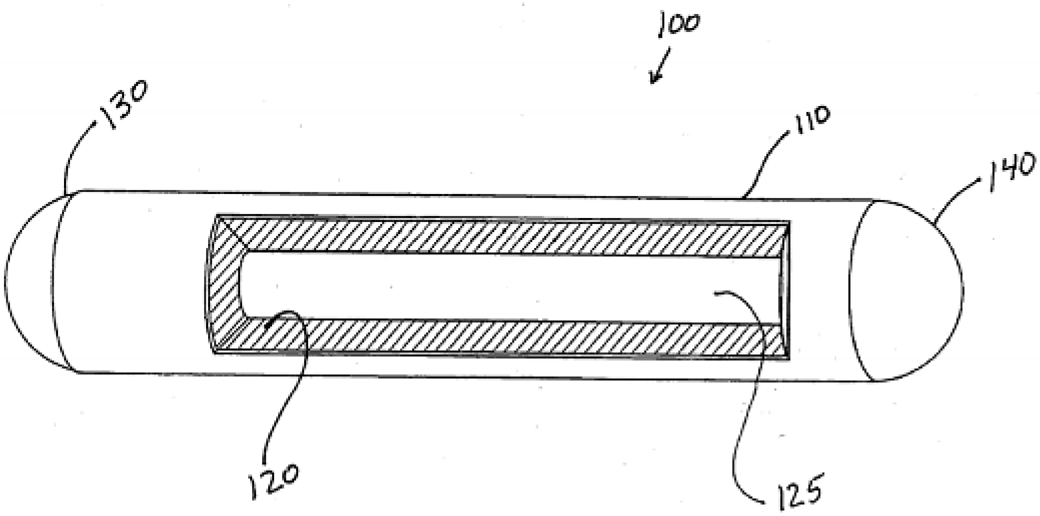


Figure XVIII : Heat pipe diagram (Rice, 2004)

During normal head light operation, the LED transfers heat to the pipe at the condensation area (130) eventually causing the enclosed fluid to boil. The fluid in this area turns into vapor and moves towards the other end of the pipe through convection. This end is called the evaporation area (140) and is placed at a lower temperature in order to create the heat transfer. A heatsink is typically coupled to the evaporation side of the pipe as its temperature needs to be regulated below the boiling point of the liquid. Here heat is transferred to the heatsink and the vapor condenses back into a liquid. This allows for a regenerative cooling process that can be implemented for LED headlamps. For this application the LEDs can be attached to a condensation area of one or more heat pipes. These pipes can terminate with a heatsink near the front covers of the lamps to prevent them from freezing.

CHAPTER III: PROCESS

The process of researching, developing and documenting this project took course over approximately seven months. The initial phase was to determine what direction the project was to go in. In order to come to this conclusion it was necessary to understand aspects of the automotive industry, headlight technology, and what issues were present that needed addressing. It was determined the project would focus on increasing the efficiency of the overly complex LED headlight drivers car manufacturers are currently using, thus boosting the efficacy of LED headlights as the primary lighting source over halogen bulbs and Xenon HIDs. In addition, if the heat from the junction of the LED could be captured and utilized more effectively it may be possible to avoid iced over or obstructed lens glass in cooler climates.

With the issues of the current market understood it was necessary to develop the actual goals and customer requirements of any improvements or changes to be made. Factors such as “plug-n-play” functionality, safety features, legal and standard requirements, cost, size, etc. all had to be considered for the final product, in addition to the improvements that were to be implemented in terms of the actual circuit. This required further research into current headlight products as well as purchasing and testing them as a baseline or minimum requirement for the team. During this time, considerations and suggestions concerning the goal of the product was taken from advisors.

The next and most arduous step was designing the efficient LED headlight driver with thermal capabilities. During this period there was much fluctuation of how this would be accomplished or even if the project direction should remain the same. At one point it had seemed there were ICs on the market that could achieve pinnacle efficiency and perform exactly the duties proposed by the circuit. At this point the choice was made to utilize these ICs and the focus was to move on to solely thermal considerations. After ordering several from four major developers such as Texas Instruments, Allegro Microsystems, Rohm Semiconductors, and Linear Technologies and subsequently testing them, it was determined these chips were far beyond the necessary scope of this project and suffered from recycled technology and “feature creep” and therefore being overly complex. After this, the focus again returned to making an original circuit from the ground up. The circuit evolution will be discussed in the following sections.

Background Research

In order to develop any product or make an improvement on an existing one it is necessary to research the current market, competitors, and what products they offer. It is also important to understand any gaps in the market or negative aspects of the most popular technologies. If this is understood, a product can be developed that will either try to fit this gap in the market or make an improvement that would add desirability. As such the very first steps in this project were to understand these aspects.

The first topics researched were who are the current manufacturers and what does the market for headlights currently look like? Most of this research was done online to get a baseline for who advertises the strongest and whose technology is going into what automobiles. Important resources were simple automotive shops websites such as Advanced Auto Parts where many consumers would purchase third party headlights if necessary or specialty headlight retailers like vleds.com. Research led to learning what makes and models of cars use LEDs in headlight technology. So, manufacturer’s websites such as BMW and Audi gave us an idea of where LED headlights stand in terms of who the cars that LED headlights are installed in are marketed towards.

Research into the different headlight technologies such as halogen, Xenon, and LED allowed for comparisons to be made in hopes of combining the advantages of these various kinds of bulbs. Through researching, applying real world experiences, and purchasing some of these bulbs for testing, it helped develop an idea of what to improve upon and how to do so. This information and knowledge also helped to understand how an LED headlight developed by a third party needs to be able to work with the cars built-in electrical harness without modifications. This would be vital as car manufacturers would want a transition of technology to be as resource efficient as possible.

Scholarly papers, legal standards, magazine articles, etc. were all used to help in this process. This helped to concrete the technical and non-technical requirements a customer or manufacturer would desire. The location where this project was performed allowed for a valuable insight into the heating and ice considerations of headlights. As very low temperatures and large amounts of snow and ice are common, the ability to keep this from forming on the headlight lens was of paramount importance where other locales may have been unconcerned with this issue.

Research then moved to the technicalities and specificities of modern LED driving circuits such as how well they perform in terms of energy consumed compared to light produced. DC/DC converters, buck and boost, were analyzed as well as typical application circuits provided by automotive IC manufacturers. Advisor advice was also utilized to provide a baseline circuit formed from electrical principle that would be the heart of efficiency and simplicity. From this analysis, the basic and most important aspect of these drivers became apparent, an LC circuit based on a PWM input. With this, development on a more efficient LED driver began and the evolution of this process follows.

First Circuit Evolution

The project started by designing a very simple power supply with only a voltage source, an inductor, a capacitor, and a resistor to represent the load. A schematic of this system can be seen below in Figure XIX. The inductor and capacitor pair in this circuit serve vital purposes. The inductor and capacitor are going to help smooth out the voltage and therefore current ripple within the system due to the power source turning on and off rapidly, also known as PWM. A side effect of the capacitor however is that when the system is powered on it will cause current and voltage overage which can destroy a system that is not prepared for such a spike. A disadvantage of an inductor with too high inductance is the system will take far longer to reach its operating current. As such, in this circuit it is a balance between choosing appropriate and realistic component values while maintaining a smooth ripple current through the load and with minimal overvoltage and current as well as startup time. The entire purpose of this simple circuit is to design the bare minimum components required to provide a constant current source to an LED load through pulse width modulation. This allows ample understanding of the fundamentals required to increase efficiency while maintaining functionality.

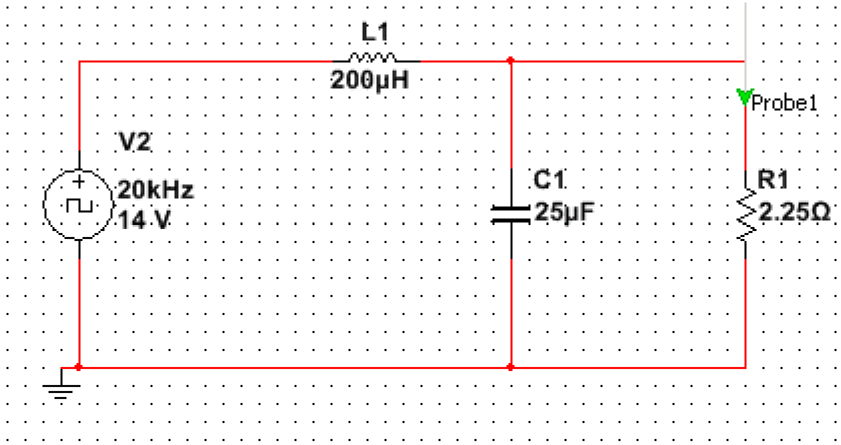


Figure XIX : First Circuit Evolution Schematic

Below in Figure XX you can see a transient analysis of this circuit running for 1ms. The simulated 20 kHz clock source can be seen as the purple square wave, this is the PWM signal. It can be seen that this signal is going from on (14V) to off (0V) with a duty cycle of 50%. This PWM signal, with its adjustable duty cycle and frequency is the starting point of efficiency gains, only having the signal high for as long as it needs to be in order to produce a current deemed constant enough. This current qualification is determined through testing varying degrees of current fluctuation whilst observing the LEDs for any noticeable flickering.

The red fluctuating signal is the voltage at the location of probe1 seen in Figure XIX and the blue signal is the current at the same probe. As previously mentioned, there are sections of this transient analysis that are important to the design of the circuit. First, the amount of time the voltage and subsequently the current reach their steady values is a facet of the components chosen and can be changed if a problem comes of this delay. Before the voltage has reached its steady value, there is the spike previously mentioned in this section. As can be seen in the figure, it is small at roughly 1V. The component selection in this case was such that the spike is of little concern, but with small variations in component values, it can quickly become a problem. The average height of this fluctuating voltage is considered the constant voltage. The current behaves in a similar manner but with all fluctuations minimized. As can be seen the current is far steadier than the voltage and this is due to the LC behavior. This pseudo-constant current is an important design parameter as it drives the LEDs brightness and visual steadiness.

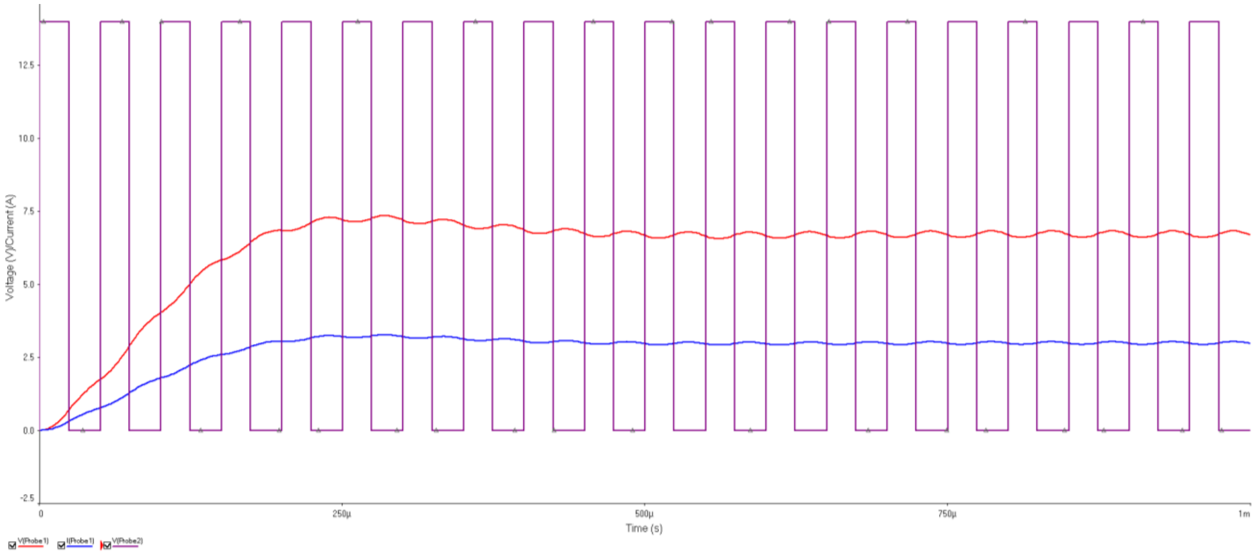


Figure XX : Transient Analysis of Circuit I

Second Circuit Evolution

It became clear that as the voltage source to the circuit cycled between on and off at a high frequency the remaining charge in the system when the cycle goes low could be taken advantage of. By placing a diode in parallel with the capacitor and load it could act as a closed circuit when the PWM clock voltage is in its zero (off) state. This will allow for higher efficiency as the current will proceed to flow through the system even for the period of time when the clock voltage goes low, mitigating the waste of energy still left in the system as well as allowing for a lower switching frequency as a potential design feature. A Schottky diode was put into the circuit rather than a standard diode. This is used because they possess the ability to handle a higher switching frequency, necessary for PWM, and have a very low forward voltage compared with that of a regular diode. This can be seen in the below Figure XXI.

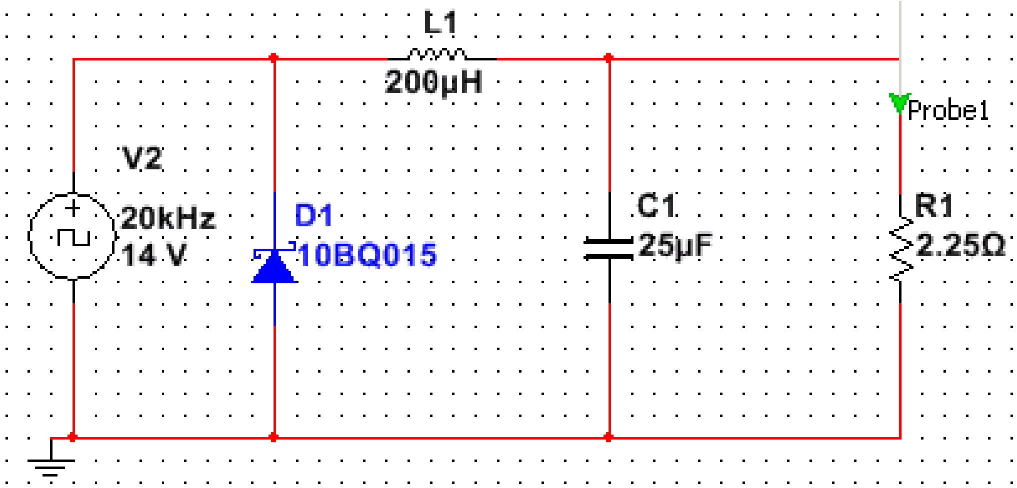


Figure XXI : Second Circuit Evolution Schematic

At this point, the selection of the given Schottky diode in the figure is not necessarily the diode that will be used in the actual circuit, but it is usable in a simulation. It should also be noted that adding this diode produces no variation in the transient analysis as it won't affect the voltage and current but its advantages will instead be seen from an energy efficiency standpoint.

Third Circuit Evolution

As can be seen in the previous circuit evolutions, up to this point an all-in-one clock voltage source was used to mimic the car battery as well as the eventual PWM driver. This is not how the voltage source will work in an automobile headlight driver and as such it was necessary to provide a more realistic simulation. So, true to a standard automobile's electrical system, a constant 14V DC source replaced the clock voltage. However, this developmental utilizes pulse width modulation to provide its constant current to the LED pair. Therefore, as can be seen in Figure XXII, a voltage controlled switch is added into the circuit to act as a pulse width modulated source, turning on and off with a given frequency. In this way, a constant voltage and current can be obtained with this circuit, based off a 14V DC input source and a simulated PWM driver. In the following evolutions, this PWM block circuit is created instead of assuming a simulated component.

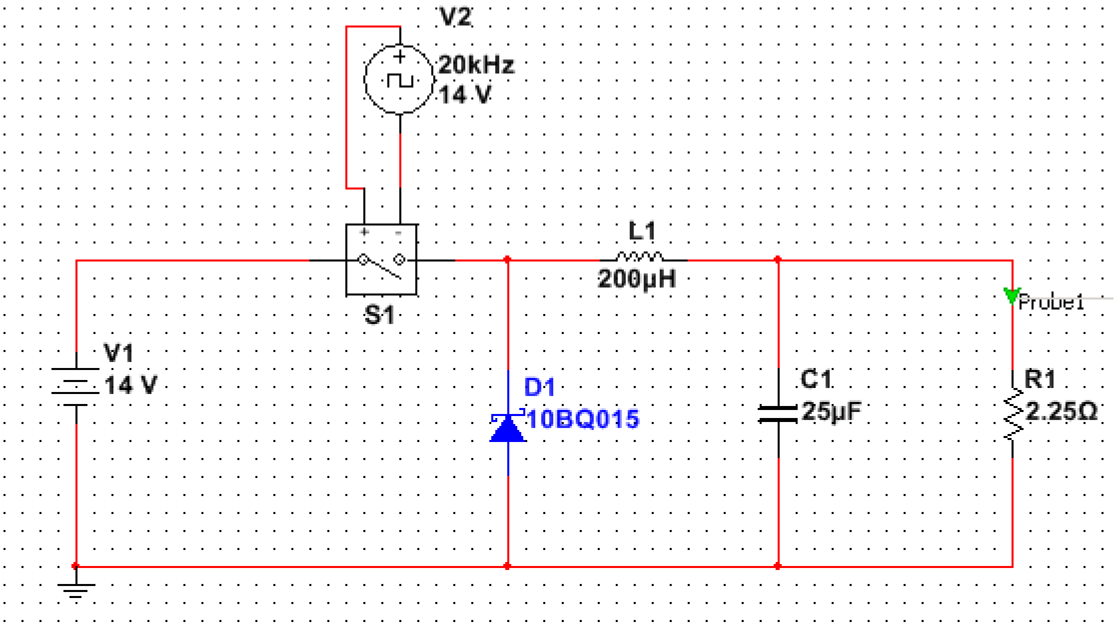


Figure XXII : Third Evolution Schematic

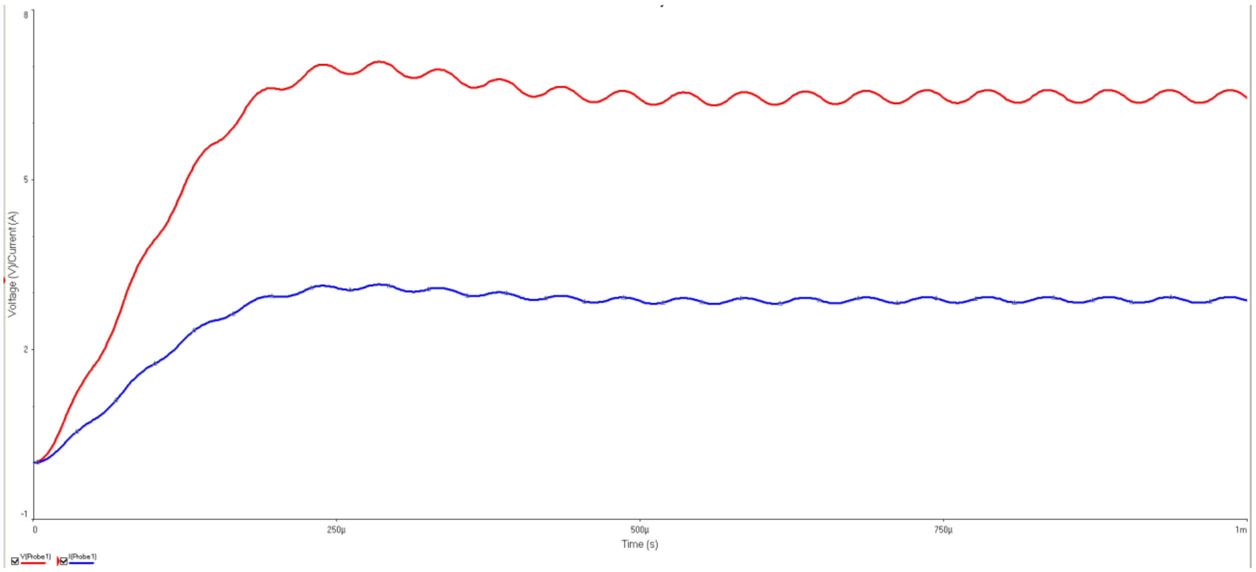


Figure XXIII : Transient Analysis Circuit III

In Figure XXII the voltage of the simulated component was set at the same as the 14V DC car battery voltage as initial considerations were all done based off a constant 14V DC source. However, as can be seen in a later iteration of the circuit, the switch is no longer operated at this voltage but a stepped down voltage as it becomes a necessary reference.

Fourth Circuit Evolution

The next evolution was to transform the simulated PWM switch into actual analog circuits that do this. As this was to become very complex, it was necessary to create a block diagram of what initial research suggested would be necessary. Figure XXIV shows the previous circuit with a block diagram now acting as the PWM source. The first block of the diagram is a Schmitt Trigger square wave generator that is sourced by a constant DC voltage. This will produce a square wave that will then be the input to a Miller Integrator. From the Miller Integrator the output goes to a comparator in order to form the square wave PWM output. This will be controllable in frequency, duty cycle, and voltage.

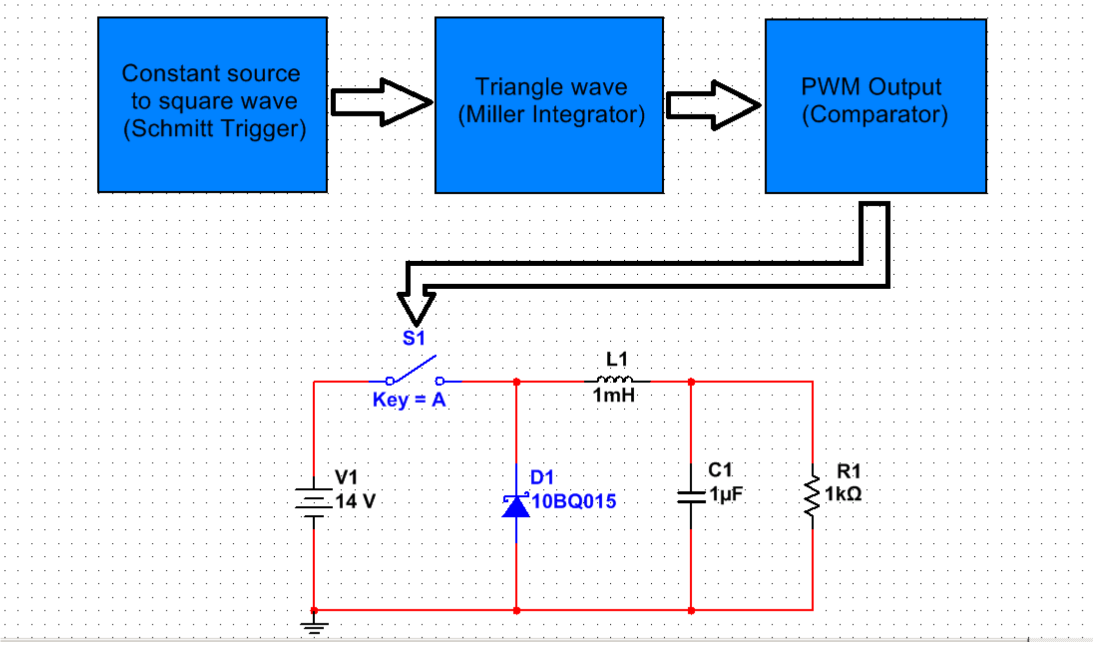


Figure XXIV : Fourth Circuit Evolution Diagram

Fifth Circuit Evolution

At this point in the evolution of the circuit it became clear that things were going to potentially take longer than what time allowed for. As such, a decision was made to look into integrated chips that provide a similar functionality. However, these chips did not perform as advertised and were overly complex, recycled, inefficient, chips in which most of their functionality was in a provided application circuit, not the chip itself. A comparison of the ICs can be seen in Figure XXV : IC Comparison Chart.

Allegro: A6213

- 3A out
- Vin~<40V
- Low cost: Not sold anymore
- Simplest design
- PWM capable
- 100 Hz-1MHz
- Automotive Rated

TI: LM3423-Q1

- 5A out
- Vin~ 4.5V-75V
- Cost: $3.75
- Buck, Boost, & Buck-Boost
- PWM Capable
- 100kHz-2MHz
- Automotive Rated

Linear Technologies: LT3763

- 20A out
- Vin= 6V-60V
- Cost: $7.00
- Can be used as battery charger, regulator
- PWM Capable
- 200 kHz-1MHz
- Automotive Rated

Rohm: BD8381EFV

- A out
- Vin= 5V-30V
- Cost: $5.53
- Buck, Boost, bad data sheet
- PWM Capable
- 100kHz-600kHz
- Automotive Rated

Figure XXV : IC Comparison Chart

From the four chips that looked like potential candidates, three were purchased, of which one was chosen to be integrated. The chip that was chosen was the "LM3423 N-Channel for Constant Current LED Driver" from Texas Instruments because it was the most simple to understand and had the least superfluous features. A large issue with all these chips was that they were far too complex for a simple constant current application. This is because they have been recycled into many different uses and as such the technology from other applications is still present, but only acts to make the circuit theory and understanding that much harder. In Figure

XXVI you can see the application circuit that we designed for eventual use. This circuit appears complex, but it is a typical set up when operating the IC for a buck application (it can also do boost and buck-boost).

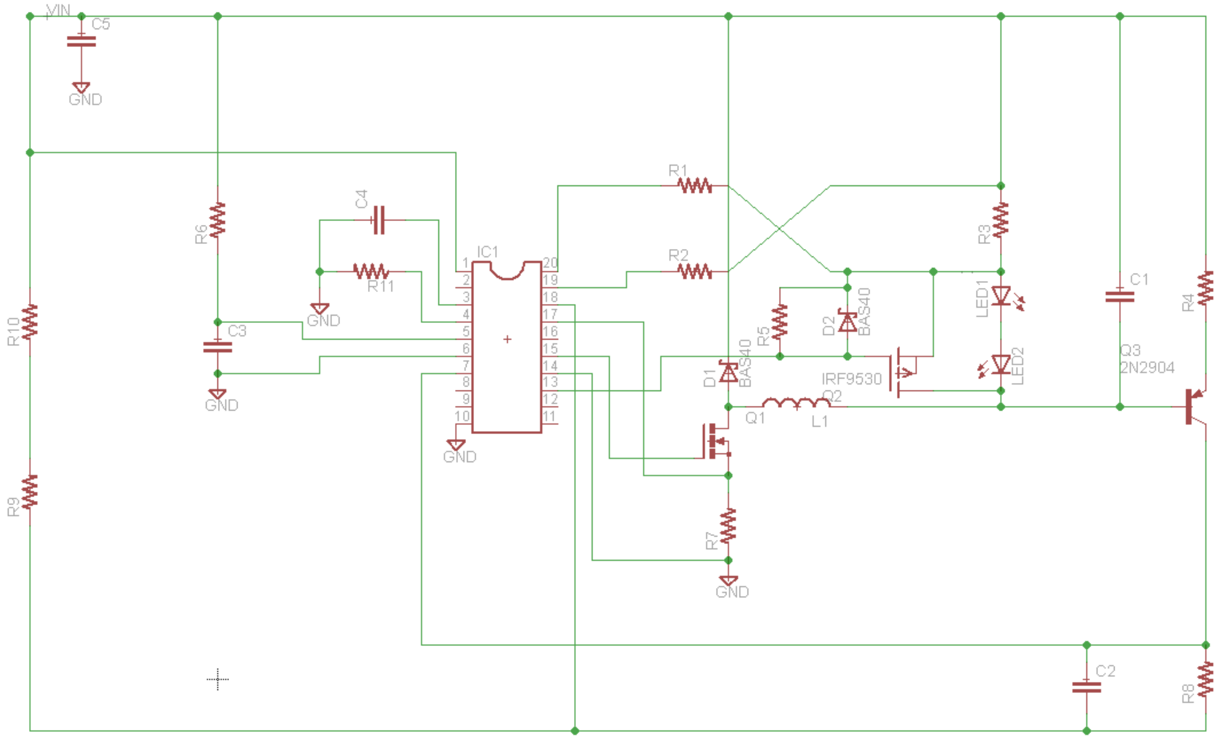


Figure XXVI : IC Application Circuit

Many of the passive components in the external circuit detailed in Figure XXVI are placed in order to protect the chip. However the first consideration in the design involves the switching frequency. For the LED headlight application, a switching frequency of 100 kHz was chosen in order to reduce the size of the inductor L1. Resistor R6 and capacitor C3 are placed on the input voltage in order to reduce the ripple caused by a varying voltage from the car battery. Resistor R3 is in the LED string and is a sense resistor used to set the current through the branch. Components R1, R2, R11, and C4 are also necessary for regulating LED current. R7 is a limiting resistor that feeds a voltage back to a comparator amplifier with a fixed input terminal at 245mV. Using Ohm’s Law the desired current limit can be set by choosing R7 appropriately. Capacitor

C1 is also important as its capacitance dictates the size of the LED ripple current. This of course is dependent on the switching frequency and the dynamic resistance of the LED string. Finally, R4, R8, R9, R10, and C2 are placed in order to protect the chip from undervoltage or overvoltage stress.

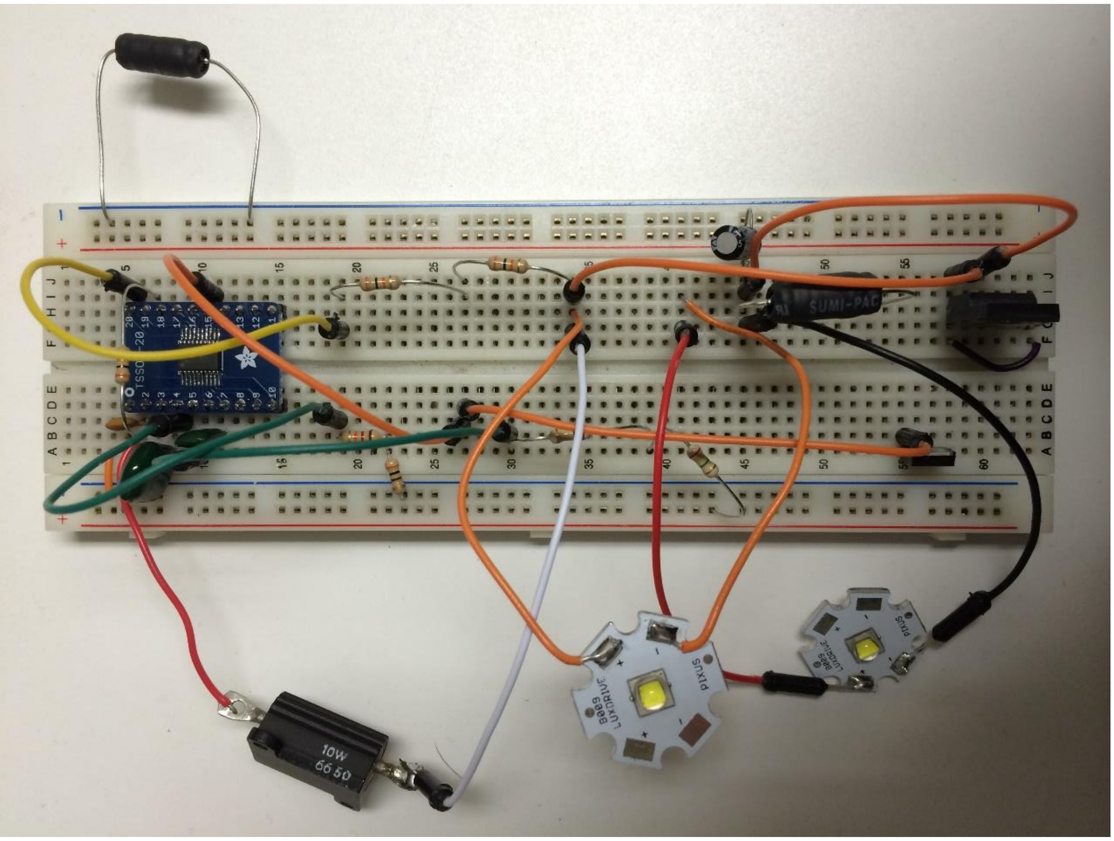


Figure XXVII : Breadboard IC Circuit

In the above figure you can see the actual breadboard circuit and the two Cree XM-L LEDs and their small heatsinks that were chosen as the lighting source. In this case two are being used however the application of an LED headlight can accept up to eight depending on the brightness of each LED and the layout of the headlight housing. The large component sizes are used as there will be lots of power dissipation through various components and in order to withstand this, they are usually larger in size. The blue board is a breakout board where the TI chip is soldered into. A close-up of this can be seen in Figure XXVIII.

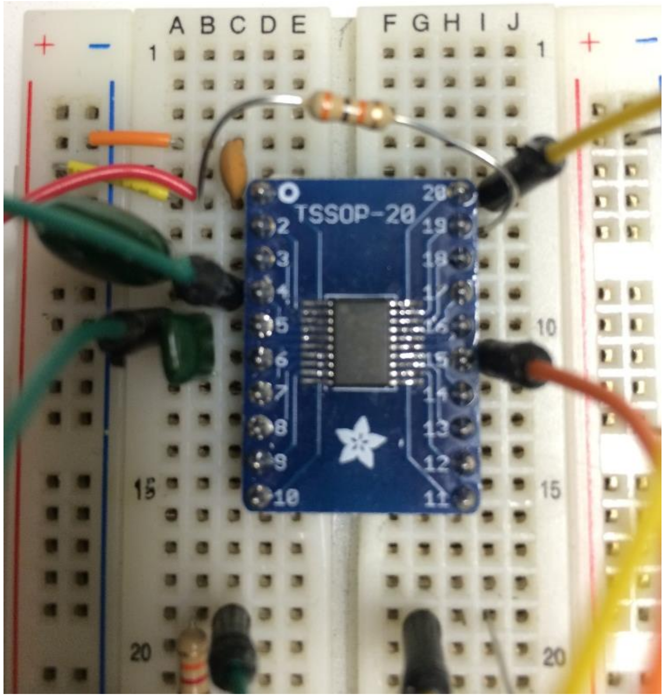


Figure XXVIII : IC Breakout Board

Sixth Circuit Evolution

After much analysis and circuit building based on the IC principle, it was eventually scrapped as it was overly complex. It would also require a thorough understanding of the internals of the integrated chip which could not be done in the amount of time required. The circuit based around the TI chip was so intricate and contrived it would not have allowed an end-user to gain a clear understanding of the basic electrical principles at work. However, the circuit that had been evolving from the beginning, the simple LC circuit, can demonstrate in an easier to understand and concise manner just why it allows for higher efficiency and simplicity.

The sixth evolution of the circuit was an attempt to go back to the block diagrams in Figure XXIV, and transform them into actual analog components and what would become a fully functioning circuit. This design involved integrating a feedback controller. This controller will regulate the current though the LEDs. Compared to the block diagram figure of the previous evolution, it is apparent how the individual blocks evolved into this current circuit. The Schmitt Trigger can be seen as the leftmost operational amplifier. The switch in previous versions has now been replaced with a MOSFET. The right op-amp now acts as a gain amplifier. It should be noted the specific part numbers of these components and even their values required tweaking.

As stated, the controller will regulate the current by having the feedback controller trigger a P-channel MOSFET. This will enable feedback control using PWM to maintain a constant supply to the LEDs. When the voltage drops too low in the system the gate closes and allows current to flow through, and when the voltage reaches a high, the system will trigger the gate to open. The voltage and current will then drop. The average of this feedback process will produce a steady current and voltage in the system and with a high switching frequency there should be no discernable flicker in the LEDs. The system schematic of this can be viewed below in Figure XXIX. There was an additional three Schottky diodes added in parallel to allow for more efficient flow of current through the system when the MOSFET gate is open.

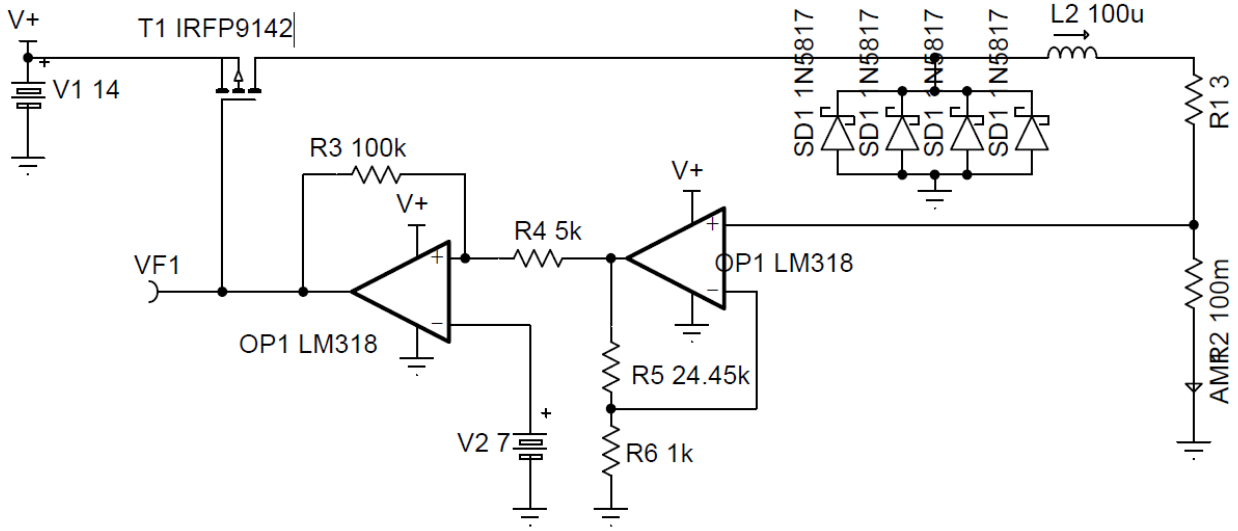


Figure XXIX : Sixth Circuit Evolution

CHAPTER IV: RESULTS

Circuit Discussion

The circuit designed and built for this project utilizes pulse width modulation to obtain a near constant current and voltage to the LEDs. Referencing Figure XXX, the two op-amps are used in a control circuit to achieve this pulse width modulated signal on the gate of the p-channel MOSFET. The first (IC1 on the right) is a non-inverting difference amplifier which increases the voltage from the sense resistor by 25. When the current through the sense resistor and LEDs exceeds 3.25A, the comparator (IC2) goes high and turns the PMOS off. Likewise, when the current provided to the LEDs through the inductor and flyback Schottky falls to 2.75A, the comparator swings low and the PMOS conducts, repeating the process. Using the inductor to supply power and illuminate the LEDs when the PMOS is not conducting results in less power drawn from the vehicle.

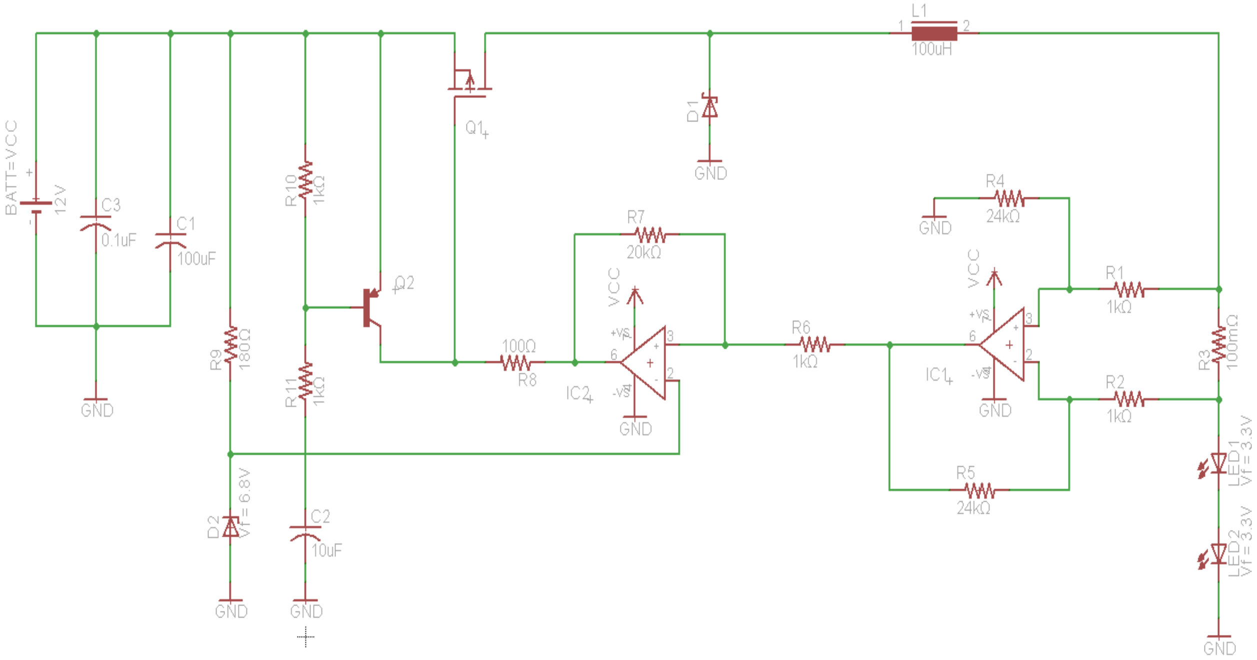


Figure XXX: Final Circuit Schematic

The supply voltage mimicking a car battery is to the left as well as some bypass capacitors on the power lines. At initial startup, the delay circuit in the bottom left will delay the current from flowing through the entire system by approximately 30ms. This was needed as it was experiencing transient latchups upon complete circuit power. This issue can be read about in the Startup Issue section. After this delay the circuit begins normal operation. Current flows through the inductor charging it up as well as creating a voltage drop across the sense resistor and LEDs. The opamps detect the desired voltage drop at which point they switch the gate of the MOSFET, opening the switch. Since there is a Schottky diode within the circuit, current is then drained from the inductor and through the LEDs. This process then repeats.

Specifications & Oscilloscope

Below in Table 4 is a summary of the useful design specifications of the circuit and how it performs. The overall system power is 24.64W and the power delivered to the load is 21.72W. This efficiency and where the power losses occur is discussed more in section Efficiency and Power Losses.

Operating voltage: 14V	**Voltage across LEDs: 7.24V**
Operating current: 1.76A	**Current through LEDs: ~3A**
System Power: 24.64W	**LED Power: 21.72W**
Switching Frequency: ~40kHz	**Efficiency: 88.15%, 77lm/W**

Table 4: Design Specifications

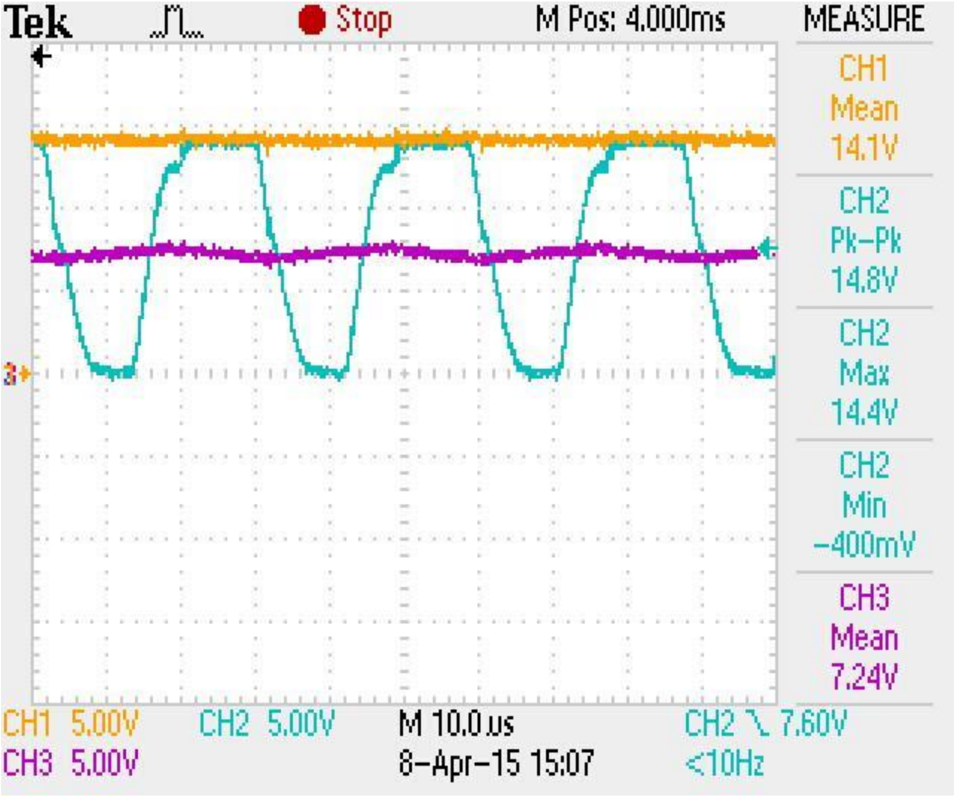


Figure XXXI: Normal Operation CH1 (input voltage), CH2 (gate voltage), CH3 (load voltage)

Figure XXXI is an oscilloscope capture of the circuit's normal operation. CH2, the blue channel, is the gate of the MOSFET. This MOSFET is switching with a 40kHz frequency and has a duty cycle of approximately 50%. As mentioned above, controlling the voltage on the gate provides for a pulse width modulated signal. It is this switching that allows the circuit to draw approximately 50% less current than running the LEDs directly from a DC source. CH1, in the orange, is a 14V supply representing the highest value an automobile battery typically maintains. CH3, the purple channel, is the voltage across the LEDs. It is a nearly constant voltage with a slight ripple in the range ± 0.5V. Since this is a lighting application and its ripple is approximately 40kHz, the eye cannot perceive the fluctuations in the current and subsequent luminescence. As can be seen in the oscilloscope capture this provides a mean voltage of 7.24V across the LEDs and a current of approximately 3A. It successfully delivers the necessary power to the LEDs to maintain the required light output but has cut power consumption in half. A standard LED bulb not using PWM may draw 3A at 14V whereas this circuit draws 1.76A at 14V.

Startup Issue

After designing the initial circuit, an issue was found with implementation. To power the opamp rails the circuit required a reference voltage of 7V. During initial testing, using a power supply as the 7V reference allowed the circuit to function properly. The first attempt to create an in-circuit reference was to use a voltage divider. However, when the circuit was powered on from a single supply the opamps would latchup due to a transient spike. This would prevent the opamps from switching the gate thus preventing pulse width modulation of the supply. After copious amounts of troubleshooting and experimentation it was determined that a delay circuit would be needed to let the system initialize before the control circuitry could start to operate.

This delay circuit was formed by utilizing a PNP transistor that holds the gate high initially before releasing it. The startup circuit can be seen to the left of the opamps in Figure XXX. The necessary delay was calculated to be 30ms and the implementation led to a delay of 28ms. This delay can be seen in Figure XXXII. CH1, the orange line, is the supply power. The oscilloscope capture shows it initially off and then being powered on. CH2, the blue channel, is the gate of the MOSFET. This demonstrates the successful 28ms delay from when the power supply is turned on to when the gate starts its switching. This solved the start-up issue that was being experienced.

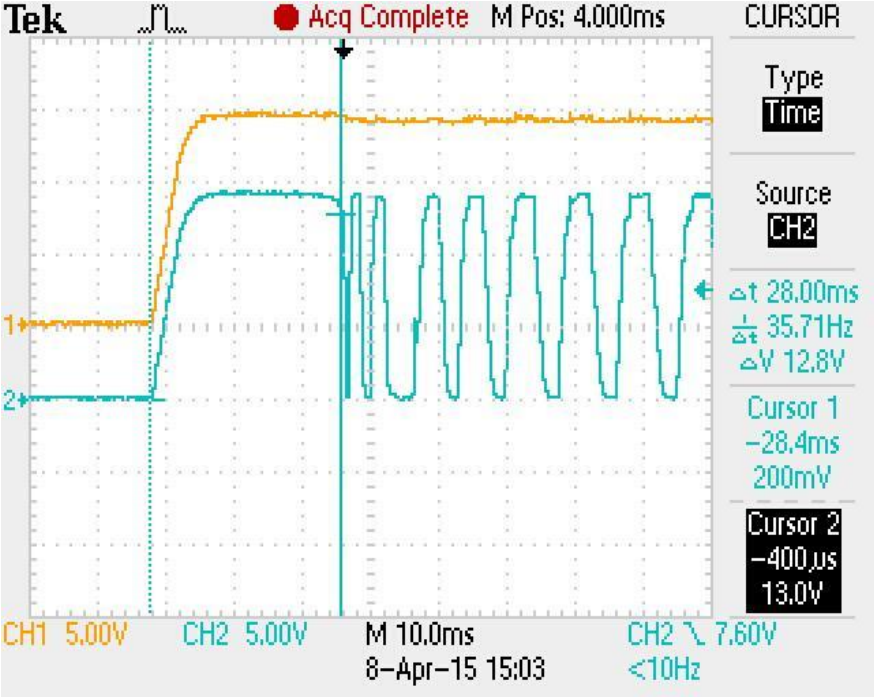
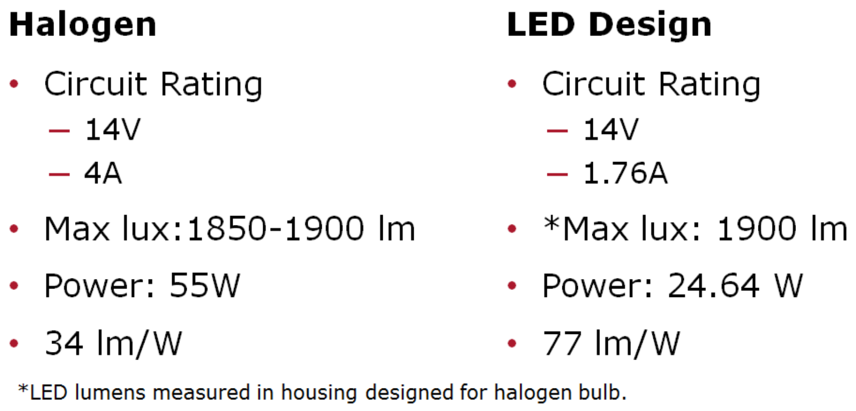


Figure XXXII: Startup Delay Capture

Comparison to Halogen

The LED system that was developed was compared against a standard halogen bulb. This was done as benchmark and to determine if the design would work as a headlight bulb replacement in the real world. When operating, the LED design used less than half the power of its halogen counterpart while producing even greater light output. The light intensity readings were taken with a lux meter. The halogen bulb is only capable of emitting 34 lm/W while the LED system is able to emit significantly more at 77 lm/W. These readings were taken using a headlight housing designed for a halogen bulb's omnidirectional light. With a headlight housing designed for LEDs, the light intensity and dispersion will be of a better quality. The light emitted by halogen bulbs is a warm yellowish color while LEDs generally produce a cool white light. Table 5 offers a quick reference for the comparison between this LED headlight driver design and the traditional halogen bulb.



Halogen	LED Design
Circuit Rating – 14V – 4A	Circuit Rating – 14V – 1.76A
Max lux:1850-1900 lm	*Max lux: 1900 lm
Power: 55W	Power: 24.64 W
34 lm/W	77 lm/W

*LED lumens measured in housing designed for halogen bulb.

Table 5: Halogen v. LED

Efficiency and Power Losses

As can be seen in the design outcomes, this design operates at 14V and draws 1.76A. Multiplying the two results gives a power consumption of 24.64W. The voltage across the LEDs is 7.24V with an average current draw of 3A which results in 21.72W being successfully delivered. This gives a system efficiency of 88.15%. Significant sources of loss are detailed below.

PMOS:

Conduction Losses:

$$P = I_{Load}^2 R_{DS} \left(\frac{Vout}{Vin}\right) = 37\text{mW}$$

Switching Losses

$$P = (C_{RRS} V_{in}^2 f_{sw} I_{Load}) / I_{Gate} = 290\text{mW}$$

$\mathbf{P_{total} = 327mW}$

Schottky Diode:

$P_{total} = (1\text{-}D)\, I_{rms} V_F =$ **675mW**; where $V_F = 0.45V$ = diode forward voltage at 3A

Inductor:

$P_{total} = I_{rms}^2 R_{ESR} = \mathbf{720mW}$; where $R_{ESR} = 0.08$ohms = inductor series resistance

Sense Resistor:

$P_{total} = I_{Load}^2 R = \mathbf{900mW}$

Reference Circuit:

$P_{total} = I_{ref} V_{in} = \mathbf{264mW}$

Total Power Loss:

$\mathbf{P_{TOTAL} = 2.89W}$

These five power losses combine to make 2.89W total and result in the 88% overall efficiency. These are all areas for improvement as the control circuity and components could be optimized to consume as little power as possible.

Printed Circuit Board

After building and testing the circuit prototype, a PCB version was developed. This board was designed with two layers and with surface mount components to reduce space needs and line losses. The PCB was developed to reduce system size for a more compact design as well as to provide a readily reproducible circuit.

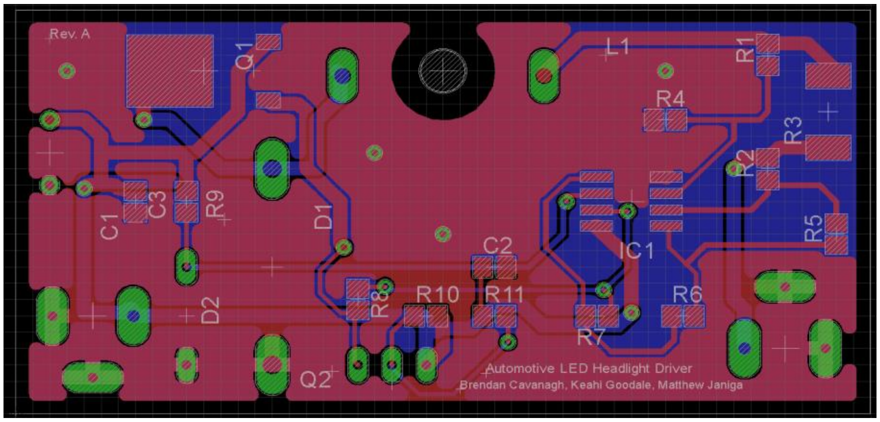


Figure XXXIII: PCB Layout

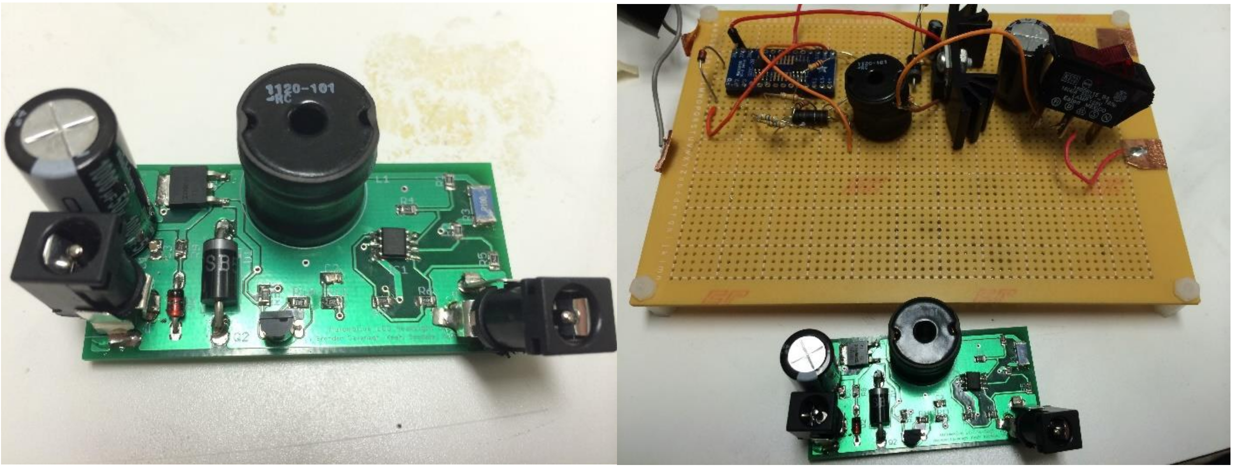


Figure XXXIV: PCB Rev 01

Above can be seen the first revision of the PCB and it compared in size to the full size prototyped circuit.

LED & Heatsink Mounting

It was necessary to create a mount that would allow the LEDs to not only receive power, but also be heatsinked within a headlight housing. This set-up can be seen in Figure XXXV. The LEDs had come on octagonal boards whose backs were metal. As such, a thermal paste was applied to them and then the LEDs applied to an aluminum rod. In order to achieve the best contact, the aluminum rod and all services touching that would need to transfer heat were lapped with a fine grit sandpaper beforehand. The thermal paste was necessary to allow for fast and efficient heat transfer from the LEDs. This rod was then drilled and tapped in order to accept a screw. A standard-use heatsink was then found which was also drilled and tapped. Thermal paste was then applied to the screw as well as the top of the heatsink at which point the two components were screwed together forming an extremely tight bond. Since thermal paste was applied to the screw and where the two surfaces combined, maximum heat transfer between the two sections was attained.

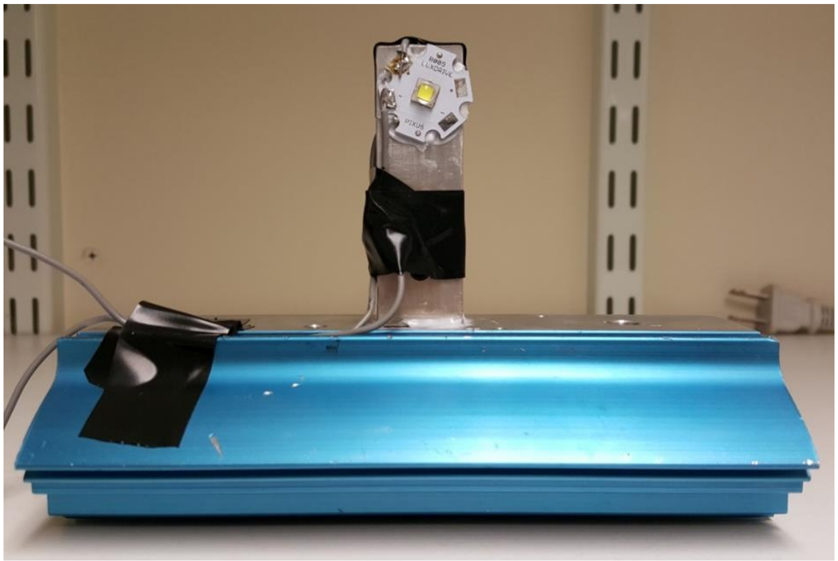


Figure XXXV: LED Mount & Heatsink

The wires leading to the LEDs were taped onto the rod and into a channel within the heatsink to allow a flush fit with the headlight housing. The heatsink used is far larger than is necessary but it was appropriate for testing as well as readily available. A smaller and more form-factored heatsink and mounting technique is open for future research. Figure XXXVI shows the LEDs within the headlight housing using this heatsink and mount. Since it was impossible to use the included fastener for this standard of headlight housing, it was necessary to a unique solution. For this preliminary prototype stage it was sufficient to use zip ties to physically attach the heatsink onto the housing and position the LEDs within the housing properly and with the correct orientation. The circuit is also powered on to demonstrate its brightness.

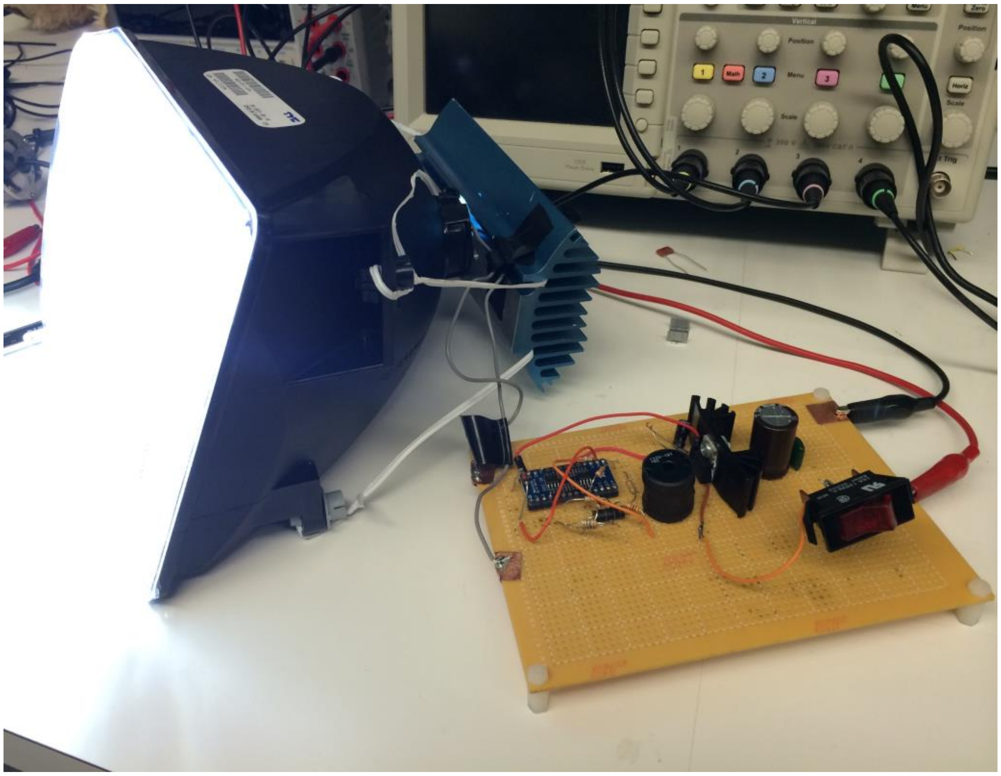


Figure XXXVI: LED Headlight Operational

CHAPTER V: FUTURE IMPROVEMENTS

This project has concluded with a readymade driver circuit and non-finalized LED headlight design. This is short of a market ready form factor complete LED headlight bulb as this was never the intent. Several features will need to be added to the circuit if it were to be transformed into a commercial product. Such features are an overvoltage protection system to protect the circuit and LEDs from burn out in the event of a voltage spike. Under-voltage protection to make sure the bulb still provides light if the voltage drops unexpectedly. More features could be overheat protection so the system does not melt as well as protection from being plugged in backwards. Improving the heatsinking abilities, the form factor of the bulb, fooling the car so low current warnings are not tripped, and lastly addressing the cold climate frost issue. All of these features are necessary to protect the consumer and ensure reliability of the product. However, in order to prove a concept and provide a highly efficient bare-necessities driver circuit, which was the original goal, the prototype is excellent.

An aspect not fully addressed by this project due to time constraints was heatsinking. In the next evolution of this prototype a custom heatsink system that mounts into the headlight housing will need to be designed. Such a heatsink would be designed to act as the housing for the driver circuit as well. Because there are components within the circuit that need heatsinking as well as the LEDs themselves, it is most efficient and space conscious to use one heatsink for all these components. Heatsinking is necessary to keep the LEDs at a reasonable operational temperature to protect them from thermal damage. A heat pipe will be used to transfer the waste heat from the diodes to the heatsink. This heatsink will spread the waste heat out over the lens of the headlight with microfilaments.

Unfortunately, the initial desire to address headlight frosting was not able to be done due to time constraints. Initially, we wished to try and solve the problem that comes with the increased efficiency and lack of heat waste by LEDs, frosting of the housing in cold climates. Though a lot of research was done on this topic and several methods of achieving this goal were analyzed, we were unable to take action with them. In the future we would like this to be a primary goal of a team that may do work on this project as it is still a crucial aspect to LED headlights in cold climates. The housing is also an integral part of a headlight design that we could not research and optimize as well as we would have liked. By taking full advantage of the optics and reflectors of a headlight housing you can optimize the quality, amount, and direction of light output. The parabolic shape must be such that the light emits in the cone shape desired rather than too wide of a spread. This is necessary so that other drivers are not blinded and the road is properly illuminated. The housing and anti-frost capabilities will likely be merged into one as they are intertwined.

These additions to the design of the system will provide increased functionality, safety, ease-of-use, and marketability. By electrically protecting the circuitry, the driver circuit will be protected from surges or abnormal voltage spikes, thus not needing to be replace. When heatsinked properly, the LEDs will last longer, be able to shine brighter, and be protected from overheating. This will also play into how we connect it to the housing itself to prevent frost in colder climates. Lastly, when the housing and optics are tailored for the optimal light distribution the driver will be able to see clearer and further than before.

CHAPTER VI: CONCLUSION

The purpose of this project was to create an efficient LED headlight driver. Most automotive headlights on the road today utilize halogen technology and as such are very inefficient. Approximately 90% of the energy consumed is wasted as heat. Overall, automotive manufacturers have lagged behind when it comes to the adoption of LED technology in vehicles. Currently they are mostly utilized for brake-lights and other signaling devices as they are easy to manipulate into desired configurations. However, LED headlight technology has not been adopted as readily, except by a few companies and only on select high-end vehicles.

The process of designing the LED headlight driver started with the use pulse-width-modulation (PWM) to regulate the supply voltage to the LEDs and to increase efficiency. The duty cycle of this system is ~50%. An inductor and a free-wheeling Schottky diode were added to the drive circuit to allow for the PWM signal as well as to smooth the ripple voltage and subsequently current. One issue that presented itself in this project occurred on the startup of the system. The whole system would latch-up when using the integrated voltage reference for the comparator circuitry. After troubleshooting, this issue was solved by adding a delay circuit that held the gate of the PMOS high for 30ms after startup. This prevented the latch-up from occurring and allowed for normal operation.

The developed system used two CREE XML-2 LEDs and was able to produce the same brightness as a traditional halogen using less power, 24.64W compared to a 55W standard halogen bulb. Both bulbs, using a headlight housing designed for a halogen bulb, produced ~1900 lm. With a housing designed specifically for LEDs, the light intensity and the dispersion pattern of the light can be improved.

To further optimize this circuit for efficiency several things can be done in the future. A more efficient PMOS could be used to decrease heat losses and sharpen the PWM transitions of the system. More LEDs could be used to reduce the drive current, thus reducing line losses. The switching frequency of the PWM could be altered to optimize the size of the inductor. Some extra circuitry would also need to be added before it would be ready for production, such as over-voltage protection. A custom heat-sink should also be utilized to maintain the integrity of the LEDs and to improve the form-factor of the system when being integrated into a headlight housing.

This project succeeded in its purpose to develop an efficient LED driver circuit using PWM. The current circuitry can be improved for future uses, however the design of the system is sound and functions as designed. The circuit can provide greater luminescence than halogen bulbs, but consume less than half the power. LED technology needs to be integrated into vehicle headlights as they offer a much longer lifespan than halogen bulbs, provide better light output, and are far more efficient than other bulb technologies. With this efficiency gain, vehicles would be able to conserve energy usage, thus increasing MPG for traditional vehicles and the effective range for electric vehicles. LED headlights will play a pivotal role in the future of vehicles as they are a better, clearer, and more efficient light source to illuminate the road ahead.

BIBLIOGRAPHY

Administration, U. S. D. o. T. s. N. H. T. S. (2004). FMVSS108 (Vol. 5).

Audi. (2013). Lighting Technology. Retrieved December, 2014, from http://www.audiusanews.com/newsrelease.do

autoevolution. (2010). Battle of the Headlights: Halogen vs. Xenon vs. LED vs. Laser. Retrieved December, 2014, from http://www.autoevolution.com/news/battle-of-the-headlights-halogen-vs-xenon-vs-led-26530.html

BathroomHeater.org. Bathroom Heat Lamps. Retrieved October, 2014, from http://www.bathroomheater.org/bathroom-heat-lamps.html

Beat, M. (2012). Understanding RGBA Vs. RGBW In Two Simple Steps. Retrieved September, 2014, from http://www.mobilebeat.com/understanding-rgba-vs-rgbw-in-two-simple-steps/

Care, F. C. A. (2014). Your Car's Electrical System.

CREE. Cree® XLamp® XP-L LEDs: CREE.

CREE. (2014). LED Lighting.

Dross, O., Cvetkovic, A., & Chaves, J. (2005). LED Headlight Architecture that creates a High Quality Beam Pattern independent of LED Shortcomings LED Headlight Ar. *SPIE, 5942*.

ebay. (2007). Xenon and HID and Plasma Bulbs-The Truth. Retrieved September, 2014, from http://www.ebay.com/gds/Xenon-and-HID-and-Plasma-bulbs-the-truth-/10000000001832221/g.html

Engineers, S. o. A. (2010). SAE J1383 (6 ed.).

Extra, H. HID Kit bulb’s manufacturing process impact on HID Kit quality. Retrieved September, 2014, from http://blog.hidextra.com/hidextra-hid-kit-bulbs-manufacturing-process-impact-on-hid-kit-quality/

Federation, L. E. L. C. (2009). Environmental Aspects of Lamps: Lighting European Lamp Companies Federation.

Finnex. (2014). DL (LED/T5 Combo). Retrieved October, 2014, from http://www.finnex.net/index.php/products/lighting/advanced-lighting-system/dl-series-4-x-ho-t5-high-intensive-led-48.html

Fire, A. H. Petzl Duo Headlamp. Retrieved September, 2014, from http://www.allhandsfire.com/PETZL-DUO-LED-5-WATERPROOF-HYBRID-

HEADLAMP-HALOGEN-5

HELLA. (2014). Technology With Vision-Welcome to HELLA in the USA and Canada. Retrieved December, 2014, from http://www.hella.com/hella-us/index.html?rdeLocaleAttr=en

Helms, J., Trumbetas, J.-K., Lowrey, J., Barie, M., & Lizotte, R. (2012). USA Patent No.: USPTO.

HubPages. The Difference between HID, LED, and Incandescent Lamps. Retrieved September, 2014, from http://ijdmtoy.hubpages.com/hub/The-Difference-between-HID-LED-and-Incandescent-Lamps

HubPages. (2011). How to Choose Suitable LED Color Temperature. Retrieved September, 2014, from http://floodlightled.hubpages.com/hub/How-to-choose-suitable-LED-color-temperature

Ideas, L. I. Cool White (5650K) LUXEON Rebel ES LED - 235 lm @ 700mA. Retrieved December, 2014, from http://www.luxeonstar.com/lxml-pwc2-cool-white-luxeon-rebel-led-235lm

Incorporated, D. (2010). AP1509.

iReach. (2014). Smart Lighting Chips Market (LED drivers, MCUs, Sensors) worth $1.05 Billion by 2019. Retrieved December, 2014, from http://www.ireachcontent.com/news-releases/smart-lighting-chips-market-led-drivers-mcus-sensors-worth-105-billion-by-2019-269115761.html

Koester, G. (2010). USA Patent No.

Krames, M., Shchekin, O., & Mueller-Mach, R. (2007). Status and Future of High-Power Light-EmittingDiodes for Solid-State Lighting. *Journal of Display Technology, 3*(2).

Lewotsky, K. (2011). Buck Regulators Make Driving HIgh Brightness LEDs Easy. Article Livrary: Digi-Key Corporation.

Lighting.com, G. LED Headlight H13 Conversion Kit. Retrieved September, 2014, from http://www.gtrlighting.com/led-headlight-h13-conversion-kit-2-200-2-600-lumen-bulbs/

Lin, Q., Chunqing, W., & Yanhong, T. (2012). Thermal Design of a LED Multi-chip Module for Automotive Headlights. *IEEE Explore*.

Lombardi, C. (2011). GE Launches Hybrid Light Bulbs. Retrieved September, 2014, from http://www.cnet.com/news/ge-launches-hybrid-light-bulbs/

Luxor, L. Top 10 Benefits of Using LED Lighting. *2013.* Retrieved September, 2014, from http://www.ledluxor.com/top-10-benefits-of-led-lighting

MadeHow. Halogen Lamp Background. Retrieved September 2014, from http://www.madehow.com/Volume-6/Halogen-Lamp.html

MadeHow. Light-Emiting-Diode. Retrieved September, 2014, from http://www.madehow.com/Volume-1/Light-Emitting-Diode-LED.html

Magazine, L. (2011). LED market grew almost 10% in 2011, with 44% growth in lighting. Retrieved December, 2014, from http://www.ledsmagazine.com/articles/2012/02/led-market-grew-almost-10-in-2011-with-44-growth-in-lighting.html

Markus, F. (2008). Blinded by the Light? Comparing New LED Headlamps with HID/Xenon, Halogen. Retrieved September, 2014, from http://blogs.motortrend.com/blinded-by-the-light-comparing-new-led-headlamps-with-hidxenon-halogen-2069.html

Mechanics, P. (2005). How to Adjust Your Headlights. Retrieved December, 2014, from http://www.popularmechanics.com/cars/how-to/repair/1347221

Mechanics, P. (2011). How Your Headlights Work. Retrieved September, 2014, from http://www.popularmechanics.com/cars/how-to/maintenance/how-your-headlights-work-2

Oba, K. (2013). Wiring Harnesses for Next Generation Automobiles. *Fujikura Technical Review*.

Philips. (2014). Philips Lumec UrbanScape LED Pendant and Post-Top.

Ramde, D. (2010). LED Traffic Lights That Can't Melt Snow Are Blamed In 1 Death, At Least 12 Accidents. Retrieved December, 2014, from http://www.huffingtonpost.com/2009/12/16/led-traffic-lights-that-c_n_393769.html

ReportsnReports. (2013). LED Lighting: Market Shares, Strategies, and Forecasts, Worldwide, 2013 to 2019. Retrieved December, 2014, from http://www.reportsnreports.com/reports/269046-led-lighting-market-shares-strategies-and-forecasts-worldwide-2013-to-2019.html

Rice, L. (2004). USA Patent No.: USPTO.

Semiconductor, R. (2014). White LED driver IC for headlamps and DRLs. Retrieved September 27, 2014, from http://www.rohm.com/web/global/news-detail?news-title=white-led-driver-ic-for-headlamps-and-drls&defaultGroupId=false

Source, S. Xenon Light. Retrieved September, 2014, from http://www.speedstersource.com/FISH/HID_FEATURES_D2C.htm

Systems, E. C. P. a. I. B. Dramatizing New Warehouse Lighting Technology's Benefits.

Retrieved October, 2014, from http://www.ecmag.com/section/lighting/dramatizing-new-warehouse-lighting-technologys-benefits

TESLA. (2014). Based on current technology, is Xenon or LED headlights better in terms of brightness, visibility, and safety? Retrieved September, 2014, from http://www.teslamotors.com/en_HK/forum/forums/based-current-technology-xenon-or-led-headlights-better-terms-brightness-visibility-and

Thomas, W., & Pforr, J. (2009). A novel low-cost current-sharing method for automotive LED-lighting systems. *IEEE Explore*.

Toyota. (2014). Prius 2015: Toyota.

Weekly, E. (2013). Car makers focus on LED headlights. Retrieved December, 2014, from http://www.electronicsweekly.com/news/components/led-lighting/car-makers-focus-on-led-headlights-2013-03/

Williams, M. (2014). New F-150 Will be First Pickup With LED Headlights. Retrieved December, 2014, from http://news.pickuptrucks.com/2014/03/new-f-150-to-be-first-pickup-with-led-headlights.html

Winstrom, B. (2009). LED traffic lights don't melt snow, ice buildup. Retrieved December, 2014, from http://www.kansas.com/news/local/article1018830.html

Wordenweber, B., Wallaschek, J., Boyce, P., & Hoffman, D. (2007). *Automotive Lighting and Human Vision*. Berlin: Springer.

Young, A. (2014). Detroit Auto Show 2014: LED Headlights Coming Of Age; Check Out Photos Of Latest In Head Lamp Technology, Including BMW i8 Laser Lights. Retrieved December, 2014, from http://www.ibtimes.com/detroit-auto-show-2014-led-headlights-coming-age-check-out-photos-latest-head-lamp-technology

APPENDIX A

WPI

Efficient Pulse Width Modulation LED Headlight Driver

Brendan Cavanagh
Nathaniel Keahi Goodale
Matthew Janiga

Advisor: Stephen Bitar
Co-Advisor: John McNeill
NECAMSID

What are the Alternatives?

- Halogen
  - ~1000 lm/bulb
  - 1,000 hour lifespan
  - ~90% of energy wasted
  - 55 Watts
- Xenon/HID
  - ~3000 lm/bulb
  - 2,500 hour lifespan
  - 35 Watts
- LED
  - ~1800 lm/bulb
  - 15,000 hour lifespan
  - 15 Watts

Purpose

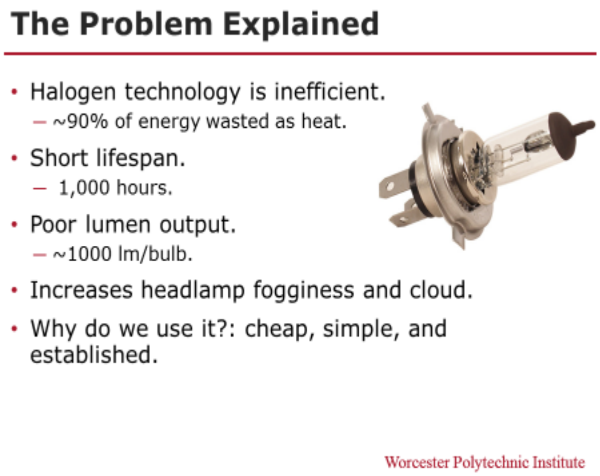
- Automotive headlights have lagged behind as lighting technology has advanced.
- Halogen bulbs are extremely inefficient.

What about LEDs?

Pros/Cons of LED Lighting

Pros	Cons
Energy Efficiency	Heat-sinking
Lumen output	Cost
Lifespan	Control circuitry needed
Flexibility	Relatively complicated technology
Less heat	Advanced optics
Light color	

http://www.audi.com



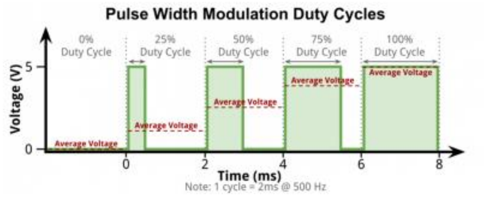
The Problem Explained

- Halogen technology is inefficient.
  - ~90% of energy wasted as heat.
- Short lifespan.
  - 1,000 hours.
- Poor lumen output.
  - ~1000 lm/bulb.
- Increases headlamp fogginess and cloud.
- Why do we use it?: cheap, simple, and established.

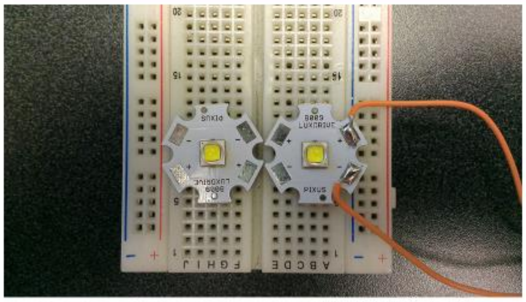
Lighting Color & Pattern

Pulse Width Modulation

- Pulse width modulation driver circuit to LED headlight bulb.
- What is pulse width modulation?



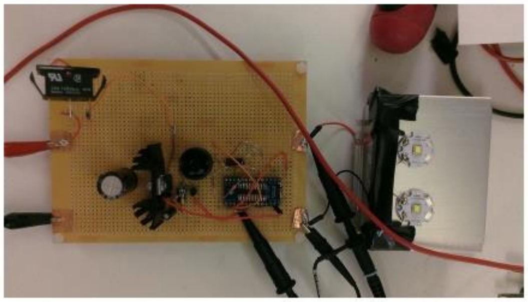
Our Circuit



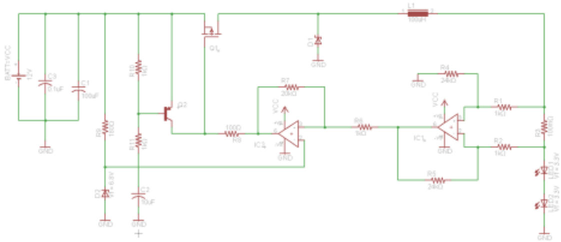
How Have We Done it?

- Simple buck converter
- Comparator circuit for current regulation
  - PWM
- Schottky diode
- Soft start delay circuit

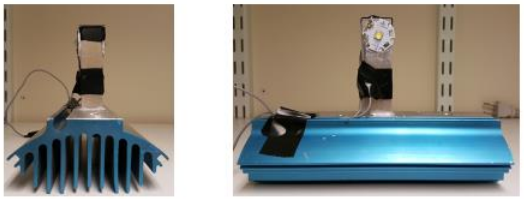
Our Circuit



Our Circuit

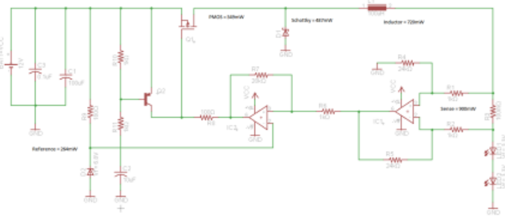


Mounting System



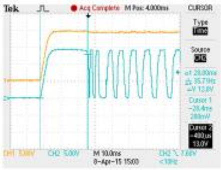
Demonstration

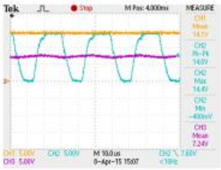
Power Analysis



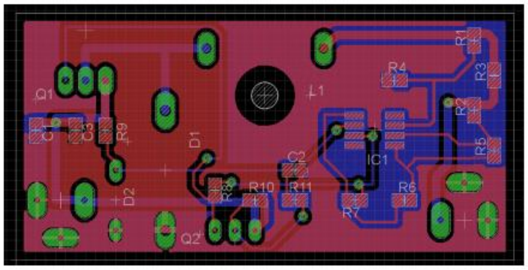
Design Outcomes

- Operating current: 1.76A
- Operating voltage: 14V
- System Power: 24.64W
- Switching Frequency: ~40kHz
- Voltage across LEDs: 7.24V
- Current through LEDs: ~3A
- LED Power: 21.72W
- Efficiency: 88.15%, 77lm/W





PCB Layout



Bulb Comparison

Halogen

- Circuit Rating
  - 14V
  - 4A
- Max lux:1850-1900 lm
- Power: 55W
- 34 lm/W

Our Design

- Circuit Rating
  - 14V
  - 1.76A
- *Max lux: 1900 lm
- Power: 24.64 W
- 77 lm/W

*LED lumens measured in housing designed for halogen bulb.

Future Improvements

- Circuit optimization
- LED headlight housing optics
- Overvoltage protection
- Overheat protection
  - Optimized heat-sinking
- Form-factor
- More LEDs
  - Lower drive current

Conclusion

- Started with simple buck converter
  - Used PWM, comparator circuitry to increase efficiency
- Driver prototype is more efficient than halogen
- Still room for improvement
  - Optimize switching frequency & inductor size
  - Sharper PWM

Acknowledgments

- Professor Stephen J. Bitar
- Professor John A. McNeill
- NECAMSID
- Bob & Bill from the ECE shop

WPI

Thank You

APPENDIX B

Efficient Pulse Width Modulation LED Headlight Driver

WPI

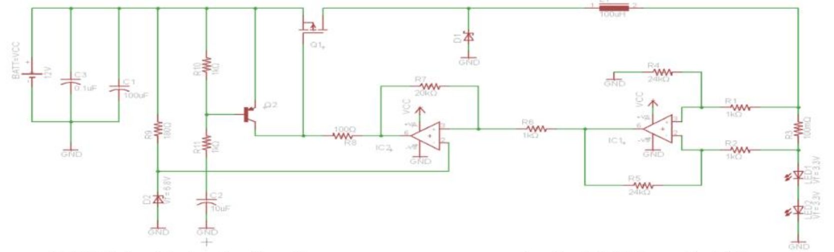
NECAMSID

Brendan Cavanagh (ECE), Nathaniel Goodale (ECE), Mathew Janiga (ECE)
Advisor: Professor Bitar (ECE)
Co-Advisor: Professor McNeill

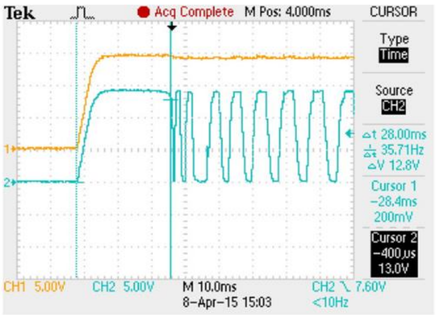
Abstract

LED headlights can provide better luminescence and less power consumption when compared to traditional halogen headlights. The adoption of LEDs in automobiles has been slow as the technology is more expensive than halogen bulbs, more complex to integrate, and younger. As such, an efficient, simplistic, and easy to use illumination driver was developed to spur on the widespread adoption of LED use in automobile lighting. The circuit developed is capable of providing the necessary illumination for a fraction of the energy input required by traditional lighting.

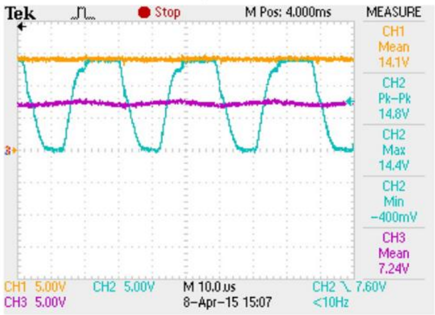
PWM Driven LED Circuit



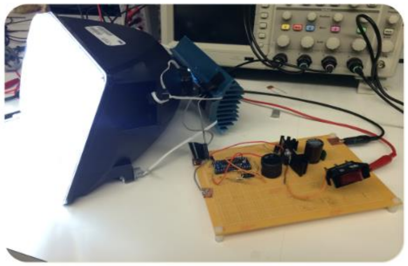
PMOS Delay Startup Functionality



Standard PWM Operating Voltages

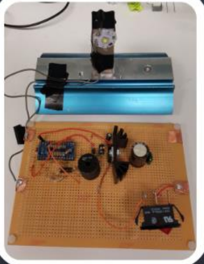


Headlight Design Test



Project Goals/Objectives

- High efficiency LED headlight drive circuit
- ~1900 lm at 15W per bulb
- Ease of integration for most vehicles
- Low cost for manufacturers and consumers
- Meets all legal requirements and standards
- Reliability and consistent performance
- Long product life span



Results & Specs.

- ~1900 lumens/bulb
- 2 LEDs x 2 headlights
- 14V from car battery
- 1.76A operating current
- Total system power: 24.64W
- 7.24V through LEDs
- ~3A current through LEDs
- LED power: 21.72W
- Efficiency% = 88.15%
- ~40kHz switching frequency
- ~77 lm/W

PCB Design Concept