2006-560: EFFICIENT COPPER REDUCTION AND RECYCLING BY FIBER OPTIC SWITCHING FOR AUTOMOTIVE LIGHTING SYSTEMS

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This paper is a summary and demonstration of an innovative senior design project. The primary impetus for this project was to reduce the Cu content in recycled steel from automobiles. Although recycling steel from automobiles is a large business and growing globally, there is little incentive to separate out the copper wiring before recycling the automotive chassis. The slow but inevitable increase in copper content with each generation of recycled steel can lead to too much variability in the mechanical and welding properties of the steel.

The project team decided to focus on redesigning the electrical power distribution system to allow for easy retrieval of the copper. Three senior students at Loyola College in Maryland worked as an interdisciplinary design team to address the question of improved wiring systems for automobiles. Interest in this project included participation by professional engineering staff at Visteon Co., an automotive components company closely associated with Ford Motor Co. The student team created a test bed vehicle from a golf cart and decided to demonstrate the principles on a car's lighting system (headlights and taillights). By using optical fiber and optical switching at the component, a reduction of the use of copper as well as its centralization into an electrical power "fishbone" distribution system was possible. The materials design focused on a copper fishbone that was easy and inexpensive to separate from the car body, thus eliminating the amount of copper in the crushed car during recycling. This was achieved with the use of inexpensive breakaway connectors at each point where the power line branched off to a component. Telephone conference calls with the industry professionals provided important context and background information for the project.

This was a highly successful senior design project which can serve as a model in a number of pedagogical areas including socially relevant design problems, interdisciplinary team building, interacting with industrial professionals and serving as an all around capstone experience to a student's undergraduate engineering science education.

Abstract

The original motivation for this project came from an interest in preserving the quality of recycled steel by reducing the amount of copper that ultimately ends up in steel production. There are a number of factors propelling this kind of research. One is that our newly mined iron resources are finite, expensive and non-renewable. By working on a project with a large motivation in recycling and environmental issues, students become aware of contemporary issues surrounding the global environment and green engineering.

One design path to reduce copper is to reduce the amount going into automobiles during their production. Another is to provide efficient means for retrieving the copper before recycling. The student design team followed both paths; substituting fiber optic switching for part of the copper circuit that controls electrically powered components in a car, and re-designing the electrical power distribution in the car so that it can be efficiently removed at end-of-life, before recycling.

Introduction

The objective of this project is redesigning the conventional automotive switching technology in cars with a fiber optic model in conjunction with a redesigned power distribution that is easy to remove. The primary advantage of this redesign is that it reduces the overall copper that is left in the car at its end life. If the costs of the redesign are comparable to current design and manufacture costs, then this is a viable, environmentally knowledgeable engineering solution.

Currently, automobiles are a primary source of scrap steel. There is a slow continual increase in copper content that occurs with each iteration of recycling steel from automobiles. Removing copper from the steel smelt or even from the car before recycling is currently cost prohibitive. The copper causes inconsistencies and degradations in steel's mechanical and welding properties. As a result, recycled steel is not currently used in critical safety areas of automobile manufacture, but is confined to less vital parts. Today there is a requirement in the European Union for car bodies to be made from a maximum of 25% recycled steel from car bodies. They would like to increase the amount of recycled steel required, but because of the safety concerns currently can not. If the amount of copper in the recycled steel was less, then its mechanical properties would be better and more could be used, thereby reducing the amount of new steel that would be needed. The construction and dismantling of cars with an eye towards environmental factors and recyclability becomes a crucial factor in curbing the copper creep in steel and thus increasing its value in the marketplace as a source of quality recycled steel.

By centralizing the copper wire power distribution system and thus allowing its retrieval to be economically viable and by substituting portions of conventional wiring methods with a new fiber optic model we hope to effectively reduce the overall amount of copper that ends up in steel smelt without substantial raising manufacturing costs.

Designs

The design specifications for this project are clear. First, there needs to be a reduction in the amount of copper at the end of the useful life of the automobile. Second, all components and parts should be comparable to conventional methods and not complicate manufacturing or raise the costs of parts. This overall new design must be cost effective to assemble, produce, repair and recycle.

The project was broken up into two distinct areas. One area focused on centralizing the copper power distribution and the other focused on creating new switching with fiber optics. A conventional wiring diagram for some automotive lights is show in Figure 1. Figure 2, shows the new design, which consists of a centralized power distribution and fiber optics for switching.

Centralized Power Distribution System

The essence of the design problem for centralizing the copper power distribution system was to settle on a design that allowed an easy, quick, efficient break away of connecting terminals. This allows removal of the copper power distribution "backbone", leaving minimal amounts of copper behind. This is a problem in mechanical and materials engineering. The opposing design requirement is that the connections do not break under the usual wear, tear, usage of an automobile in all of its sometimes challenging thermal and vibration environments. The pre-determined break away feature should not fail during the course of normal automotive operations, which would result in the loss of power to car lighting systems, such as headlights, for example.

Some alternatives that were considered included: a bundle assembly of wires, a stamped sheet of copper, or a ribbon cable of wires for the power distribution system. The bundle assembly is a conventional way to distribute wiring, and should be easy to route. However it would also be bulky and difficulty to hide under the upholstery if it is laid out from the front to back of the car. It also would not substantially improve the removal process, since individual wires will not be prone to break at a predetermined point, making it difficult to remove the entire core of wires without leaving a lot behind. The stamped sheet alternative should be simple to manufacture and easy to install and hide under the upholstery, but the connections are more susceptible to fatigue failure than the wires and thus reduce the reliability of the power system.

A ribbon cable design was employed because it should be the sturdiest and the easiest to remove. Flexible, stranded 20 gauge wire, insulated in a sheet and easy to remove and easy to peel off for individual connections to components using spade clips was the design of choice. The design innovation involved sequential slacking of the wire to reduce the force required for removal by providing a "zipper effect", sequentially breaking one set of component connections at a time. Spade clips are located at each component to ensure complete removal. The minimal cost increase of this ribbon cable system should be more than offset by the recycling advantages and should be easy to manufacture. This team was more focused on the technical prototyping of the project, but this would be an excellent area for a diverse team of students from business and engineering to conduct an engineering economics analysis of the new design.

The design team used formalized mechanical testing techniques on prototype mock-ups to ascertain the proper design parameters for the new break away terminals and power distribution system. Figures 3 and 4 are digital photographs of the student work, showing the sequential slacking design and the testing of the terminal connectors. The student team was able to learn a great deal about standards, test and measurement by construction the following procedure for the mechanical testing of the coupling strength of the breakaway electrical terminals. The terminals have two competing design objectives, to breakaway under a reasonable force properly applied and yet to remain intact under conditions of ordinary usage and automotive operation. The details of the test procedure are outlined below and refer to other national standards, such as those from the society for automotive engineers (SAE).

Mechanical Testing of Electrical Terminal Coupling Strength

1. Terminal/Wire Assembly Disengage/Extraction Force
    - 1.1. The following test is designed to match the specifications required in SAE/USCAR-2 Performance Standard for Automotive Electrical Connector Systems. (3-02-01).
2. Purpose
    - 2.1. This test determines extraction/disengaging forces associated with compatible male and female terminal pairs and the connection between the wires and the male/female terminal pairs. This testing is to ensure that the terminal is retained in its housing with sufficient strength to withstand the rigors of the wiring harness and vehicle assembly processes yet is not greater than the tensile strength of the connected copper wires.
3. Equipment
    - 3.1. Instron Model 5590 tensile testing machine.
4. Procedure
    - 4.1. Completely identify and number each terminal assembly to be tested. A minimum of 10 connection pairs (male and female terminals) are required.
    - 4.2. Insert and consistently crimp copper wires into each of the male/female terminals.
    - 4.3. Connect the male terminal to the female terminal.
    - 4.4. Secure the terminal-wire assembly in the tensile testing grips by gripping the wire at each end, 3 cm behind the back edge of the terminal. Make sure that the sample is aligned so that the force is applied parallel along the length of the wire/terminal assembly.
    - 4.5. Load at a head rate of 50cm/min.
    - 4.6. Record the force required to disconnect the assembly and the identification number of the assembly.
    - 4.7. Indicate the point of failure (male or female terminal junction, terminal-wire junction, along wire length).
5. Acceptance Criteria

5.1. If the assembly disconnects along the length of the wire, then the sample automatically fails. If more than one sample in the lot breaks along the wire length, it is recommended that tests be repeated with wire of lower gauge size.
5.2. Any test that disconnects at a wire-terminal junction, or the male/female terminal junction is acceptable.
5.3. Acceptable assemblies disconnect at a minimum force of 20 Newton and a maximum of 50 Newton.

This proved to be an important and valuable part of the senior design project and process and was a key area in which students learned to apply their quantitative and analysis skills to questions of test and measurement.

Fiber Optic Switching

In order to effectively implement a new switching design, the team decided that they must incorporate cars current power specifications into the design. Each new component must be able to operate off of a car's 12V DC battery. The circuitry to be able to adequately perform during normal driving conditions as currently tested and specified by major companies in the automobile industry. These conditions include: wind, rain, snow, a fairly extreme range of temperatures and vibration conditions. Reliability and usability, familiarity and ease-of-use for the operator are two key design criteria for the fiber optic switching alternative.

There are two vital circuitry elements required in the use of fiber optics. The first is an emitter circuit, which will send light down the fiber optic line. Then to receive this signal will be a receiver circuit.

Two switch designs at the dashboard were considered. One type is a mechanical/optical switch. In this design there is a mechanical switch at the dashboard that either allows light to flow or interrupts it. This switch has a central emitting circuit located close to the power distribution system "backbone" that is continuously emitting light via an LED while the car is on. This type of switch is very useful because it removes a large amount of copper from the dashboard, which would be rather difficult to remove at the time to recycle the car. Also, with this reduction of copper there is less chance of electromagnetic interference problems occurring. There are maintenance advantages as well because fiber does not corrode like copper does.

The other type of switch in the dashboard is an electrical/optical switch. When a user toggles the switch it completes an electrical circuit that in turn activates another circuit and the LED to allow light to flow down a fiber optic line. This method of switching does not require the LED to be continuously turned on. Instead, it is only on when the user activates the switch.

The emitter circuit is a very general circuit that will be the same for all components. Basically, when power is applied to it, light is sent down the fiber optic line. It contains an LED, the IF-E92 that is protected by current limiting resistors, essential in any electro-optic application. For all components this will be similar. For the mechanical/optical switches these circuits will be located near the power trunk, while in the electrical/optical method these circuits will be located in the dashboard.

The central emitting circuit (see Figure 5) services all the mechanical/optical switches. The central emitting circuit is energized when the car is running or the key is turned to the accessory ‘On’ position. Several fiber optic lines are coupled to the LEDs, which allows for light to be sent down the fiber optic lines to the mechanical/optical switches in the dashboard.

The receiver circuit (see Figure 6) uses this fiber optic light and transforms it into a current to supply power to the components. The fiber is coupled to the IF-D92 light sensor. The sensor produces a small current that is supplied to the base of a power transistor. The power transistors, when triggered, allows current to flow to the component. For some of the most basic electrical loads, this circuit will produce enough current to turn on the component. However, some components require more power as well as other slight modifications to the circuitry in order to function properly. These different circuits contain all the components of the general receiving circuit, but with some extra elements.

The headlight circuitry requires more current to power on properly. In this case, an extra transistor (2N3904) will be required before the power transistor to bump up the current going into the power transistor. This will allow the power transistor to produce more current for the headlights. Figures 7 and 8 show a simplified system schematic and the circuitry used to power the headlights. Also note that the power transistor needs to be surrounded by a heat sink, which allows the transistor to cool remain with specified temperatures, even with the higher current.

Another circuitry modification that would be needed is for the hazards and turn signals. In order to get lights to blink properly, a thermal flasher needs to be inserted. In addition, another transistor has been added (2N2222) to provide a sufficient amount of power to the components. The hazards and turn signal circuit can be seen in Figure 9.

Time Table and Implementation

The project was divided up into several sections: Research, design, bench modeling, debugging, and implementation on the test bed or “mule”. In this case a golf cart was used as the “mule”. One student work on this process for the redesign of a breakaway copper backbone for centralized power distribution, and two other students followed the same general design and build process for the component side of the project. The trick was merging the two paths together. For example the student working on the power distribution system needed to know how much wire to draw for the mule, and that was dependent on component location and the type of switch being implemented, whether it was the electrical/optical or the mechanical/optical. In the context of a year-long senior design project the student team also knew that there were very real deadlines they had to face in constructing something to present by the end of the spring semester. In general the course focuses in the fall on processes, project management skills and general design and the spring would be a time for prototyping and an iterative cycle of build, test, and redesign. The students' quickly learn that time management and recognizing the critical path for product development is the key to success in their project.

Cost Analysis

There are three components of cost to evaluate: product price (including cost of materials, cost of manufacture), testing price (including costs of development, prototyping, and testing), and other costs to society (environmental and recycling costs) that are often not included in traditional engineering economics. Our goal is to make this project as affordable as possible so that it is competitive with conventional standards. Looking at these various elements of cost will help determine the design's competitiveness.

In both of our designs (for headlight circuits), we need 16 transmitter circuits ($2.95ea.) and 16 receiver circuits ($2.75ea). We also need at least 16 power transistors ($1.30ea.). If we use the mechanical/optical switch at the user interface dashboard we expect to use 60 meters ($1.70/meter) of fiber optic cable. This design would cost us approximately $200. If we use just the electrical/optical switch at the user interface dashboard we expect to use 30 meters of fiber ($1.70/meter) and 30 meters copper wire ($.24/meter). This design would cost approximately $160. We originally planned on using both designs on our test bed, but ultimately only employed the electrical/optical switch. Therefore to construct the prototype electrical system on the cart only cost us approximately $160.

The second component of cost involves the testing period. Visteon provided a figure of how many hours they spend testing a car's electrical system. They on average spend 10,000 hours testing. A good portion of that time is spent reducing electro-magnetic interference (EMI). Since fiber optic cable produces no EMI, we expect a reduction in the testing hours and a savings in the overall cost.

The third component to cost is difficult to determine because it is a cost incurred in the future. If this car is purchased and trashed at the end of its life, can we expect it to have any negative externalities? Currently the European Union (EU) requires most products to be bought back by the manufacturer for recycling purposes. In order to do this, the manufacturer needs to increase the price of the product it is selling today. Cell phones have increased in price of $3.50 and monitors and TV's $30 because of recycling charges. We don't know the price for cars. We are confident that cars with our fiber optic and power trunk system will be cheaper to recycle.

Another aspect of cost that is incurred in the future is the environmental cost. Our steel industry limits the use of pure iron ore in steel production and a large percentage of steel making derives from scrap. Variability in the copper content of steel due to the recycling of cars containing copper is a problem. We expect our fiber optic power switching design with an easily removable power trunk will allow the use of recycled steel in critical components without degradation of the steel by copper.

Budget Analysis

The budget for student senior design projects is set at $200 per student. The team of three students needed to complete this project within a budget of $600. Many of the project components were donations such as the golf cart, plexi-glass, and tools donated or from the Technology Services group at the college. Shown in Table 1 is a list of the products and vendors from which they were purchased. The group slightly went over budget because in the initial trial and error associated with development design and prototyping items were purchased that were subsequently not needed. This is an important part of the learning experience for engineering students because that kind of planning for unintended, unforeseen but necessary budgetary expenses often frustrates even experienced managers and engineers.

Conclusions

This was a highly successful senior design project that had authentic meaning for the students. It contained elements of industrial partnership, interdisciplinary teaming, social and environmental relevance. This project presents students with an application of the importance of materials testing in deciding on various design alternatives (in the possible central power distribution arrangements). It also presents students with an interesting application of circuit design for the fiber optics switching components. A number of possible extensions to this project are possible for the future with other student teams. For example there is interest in the automotive industry in centralized, high speed data distribution through many of a car's subsystems, such as navigation, entertainment, and system status sensors and display, to name a few. A fiber optic backbone would be crucial to that endevour. Also the redesign of the fiber optic system with the use of a microprocessor and the use of LED lighting would require some interesting refinements of the design. Further materials questions and testing would also be necessary as prototypes are refined and put into production.

TABLE 1: Project Budget

Costs:	Products	Retailer
$75	Headlights, Tailight assemblies, Blinkers	Crazy Ray's
$105.45	Wire Spools, Transistors, Heat Sinks, Test Lights, Switches, Potentiometer, Proto Board	Baynesville Electronics
$104.53	Wire Clips, Mounting Wood, Various fasteners, WD40, Paint, Adhesive Tape, Epoxy	Home Depot
$366.25	LEDs, Phototransistors, Fiberoptics Jacketed/Unjacketed, Various FO Fasteners	FiberopticProducts.com

Cash Assets =
$600
Total Cost =
$651.23
Cash Balance =
$600-$651.23=-51.23$

FIGURE 1:

Simplified schematic of a conventional wiring diagram for a car lighting system (headlights and taillights).

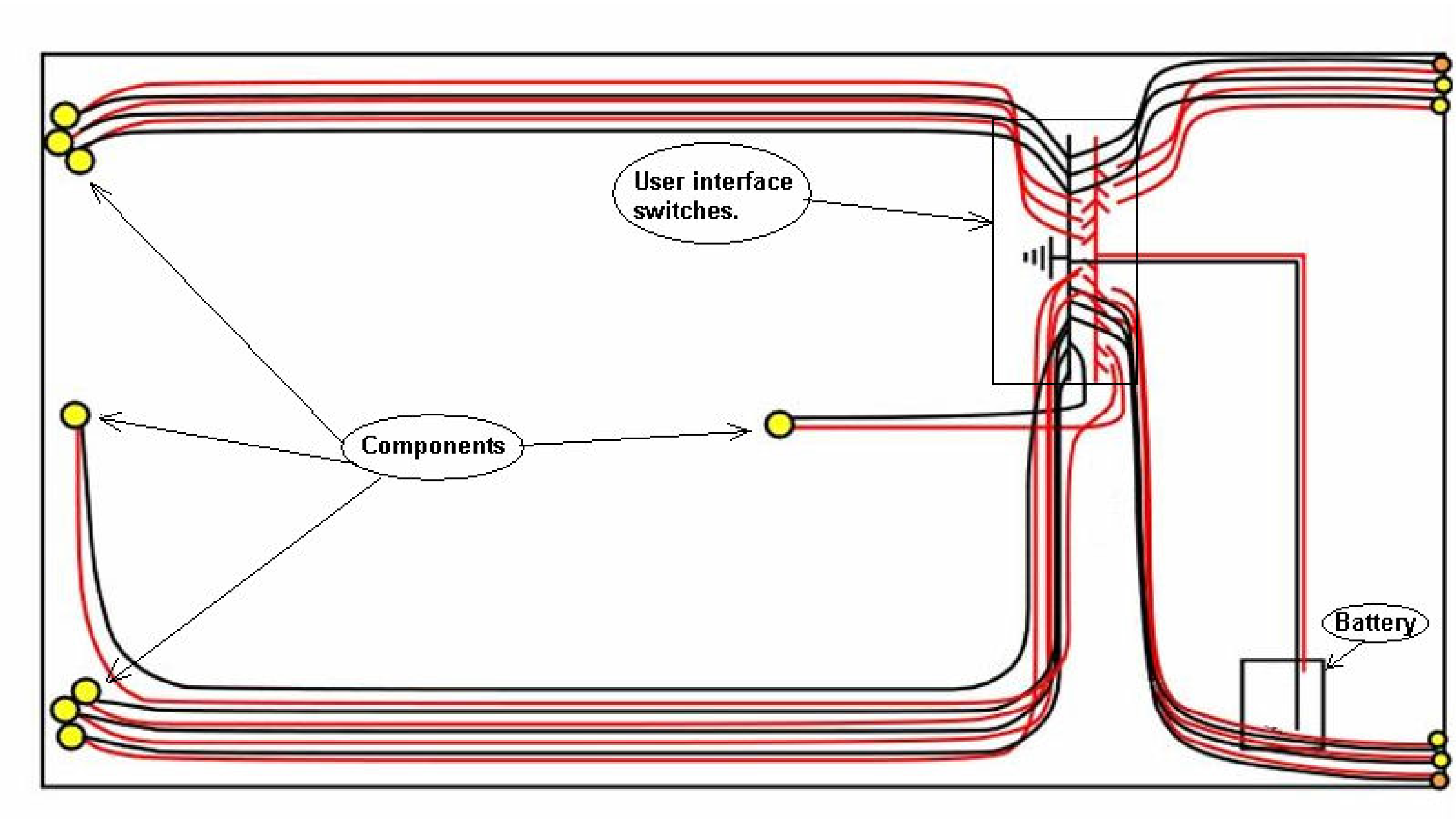

FIGURE 2:

Simplified schematic of proposed centralized power distribution backbone and fiber optic switching system.

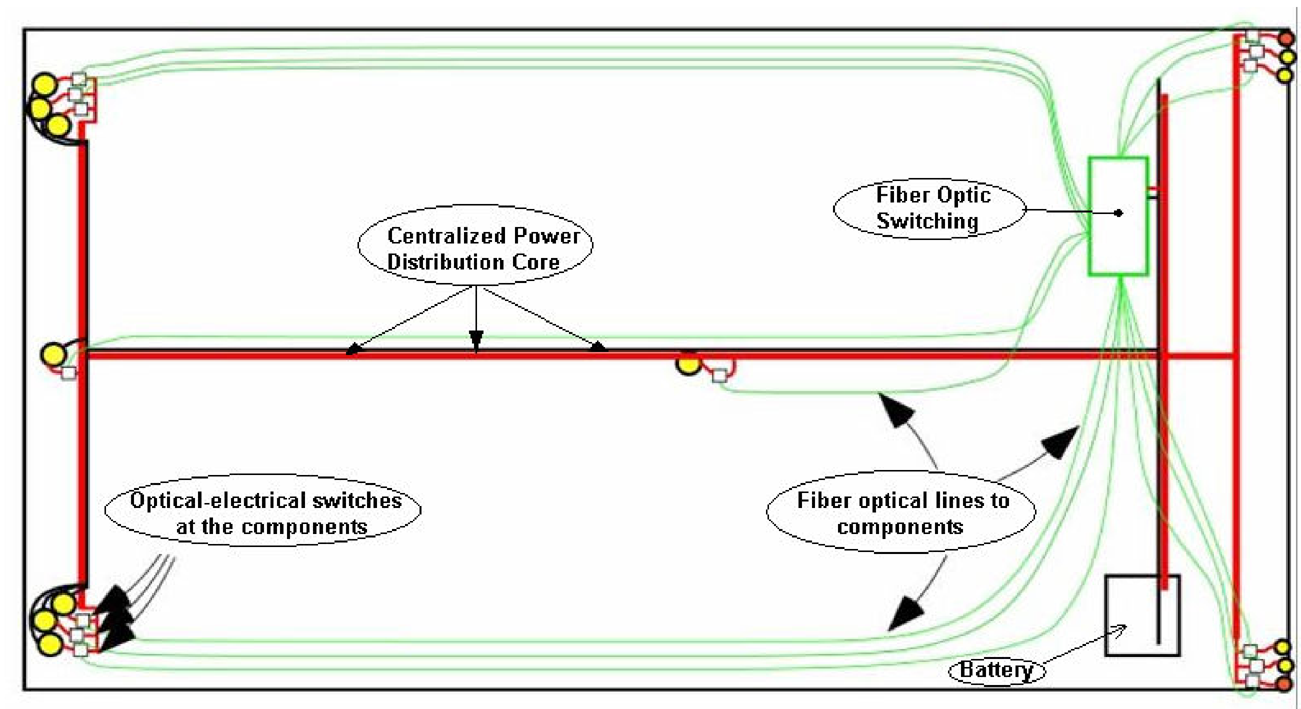

FIGURE 3:

Testing of terminal connectors and slacking configuration to allow easy removal of the central power distribution backbone.

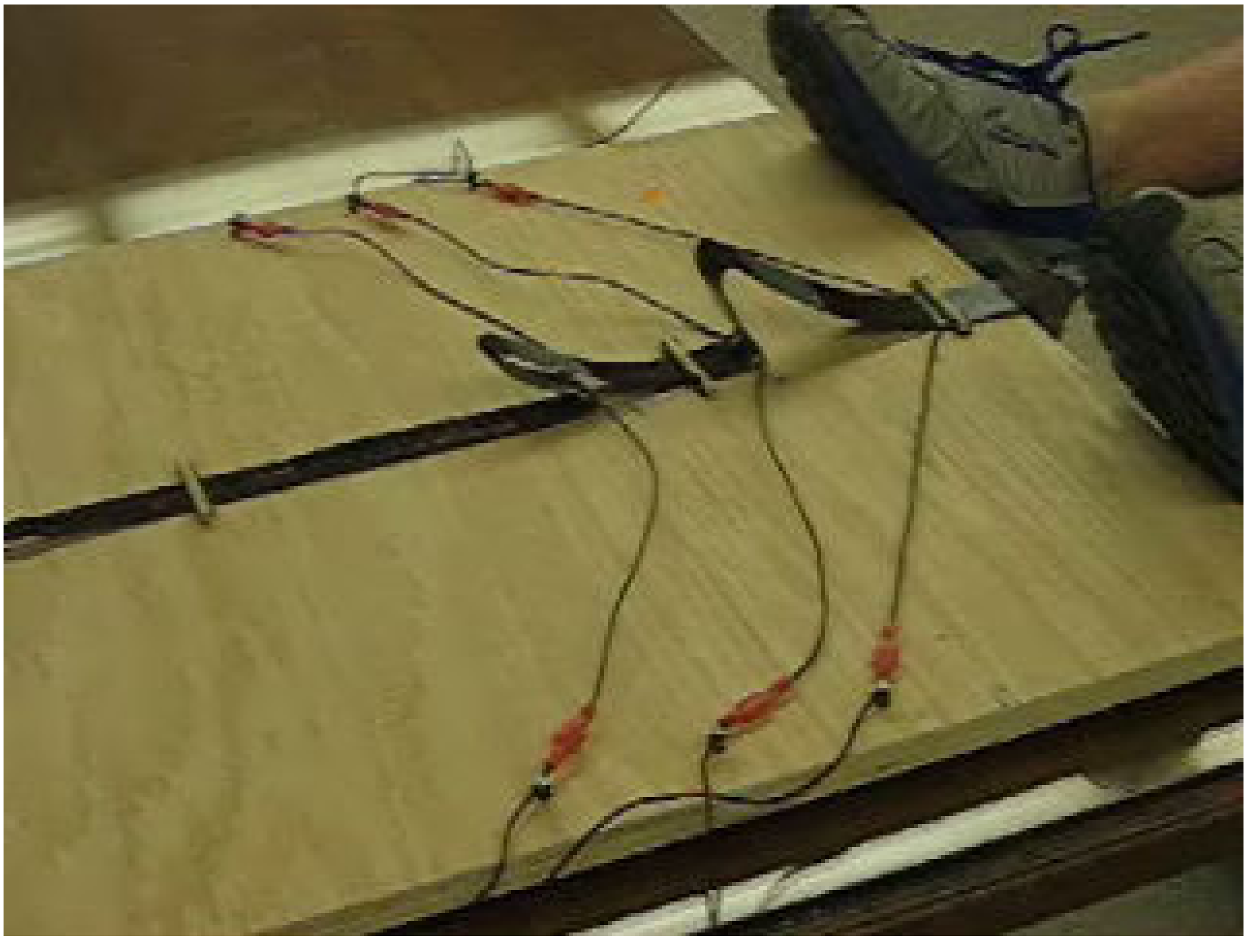

FIGURE 4:

Mechanical testing of terminal connector (above) and close-up (below).

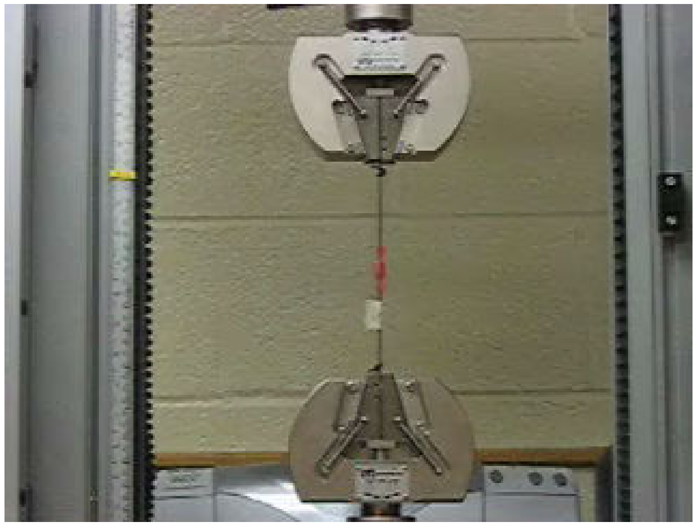

FIGURE 5:

Schematic for emitter crcuit.

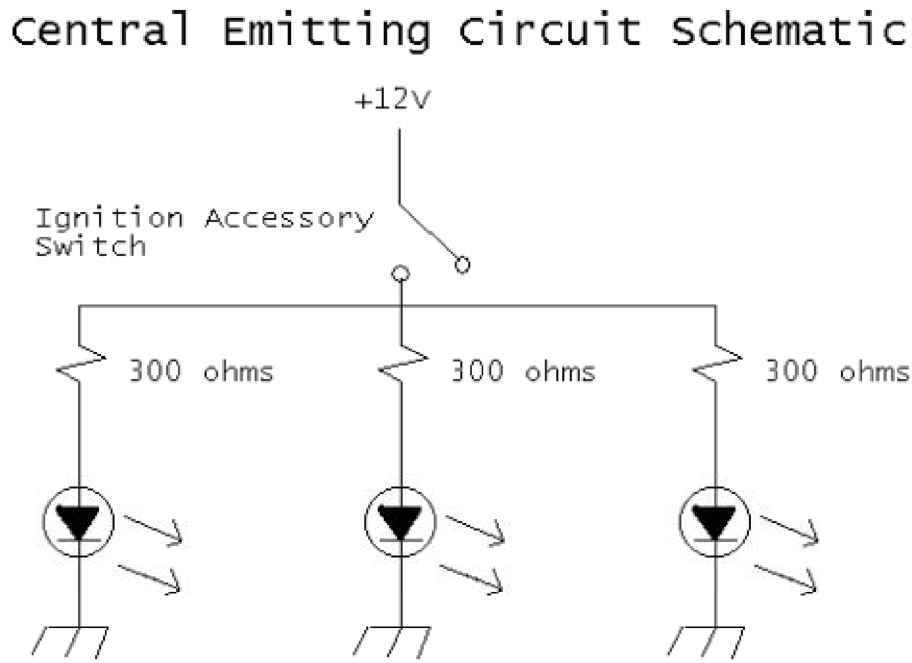

FIGURE 6:

Schematic for receiver circuit.

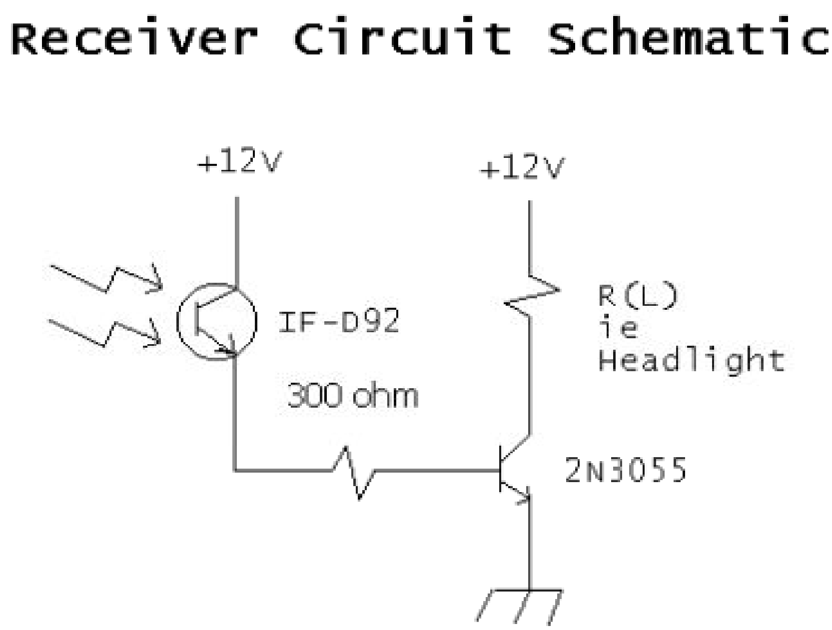

FIGURE 7:

Simplified schematic of the headlight circuit utilizing fiber optic switching at the components.

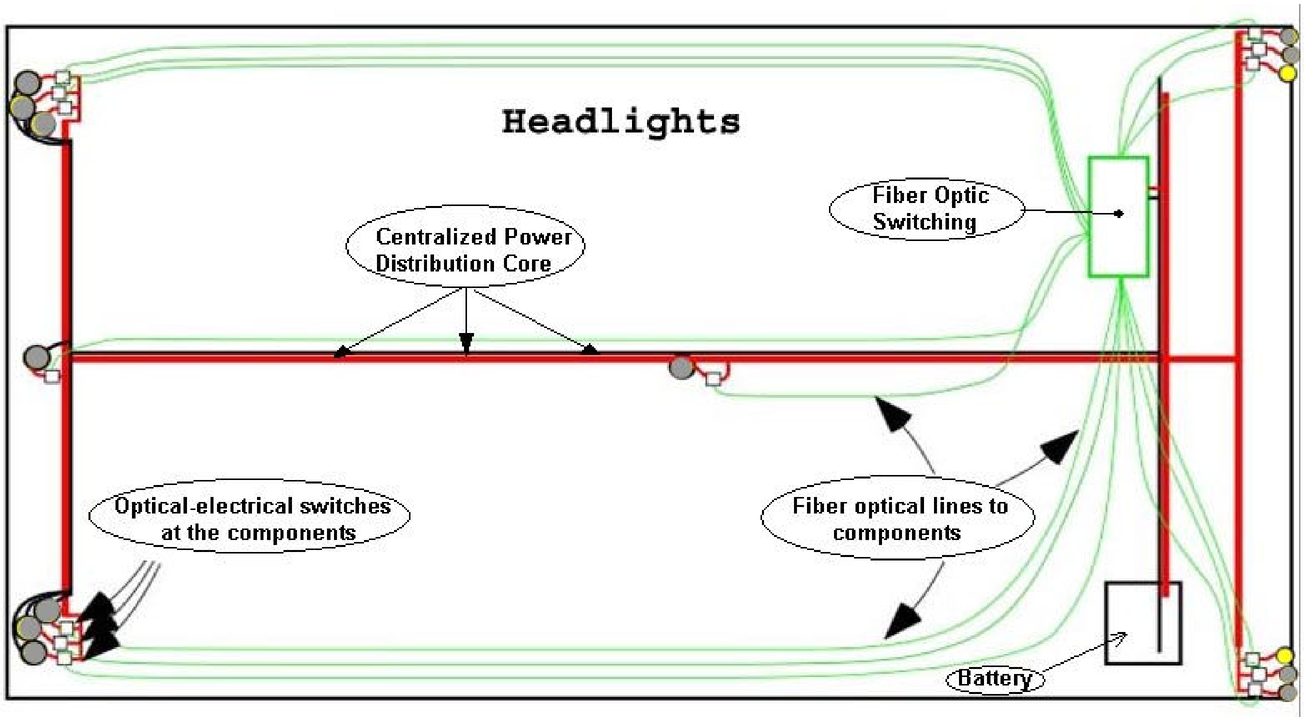

FIGURE 8:
Schematic for receiver circuit modified for headlights.

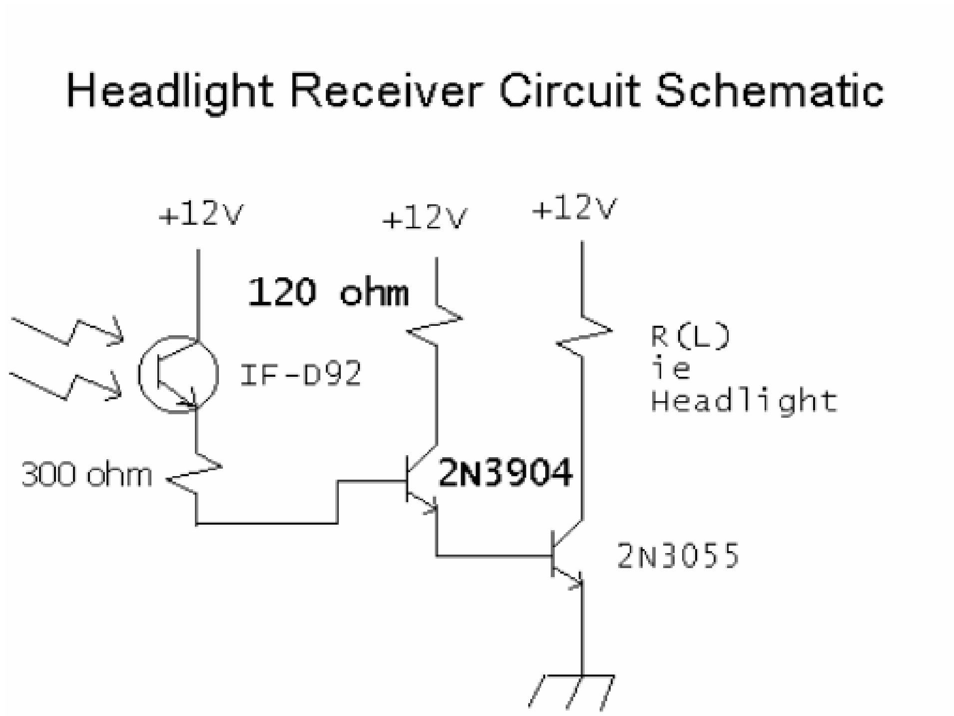

FIGURE 9:
Schematic of receiver circuit modified for turn signal or hazard light.