MOSFET Slot Car Controller Mysteries Revealed

What the Manufacturers Haven't Told You – Yet!

by Jeff Goldberg

JayGee Racing
www.jaygeeracing.com

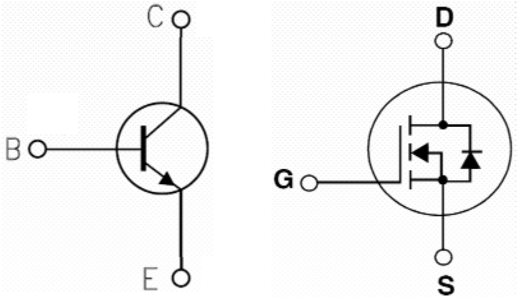
MOSFET based speed controls have been industry standard for decades in R/C car racing, yet MOSFETs have only begun to appear in the braking circuits of commercial slot car controllers during the last several years…and not at all in the motor drive circuit. Virtually all major brands sold in the U.S. still rely on power transistors for the motor drive despite their voltage drops, heat sensitivity, need for increasingly expensive heat sinks and labor for installation.

While there are characteristics of power transistors that continue to justify their use in slot car controllers, continual advances in MOSFET technology, MOSFET drivers and protection devices make it smart for leading edge controller manufacturers to periodically reevaluate using MOSFETs for motor drive. In this article, I'll compare and contrast MOSFETs and power transistors, discuss their benefits and tradeoffs as it applies to slot car controller design, then cover design issues addressed during the development of an experimental PWM motor drive circuit for HO and home set style cars. Anyone that has a basic understanding of electricity and controllers can easily follow along. And you engineers and technicians out there – please excuse the generalities and simplifications, this ain't college.

Figure 1. JayGee Racing Experimental PWM MOSFET Drive

Don't worry…I'm not going to cover semiconductor physics here! I'll just go into enough detail to explain the differences between power transistors and MOSFETs as it relates to their use in a slot car controller.

Figure 2. Bipolar Power Transistor and MOSFET



Bipolar Power Transistor **MOSFET**

A bipolar power transistor is a current amplifier. A small current driven into the transistor's base (B) controls a larger current flowing from the transistor's collector (C) to its emitter (E) terminal.

The larger current flowing through the collector is proportional to the smaller current flowing through the base…and the amount of current amplification is dependent on the transistor itself, the circuit used to drive it and the motor load.

Drive enough current into the base and it becomes fully saturated (as under max throttle conditions), allowing the transistor to deliver the maximum voltage to the motor that it can. However, even when saturated, there is always a significant voltage drop across the transistor, called the saturation voltage. Saturation voltages typically range from 1 to 2 volts, depending on the transistor. The saturation voltage is the reason that manual bypass contacts and/or blast relays are required to deliver full power to the motor.

A MOSFET operates on a completely different principle than a bipolar power transistor. The MOSFET is a voltage controlled resistor. Apply a voltage to the MOSFET's gate (G) and the resistance between its drain (D) and source (S) terminals decreases. Apply enough voltage to the gate and the MOSFET's resistance can drop to 3 milliohms or less, less than the resistance across a 50 amp blast relay's contacts!

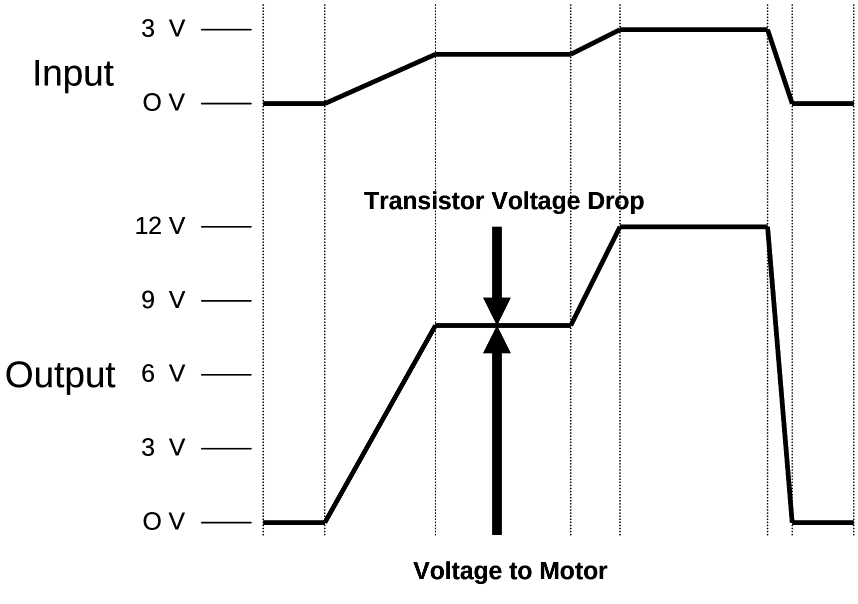
This means that under a 10 amp load, the voltage drop across that MOSFET would be 30 mV, compared to 1 to 2 volts for a bipolar power transistor. By comparison, under the same conditions, the voltage drop across a typical blast relay with a 5 milliohm contact resistance would be 50mV.

This low resistance is the major reason MOSFETs are so attractive for use in controller motor drive and brake circuits.

The operating characteristics of power transistors and MOSFETs lend themselves to different design approaches. While power transistors are current amplifiers, the design of the circuit using the transistor and the way it's connected to its load ultimately determines whether the circuit is amplifying current and/or voltage.

The transistor's output follows the shape of its input, except with larger current and/or voltage swings. Figure 3 shows the inputs and outputs of a power transistor speed control circuit that has a maximum output of 12 volts and a voltage gain of 4x (the output voltage is always 4 times the input voltage, up to 12 volts, max).

Figure 3. Linear Speed Control Inputs and Outputs

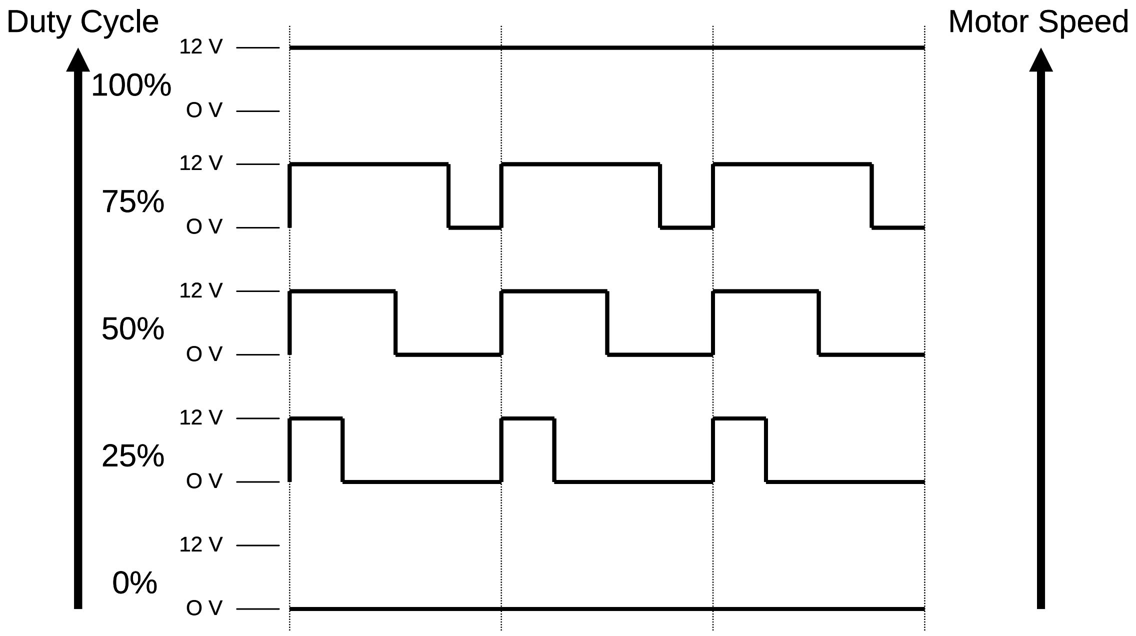


Power transistors generate a great deal of heat because the transistor spends a significant amount of its time in its linear operating zone (under partial throttle conditions, when it's not saturated), where the output voltage is somewhere *between* zero and its max voltage. In this zone, any voltage not delivered to the motor is dropped across the transistor as shown in Figure 3, even though the transistor may be conducting high currents. The resulting power is converted to heat which must be dissipated by large, heavy and increasingly costly heat sinks that are often external to the controller handle.

Due to their operating characteristics, MOSFETs lend themselves to being used as an electronic switch in switch-mode power supplies and pulse width modulated (PWM) motor speed controls, particularly in energy conserving "Green" and mobile consumer products. In these applications, the gate voltage is driven to levels that rapidly reduce the MOSFET's resistance from infinite (its OFF state) to a few milliohms (its ON state). When the MOSFET is switched on and off by a series of voltage pulses, any motor driven by the MOSFET is switched on and off as well. When switched on and off rapidly enough (anywhere from 5,000 to 20,000 times a second) motors driven by PWM speed controls won't slow down appreciably between power pulses and their speed is relative to the power pulse duty cycle, as shown in Figure 4.

.

Figure 4. PWM Speed Control Power Pulses



MOSFETs generate less heat than power transistors because they are much more energy efficient. Once turned completely on, a MOSFET's resistance is very low (typically 3 milliohms or less). That means its power dissipation is low even when it is conducting large currents. Once turned completely off the resistance is very high, but since no current is flowing no power is being dissipated. MOSFETs only consume power and generate heat during the time their output is swinging from on to off and vice versa (which is why MOSFETs run hotter at higher switching frequencies).

How much power needs to be dissipated by a heat sink for a power transistor vs. a MOSFET? Let's throw some numbers at it, chosen for simplicity to understand the concept. Let's assume the track supply is 12 volts, the controller is dropping 5 volts (delivering 7 volts to the car) and the current draw is 10 amps.

Let’s look at the power transistor first. The power dissipation is purely resistive since a constant current of 10 amps is flowing through the transistor while it is dropping 5 volts. Using the following equation:

Power Dissipation = Voltage x Current

The transistor will dissipate 50 watts.

Now let’s take a look at a MOSFET used in a PWM controller. The power dissipation calculation is a bit more complex because in addition to the resistive dissipation, there is a switching dissipation due to the MOSFET being constantly switched on and off.

Power Dissipation = Power Dissipation (Resistive) + Power Dissipation (Switching)

Now, at this point the engineers out there are going to scream because I’m not going to calculate the switching power dissipation. I simply don’t know how to explain the calculation in lay terms. For all of you other readers, I’ll simply say that the switching power dissipation is often greater than the resistive power dissipation. Proper design techniques reduce it to levels that can be handled with heat sinks much smaller than what would be required for a bipolar transistor. In fact, in many cases its possible to eliminate the heat sink altogether.

The MOSFET only dissipates resistive power when turned on, so the power is proportional the PWM’s duty cycle...and since the duty cycle is proportional to the ratio of output voltage to track voltage, the following equation can be used:

Power Dissipation (Resistive) = Voltage x Current x 7/12

Since the voltage across the MOSFET can be expressed as:

Voltage = Current x Resistance

Its power dissipation is:

Power Dissipation (Resistive) = (Current x Resistance) x Current x 7/12

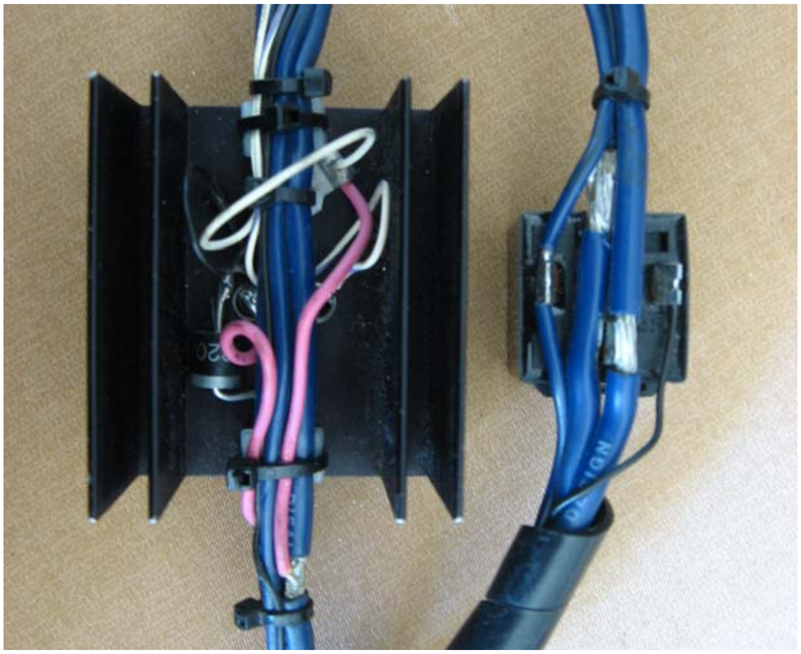
Under the same conditions as before, the resistive power dissipation is 175mW. Even if the switching power dissipation were 10 times that amount (1.75 watts), the total MOSFET power dissipation would be less than 2 Watts, far less than the power transistor’s 50 watts.

This reduction in power loss, resulting in reduced size or complete elimination of heatsinks makes MOSFETs attractive for use in motor drive circuits.

Because power transistors dissipate so much power, extra manufacturing steps are required to install them in a controller. Virtually all slot car controller manufacturers mount the transistor directly to the heat sink. Some even have to drill holes in the heat sink to mount the transistor. If you take a close look at a typical electronic controller’s transistor and heat sink, you’ll see a small circuit board and/or protection diode mounted and soldered directly across the transistor’s terminals and numerous wires that have been carefully stripped, soldered and spliced into place. If a blast relay is used to bypass the transistor, the controller’s power cables must be stripped back by hand in a second location, then four additional wire connections must be made (two for the relay coil, two for the power contacts. All of these manual steps take time, which translates to additional costs that must be absorbed by the manufacturer or passed on to the controller purchaser.

The electronic controller transistor module shown in Figure 5 illustrate these points.

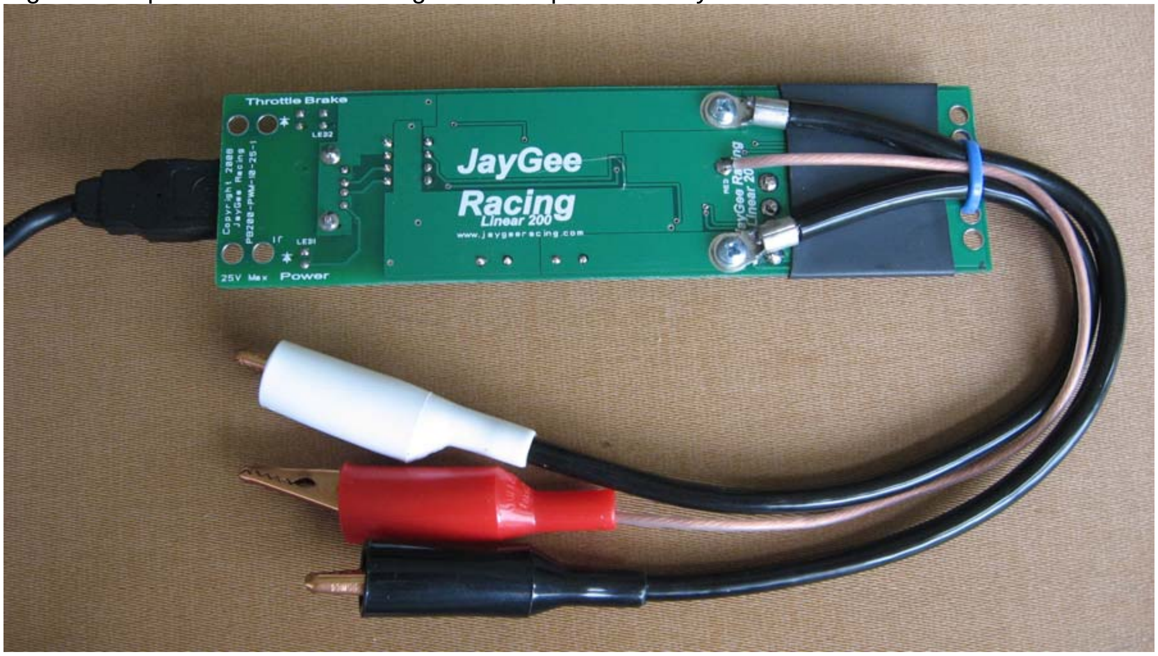
Figure 5. Hand-Wired Transistor Module



Because MOSFETs dissipate so little power, they can be mounted directly to a printed circuit board instead of a heat sink. This allows the manufacturer to reduce assembly time by using low cost automated circuit board manufacturing processes to mount and connect them to their drive and protection circuits instead of hand wiring them during final assembly.

In fact, it’s possible to design a transistor module that requires no hand wiring other than for the power cables that connect it to the track! That’s why the experimental PWM MOSFET drive board sports a USB socket for direct connection to a production Linear 200 controller handle and requires only three solder joints / terminals for the power cables.

Figure 6. Experimental Board Designed for Rapid Assembly



This reduction in assembly time, resulting in lowered costs for final assembly, makes MOSFETs attractive for use in motor drive circuits.

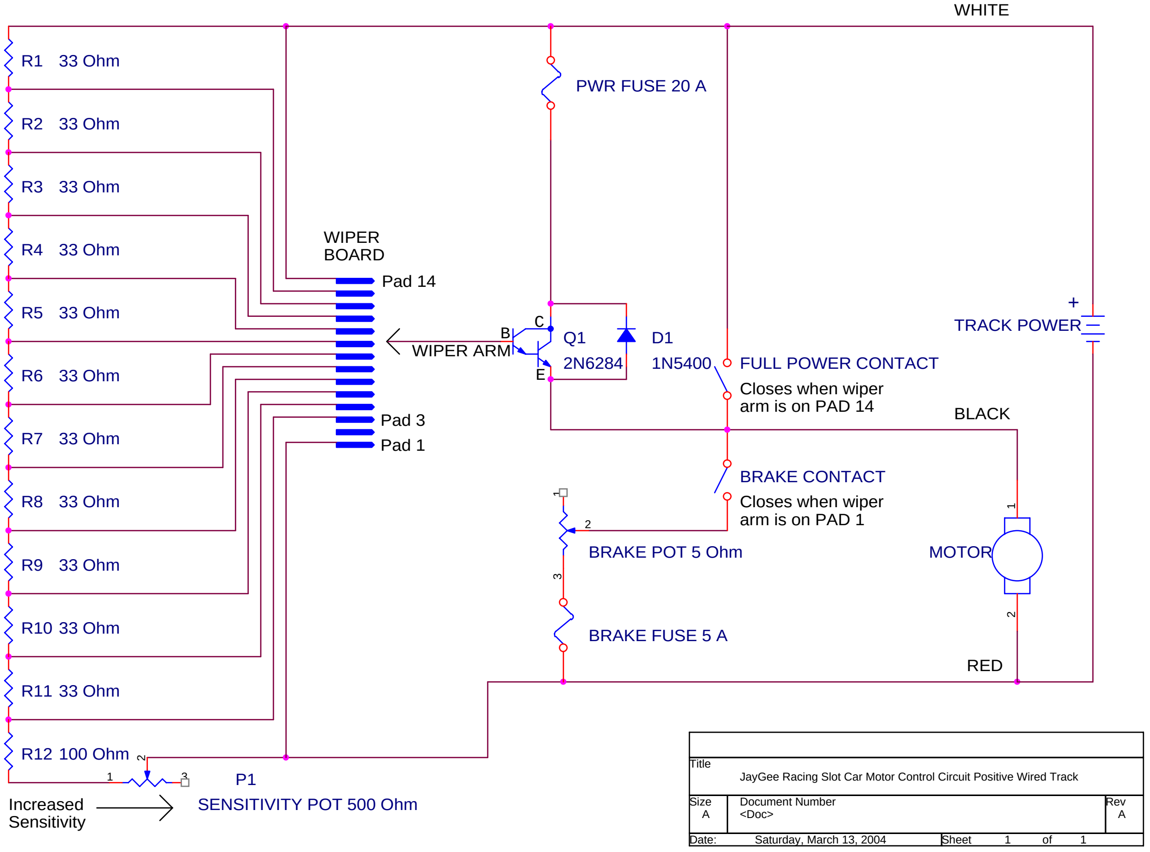
To recap, the reasons to use MOSFETs are:

- Their resistance is as low as a blast relay
- They dissipate much less power than a transistor, eliminating or reducing heat sink size
- They can be surface mounted on a printed circuit board for reduced final assembly costs

So what advantages do power transistors have in a slot car controller? First, the control circuits for a power transistor based slot car controller are relatively simple to design, requiring nothing more than a couple of dollars worth of resistors and two potentiometers.

An example of one such controller was JayGee Racing's first generation product, the Linear 100.

Figure 7. JayGee Racing Linear 100 Prototype Schematic



Second, since the power transistors and relays are hand wired, transistor modules can be built to order using components that are ordered in low volume. Wiper boards can be built using older, thru-hole resistors or resistor arrays suitable for prototyping and low volume production. However, the electronics industry has long since moved on to surface mount technology for production volumes, where components are mounted on the board's surface instead of on leads that poke through it. While surface mounting is much less expensive to manufacture in the long run, it's more expensive to prototype, entails higher set up costs and larger production runs to be cost-effective, and the components have to be purchased and paid for in advance for the entire production run.

Last, because power transistors are mounted to the heat sink and are hand wired, racers can replace the transistor and crowbar protection diode themselves, although admittedly, many racers still need assistance determining if the diode or transistor is bad in the first place.

To recap, the reasons to use power transistors in controllers are:

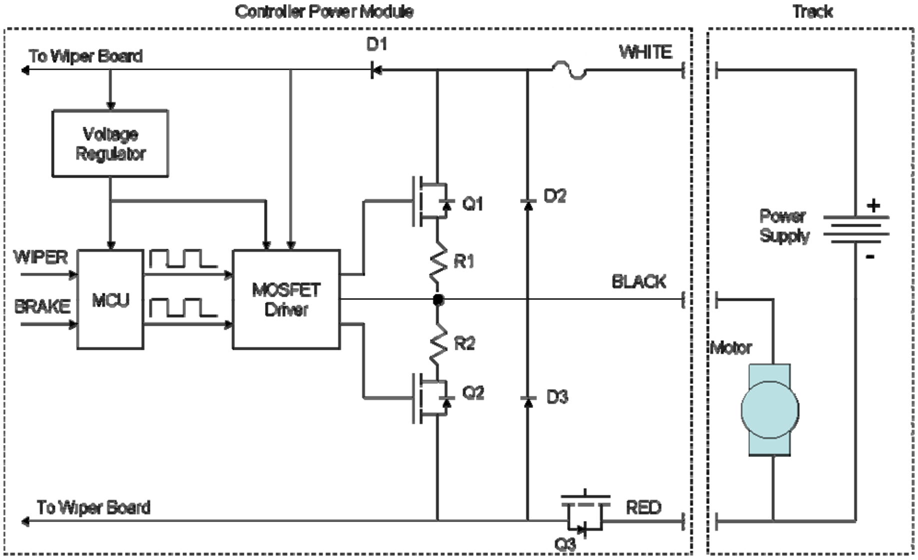
1. Simpler to design resistor drive circuit
2. Less expensive to prototype and produce in low volume
3. Easier transistor and diode replacement

Items (1) and (2) are really issues for the controller manufacturer to contend with, not the customer. That is to say, the customer probably cares more about how well the controller works and how robust it is than about how many hours the manufacturer spent designing it. Item 2 is purely an economic decision. The customer just wants a great controller at a fair price. If using MOSFETs and surface mount technology enables the controller manufacturer to deliver a better value, everyone wins!

The last issue is a valid customer concern. It's unreasonable to expect the average racer to diagnose and replace surface mounted components. Board failures must be minimized by proper component specification, use of conservative design rules and adoption of circuit protection techniques used in high-rel electronics. I can tell you from personal experience that the greatest challenge in controller design is protecting it from the innumerable ways it can be mis-wired. Controller design would be much simpler if driver's panels featured polarized plugs!

So let's take a look at the MOSFET drive and protection circuits used in the experimental PWM board. PWM MOSFET drive circuits, while more complex than the simple resistor networks used in today's controllers for power transistor drive, are still relatively simple. The MOSFET input pulses are created and their width is controlled (or modulated, in engineering speak) by complex integrated circuits (ICs). Although the ICs are complex, they are relatively inexpensive, offer precise control of the pulse width, consume very little power and can generate sophisticated motor acceleration and braking curves under the control of simple, low cost microcontrollers. The ICs do require additional support components such as resistors and capacitors, MOSFET drivers, voltage regulators and/or reverse battery protection circuits (ICs smoke instantly when hooked up backwards).

Figure 8. Linear 200 PWM Controller Module



This module works with the USB connected handle and cable that comes with the Linear 200 Pro 40 and Pro 40E controllers. Power and ground are supplied to the handle's wiper board to generate the voltage drops across the wiper pads and the brake control voltage. The handle's brake pot and wiper drive MCU inputs, just as in the other Linear 200 controllers. The MCU reads the voltages present on its wiper and brake pins, then generates the appropriate throttle and brake pulses.

The programmable MCU provides the design flexibility that allows the PWM module to be tailored to the car's requirements while still using the same exact hardware. For example, ultra-light home set cars can benefit from a soft bottom end in the throttle response and an extended PWM brake profile. Hi performance HO cars require a powered coast where a small amount of voltage is still fed to the motor when the trigger is in the brake position. And of course, I still wanted to experiment with the Brake N' Release profile for these car classes as well.

These radical changes in controller functionality go well beyond the simple sensitivity and power curve adjustments that could be achieved with pot adjustments and plug in resistor packs …different circuit designs would be required. Rather than build completely different boards, change brake and throttle pot values and/or add additional switches and controls to the handle, changes to throttle and brake functionality are handled in software. The appropriate MCU is then plugged into the board during final assembly. Since the same PWM board and handle can be used in multiple controller designs, they can be manufactured in higher volume using surface mount technology to reduce overall costs.

The voltage regulator is a simple 3-terminal linear regulator, allowing the controller to operate with track voltages from 10 to 25 volts while supplying the voltage and current required by the MCU and MOSFET drivers.

The MOSFET driver block needs to be able to supply full power to the car without any delays at the start of a race and to protect the MOSFET in case of a short circuit. The rapid start capability is provided by a charge pump that can fully turn on the throttle MOSFET Q1 at power on. Current sensing amplifiers in the block monitor current flow though the MOSFETs, shutting the MOSFET off if a short circuit occurs.

Now on to the most challenging aspect of the design, circuit protection. I specified the protection scheme very conservatively, making it capable of protecting the controller even when hooked up to high power commercial raceway power supplies. I figured that if the controller could be protected on a commercial track, then it would certainly be fine for any power supply found in a club or home setting.

The low power control electronics were easily protected against reverse polarity by a blocking diode, D1. However, a blocking diode couldn't be used to protect the MOSFETs without impacting performance. While blocking diodes and PTCs are often employed in industrial applications because they are simple and easy to use, they would introduce unwanted voltage drops when used in a slot car controller. That's why more energy efficient methods were used in this design.

I first explored the use of simple, inexpensive automotive blade fuses to protect the MOSFETs. They met my criteria of being readily available and having only a few milliohms resistance. However, I discovered that protection circuit reaction time is critical as high quality power supplies used in commercial raceways can pump out hundreds of amps for several milliseconds before their own safety circuits kick in. While a properly rated MOSFET can conduct 20 amps or more for hours while remaining cool, it will only last a few hundred microseconds when conducting hundreds of amps. Since automotive blade fuses can take milliseconds to burn out under those conditions, faster responding protection solutions are required.

I didn’t bother exploring “quick blow” glass fuses commonly used to protect electronics since they are not as readily available as automotive blade fuses. Instead, I went to a fully electronic short circuit protection scheme with its added user benefit of being auto-resetting.

The brake protection circuit consists of reverse wired MOSFET Q3 and current sense resistor R2 and is identical to the circuit used in the Linear 200 Pro 40. When wired in this fashion, Q3 behaves as a “perfect diode”, blocking current flow if the controller’s brake line is connected to track WHITE but introducing no voltage drop when the brake line is properly connected. The MOSFET driver monitors the current flowing through R2, who’s resistance is equivalent to that of an automotive blade fuse and much lower than the PTC fuses used in other brands of controllers. If the current exceeds a predetermined amount, as would occur if the controller’s black line were to touch track WHITE, the MOSFET driver would shut the MOSFET off before it is damaged. An automatic retry built into the MOSFET driver circuit enables the brakes to begin working once the controller is properly wired. This circuit provides the powerful braking that the Linear 200 has become known for, while proving to be very reliable without any component failures on the board in over 18 months of production.

The throttle protection circuit consists of current sense resistor R1, three power diodes wired in parallel represented by D2 and an automotive blade fuse. Just as in the brake circuit, the current through R1 is monitored by the MOSFET driver. If a short circuit occurs on the track or the controller’s black line was to touch track RED, the driver would shut the MOSFET off in microseconds.

The automotive blade fuse and diode D2 implement a crowbar circuit that protects the controller when it’s misconnected in such a way that the electronic protection circuitry isn’t powered. If the controller’s black line touches track WHITE while the white line is touching track BLACK or RED, current would flow backwards through the MOSFET’s intrinsic diode, just as it would flow through a power transistor’s intrinsic diode in conventional controllers. The MOSFET would eventually overheat and self destruct. Instead, the current bypasses the MOSFET and flows through the power diodes, blowing the fuse. This crowbar circuit is identical to that used on the Linear 200 Pro 40 without any component failures since its introduction in 2007.

So how well did the experimental module work? I started off by testing the circuit protection scheme on the Midwest Monster’s massive power supply at Mid-America Raceway using the test suite developed for the Linear 200 Pro 40. The electronic current sensing protection protected the brake and throttle MOSFETs just as it was designed to do, without the MOSFETs heating up or blowing the crowbar protection fuse. (Remember, the current sensing circuit reacts faster than the fuse.)

Of particular interest was how well the controller performed when the controller’s white line was properly connected, the black and red lines were swapped, and the trigger was held in the partial throttle position. In a conventional electronic controller, the bipolar power transistor could be damaged by overheating since it’s now wired directly across track WHITE and RED…the fuse not blowing because the current is limited by the transistor voltage drop at partial throttle. However, in a PWM electronic controller, the MOSFET pulses on and off when the trigger is in a partial throttle position. When the MOSFET turns on there is a dead short from WHITE to RED. The current sense circuit detects the short immediately and shuts the MOSFET off to prevent it from overheating.

I then proceeded to test the crowbar protection circuit. I initially started off with a small 5A automotive blade fuse, then increased the fuse size to 20A without damaging the three protection diodes or the throttle MOSFETs they were protecting. That means the module could conservatively be protected with a 10A fuse, far above the current draw of HO and home set style cars it is designed for.

With circuit protection testing complete, I verified that the controller wouldn't delay sending full power to the car when the track power was turned on. I simulated a race start condition by looking for any discernable power-on difference between a PWM module driven car and a car driven by a Pro 40 module. I placed the two cars side by side, held both controllers full on and turned the track power on. As expected, there was no difference…microcontroller boot time is just a few milliseconds, unnoticeable at power on.

Would the low-voltage control circuit regulator stay cool when track power was turned up? Would the drive MOSFETs be able to handle the current w/o any additional heat sinks? To find out, temperature testing was performed on both the bench and on the track.

A bench setup was used to test the regulator under load conditions. I installed a 16D motor in my controller test fixture and wired it up to a bench-top power supply. I cranked up the supply as high as it would go, just over 22V. The controller was adjusted to provide 3 volts to the 16D motor, just enough to break it in w/o over-revving. This setup loaded the regulator because control circuits were fully operational. After running for ½ hour, the regulator was still cool to the touch. I also noticed that the motor drive MOSFETs were still cool, despite 19V being dropped across the module.

Track testing was performed on Mid-America Raceway's Midwest Monster, site of the 2009 SCX "Nats" Midwest Qualifying Race. Testing with SCX and BRM home set cars, and even 16D powered flexi cars, revealed that the motor drive MOSFETs also remained cool under load conditions. The soft bottom end throttle profile was ideal for the home set cars. As expected, that profile was too soft on the bottom end for the 16D powered 1/24 scale car. It was much happier with a completely linear throttle profile.

Figure 9. Look Ma, No Heatsink!

Brake circuit testing did uncover one design error. The control circuit continues to monitor trigger position for a few moments after the track power shuts off. If the trigger is held in the throttle position, the car is allowed to coast to a stop. If the brake contact closes during that time, the brakes are engaged. The holding capacitor used to power the MCU and MOSFET driver was too small, so the controller had no brakes after the track shut off. A quick capacitor change solved that problem.

Now that my work was done at Mid-America Raceway, it was time to check how well the module worked for HO cars.

Slot Pro Speedway's Jim Nagy was kind enough to test the controller with a variety of HO cars and power supply settings on his home track; T-Jet at 18V, G-Jet at 12V, Wizard Thunderstorm at 15.7V, Super Stock BSRT 910 at 19.5V.

I replaced the microcontroller with one I had programmed for HO use; linear throttle response with the powered coast feature. Jim remarked that the controller seemed to be too sensitive to be driven comfortably. It also appeared that the powered coast voltage range needed to be raised. Both those issues can be addressed with software changes. Back in went the home set microcontroller with its soft bottom end throttle profile and extended range PWM braking. The softer throttle and brake profiles made a huge difference, making the controller well suited for the lighter, low powered HO cars…and when the throttle sensitivity knob was cranked up, equally well suited for the higher powered magnet cars.

Jim was also curious to find out if the module worked without the brake line attached. While not a design goal for the experimental module, it appeared to do so.

All in all, testing showed that a PWM MOSFET drive can be made robust enough for slot car controller use. The programmable microcontroller provides the design flexibility required to allow one board and one handle to be used for multiple controller designs. It's also clear to me that if the board's manufacturing costs can be brought down enough to allow the module to be priced aggressively at reasonable volume, MOSFETs will have a place in controller motor drive circuits sold in the U.S. While the experimental board is limited to home scale and HO use, the lessons learned could eventually be applied to higher current modules suitable for all forms of slot car racing.

Afterword

The technology is already proving its worth on the race track. Colin Schmitt used the PWM MOSFET module and teamed up with his mom, Laura, to give JayGee Racing its first World Championship, winning the GT Car World Endurance Championship in July in Toronto. Dave DeMott qualified for the SCX National Championships with his outstanding performance at the SCX Nat's Philadelphia Regional Qualifier in June with a controller that he never used before. Both Dave and Colin used control chips set up with the soft bottom end throttle profile and extended PWM brake profile.

When Chris Barnes approached me with a request to soften up the throttle response of his Linear 200 Pro 40, we decided to explore how well the PWM MOSFET module equipped with the soft bottom end throttle profile worked for retro racing. Chris promptly TQ'd in the CAN-AM class at the July "Retro Slots @ Abbeville" Series race and won that race as well. He followed that up with wins in both F1 and CAN-AM at the August event.

While I expected the PWM MOSFET module to perform well, I never expected it to achieve this level of success so quickly…robust enough for endurance racing at 19 volts, easy to dial in by first time users, and versatile enough to win in retro racing.