Brainpower
always beats
horsepower

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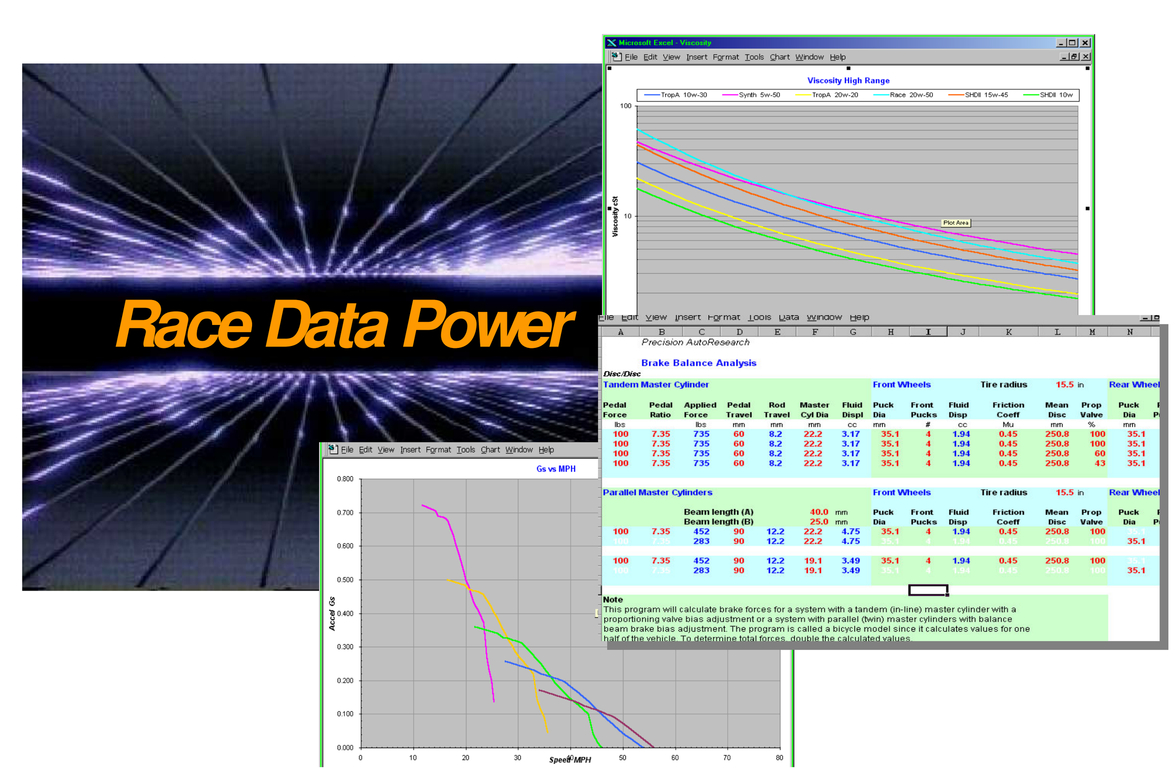

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Who We Are

David M. Redszus, PhD.

Dr. Redszus is president and founder of Precision AutoResearch, a provider of advanced research and engineering services for the motorsports industry. A life-long racing “junkie,”——beginning with brake jobs at the age of 10 — he probably has more coolant on the brain and oil in his veins than some of the cars on the track!

As technical consultant, engineer, coach, and driver, he has experience with a broad spectrum of sanctioning bodies, vehicle types, manufacturers & suppliers, advanced driving techniques, and racers. He has worked with numerous professional, semi-pro, and amateur racing teams, in a variety of motorsports. He also serves as a design judge for *FormulaSAE™*, an international collegiate competition for the Society of Automotive Engineers. Among the many articles and papers he has written over the past 25 years, you’ll find his most recent contribution as author of an article on team approach towards electrical systems development, in the “Learn and Compete” publication for FSAE teams.

David has also done extensive engine research and development in the areas of combustion analysis, fuel chemistry, and wavefront propagation. These topics, among others, have led to the development of the groundbreaking ***RaceDataPower*** software suite. This unique product provides racers, at any level, advanced engineering capability previously seen only at the Formula-1 level. Utilizing modern tools, coupled with hands-on experience, Dr, Redszus and his team are transforming “old school” racing knowledge into *Racing Intelligence*. It seems to work, as they have just celebrated their 350th major championship win, among various types of racing!

Precision AutoResearch is the premier provider of data collection systems for professional and amateur racing teams. Assisting teams with selection, installation, and interpretation of data, they provide teams with valuable insight, saving money and adding functionality previously unseen in this fast-paced industry.

Outside of racing, David is an expert in large-scale systems analysis and non-linear management dynamics. He has consulted for the US military and private sectors, including most of the major automakers in the United States and abroad.

Dr. Redszus holds Ph.D. and M.S. degrees in Industrial Engineering from the McCormick School of Engineering at Northwestern University. His undergraduate work yielded a dual major in both Industrial Engineering and Economics. He also completed and instructed in the masters curriculum at Northwestern’s Kellogg Graduate School of Management.

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CHAPTER 14

Electrical Systems Integration

What the ME's don't (nor want to) know ...!

By David Redszus

Synopsis

This chapter discusses a critical, long-emerging area of vehicle development: electrical systems and their evermore complicated peripherals offer great performance and diagnostic opportunities. Yet, implemented poorly, they can be a source of unreliability and immense frustration. Electrical systems touch upon nearly every mechanical subsystem on the vehicle. It is little wonder the mechanicallay focused engineer-in-training finds this category intimidating. Regardless of one's existing sophistication in this area, however, any engineering student should be up for the required tasks.

Unfortunately, FSAE® student programs have been excessively focused on mechanical details, especially over the past decade. SAE is the society of *Automotive* engineers, not *Mechanical* engineers. Automobile development has progressed over the past century to encompass many non-mechanical disciplines: Aerodynamics, Chemistry, Emissions, Electrical, Electromechanical, Ergonomics/HFE, Rules/Regs compliance, Data Acquisition, and more. The most highly successful FSAE® teams have typically done a good job of embracing such non-mechanical disciplines.

If you want to succeed in this competition, and in your career in engineering, you cannot ignore the importance of electronics integration. This does not imply that you must become an electronics expert, or a software guru. Having a pocket protector in your shirt is no guarantee. Merely understanding the principles will take you a long way towards becoming a productive engineer in this contemporary age. Yet, we still see FAE® teams who don't have a clue about the importance of this field. Care to guess their results at competition? Somewhere between miserable and incomplete...

Electrical system integration can be defined as successful management of the wiring, modules, and software on the vehicle. Notice the word successful. Merely installing the parts and stating "it worked" is hardly integration. An integrated system has interfaces between components that perform many diverse tasks, even comprising redundancies which enhance vehicle reliability. Further, diagnostics often facilitate faster identification of problems of both mechanical and electrical systems. The more advanced electronics integration offers performance potential beyond mechanical systems. ABS, TCS, VSC, EDC, PDM, ECM, Active Damping, Data systems, etc. It may be alphabet soup to some, but, if you can harness these technologies, you'll be a step ahead.

So, how does a team create and successfully manage an integrated system? Well, surprise-surprise, it all starts with some basics...

Consider the electrical system (let's call it a Network) on the car to be loosely analogous to a human nervous system. The wiring harnesses are like nerves. Individual wires are axons. The connectors are synapses. Sensors are neurons. And the electronic control unit(s) are like one or more brain. (Yes, many of your cars possess several brains!)

Think NETWORK, not COMPONENTS! Plan from a high-level view, not just the desirability of components. Start simple. Think together as a team.

If you follow the nervous system analogy, you'll undoubtedly understand that the components of such a system cannot be pulled apart and run independently. They must work together to have value. The same is true of the vehicle electrical system network, as well. So, does it make sense to dwell on the subsystems without context of the whole system? Of course not.

As a team (there will be more than one of you building this system, right? Good. Two or more makes a team. One makes a martyr. Three or more...politics!), it is imperative that you have an overall objective for such a system, prior to purchasing or building any components. Do not hand the electrical system off to a junior member of the team in a passive way. You'll do a huge disservice to that individual and the team.

Early in the vehicle concept stage, schedule a team pow-wow and determine what electrical/electronic functions are *required, desirable*, or *barely attainable*. Notice the focus is on functions, not components. Components are merely the physical means by which a function may be implemented, coupled with your competency. Early on, focus on high-level functions, not components.

Commit yourselves as a team to the *required* functions; like it or not, they will not go away. If you have to research a bit to implement these functions; so be it. You need an autonomous starter function on the car. Saying you don't know anything about starters and their functions does not change the fact that your car still needs to start without external assistance!

Desirable functions may require some negotiation among team members. Time and budget constraints may be mitigating factors. Exploring desirable vehicle functions early among the team may generate surprises about individual expertise (or lack thereof), which will affect the team enthusiasm for a particular function. Though these are optional functions, they are often the most enjoyable and educational to execute. Do not be shy, but be realistic! If you commit to a function, the team's success may well depend upon that function to succeed.

Selecting and pursuing the *barely attainable* functions is what separates the mature teams from the immature (and typically unsuccessful) teams. If the function is barely attainable, it should probably not be implemented in the current season. Doing so will serve as a distraction from basic functions. Rather, barely attainable functions may be slated as legitimate desirable functions for next year's car. As such, some research and development could be pursued by one or more students during the current season. Establishing proof of concept and familiarity will help push its implementation next year. By pushing it off, the pressure to perform (and too often, one or more disastrous shortcuts) is reduced. This is typically how successful teams develop all those whiz-bang parts you see. They are an accumulation of several years' investment.

So, when should you design and build the network? Hint: Early! Also face the fact that you may never be done with this iterative process…

Short of a random walk of development, there are two methods for network development:

Complete the network design very *early* and stick to your guns.

Wait and see what evolves, then respond, while keeping basic functionality in mind.

To a project manager, the first approach looks very appealing. With a network design in place, one can plan around that network. Component placement and harnesses can be built early and the details of programming can be started. The team managers will have a good feeling that "visual progress" is being made.

The second approach outwardly seems a project management nightmare. The team does not know where components will be fitted, where harnesses will run, what sensors will fit, until the physical vehicle design is complete. Beyond the team determining such factors, there are also inherent delays from suppliers of various components. Wait too long, and you are in a heap of trouble.

Most SAE judges would argue that the second approach is a bit haphazard, and results in many loose ends still dangling at competition. The pursuit of flexibility may result in an incomplete car, or the network development becoming a bottleneck in the vehicle design. As the final stages of vehicle development (aka, *Design Crystallization*) approach, the loose ends tend to get cut off or sub-optimized. Inter-personally, this approach also is a default subordination of the "electron-guys" on the team, as those who visually complete their sub-system sooner tend to get their way.

Yet, the first approach offers its share of problems as well. A fixed network design offers little flexibility to design changes in the mechanical structures of the car. Something will have to budge. The time and expense of building a sub-system prematurely will add to the overall time and cost, as considerable rework/patchwork must be conducted. So, those "premature developers" who strive for visual progress may fall harder with more rework late in the game. By the way, this applies to any sub-system development, not just the electrical/electronic subsystem...

So, the reality is you'll likely start conducting the first approach, then inevitably default towards the second approach. A balance must be coordinated among the various subsystem teams on the car, which means keeping your options open. This is the crux of management: to know when such a balance is out of kilter, and when a modification decision can wait no longer!

Remember that all functions may not be implemented to your liking by the start of competition. Instead of thinking of this as a failure, consider it the reality of vehicle development. The perfect car – FSAE® or otherwise – has yet to be built...there are always woulda-shoulda-coulda clauses attached to a finished product. Rather than dwelling on this, ensure the critical tasks are working (eg the car must start and run repeatedly), so you'll complete the endurance portion of competition.

Complication vs Complexity: Consider that raising the number of components (complication) of a system makes managing it much more complex. The number of interfaces between components grows geometrically with the number of components. Assess your team's capability to manage this.

As your team advances its electrical/electronic integration, consider a few fundamentals when assessing the interfaces among components. Think of the number of possible interactions between the neurons in your "nervous system".

Those of you who've studied networks in your Industrial Engineering classes will recall that the number of possible interfaces *I* in a communication network goes up with the square of the node (device) count, *N*. The relation is as follows:

I (two-way) = N^2-N

I (one-way) = (N^2-N)/2

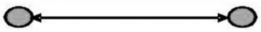
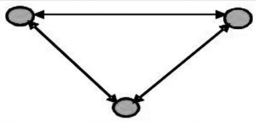
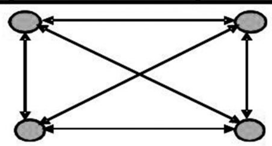
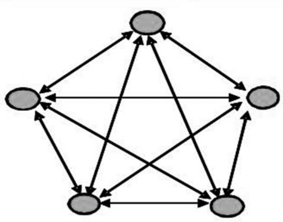
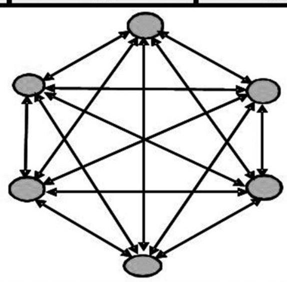
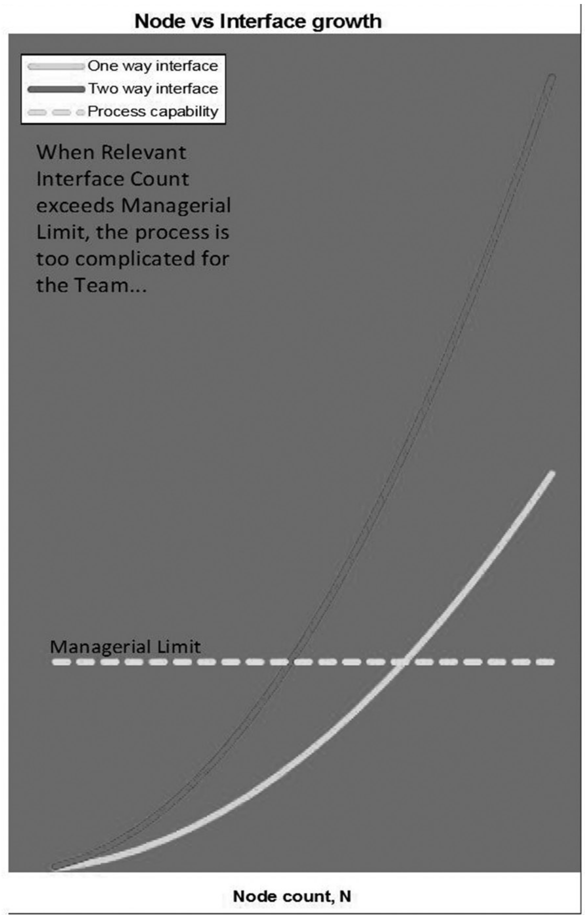
Nodes	Interfaces	
	One way	Two way
N	$I_1 = (N^2\text{-}N)/2$	$I_2 = N^2\text{-}N$
Dots	Lines	Arrowheads
2	**1**	**2**
		
3	**3**	**6**
		
4	**6**	**12**
		
5	**10**	**20**
		
6	**15**	**30**
		
7	**21**	**42**
8	**28**	**56**
9	**36**	**72**
10	**45**	**90**
11	**55**	**110**
12	**66**	**132**
13	**78**	**156**
14	**91**	**182**
15	**105**	**210**

Diagram of interfaces nodes and interfaces

The lowest number of interfaces is the uninteresting condition where each node is only attached to one other node, so this is merely $I = N$ if one way, or $I = 2N$ if two way.

When you've doubled the number of control units, you can expect about four times the amount of work, right? Not so fast. Recall that all the associated sensors, switches, lights, and control units each have their own multiple connections. So your *N* count may be much larger that you anticipate. Consider an engine ECU with 75pins, connected to a dash with 32pins. Potential one-way interactions among these could be over 5600!

The difference here in approach is huge. A *complicated* network is associated with the *N*-count. The *complexity* of the network is more associated with the *I*-count. It is not at all uncommon to see *N*-counts in the region of 150-200 on a FSAE® car. The *I*-count could be up in the 10,000 or more region. Clearly this is too much to manage, even if you had a large crew on your team dedicated to this electronics integration task.



Complexity *versus* Complication chart

Don't let this concept scare you. There are ways to make the *I*-count considerably smaller than indicated above by reasonably eliminating certain theoretical interactions (eg your front brake pressure sensor will not need to interface to the water temperature sensor) and through the use of CAN networks, which we will discuss a little later.

The point is still very important. Certain circuits (such as ground or power circuits) may prove critical to the vehicle operation and may interact with numerous functions. Let this get out of control and you can have some very painful ripple effects. Remember, your job is to make the nervous system so good (and stable) that it doesn't make the team nervous!

Below are several categories of components. In each area, teams have proven themselves capable of stumbling. Learn from previous mistakes and don't repeat them.

Connections: A prevalent source for electrical system breakdowns. Think about preventing failures, while still in the design stages. Also some techniques for proper connector assembly.

Before we even consider talking about the trick bits, let's cover the foremost source of breakdown in systems, the connections. How difficult is it to ensure that connectors will not come apart? The answer is it is very simple. Understand the conditions the connecters will be subject to (hint: mechanics break connectors more often than on-track activity), and you'll immediately improve your approach to selection, assembly and maintenance of connections.

The first step is to think about *how many distinct connectors you really need on the car.* While it is tempting to make every single wire easily dis-connectable, that will result in a lot of clutter and ultimately more potential sources for failure. Better to group wires of similar functions into bundles that will share a multi-pin connector. Connectors may accommodate from 1 to 100 or even more separate wires. In a practical sense, 2 to 12 wires are used per connector. The exceptions are those used at the ECU or data acquisition system, which may use from 20 to 80 connections per bundle. But alas, these are typically determined for you by the brain-box manufacturer.

Next, *select a good quality connector that you can easily service*. There are special insertion/removal and crimping tools required for certain connectors, which may be outside of your budget. If you don't have these tools and need to service in the field, you may be stuck. Though Autosport or Mil-spec circular connectors are great, they are more pricey. Inexpensive connectors can be surprisingly good. We utilize Deutch DT/DTM/DTP type connectors, and they are durable, waterproof, and easy to service, if a little bulky. And at about 1/5 the price of mil-spec units, they are very attractive. Search industrial automation supply houses for attractive pricing.

Select the connector according to its function and placement. If it is a dirty environment, then select a sealed connector. Tight space constraints or highly abusive environment? Then a compact Autosport (type AS or ASL) connector may be needed. If the connector will be placed in a high temp environment (say over 100°C), then choosing a cheapo polyethylene molded connector is asking for trouble. I prefer heavy duty (often referred to as high-temperature) ring-terminals attached to a bus in an enclosed box for any mission critical (especially high-current) applications. Try to avoid blade or barrel terminals wherever possible! Maybe there are some good ones out there, but the majority are JUNK.

Assemble the connectors properly. Newsflash! The pliers in your toolbox are NOT suitable for crimping connectors! Though professionals love their DMC crimp tools, they are expensive and specialized turrets are needed for different terminals. Keep in mind the task: ensure the wire does not come out of the terminal. Ask your connector supplier about which alternative crimp tools may be suitable for your low-volume application.

Crimp or solder? This has been a long-standing debate among system assemblers for years. Some say you must crimp, never solder. Yet look around, there are perhaps an order (or two) of magnitude more solder joints on your car than crimp joints. Look at any of your ECU/Data/PDM circuit boards – all solder joints. Many data system harnesses now use solder-based connectors. So what gives?

Whether you are making an in-line splice or attaching a wire to a connector terminal, it all comes down to how well you can isolate the solder joint from wire movement. Though solder can be an outstanding electrical connection, it is a troublesome mechanical connection. During the soldering process, solder is drawn along the wire strands adjacent to the solder joint. When such strands subsequently are bent in the field, they need to slide among one another (hence the reason for using stranded wire, never solid wire). With solder locking them together, micro-fractures form, which grow into full wire breaks over time. Solder itself has poor shear strength and cannot withstand bending. So, do not let the joints bend. Do not use excessive solder, as this just increases the problem. To prevent premature corrosion, wash off the excess flux on the solder joints, if you use this method.

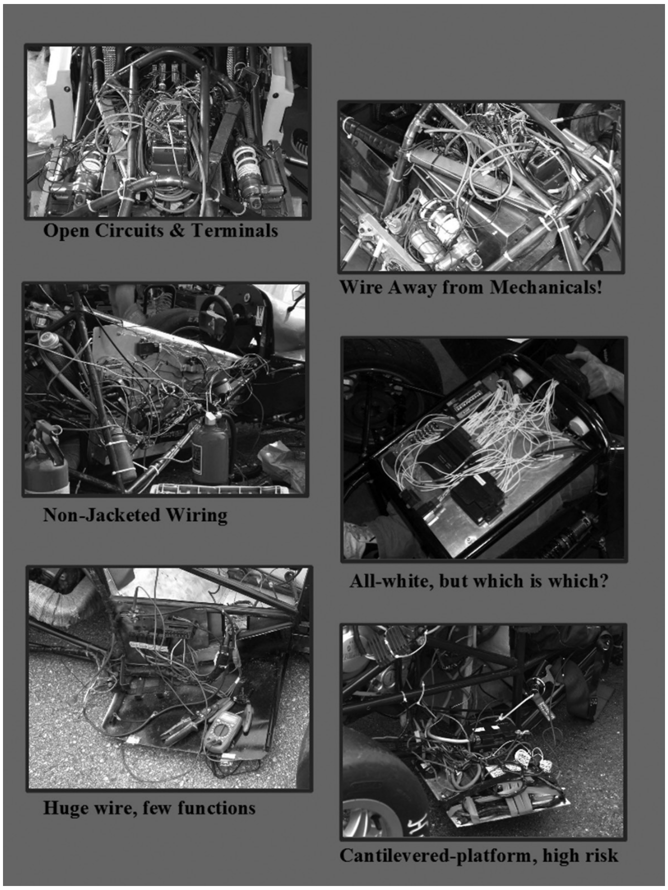
To prevent wire motion within the connector, several tricks can be employed. Strain-relief back-shells can prevent internal wire motion. Also, a high-quality adhesive-lined heat-shrink may also be used to secure the wire to the connector. I have worked with RTV (non-conducting) silicone internal to connectors, particularly for our extreme foul-weather applications. I cannot say this contributes to wire containment, but rather was helpful to avoid oxidation. Unfortunately, it also makes the connector almost unserviceable once that goop cures inside.

OK, now that I have upset a few of my crimp-connection advocates, let me say that a proper crimp connection is still consistently superior to any solder joint you will likely be able to perform. And, they are typically a bit easier to service in the field. So, use your best judgment determined by the application.

Cleanliness is next to godliness… As for servicing issues and connections, consider that the better connections have more precise fitting clearances. So, you'll want to keep them free from grit and debris. It is a reason to keep connections out of debris zones. If contaminated, clean connectors before unplugging. An occasional blast of compressed air will also help keep them clean.

Wire Selection/Installation: Consider the appropriate sizing, marking, protection, and routing of wires. Bigger is not necessarily better!

This area is probably the severest bane at FSAE® competitions. I see barrels of snakes consisting of excessively long unmarked wires, of all different colors and gauges, seemingly haphazardly (no, make that hazard-ly!) incorporated into the vehicle. In these cases, it is clear that wire selection and management was not a priority. When judging and I see this, the first thing I ask for is a copy of the vehicle wiring diagram; what do you think I get?



Composite photos of poor wiring

In some cases, the potential danger is pretty severe. Poorly constructed 12 volt power wires, sometimes even batteries, placed within a few mm of the fuel tank...or how about a fuel pump and/or its wiring nearly dragging against the ground? Power leads adjacent to or passing through CARBON-Fiber tubs…Carbon is conductive!) Are those cars built as educational engineering vehicles, or suicide machines?

Don't play around with cheap wire. Tefzel (Mil Spec 22759 series) stranded wire is readily available for under 20 cents/ft. It comes in a wide variety of sizes and colors, is durable, and is slippery enough to slide through looms easily. Its Teflon-based jacket can handle temperatures (150ºC) that we typically witness (especially from heat guns) just fine. And it is flexible enough to route around corners without internal strand damage. If you discover or have access to better wire, then go for it. NEVER use solid wire on a vehicle. It will break at the wrong time. When you buy wire, budget for at least three times as much wire as you think you'll need. You will be surprised at your wire consumption during prototyping.

Use a little science to determine wire size. Get handy with AWG wire sizes. Larger numbers correspond to smaller wire. For metric sizes, diameters are typically expressed in mm. Excess diameter and length just adds weight, as the wire is copper (it better be!). Insufficient wire sizes are susceptible to failure. From a wire heating point of view, the size wire you should use depends upon the sustained current being transmitted, the length of the wire, the ambient environment (temperature, heat sink or jacket insulation) and the specific resistance (ohms/1000ft). Software tools are available to determine this, such as the *RaceDataPower* workbook in the illustration. But, this establishes the minimum size. The actual wire size may need to be larger, based upon the localized physical environment. Unless it is in a dedicated sensor loom, say for very low power applications (eg sensors), I see no need for wires smaller than 20-22ga to be used in your car. By the same token, if I see huge 0 or 00 gauge starter motor wire in use, I can be pretty certain the team has not performed their current-load calculations.

RaceDataPower
Wire Reference Data
copper wire with no jacketing

Help
Main Contents

Wire Gauge	Dia. in	Dia. mm	Area in²	Area Circ. Mils	Area mm²	Weight lbs/1000ft
0000	0.4600	11.68	0.16619	211,600	107.219	641.00
000	0.4096	10.40	0.13179	167,807	85.029	508.33
00	0.3648	9.27	0.10452	133,076	67.431	403.12
0	0.3249	8.25				
1	0.2893	7.35				
2	0.2576	6.54				
3	0.2294	5.83				
4	0.2043	5.19				
5	0.1819	4.62				
6	0.1620	4.12				
7	0.1443	3.66				
8	0.1285	3.26				
9	0.1144	2.91				
10	0.1019	2.59				
12	0.0808	2.05				
14	0.0641	1.63				
16	0.0508	1.29				
18	0.0403	1.02				
20	0.0320	0.81				
22	0.0253	0.64				
24	0.0201	0.51				
26	0.0159	0.40				
28	0.0126	0.32				
30	0.0100	0.25				

RaceDataPower
Standard Wire Resistance
per 1000ft @ 77°F

Wire Gauge	*Wire Diameter* in	*Wire Diameter* mm	*Solid Silver*	*Solid Copper*	*Solid Aluminum*	*Solid Tungsten*
			Resistance in ohms /1000 ft			
0000	0.4600	11.68	0.046	0.050	0.081	0.162
000	0.4096	10.40	0.058	0.063	0.102	0.204
00	0.3648	9.27	0.074	0.079	0.129	0.257
0	0.3249	8.25	0.093	0.100	0.162	0.325
1	0.2893	7.35	0.117	0.126	0.205	0.409
2	0.2576	6.54	0.147	0.159	0.258	0.516
3	0.2294	5.83	0.186	0.200	0.325	0.651
4	0.2043	5.19	0.235	0.253	0.410	0.821
5	0.1819	4.62	0.296	0.318	0.517	1.035
6	0.1620	4.12	0.373	0.402	0.653	1.305
7	0.1443	3.66	0.470	0.506	0.823	1.646
8	0.1285	3.26	0.593	0.639	1.038	2.075
9	0.1144	2.91	0.748	0.805	1.308	2.617
10	0.1019	2.59	0.943	1.015	1.650	3.300
12	0.0808	2.05	1.499	1.614	2.623	5.247
14	0.0641	1.63	2.384	2.567	4.171	8.342
16	0.0508	1.29	3.790	4.082	6.632	13.265
18	0.0403	1.02	6.027	6.491	10.547	21.095
20	0.0320	0.81	9.582	10.320	16.769	33.539
22	0.0253	0.64	15.237	16.410	26.665	53.329
24	0.0201	0.51	24.226	26.092	42.395	84.791
26	0.0159	0.40	38.520	41.487	67.410	134.820
28	0.0126	0.32	61.257	65.975	107.199	214.399
30	0.0100	0.25	97.398	104.899	170.446	340.891

AWG wire size table

RaceDataPower
Wire Voltage Drop

Power Consumption	**200**	Watts
Line Voltage	**12.3**	Volts
Current Loading	**16.26**	Amps
Standard Resistance	**4.082**	Ohms/1000ft
Wire Length	**4**	ft
Temperature	**135**	°F
Wire Resistance	**0.018093**	Ohms
Voltage Drop Actual	**0.294**	Volts
Voltage Drop percent	2.39 %	

WIRE TOO SMALL OR ELECTRICAL LOAD TOO HIGH!!

Note
Program will calculate the minimum wire size required in order to avoid an excessive voltage drop. Voltage drop is evaluated in order to assess the current capacity of a wire, given its power requirement, gauge, length, material and operating temperature.

Enter the expected peak power consumption in Watts. Enter the lowest expected voltage of the circuit. Program will return current loading in amps. If amps and volts are known but wattage is not, adjust wattage until volts and amps are in agreement. ***Watts = Amps x Volts***

Enter the wire Standard Resistance from the Standard Resistance chart. Enter the wire length and expected operating temperature of the wire.

Program will return actual wire resistance, actual voltage drop and percent voltage drop. For safety and longevity of wires and electrical equipment, voltage drop should be minimized. For best efficiency, drop should be less than 2%.

To reduce the voltage drop, either decrease the wire length, increase the wire size, or increase the line voltage. Note that a doubling of the voltage will reduce the percentage voltage drop by a factor of four! This is why high voltage power transmission doesn't require correspondingly larger power lines.

And it's a good reason to operate a vehicle at the highest possible battery voltage.

Wire sizing workbook page

Mark and color-code wires by function. Design the wiring for serviceability. If you are in the field, attempting to make an electrical repair, how much time will you waste checking and double checking which wire is which? The first step is to color-code each wire. This rapidly helps with identification. If you supplement the coloration with wire markers (I simply use a small-font label maker, wrap each end of the wire with a little label, and protect it with clear heat shrink tubing), you'll find your downstream efforts a lot easier. And, if you are not there, your team-mates will have a better chance at deciphering what you've done!

Looming (jacketing) of wires is a big help, and a bit of work. There are many advantages to grouping wires within a loom going to the same vicinity. They are protected from the elements, and are stronger as a group than a single wire (lest your team-mate has a proclivity to get rough with your wire). Dangling/loose wires are more likely to get snagged in operation or in the pits. Have I mentioned the primary reason for wire failure is abuse during vehicle servicing?

There are vehicles built with a single master harness, containing nearly all the wires. This can be attractive for weight and space saving, but often is not necessary, nor desirable. I find it better to build smaller, system-specific harnesses, so you can remove and service each individually. As your cars are essentially prototypes, you will inevitably need to make changes during the build process, which will require wiring modification/addition. Not a pretty site when you've already built a master loom.

The best protection is offered by utilizing high-quality heat-shrink tubing. Aircraft industry standard (DR-25 from Raychem) is durable, oil and water resistant, and remains flexible, though it can get expensive. For looms, it is usually best to utilize such heat shrink tubing without adhesive lining. This permits easy pull-through or push-through of your wires and will also provide strain-free motion of wires as you bend the loom during installation. Contrast this to the connector ends, where adhesive-lined heat-shrink is preferred.

In many cases, polyolefin tubing works just great, and costs a bit less than DR-25. Polyolefin is readily available from many industrial automation suppliers, and comes in a better variety of sizes, thicknesses, colors, and adhesive/non-adhesive options. Avoid PVC (it shrinks rock-solid, with poor flexibility and temperature sustainability) and PTFE tubing (its shrink temperature is so high, you'll melt your wire's insulation inside!).

There are times where a high shrink-ratio is desirable, say to get over a connector that has already been added to a harness. (DR-25 has just 2:1 ratio, a little limiting at times). Though I have seen some as high as 6:1 shrink-ability, the pricing goes up dramatically when you ask for more than 3:1.

If you are going to build a nicely loomed harness, you'll really have to *think ahead*. This is one of those areas where order of operation makes a difference. You will measure, re-measure, perhaps re-re-measure, and then end up asking how you came up short after assembly! When building your multi-branched *nerves*, it is usually better to start in the middle (where the bundle will be largest), and build outward. Be patient. Otherwise you may find yourself "painted into a corner," unable to assemble the branch. Do I need to mention that you must have all your wire size and length requirements worked out before building the harnesses? And that your connectors will be among the last items to be attached to a loom? Hint: make a drawing (even hand-written) laying out the harness details prior to attempting assembly.

A shortcut method is to use split-loom tubing. While it may look decent, beware that a lot of split-loom tubing is not suitable for the operating conditions we experience. Spiral wrap offers almost no protection from heat and chemical attack. And some tough versions that can handle the chemical and temperature extremes have a terrible tendency to have very sharp edges along the split and at the ends. Unless you have accounted for that, you can end up with damaged wire after just a little campaigning. If forced to use split looming, I really like Roundit 2000, for its pliability, abrasion resistance, and tight-wrapping properties, with near zero risk of wire damage.

Wire placement. This seems so obvious, it seems almost trite mentioning. Yet, the reasoning behind certain placement of wires and harnesses on FSAE® cars can be quite befuddling. If you stick a wire or loom in a high-traffic area, it will get snagged, or moved enough to become cold work-hardened locally, and then break as it loses it flexibility. So, don't fall into this common trap. Wiring typically does not get along well with exhaust pipes, linkages, wheels/tires, brake components, driver controls and limbs, and of course, the physical track!

Wire does not get along with the sharp edges of carbon, steel, or plastic bodywork. The jacketing and wire insulation may easily cut, particularly with repeated rubbing over time. So, avoid such areas. Convenient wire paths are along chassis tubing, on floor/wall intersections, either inside or outside the chassis. Wire should always be within the confines of bodywork and rarely, if ever, attached to bodywork.

For easy engine removal/install, consider a bulkhead connector for all the engine wiring. Then, when you need to pull the engine out, the electrical disconnect is in one place, unlikely to be plugged in incorrectly. This obviously requires some forethought about what engine electrical wiring is needed, or will be needed. Note that it is ok to use a connector with more pins than you really need initially, in case you want to add circuits later…

When routing, also give yourself a little slack. Wires are not cables to be pulled on; they will break fairly easily (even if you don't see this with the naked eye). If you give yourselves insufficient slack, how much will you have available if you need to make a field repair? Also, presumably by now you've discovered that your car has a flexible frame. You need to allow for such motion in your wires as well. Otherwise, you may find that one critical connector "keeps coming loose." Or worse, it shorts and results in irreversible damage…

The perfectly invisible harness. When you are complete, your electrical system/wiring should be unnoticeable. All wires should be hidden from view, and there should be no exposed terminals, if at all possible. Yet, all connections are easily accessible. Consider building an enclosure or panel to permit access, while protecting from the evil elements (aka drivers and mechanics!). It will not hurt your aesthetics score either…

Standardization: Benefits (and hazards) of standardizing/systematizing components. Also, standard communication protocols (CAN, USB, Bluetooth, RS232, etc) must be determined early, particularly if you plan on wireless networking.

Just as in the mechanical areas of design, there are benefits to standardizing throughout your nervous system. First, the high number of connection, wires, sensors, etc makes for a lot of different SKU's. Don't make your spares requirements even more onerous. There are practical considerations as well. Interchangeability of sensors and switches makes field replacement and setup/programming a little easier. If they are wired in a similar fashion each time, mistakes are minimized and vast time is saved when it really counts (ie at competition)

Over-standardization. Paradoxically, there is case against standardizing everything. Identical connectors throughout can present problems. You do not want to let your esteemed team-mates accidentally plug the same looking connector into the wrong loom. Rather, you are better off distinguishing connectors, at least in local regions of the vehicle. For instance, it is desirable for all the speed sensor connections on the car to be similar. But, within each corner of the vehicle, make them different than those for your shock-pots, or strain-gauge, or tire temp sensors. If you must use the same connectors, then color-code them to reduce the likelihood of confusion, or loom them to different locations, so the temptation to plug them incorrectly is reduced. You'd hope that nicely marking the connector would be enough. But that means reading, which some FSAE® students just don't like to do!

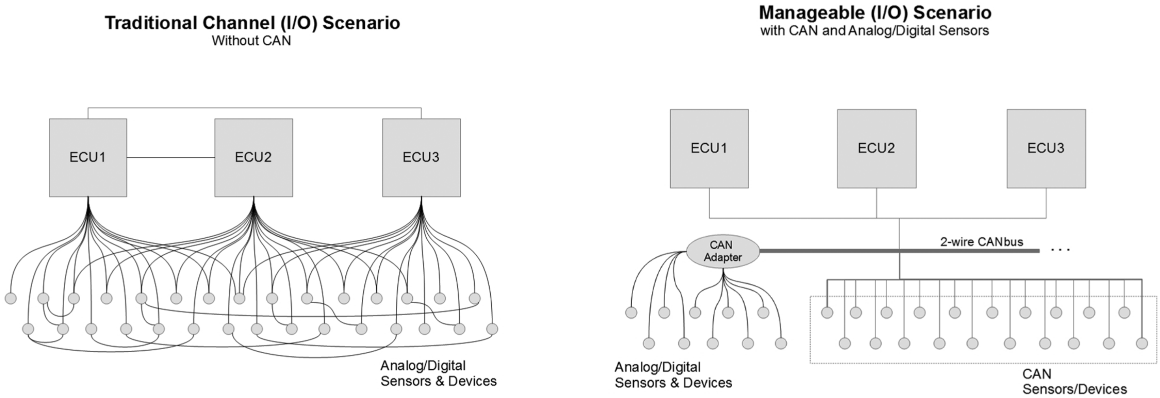
One way of resolving this is to standardize on the same class of connector, but with different specific model/keyway orientations. For instance, the Deutch AS Micro line (5pin) connectors has six different keyway orientations, each color coded for easy identification. The Deutch AS lineup has 25 different pin arrangements (ranging from three to 128 pins), with six alternative keyway orientations. Employing such connectors permits you to still use the same tools and pins, regardless of the specific connector shell.

Standard pin locations: If possible, try to establish a team standard with respect to placement of pins in connectors (eg for sensors, Ground = pin1, Signal = pin2, Power = pin3). So, if the connector gets plugged into the wrong sensor, no damage is done. For power circuits, ensure the power supply side of a connection is the more protected side (say with female pins). This reduces the likelihood that a stray wrench or conductive part can short a live power circuit when the lead is dangling.

Standard wire colors: A standardized wire color scheme (eg Red = 12v, Green = switched 12v, Blue = 5v, Brown = ground for power circuits, Black = ground for sensor circuits, other colors are function-specific) helps on several fronts. First, it makes wire tracing far easier. A circuit wire that starts yellow should stay yellow until it terminates on the other end. We have seen too many "patchwork" circuits that have been pieced together with various colors along the way. A diagnostic disaster.

Second, if the wire function is known by color, assembly and field repair is much easier. One of my data system suppliers uses a standard code for each of their sensor harnesses: White = Signal (pin1), Black = Ground (pin2), Red = 12v (pin3), Blue = 5v (pin4) with the identical connector type on all. Any and every cable we use or make for those systems is used the same way. I cannot estimate how many thousands of hours we've saved as a result of this simple code.

Communication/protocol standards: Non-physical standards should be considered, as well. Communication standards can be used to your benefit to drastically reduce wiring. The most popular today is the Controller Area Network (CAN). Developed by Bosch almost 30 years ago, and an acknowledged automotive standard since 1994, CAN is used in nearly every passenger car (and high-level racing car) today. Nearly every modern engine controller has CAN capability, so it is a natural standard to utilize for your data and control network. Specialty forms of CAN, such as LIN or J1939 are also widespread, but are not typically appropriate for FSAE® cars. The beauty of CAN networks is that data may be shared among multiple devices with a simple two-wire arrangement. Multifunctional new sensors are being introduced with CAN output, that have the potential to make wiring and sensor placement even more tidy. So, you'd be getting your I-count a lot closer to your N-count...



CAN-network *versus* Traditional network illustration

Legacy hard-wire networks such as RS232, RS422, RS485, Ethernet, and USB have been used, but are more susceptible to on-board electrical interference and/or limited bandwidth (how much data can be transmitted per unit time). More recently, wireless network standards have come forward as potentially suitable. Bluetooth, ZigBee, even 802.11g (WiFi) have been tried with limited success in FSAE®. These commercial communication standards are ok for stationary systems, but are problematic as the car gets out of range. So, they are limited to short-range communication on-board the car itself. With further development, these, as well as Pulse Code Modulation (PCM) standards used in defense telemetry systems, may be adoptable for consistent wireless transmission.

On professional level racing cars, VHF/UHF telemetry has been employed for many years, utilizing RS232 and/or RS485, if your control units have that available. Transmission rates are still low (typically 19,200 bps or less). Microwave uplink is great for high-bandwidth needs, but really out of the budget of FSAE® applications. But, any of these are only suitable if you are looking to develop your own control modules (see below). For the vast majority of the teams that will utilize commercial engine, power distribution, and data/control modules, without the need for telemetry, CAN is the de facto standard – and will be for years to come.

I have yet to see an efficient set up which will permit wireless sensing technology across the vehicle. Though we use wireless sensors in a few areas such as tire pressures and strain-gauges on rotating shafts, it carries a bit of excess hardware which makes it impractical for all sensors. The technology (and cost effectiveness) is just not here...yet.

Module selection and management: Considerations of compatibility, grounding, current loads, and interference.
Electronic Control Modules (ECMs) are the distributed "brains" of your car. Their functions are wide-ranging. In a FSAE® car, some such modules include the following:

- *Engine Control Unit* controlling your engine parameters (ignition timing/dwell, injection pulse/timing, and controlling engine accessories such as alternators, waste-gates, and water pumps, etc)
- One or more *Power Distribution Modules*, monitoring and controlling electrical current and voltage supply, including circuit-breaker safety controls, user-defined logic control of electrical functions, and battery charge monitoring
- *Powertrain Control Modules*, including electric transmission shifting, clutch and differential control
- *Anti-Lock Braking* and *Brake Proportioning Control Systems*, managing the pressures at each wheel, for stability and improved deceleration/turn-in control
- *Multiplexers* of data channels, translating multiple distributed channels into a common digital format for reduced wiring

- *Driver Control units*, processing driver requests into formats decipherable to other modules, for tuning/suspension control. This also encompasses drive-by-wire, steer-by-wire and brake-by-wire systems. Though these are not all currently permitted in FSAE®, the industry is rapidly moving in this direction
- *Driver Feedback* controls, offering selected information to the driver, visually or aurally
- *Data Acquisition/Recording systems*, monitoring and recording details for later in-depth analysis
- *Global Positioning System receivers*, providing satellite-based position and coarse trajectory views of the vehicle
- *Active Suspension Systems*, monitoring and controlling damper characteristics, ride heights, even wheel toe and camber
- *Data-Video Recording systems*, recording visual events in synchronization with on-board data
- *A Telemetry Data Processor and Radio(s)* for wireless data communication back to the paddock of many vehicle parameters. In select cases, information and control signals may be transmitted back to the vehicle, as well. Increasingly, sanctioning bodies use such systems to communicate/control.

There are a few traditional modules that should be added to this list, though they may not seem electronic, per se:
- *Alternator/Generator* for maintaining battery charge
- *Starter Motor and Solenoid* for starting the car
- *Electrical Pumps and fans* for fuel, coolant, and/or air supply.
- *Switches* for turning components on directly
- *Indicating LEDs and lights* for status indication and brake lights
- *Transponders* for Timing and Scoring.

If you are employing even just four or five of the above ECM types, you have several considerations to evaluate early in your development process:
- Make or buy decisions
- I/O sharing
- Power management/current loads
- Grounding
- Interference
- Placement.

Make or buy: Some teams have taken the leap to develop custom modules internally; others choose to utilize commercially available units. Though the purist would suggest the former is more educational, I believe it is perfectly reasonable to buy certain modules, provided the team learns the importance of integrating these components with one another. This is effectively how development is done by manufacturers today. Special module design details are handled by the supplier, and integration tasks are the domain of the vehicle manufacturers. Unless you are working towards an electronics degree, think of yourself as an integrator, rather than designer.

I/O sharing: Each module has both inputs and outputs that need to be managed. The output of one module may be used as an input to another. You MUST consider the compatibility of such interfaces. A 0-5v output might be incompatible with another module's input looking for a switched (sent to ground or power) value. In some cases, pull-up or pull-down resistances need to be employed for sensors to "drive" a module. In other cases, one or more relays or diodes between modules is needed to avoid circuit damage. We've encountered cases where the inadequate internal impedance of a module affected the original low-current supply signal. Again, you must think ahead how each interface will be affected by new components. If you utilize the above mentioned CANbus network, your ability to interface among components without damage is improved dramatically but, it does not necessarily make it easier! Instead of reading voltages and currents, you will be troubleshooting hex values and offsets. A different world, to be sure, but no less real. Studying never got to be so much fun!

ECM power management. We'll discuss vehicle power supply in a moment, but you must first understand the ECM power supply requirements and limitations. Most vehicle ECMs are capable of running on 9-15VDC power, unregulated. This is good, as it is essentially battery/alternator power levels. Certain ECM accessories, such as lambda sensors or specialty sensors have current loads which require external power, not direct from the ECM. If you understand the loading capabilities of the ECMs, you can make intelligent choices about how to power (and loom) your accessories. Data systems will typically have regulated 5V supplies (and sometimes 8V or other supply values, as well). Do not assume that these are adequate for powering your sensors! You may damage (or trip an internal circuit breaker) if you exceed pre-defined current levels. Find out from the ECM manufacturer about such limits!

For those "low sophisticated" modules, especially the starter, the current draw may be very significant. It may be so significant, in fact, that your supply voltage to ECMs may be sacrificed during engine cranking, resulting in a no-start condition. It may be even worse when your other accessories (pumps, fans, etc) are on and the battery has been previously depleted. Battery capacity and wire sizing must anticipate this.

Most modern ECMs have reverse polarity protection, so you can provide power and ground backwards without damaging the unit. This is not universally the case, however! Further, if you do accidentally power it wrong, there is no guarantee that other parts of your system will not be damaged. *Don't try this at home*: place 12v to ground and watch wires start on fire! By the way, did you remember that carbon-fiber is a very good ground??

Carbon fiber is a ground!

Grounding: After broken/dis/mis-connected wires, poor grounding is a leading cause of electrical system malfunction – and yet, it is the easiest thing to fix! Everyone knows that a powered device needs a ground, right? And each device should operate on the same ground plane right? Well, such simple knowledge is not demonstrated by quite a few car builders out there.

What is a good ground? A good ground connects the negative side of a circuit back to the battery negative, with minimal electrical resistance (ohms) and adequate capacity (amps). Grounding capacity should equal or exceed the supply capacity, to avoid heat buildup (a ground wire is still part of the powered circuit until it reaches the battery…) and provide for deterioration, contamination and corrosion of terminals.

Good grounds could include:

- Battery negative post (inconvenient for all leads to go there)
- Metal chassis framework (tubing), provided it is then connected to battery negative (most common place to run ground leads)
- Carbon-fiber chassis framework (a real surprise to some!)
- Aluminum or iron engine block (if stress-mounted to the chassis and/or with strap to chassis/batt (-))
- One or more dedicated grounding posts (if cabled to the battery or chassis).

Poor grounds include:

- Fiberglass panels!
- Wood panels!
- Plastic Seats!
- Sheet-metal riveted or loosely fastened to the chassis
- Painted metal parts! (just because it is bolted together, don't assume it is grounding)!
- Cylinder heads! (Often, they are insulated via the non-metallic head gasket and water hoses, and it is too hopeful to think the timing chain is a consistent ground)
- Radiators!
- Any clear-coated parts (unless you have removed such coatings).

Often, engine-based electrical components are grounded to the engine and chassis-based components are grounded to the chassis. This is convenient and works well. To ensure the engine and chassis and chassis are on the same ground plane, an auxiliary grounding strap between the two is desirable. Ensure the chassis is, in turn, grounded to the battery. In essence, if you are in doubt about the validity of your ground, run an auxiliary ground wire. Such redundancy is desirable.

Interference: Interference of electrical signals originates either as electrical or magnetic waves, usually the result of a spark or electrical arc. They may have a significant effect on electronic ignition systems, engine management computers, radios and data collection. They can cause ignition misfiring, multi-firing, incorrect instrument readings and irregular or incomprehensible data traces. Under extreme circumstances the electronic control units may permanently malfunction, as their internal circuitry is affected.

While OEM manufacturers go to great lengths to identify, isolate and suppress interference, this is rarely considered with racing vehicles. Consequently, such vehicles are often plagued by electrical bugs of unknown origin that detract from optimum performance. In fact, resulting performance may be substandard without the team even realizing the existence of a problem.

The methods of elimination or prevention of such interference depends upon the source and the methods by which it is propagated. The most common sources of interference are spark plugs, alternators, and localized arcing (typically due to loose connections).

A variety of methods can be utilized to minimize spark-plug interference. For inductive-based ignitions, resistance plugs or resistance plug connectors (~5Kohm) may be employed with no perceptible reduction in spark performance. For CDI-ignitions, such resistance plugs and/or connectors may indeed reduce spark, as the reserve current in CDI ignitions is lower. Coil-on-plug applications may use a similar strategy as traditional inductive ignition, though the interference propagation is lower in such applications.

If using spark plug wires, avoid distributed resistance or "spiral wound" plug wires. They do little to help reduce interference propagation, and may more easily break internally, creating even more problems. Use multi-stranded copper wire conductors with high dielectric resistance insulation. They are less likely to break internally and total resistance can be controlled more accurately (cylinder-to-cylinder) with plug ends.

Shielded wire can be used to limit the propagation from a noise source. Essentially, it is performing as a Faraday cage, and there are several methods to create this device on your wires.

- *Foil shield* (typically aluminum foil laminated with polyester or polypropylene film) is effective for AC coupling effects.
- *Braided shielding* (copper or aluminum strands weaved clockwise and counterclockwise around the signal wire) is more effective at attenuating diffusion coupling
- *Spiral shielding* (tightly wound in a spiral fashion around the signal wire) is used for shield against both diffusion and capacitive coupling, but only at audio frequencies
- *Multi-layer (combination) type shielding*, however, can be most effective for ignition-source interference. It combines the potential coverage of foil, with the low-resistance of braiding. Regardless of the shielding style you use, it is virtually useless if you do not ground the shielding.

If you are going through the trouble protecting wiring from interference, it is useful to realize that only certain circuits are affected. Specifically, ultra-low current and low voltage circuits are susceptible. Trigger sensors for engines and wheel-speeds, k-type and t-type thermocouples, radios, and GPS antenna are the most common circuits to need protection.

When you implement CANbus technology, you'll find that twisted pairing of CAN+ and CAN- is the norm. In addition, terminating resistors are used at the end of such busses, to minimize RF effects by reducing the impedance between the circuits. Effectively, the objective is to not turn your wires into antennae.

Most ECM enclosures are internally grounded via circuit breakers to the ground wire on the power harness. But not all... So, you should consider grounding the ECM chassis, particularly if you have rubber mounted the ECMs in question.

Placement: Where you place your ECMs is largely a matter of choice and convenience. For formula cars, common areas are behind/under the seat, on one or more side-pods, or forward of the steering column. Perhaps a better way of looking at this is where NOT to mount the electronics. Avoid crash zones (that could get expensive), engine exhaust (heat and electronics can be problematic), cooling and fuel system hoses and components (electrics and water don't mix, and only rarely do electrics and flammables mix). As we discussed with wiring, if you are physically tripping over it, you will eventually break it. So, think ahead.

An enclosure to house the ECM's is a fine idea, but you may need to ventilate or heat-sink the enclosure to keep the temperatures under control – and an enclosure should not be used as a cop-out for sloppy wiring! We've seen that all too often…

Enclosure wiring mess graphic

Power Supply & Distribution: Battery selection considerations, power distribution management, battery isolation concerns.

I am going out and saying it right now: Don't run a car without a charging system. The power losses from a running alternator are minimal compared to the potential loss of ignition and injector performance when the battery voltage drops off. You can get creative about how to run the alternator (off the engine, half-shaft, with/without field current interrupt at full-throttle, etc); that's up to you – but don't fool yourself into thinking your battery will last on its own. When the battery can't start your car after your pit stop in the endurance event, you'll know what I mean.

What battery should you use? Again, that is your choice. There has been much interest in lightweight batteries, particularly appealing for a FSAE® car. Here are some things to consider while determining how to win design, dynamic, and cost events...

The darlings of the battery industry, largely because of the increased use of portable consumer electronics, involve Lithium. Unfortunately, the costs are significant when scaling up power requirements for starting and operating an engine. And you must be careful about charging protocols for these units.

The best power to size/weight units are *LiP (Lithium Polymer)* batteries. Unfortunately, these have very specific charging and over-voltage restrictions. If you ignore these restrictions, you will be in a world of hurt. So, be very careful with these units. And they are very expensive, perhaps 30 times that of a normal lead-acid battery.

Next down on the list is the *Li-Ion (Lithium Ion)*, which comes in several variations. The high-charge density version is also known as Lithium Cobalt Oxide, and is similarly affected by careless charging and elevated temperatures that may cause them to burst or even ignite. A few OEMs have recently adopted this battery type, but have insured that charging management circuitry is built into the battery – and they are still very pricey. At least, I think $2000 for a battery to be pricey!

A safer variation of the Lithium class batteries utilizes *Lithium Iron Phosphate ($LiFePO_4$)*. This has less charge density, but is more receptive to classical charging and discharging operations. Not quite as efficient, but still half the price of the Li-Ion. It has proven popular in professional endurance racing cars.

The more traditional lead acid battery has three main variants; with 1/3 the charge density of the Lithium Iron Phosphate (Read that as three times the weight...)

The *Gel Cell* battery uses traditional lead plates similar to a standard lead-acid battery, but uses a gelified electrolyte (acid with a micro-silica added), which prohibits liquid flow with different orientations. The gel cell batteries have good resistance to vibration and temperature extremes. They are suitable for racing application, if you are willing to pay five times the cost of a standard lead-acid battery, with no real power-weight advantages.

An *Absorbent Glass Mat (AGM)* battery wicks the battery acid up, so the internal electrolytic plates maintain charged, even if the fluid level is low or if the battery is tilted. It is also suitable for racing, at about twice the price of a standard battery. Again, no real energy to weight advantage here.

Which gets us back to our old standard: the *lead-acid battery*. It has been in the marketplace for 150 years because it works! It offers good cranking power density, despite the overall energy per unit weight disadvantage compared to the above batteries. It is also much more forgiving of casual charging practices. Unfortunately, this battery will leak acid if tilted, which may wreak havoc on your design. And it does not handle vibrations very well, which can result in premature failure.

If you plan on using an alternative battery-type, be sure to investigate the specific battery technology and its performance/safety characteristics. Recent energy research means specifications are changing rapidly in this field.

Any serious modern race vehicle utilizes one or more programmable *power distribution modules*. Think of it as an intelligent eye, watching and managing your circuits at all times. There are race-ready professional level units from Motec (Australia) and EFI Technology (Italy), but many others out there, if you look hard enough. Or perhaps choose to make one of your own. A good system monitors current loads and voltages for each major circuit on your car, has individual circuit protection (via user-programmable circuit breakers), and lets you log it all into your data acquisition system. You can couple them with remote switches or use other modules (via CAN) to control them real-time. It is a great way to improve reliability while learning about dynamic current loads in your system – and since your vehicle is essentially a prototype, there will be plenty of surprises!

Lacking a PDM-type technology, *all circuits on your network should be fused*. You never know when or where a short-circuit will occur. Safety is a big concern here, as we do not want to see an electrical fire. Fusing is very simple; all fuses may be placed in a common fuse box, and may even be jazzed up with LED indicators to show a circuit is ON. Beware of single element glass fuses. They and their spring-loaded holders are not well suited to high-vibration environments. Better to use blade-type fuses, mounted securely in a dedicated fuse block or inline receptacle. Alternatively, circuit breakers may be used for this purpose.

In-harness fusible links have been used by some OEMs, essentially as a cheap substitute for a circuit breaker. I've never understood their use on a racing car, where serviceability is essential.

Switches. We see a wide variety of electrical switches on FSAE® cars. Mostly, their selection is a matter of team preference. Yet, some teams seem to figure out ways to under-engineer even this area. Though it is possible to spend a small fortune on some mil-spec units, a little thought can help you select without breaking the team bank account.

Ensure the switches you use can handle the current load. All switches are rated for their amperage carrying capacity. Do not exceed this. Remember, high-current switching will create momentary arcing across the internal terminals of a switch, reducing life. Miniature, low amperage switches may be cheap and effective, but then require relays, adding to the cost and wiring. Perform your total cost analysis here.

Use ring-terminal switches. Avoid solder lug or flag terminal type units, unless you've thought through your strain-relief and modes of disconnect.

Consider multi-function switches. Unless you have a specific need to turn on each circuit individually, you may turn on several circuits with the same switch.

Status indication. It is fine to utilize LED switches which come on with switch power-on, or to have an auxiliary LED mounted above each switch to show on-off status. Beware as this adds some mess behind your instrument panel, so think ahead if it is worthwhile. If the switch turns on your dash, a switch LED is probably not necessary…

Mark your switches! Five switches on a panel or steering wheel with no marking as to their function is an invitation for driver mistakes. Color coding is not enough! (eg if a switch turns on the fuel pump, mark it as FuelP, Fuel, FP, or even F).

Battery isolation is mandatory. If you use a master switch, it is ideal for all circuits to be powered from that single point, from a safety crew point of view. This way, master-OFF means OFF for *all* electrical functions on the car. In fact, the FSAE® rulebook specifies this requirement. Do not get caught out.

As we see on many OEM vehicles, many teams by-pass the master-switch with their starter and alternator cables.

Beware this means there is still power to the starter and alternator lugs, even though the master has been shut off! If you have such an arrangement, then be sure to disconnect the battery whenever servicing the charging or starting system. Or, place an additional master switch in the engine area, to shut off this circuit. If you are running in the US FSAE® competition, this second switch is required.

If you run ALL systems through the master switch, you've isolated all circuits from the battery. Unfortunately, this does not necessarily enable one to shut a running car off with the master. Why? Because a running car does not need a battery! The alternator may continue to provide power to the ECU and coils even with the master shut off…

There are several methods to alleviate this problem, while still isolating the battery. The easiest is to acquire a multipole master switch, with two or three isolated circuits. Then, killing the master key also grounds the alternator field wire (typically using a resistor), and/or disconnects the ignition as you choose. Or, an even more common method today (if permitted by rules) is to use a high-amperage multipole relay, triggered by one or more switches conventional at different locations around the vehicle. The point here is that whatever method you employ, THINK through the possibilities and pitfalls prior to blindly assembling parts.

FMEA/Planning: How well have you planned for component failure? Are you doomed, or just inconvenienced? Will other components in the system be affected? What contingencies are in place? Establish a CIL, and design around that.

The perfectly reliable car has yet to be developed. A component is bound to fail, sometime – and the more components you have, the more likely something will fail. How will your vehicle's performance (or even basic functionality) be affected?

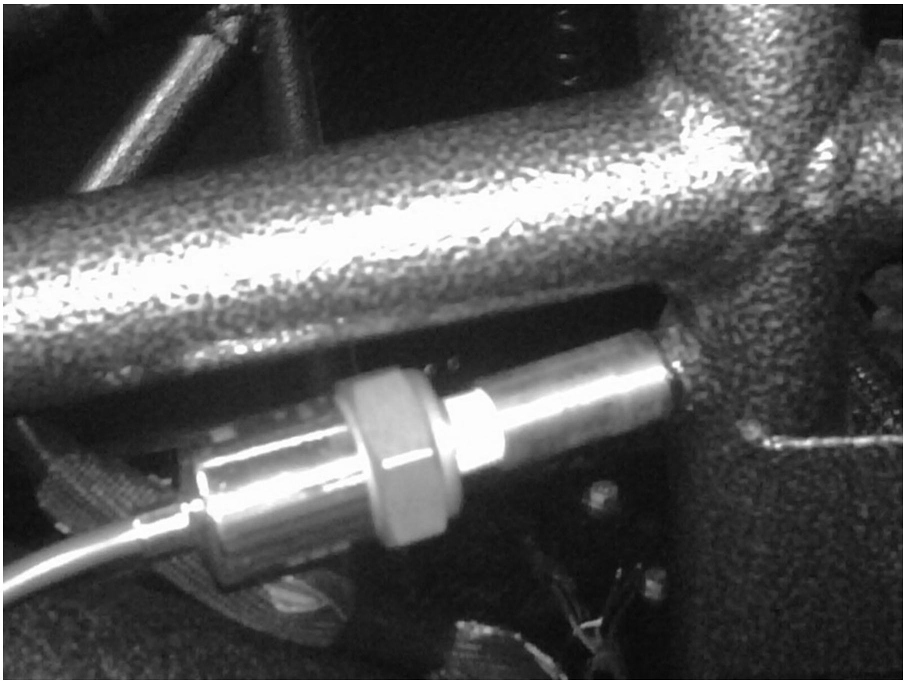
Will the car be debilitated? The driver slightly inconvenienced? Or will the problem not be noticed by anybody, but a few insiders? That is largely up to how you've conducted your failure mode effects analysis (FMEA) and how well you implement a response plan.

In mechanical systems, there are just a few areas where functional redundancy can be implemented. In your electrical "nervous" system, there are many areas where this can be accomplished. Parallel circuits can be built. Surrogate sensors or methods of estimating a sensor's status with readings from other sensors can be performed. The microprocessors you choose to incorporate may actually make problems seem invisible! At a minimum, you should have a read on problems before they become mission debilitating disasters.

Compared to machinery in the aerospace or production automobile industry, a FSAE® car is a fairly simple piece of machinery. Certain critical areas are needed to keep the car operating. Focus on the critical systems that MUST run, and determine how to keep them going. This is known as a *Critical Items List (CIL)*.

Collaboration between the data acquisition, engine control and power distribution systems can go a long way to ensuring that electrically-identifiable issues are resolved early. For instance, if erratic fuel pressure is coupled with increasing (above normal) current to the fuel pump, one may conclude there is a blockage in the fuel line. The system can cycle the fuel pump to save the pump, switch to an alternative pump, or merely alert the driver and shut the engine off. In any case, broken parts can be avoided.

In another example, an FSAE® team mounted an air pressure sensor and Schrader valve into their chassis tubing. Why? They pressurized their frame and monitored to see if the pressure dropped while running the vehicle on-track. If so, they knew they had cracks in the system! Perhaps this is not ultra-high tech, but it is an effective use of previous unrelated fields being merged to a new solution.



Tube-frame pressure sensor

With a robust, integrated electrical system, you can perform an endless number of what-if scenarios, and program your modules to help monitor/resolve issues quickly. Choose your sensors and control modules carefully, in collaboration with members of other subsystems design. Initially, look for simple relationships to be managed. With some confidence-building experience, you'll find your sophistication level increasing pretty quickly, and your reliability improved.

Diagnostics & Testing: Electrical Toolbox for ensuring the health of your vehicle's nervous system, and a few methods for administering/logging on-board/real-time diagnostics.

It is real shame that many cars arrive at the track with a nice harness which becomes hopelessly disheveled after some emergency servicing. Largely the cause for this is incorrect tools and spares available at the track, resulting in makeshift solutions. Of course, some of this at-track chaos could have been prevented by proper test/diagnosis methods prior to arrival at the track.

Electrical Toolbox: As with mechanical systems, special tools are important to develop and maintain electrical systems.

Be prepared. I recommend your team has a dedicated toolbox with all the common tools used for testing and servicing the systems. At minimum, your team should have the following always available in your "Electrical Toolbox":

- Multimeter (Automotive Ohmeter/Voltmeter, with frequency or rpm input is fine)
- Proper Wire Strippers (razor blade works in a pinch)
- Wire Crimper(s) for all terminal types you use
- Connector pin insert/removal tools(s)
- Soldering Iron/Solder
- Test Probes
- Alligator Leads/Clips
- Wire splices
- Heat Gun (not a big fan of cigarette lighters next to fuel tanks!)
- Heat-Shrink Tubing assortment (various sizes, adhesive and non-adhesive types, in black and clear)
- Electrical tape (yes, there are places for that, still!)
- PC interface cables for every ECM.

When developing the system, or when conducting preliminary testing, the following are also very helpful. Though these are inexpensive now, they are likely available in the labs at school already, so might not need to be purchased:

- Compact label maker (for marking wires)
- CAN Analysis module
- Portable 2+ channel oscilloscope (recording scopes are nice, but not necessary)
- Function Generator.

Spares. We all know that spares are a good idea. Yet, few teams can afford the expense or space to carry spares of everything. Luckily for the electrical system engineer, most items are not expensive and do not take up much space. So, there is little excuse for not bringing adequate spares with you at all times the car is campaigned. And, since you've standardized so much, the number of spares you'll need is even less… Minimum spares contents include:

- Terminals (pins, sockets, rings) and relevant connector housings
- Moderate lengths (3-4ft) of each wire type used on car
- Switches, lights/LEDs, and plugs/sockets which are critical to vehicle operation and rules compliance
- Fuses and/or Circuit breakers
- System-critical sensors

It may also be possible for major electrical components to be available as spares, if you have had similar devices on previous year's cars, or if a supplier is willing to bring them along. Again, think about your CIL. Expected major-item spares would include:

- Engine ECM
- Power Distribution ECMs
- Data Acquisition Recorder
- Starter motor
- Alternator
- Pumps
- Electro-mechanical actuators
- Sub-assembly harnesses

Custom Diagnostic Panels/Breakout boards. If you have the time, it is very helpful to create plug-in tools. A diagnostic panel may be as simple as a remote set of switches to turn functions on/off, or even have a graphic display for the diagnostician. A breakout board plugs in-between mating connectors, and is very helpful to check the status of all pins in assembled connectors, while maintaining normal vehicle functionality.

Testing Protocols: Presumably you have tested your circuits methodically during your network assembly and made notes along the way. Keep your records handy as you will want them later. As the sophistication of your system grows, you will need to be even more structured in your diagnostic methods. In fact, it is desirable to establish and implement a testing protocol for your electrical system, as it approaches completion, as well as periodically during the season.

Basically, it is a check that all electrical sub-systems and sensors are working. This can and should be conducted on several dimensions. Think of this as analogous to a "nut and bolt" torque check that we do for mechanical systems:

- *Visual Inspection* of harnesses, components, and sensors (ie is there any visible damage?)
- *Basic check* of fundamental systems (eg does each module power up?)
- *Detailed check* of system input/outputs (eg does each switch/light/sensor work?)

- *Online/PC* check of all sensors and output functions
- *Wiggle test*. Check that the above work, even while wiggling connections or questionable harness areas. A custom diagnostic panel and/or breakout board is helpful for conducting these tests

As we discussed earlier, the I-count goes up geometrically with the number of nodes/devices (N). So, you could have a huge number of interactions. To test every one individually will be a large time sink so look for methods by which you can check several items simultaneously. It is useful to create a lookup/check-off table of your tests, so you do not need to repeat yourself. And, such a diagnostic table could be implemented by other team members in your absence.

Documentation/Diagrams: Where do all those wires go? Which pin on the plug does it go to? What does each module do? The importance of documentation, for all members of the team to understand…

As a design judge, I expect the team to document their vehicle characteristics thoroughly and clearly, in a fashion that anyone can understand. This is particularly essential with the electrical system. Well defined wiring schematics and connection lookup tables should be treated as mandatory by the team. Conducted properly, such reference documents demonstrate some sense of developer organization. It is also helpful from a few other perspectives:

Recall. Information science long ago documented that the human mind has difficulty remembering many more than seven items at once. Though certain memory algorithms can be employed to extend this, it is unreasonable for developers to remember every pin assignment or other component detail. Wiring documentation helps you quickly recall what was done, for your own use.

Easier/Faster servicing: Reference documents are essential for quickly and accurately identifying pin and wire locations, for servicing/testing. Less time needs to be spent tracing a wire or, worse, tugging a wire to check which is which. And, less time spent determining which wire goes back where, after an esteemed team-mate has disconnected several…

Team communication/training: It is useful to reference a document when communicating system details to a team member – and if training another team member on the workings of a system, such documents are lifesavers. A top team from just a few years ago thought they had a competition sewn up, until one of their drivers told us that "they did not know" the function of certain buttons on the steering wheel!

Surrogate servicing: If you, the system developer, is not present, how will the team know the workings of the system? How will they perform service in your absence? Documentation will help your team-mates in times of need.

Technical memory should remain after you graduate: It is amazing how often I have run across teams which use legacy components and harnesses, and they know next-to-nothing about their operation. To state: "A previous team member did that X number of years ago, so we don't really know the details," will win very few points in the design competition. Do your alma mater's team a favor and document electrical system details.

Evolution/Modification baselines: All systems are perpetually in evolution. If you need to add a function, component, or change an existing function, it is very useful to have documentation of the AS-IS condition. Then you can better determine how a change should be made.

Summary

The electrical system has evolved on modern cars to encompass more than just powering a fuel pump, starter motor and brake lights with electro-mechanical components. The number of components and resulting wiring on the car has reached a state where serious considerations have to be made about time management, training and management of complexity. Rather than a liability, this should be considered an opportunity to learn about the very technology and management dynamics in modern technical and automotive organizations. Done properly, development of an integrated electrical system can pay many performance and reliability dividends, and better prepare engineers for their future careers.

To embark on a sophisticated electronics integration project, the team must maintain a level of organizational competency, or they will be lost. Don't bite off more than you know you can swallow.

If you want to learn to win, *focus on the basics first*. Don't feel you must incorporate certain technologies, merely because another team has done so. The primary objectives must be to ensure the system is safe and reliable, and that your accumulated knowledge foundation is strong.