Why Won't the Engine Start?

A Short History of My Time in Formula SAE at UCLA

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Contents

1 Abstract

The purpose of this paper is to discuss and share my experiences from the last four years on Bruin Formula Racing (aka UCLA Formula SAE) as well as discuss the team evolution during this time. In the first part, I share both background of my roles on the team as well background on the team itself. I next move into a more in depth discussion and commentary on my various roles. As a lead for all four of my years on the team, I learned a great deal of valuable lessons and insights–this background serves as the basis of the next part, where I share my insights in both leadership as well as design. This paper aims to use the UCLA Formula SAE team as a case study in the larger realm of Formula SAE as well as engineering design and management in general. While this paper was written especially as a resource for leads, this paper may be used by many others as a general perspective on Formula SAE.

2 Introduction

Fall of my Freshman year, I decided to join Racing, as I had previously done FIRST Robotics in High School and loved the hands-on aspect of engineering. I ended up choosing Formula based on the team growth potential as well as an ability for myself to have a larger role. At the first GM, by chance, I ended up talking with Alex, the controls lead for the team. He had a lot of projects to work on, and I ended up deciding to participate on the pneumatic shifting team. Given my previous experience with pneumatics on robotics, I soon became de facto in charge of that project, as Alex was busy with other controls projects. This began a two year stint as pneumatic shifting lead for MKII. My freshman year, I also had help from Zoe, a member who had previously been on Formula. Together we co-led responsibilities of the team that year. We more or less started from nothing but the idea, and eventually built the entire system.

After two years, in which pneumatic shifting was installed on MKII for competition in June 2016, I transitioned to a new role. The team made the decision to can pneumatic shifting, as the system was overall unreliable and a bit premature for our young team. Instead, I took the mantle as the data acquisition lead for MKIII, aiming to outfit the car with sensors which would allow us to gather valuable design validation. Again, I was building a new team from the ground up– most of my members were new. Over the coming weeks, I worked with the various mechanical leads to integrate the sensors mechanically into their designs while also making considerations for the electronics which would power our data acquisition. In January, my team soon had an alternate goal– we needed to work on the engine EFI (Electronic Fuel Injection, basically the system that makes the engine run), as we had not made much progress with that. By April, I was also in charge of the mechanical side of powertrain as well, as the team was falling behind as well as in need of better organization. By May, I was the heir apparent for technical director, a mantle I officially took over in June. In the oncoming year, I worked with sponsors, plunged headfirst into learning about other subsystems, worked on media and branding, plugged leaks in different subsystems, made final technical decisions, and took on overall team project management. By the end, we had the most successful car ever built in the young UCLA Formula SAE's history–yet one that certainly had room for ample improvement.

In this paper, I want to use my time on Formula SAE to serve as a backdrop for the numerous lessons and philosophies I've gathered. As a member who stepped into a leadership role my Freshman year and continued through all 4 years in varying roles, I actually was a lead longer than anyone else in the history of UCLA's Formula SAE team, which I feel gives me a unique perspective on leadership of all sorts and sizes. These mantras have been honed over the 4 years, and while I offer them as general advice, I know that each person has different style. I've organized my ideas into what I believe are essential to team management and design, but there are surely many other principles that I will not discuss. In short, these directives on leadership and design will serve as a basis as opposed to a definitive guide.

3 History of the Team

3.1 MKI

Figure 1: MKI in Lincoln, Nebraska for 2014 Formula SAE West competition.

MKI was the first ever car built. Kevin Liu was the heart of this team. Featured exclusively 0.095" wall thickness tubing, MKI was a beast. A 2006 carbureted Honda CRF-450X powered a spool final drive. Failed to pass the braking part of technical inspection, in part because of the manual clutch and the inability to drive a stick. 65th overall.

3.2 MKII

Figure 2: MKII in Lincoln, Nebraska for 2016 Formula SAE West competition.

MKII was essentially an entirely redesigned car. Weighing 420 pounds, featuring a custom EFI using AEM EMS-4 ECU featuring the same Honda CRF-450X, but with a hole drilled in its head for an AEM EPM (which put a cam sensor into the engine). Had huge powertrain reliability issues, terrible wiring, but somehow still ran. Suspension done in Matlab. Custom wheel assemblies CNC'd by Q-Mark, first year Q-mark sponsored the team. Double muffler exhaust, pneumatic shifting, Rekluse autoclutch. Quaife differential. 59th at competition, passed tech and competed in endurance for the first time.

3.3 MKIII

Figure 3: MKIII in Lincoln, Nebraska for 2017 Formula SAE West competition.

MKIII was an optimized version of MKII as well as the first one-year car. Weighing 380 pounds, featuring redone EFI with AEM Infinity 3 Series. New Yamaha YZ-450FX engine installed. Featured some Data acquisition implementation, newly designed pedal assembly, custom 3D glass filled nylon intake, Drexler differential, first year using titanium exhaust. Finished 49th at competition. Passed tech Friday midday, trouble with muffler blowing up and passing sound. competed in autocross for the first time, completed 12/16 laps of endurance before car stalled out.

3.4 MKIV

Figure 4: MKIV in Lincoln, Nebraska for 2018 Formula SAE West competition. Taken before endurance event, with drivers Sean Velandia and Ben Gerber.

MKIV featured the introduction of a new aerodynamics team for the first time, as well as an expansion of composite elements. 400 pounds. Small changes were made in each subsystem, with main focuses on weight optimization and better geometries. Focus also given to speeding up testing timeline. Powertrain focus on reliability resulted in significantly more run time of the car. Suspension done in Optimum G Suite, also using tire data. Passed tech Thursday midday, competed in skidpad and acceleration for first time before powertrain/ECU issues sidelined car for rest of competition. Briefly participated in endurance before ECU/EFI issues prevented the car from completing a single lap. Finished 47th overall, with most improvements coming in presentation event.

4 What I did: An In Depth Discussion on my Role through all 4 years

4.1 Pneumatic Shifting

The pneumatic shifting project aimed to install a pneumatic shifting system which would replace a manual push-pull cable shifting system. Instead, a pneumatic piston would actuate a transmission lever.

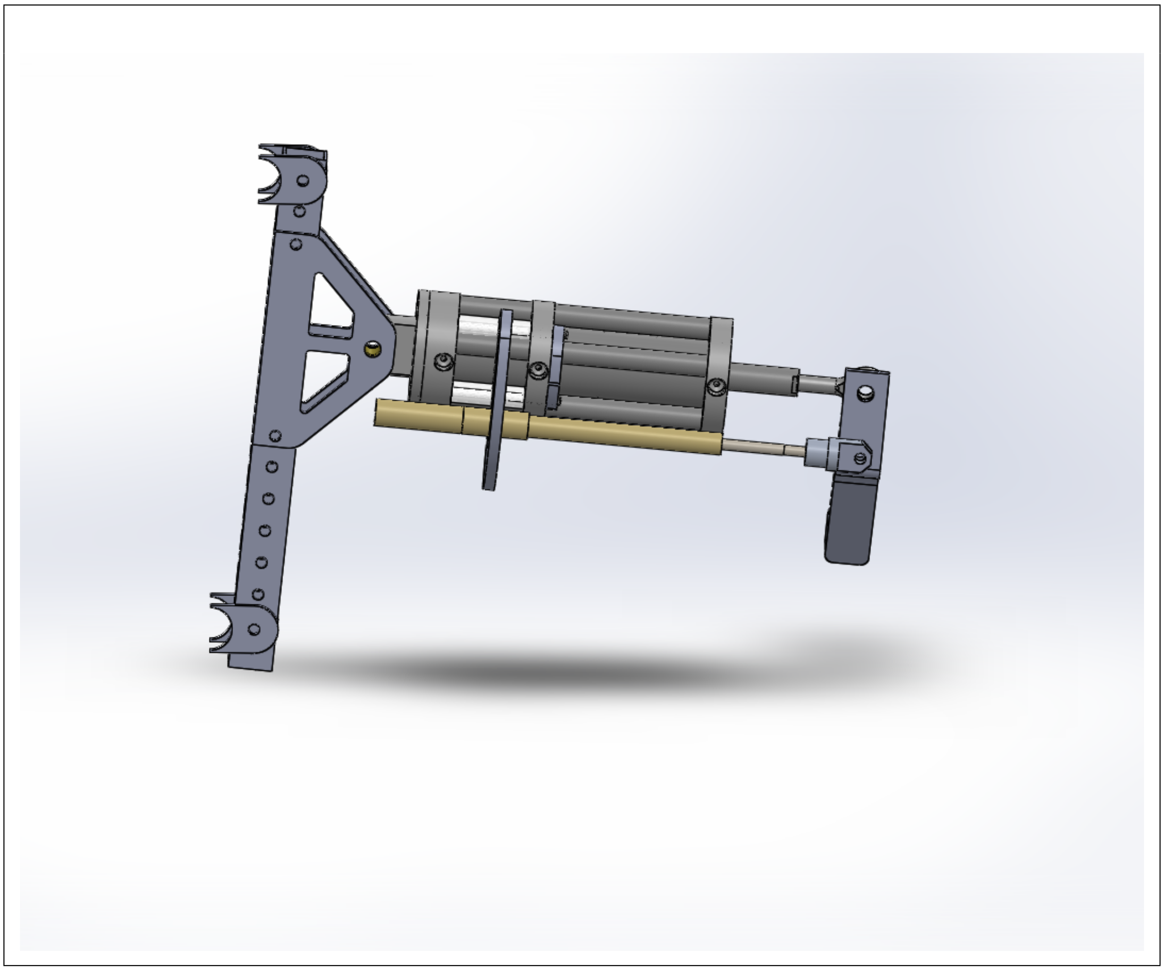

Figure 5: Rear shifting mechanism.

This pneumatic piston was controlled by an electronic solenoid, which in turn was controlled initially via an Arduino controller (although we eventually hardwired the buttons straight to the solenoid). The driver would have access to buttons mounted on the steering wheel.

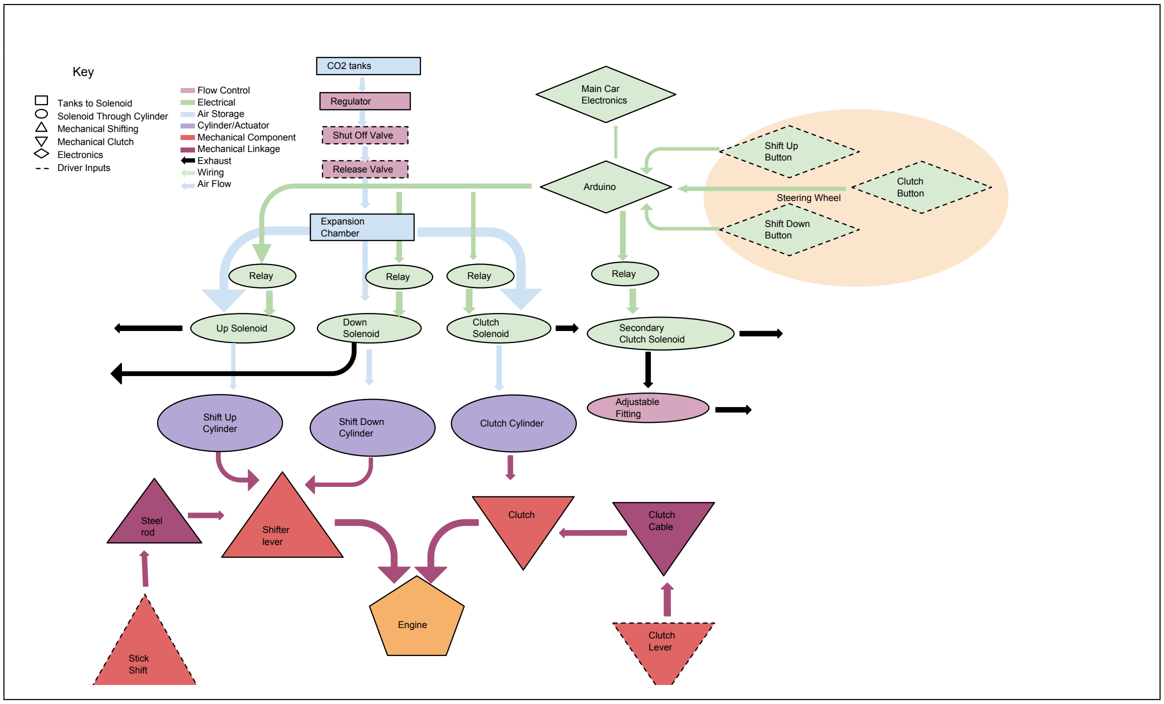

Figure 6: Schematic for Initial Pneumatic Shifting System.

We initially thought about paddles, although we ultimately went with buttons which were panel mounted to the steering wheel for ease of manufacturing and simplifying controls. To ensure that the steering wheel remain quick-disconnect, I used an audio cable jack in the center of the interface. This created some issues as the jack wasn't as durable as I would have liked, and I now know that there are hundreds of better options out there.This project was a two-year design, started my freshman year and continued through my sophomore year. While there was never a point where I officially became a lead, midway through fall quarter I was starting to accumulate real responsibility and delegate tasks to others. This position of authority mainly stemmed from my knowledge of pneumatics from FIRST robotics. Interestingly, I had very little knowledge about how cars worked, and still didn't through much of my first two years on the team. With that little bit of knowledge, and also a curiosity which led me to conduct research on pneumatic shifting systems, I continued being the most knowledgeable on pneumatic shifting, and thus the position of authority. Soon, I started leading my own meetings, with the help of Zoe Nuyens, a member of the team who had stayed on from the building of MKI. Together, we headed the pneumatic shifting team, a team which grew to 8 members (one of the largest on Formula at the time). As we didn't have a good understanding of the project, nor a complete test vehicle to check things out on, we mainly relied on prototyping boards such as the one below, as well as simulations and calculations. I also implemented many of the organizational tools that I ended up using throughout my time on racing, including the organized parts spreadsheet.

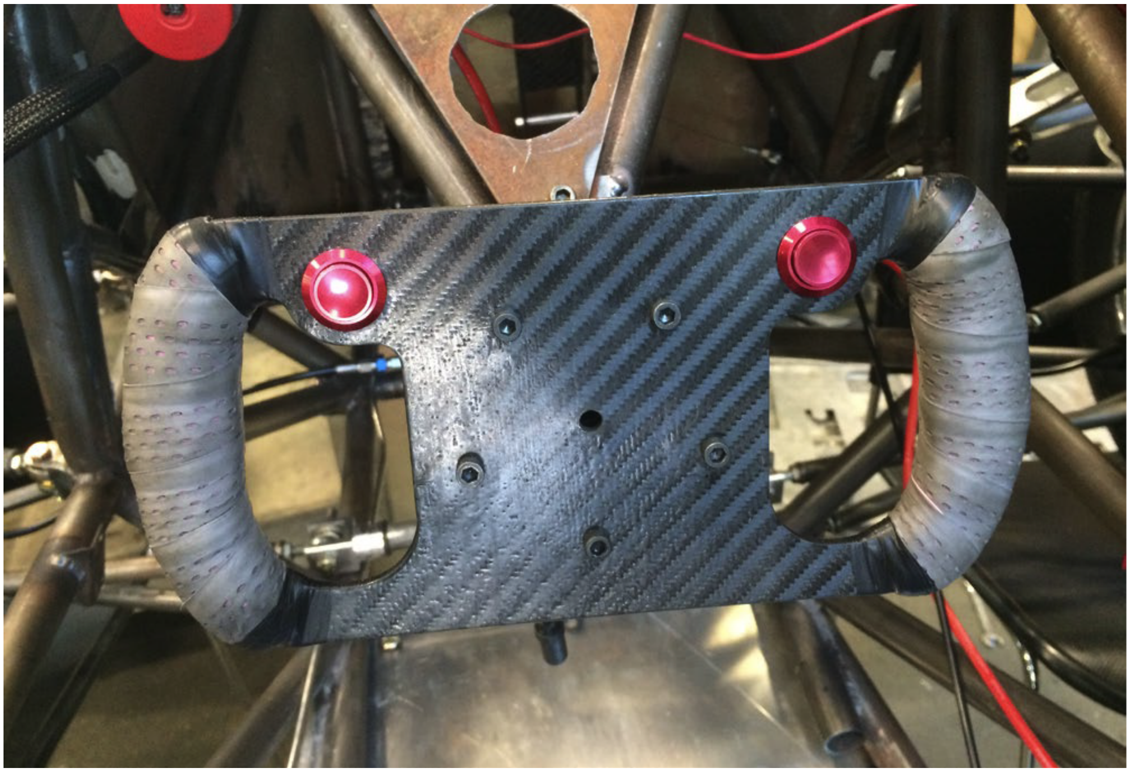

Figure 7: Finished steering wheel with buttons for shifting.

Some thoughts I have on the pneumatic shifting project: definitely was a bit ahead of its time. The primary focus for the team should first be simplicity and reliability, two things that pneumatic shifting did not add. However, it was really cool; shifting without a manual shifter just has a certain excitement factor. In the future, I would recommend shrinking the pneumatic cylinder and solenoids, and especially consider mounting the cylinder off the engine itself. The other thing I would recommend is make sure it is 100% reliable. If at any point the system becomes unreliable, the system needs to be axed. Another recommendation is to make sure that the electronics to the steering wheel are robust. Whether this involves a long coiled wire or a well-specced connector, that thing will be abused. I also believe a weight analysis is necessary to justify manual versus semi-automatic.

On the management side of things, this is where I first learned that commitment and drive is more important than just being smart or having technical skills. As a freshman who had little experience with cars, I did not have the technical skills of many members of my team. This really allowed me to grow rapidly though, and learn my strengths and weaknesses and plan accordingly. Every lead is not expected be the best at everything on their project. Along the way to completing this project, I got significant design help from Hunter Jones especially. While not knowing the nitty gritty of every element of the project, especially considering my lack of knowledge with Solidworks, I was still able to dictate the overall flow by assigning tasks with specific goals in mind, as well having a good enough understanding to be able to make informed decisions. This is where I also learned to manage people, because I couldn't do everything myself I learned more about which people were strong in what areas, who were the most reliable, etc. One thing that is critical is a hunger for learning. Over the first two years, I largely self-taught myself everything about pneumatic shifting. Reading papers, consulting with pneumatics experts, I worked to fill in the gaps in my knowledge.

4.2 Data Acquisition

The data acquisition team aimed to outfit numerous sensors on the vehicle to start collecting data on the performance of our vehicle. This included the proposed implementation of accelerometers, wheel speed sensors, steering angle sensors, strain gauges, shock pots, engine data logging, brake pressure, pyrometer data, GPS, and more. In adding these sensors, the team aimed to learn more about our vehicle performance and handling, with an eye towards future vehicle designs. Starting in the summer, I consulted with leads to get their priority list of valuable data to them. From there, I generated a list of proposed sensors. Working with the mechanical design leads, I spent much of fall working on integration of these sensors into their designs. Much of this was modifying existing designs to work with my sensors.

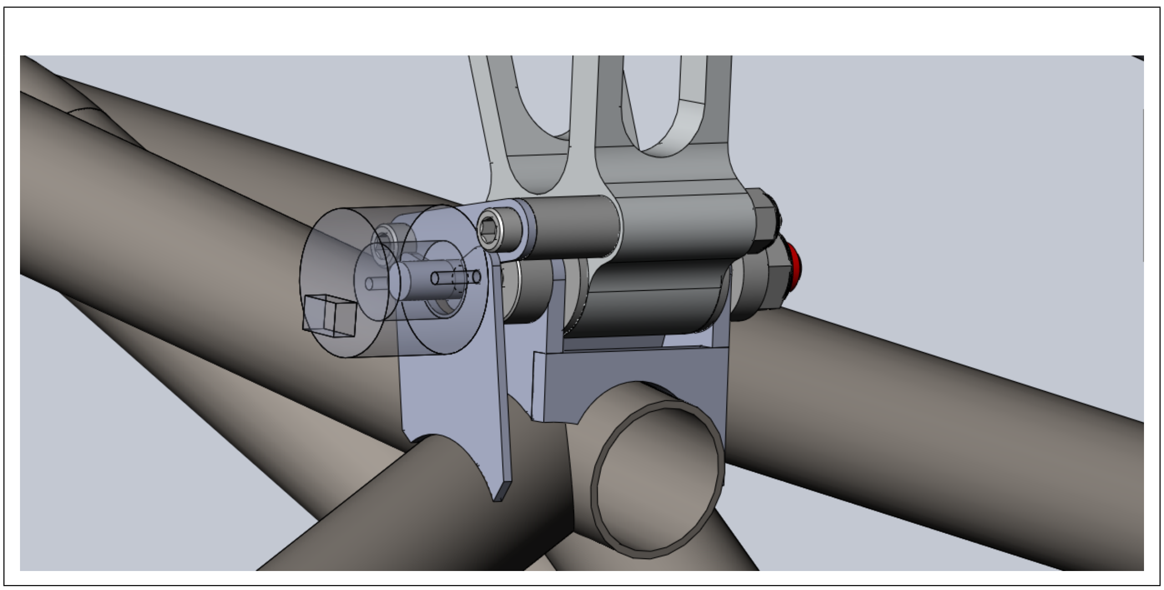

Figure 8: Front shock pot mount

While many of the sensors got mechanically implemented, the electronics side was never completed, as the data acquisition team soon merged with the electronics and powertrain team to work on EFI.

I really liked this project as a cross-disciplinary project which combined electronics, mechanical design, and data processing. In the future, some key focus points would be to implement data acquisition more completely on a previous car– it is a lot harder to fully wire a new car with data acquisition when the primary focus of the car is getting it to run at that point. Data on the new car is very valuable, so if it is possible to implement new sensors and actually get them all to work that is a good priority, but from a logistics perspective, it doesn't make sense for the data acquisition team to be working for 20 weeks on nothing while the car is being finished. This project in the future should be better mechanically integrated into designs as well as prioritized more during manufacturing and assembly. Leads often complain about having no data for their subsystems while also not prioritizing the physical implementation of these sensors. While data acquisition has the potential to be a cross-disciplinary team, my guess is that it will mainly be composed of electrical and computer science majors. Therefore, this gap must be made up on the mechanical subsystem side. Data acquisition is the next huge step of UCLA's Formula team, and should be a primary focus for the immediate future.

4.3 EFI and Powertrain

I joined EFI and Powertrain in various capacities starting in approximately January, continuing on to a full leadership role of Powertrain by late April. EFI and Powertrain were perhaps the longest and most stressful hours I've spent on the team. For many weeks, I spent 12+ hours each Thursday, Friday, Saturday working on the engine and related EFI. Many times we worked from 4pm to 4AM, and by 4AM we were cranky, exhausted, and still at a loss for what to do. Shoutout to Josh Ho for keeping me company through the whee hours of the morning. We had the task of outfitting our new engine, a 2017 YZ-450FX with a 22mm restrictor (in comparison with the 40mm stock intake). We also swapped out every part of the fuel delivery system, as well as added a custom exhaust. All these changes meant that the existing stock setup had to be modified. We initially hoped to use the stock ECU and the corresponding Yamaha PowerCommander tuner. We had tried augmenting the PowerCommander with a sort of piggyback ECU in the form of an Arduino which would modify the existing map sensor and throttle position sensor outputs to artificially increase or decrease throttle, but these changes still didn't help our engine run well enough.

It eventually became clear that we weren't given enough range with the PowerCommander. This makes sense, as the PowerCommander is designed for an amateur racer to adjust his completely stock bike. The PowerCommander could not give enough range for taking the intake and reducing the cross-sectional area by nearly 75%. This decision occurred right after Spring Break, in early April. We then had roughly 10 weeks to redo the EFI from the ground up with the Infinity 3 series ECU we had previously purchased. Thus began an urgent quest, in which we were temporarily behind but also hoping to surpass our existing stock setup. We eventually realized we had to replace our ignition coil, implement a fuel regulator, and other changes to the EFI which we had previously no idea about. We eventually had a lot of tuning help from Church Automotive Testing, who helped us pass a critical roadblock, when our O2 feedback sensor was displaying "lean" fuel conditions even though we were dumping fuel in large amounts. They helped us realize that the O2 sensor had some noise which was causing the error, and the fuel conditions were actually far too rich. We eventually were able to use their dyno, and their tuner Daniel helped us to get a viable fuel/ ignition map.

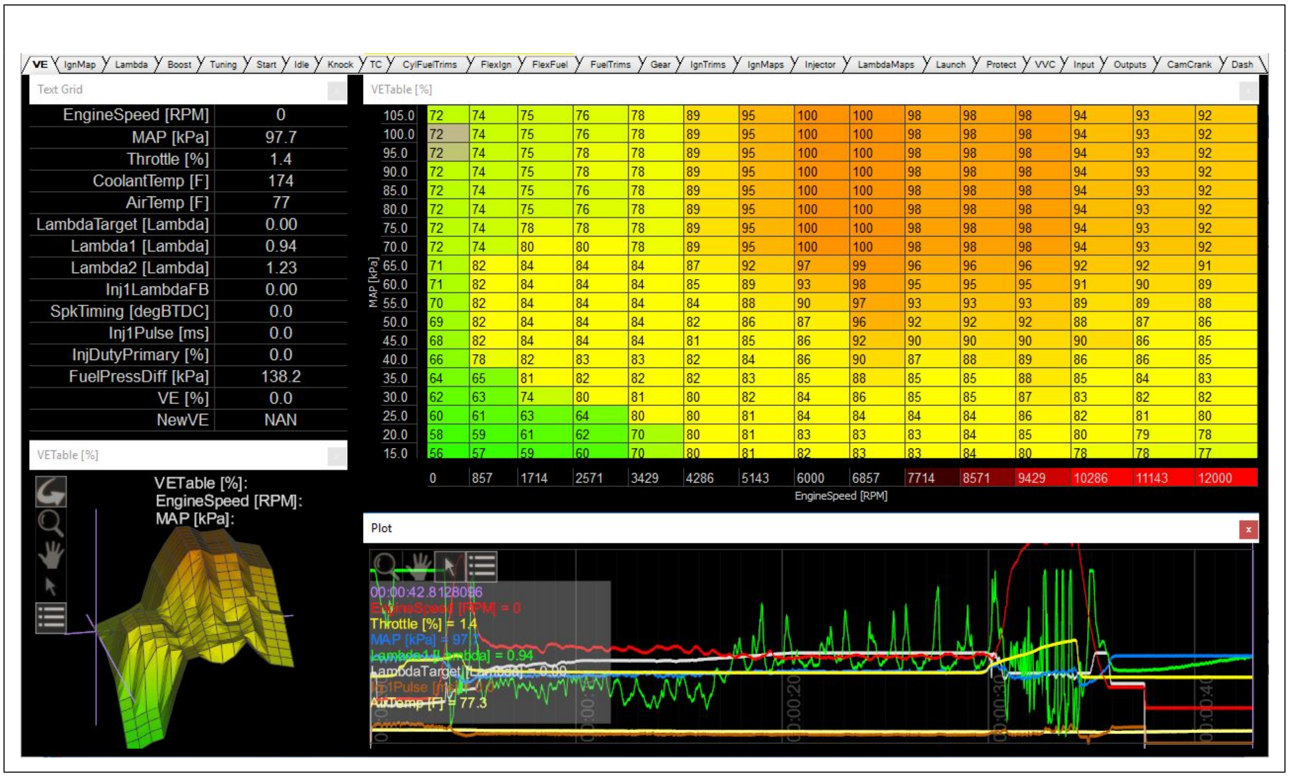

Figure 9: AEM Infinity Tuner software showing VE Table and sample testing log for MKIV.

On the mechanical side of things, I mainly focused on Powertrain subteam organization and parts management. The powertrain team up to that point was fairly large, but also fairly behind. I aimed to implement organization tools (the return of the almighty spreadsheet!) to help make sure that every part was fabricated, welded, and assembled in a timely manner. I ended up conducting several engine rebuilds during my time on Powertrain. The most dramatic one followed the implosion of our intake. Several glass-filled nylon chunks had been sucked into our engine, and so a top-end rebuild was necessary. Following removal of these chips, the engine was reassembled, and yet the car still wouldn't start. We soon realized that the cylinder was still not holding good compression. Having already swapped the head gasket, we got some advice that the piston rings likely weren't sealing from Brendon

Anderson. Through 10th and finals week, we took apart the engine again, removed and cleaned the piston rings. We also noticed that the piston rings had likely gotten stuck and prevented from “springing out” possibly due to the intake debris or from poor engine break-in procedure. Having finally reassembled the engine, it was a joyous and exhilarating moment when the car first started again. This was Wednesday of finals week– it was a miracle that we had finished in time for competition.

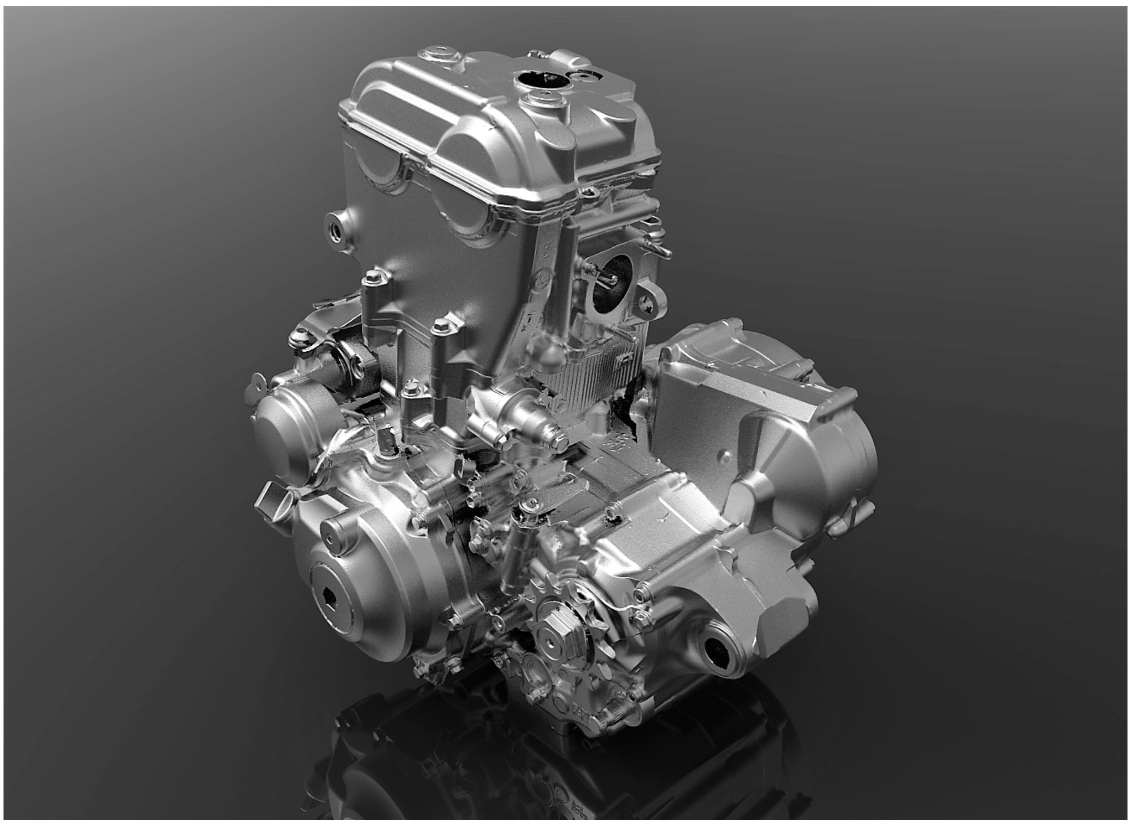

Figure 10: 3D scan of our 2017 YZ-450FX engine

One of the largest issues with the entire EFI and Powertrain debacle is that there were so many things that could (and often did) go wrong, combined with a severe lack of knowledge. There are so many reasons why an engine won’t run– bad spark, bad ignition signal, bad fuel injectors, bad ECU map– all were options and we didn’t really know how to diagnose each one. The other issue was that, while primarily getting the car to run is a software-based issue with the ECU map, real mechanical problems come into play very often, and the personnel for each were not both always present. This resulted in a lot of cross-disciplinary interaction in which the EE team would be forced to mess with the fuel injection system, and the MechE team would occasionally have to pull out InfinityTuner to make adjustments. Along the way, we also learned that fuel pumps are supposed to be used in conjunction with fuel regulators, and that using alligator clips as the basis of your EFI system is not a good idea.

This is really where I learned how to manage effectively. Everything I had learned from working on pneumatics and data acquisition was magnified. I knew nothing, and yet was expected to produce results in a very small amount of time. Tasked with a definitive and yet seeming impossible overall goal, we worked to break down the tasks into easier, more manageable chunks, broken down week by week. Facing a huge time crunch, I also learned how to prioritize, and learned when to take the time to do it right the first time and when to improvise to speed progress along. I also learned much more about people management, as this was by far the worst time crunch I've ever dealt with. This is where I felt a bit like Ender from Ender's Game. I couldn't let the best members I have burn out, but also had to lean on them hard to get the hardest work done. Weekly mandatory meetings helped keep everyone accountable, and documentation helped us remember what we had learned the night before. One of the key things which really helped– after every late night session we debriefed before we left. This helped immensely with making sure we knew what our plan of action was, while also documenting what we had tried so we wouldn't try it again. This is also when I was definitely the most miserable on Formula. What kept me going was again the strong sense of duty to my team– I didn't want to throw away an entire year's worth of work because we couldn't get the engine started. I will say, the immense amount of effort put in really gave me an equivalent amount of pride when the car ran.

4.4 Tech Director

Oh boy. While certainly the most work, directing the team was also the most rewarding. Being in charge of the overall vehicle, and seeing the car unfold was really inspiring. At the beginning of summer, I mainly focused on determining overreaching subteam goals. Mainly, we wanted to be able to back up our designs better, from both a data perspective, as well as a simulation perspective. The second goal was to reduce weight where we could, in anticipation of the addition of a new undertray. I spent the summer learning especially learning how suspension worked, as well as familiarizing myself with all the other subsystems on the vehicle. I also started reaching out to sponsors for possible donations or other assistance. I spent a lot of time just staring at the full vehicle assembly in Solidworks. We had established an aggressive design and manufacturing cycle which was supposed to give us 8 weeks of testing. I would say everything worked out fairly well– we got about 6 weeks of testing time in. The biggest challenges were composites, for the shear amount of manpower needed, as well as the debacle of getting things welded. Not being able to weld is a huge disadvantage for our team. We were lucky enough to have a great welding sponsor, Luis Gonzalez, but he worked on his schedule, not ours– and such we were a bit at the mercy of him. We also had an issue with a sponsor where our parts were not CNC'd for over 5 months, and then we lost communication before we got our parts back. These incidents relate to one of the challenges of leadership. How do you make up for things that are out of your control? While blame certainly couldn't be pointed, someone still has to fix the problem. Collectively, the challenges fall under the "we're doing everything we can but its still not enough" category– and often these challenges can only be met with more perseverance and creative solutions.

Figure 11: MKIV before assembly

As technical director I took on a lot of roles I wouldn't have necessarily expected to. A lot of those were with the team's image– I worked really hard on the aesthetics side and media creation. I created t-shirts, posters, and renders for the car. I also worked a lot with sponsors of all different sorts, from chassis to welding, to tuning. Technical directors have the unique position of being responsible for everything and yet nothing. While every issue was usually "someone else's problem", namely another lead, in the end they were all my problems. This led to me having to delve almost every subsystem, from coordinating chassis tube profiling file preparation to designing mounting for aerodynamics, to still having to fix the problems with the engine– in the end I got a taste of problems from every subsystem.

Figure 12: MKIV render done in Solidworks Visualize

5 How to Lead and Manage a Team

5.1 Overall Management Philosophy

How can you get people to volunteer their time to do something that isn't necessarily always fun? That is the hardest thing for a lead on Formula to figure out. We are all volunteers and students, taking rigorous engineering classes, trying to also have fun outside Formula SAE. There are several keys that I've found.

1. **Commit to it.** If you don't buy in to what you are doing, why would anyone else? People look to your lead, if they see you not caring, they aren't going to either.

2. **Making it as fun as possible.** Yeah Formula is overall about engineering and work, but try to have fun with it. Form friendships, get food together, having a good laugh together. Formula to me is as much about the car as about the friendships. If you're only in it for the engineering you're gonna have a bad time. Food is a great way to motivate people, as well as a welcome break from work.

3. **Responsibility to a team.** Instill a sense of responsibility that starts with yourself. We're building to an ultimate goal of a working car, and its important that every person know what their role is in that. Giving someone a specific project, no matter how big or small, is a great way to making people stick with it.

4. **Communication.** Constant availability, clear communications. Flexibility with text, email, phone, in person– a good lead knows when to use each. In general, the order listed is the order that the severity of an issue should follow. Text is the easiest way to communicate, and the most casual, official things should be documented in an email so they don't get lost. Phone is important for clarifying things when you start going in circles in text, and in person is the best way to communicate especially when making big or complex decisions.

5. **Organization.** When people get lost they give up. If you give someone ambiguous instructions, or there is the possibility of confusion, they will either do it wrong or not do it. This follows the communication bullet, but keeping on top of your organization (especially during manufacturing) is key to making sure that everything runs smoothly. Scheduling is a huge part of what we as leads have to do– its one thing for parts to be manufactured by competition, but everything is contingent on everything else. Knowing your assets and your tasks are key to this. That includes knowing who your top people are for each type of task.

6. **Delegate.** You are but one person, your subteam is hopefully more than that. The best lead simultaneously delegates most things while also verifying everything. The more responsibilities you can pass off, the more involved your members will feel and you can also move more into a verification/top-level role. Obviously, you still have to check up on their work, but the more tasks you can pass off, the more time you will have to check up on the overall subteam as opposed to spending your time making spacers. You can't just blindly delegate tasks either. This leads to a whole lot of "Well this person was going to do it but he hasn't". In order to delegate you have to know your team– know who is going to be fine working by themselves, who you should be checking in with, know which people who you have to give smaller roles in case they fail to complete their tasks. It has to be said: trust no one until they've earned it.

7. **Lead from the front.** Take charge of your subsystem, you are the final authority. That includes not only being able to rationalize your decisions, but also being able and willing to step in and help projects beneath you. While you can delegate roles accordingly, you will still have to make decisions for that task. This partially relates to the fact that while you don't have to be the most knowledgeable about a specific thing, you have to be the most knowledgeable about the overall section you are managing. While self-explanatory, the more you know, the more comfortable you will be in making these final decisions, as well as being able to consider proposals in the grand scope of the project. You are still the one ultimately responsible for everything in your subsystem, you can't blame your members for when your system is behind schedule.

8. **Be Realistic.** Don't assign people to do an impossible task. Ask people what they think is reasonable for them to complete so they buy in and you can point to them saying they could complete the task. Remember that we are still struggling to find funding for our car, and that we still have not completed endurance ever. Establish realistic deadlines and goals.

9. **Document everything.** Write things down. Keep clear records of when decisions were made, for what purpose, what the considerations were. Then when you are second-guessing yourself, or your proposed solution becomes impossible, you have other material to reach back on. Not only that, but you are going to be on the team a maximum of 4 years. In order for team to continually grow, it is critical that we develop documentation to explain previous designs, processes and strategies.

5.2 Design Management

1. **Establish a motive.** There are hundreds of ways to optimize a part. Just a few: optimizing for cost, manufacturability, weight, strength, reliability, ease of assembly. What are you specifically targeting? Why?

2. **Establish a goal.** What do we think is possible given the resources of the team and the design knowledge?

3. **Establish a schedule.** Aerodynamics could benefit from running CFD 1 million iterations. Unfortunately we just don't have that type of time. Establish a schedule for what results we need when. Plan in buffer time for late work and unexpected challenges. Be ready to ax things if they can't meet the deadlines. Be prepared to stick to your deadlines. Sometimes you can give a bit of leeway especially if its more an example of something just taking way longer than anticipated as opposed to poor time management, but you need to be prepared for if its too late. Pushing back deadlines should be the exception not the rule. If you establish your deadlines as guidelines, or "I wasn't planning on you guys finishing by then anyways" you will lose the commitment of your team to deadlines as they will think your deadlines are arbitrary.

5.3 Manufacturing Management

1. **Organization is key.** Manufacturing is often the hardest phase for leads to manage. Most were chosen based on their commitment based on number of hours, or design skill. Almost none were chosen based on their ability to organize, which is mostly what the manufacturing stage is. Clear spreadsheets are needed with each part, quantity, status, assignment and deadline. More spreadsheets are needed listing each task and those deadlines. Your time is better spent smoothing out the organizational details than machining parts yourself.

2. **Recognize your leadtimes.** McMaster-Carr is the greatest distributor when it comes to Formula. They'll get your parts to you in 2-3 days tops. But they will cost you an arm and a leg. With other companies it isn't so easy. Places with online ordering can usually get you an order within a week or two, but custom orders can often take a month. Low-volume parts such as the differential, the wheel rims, etc. can often take months. Recognize your leadtimes and know which parts depend on what. If we can't manufacture the engine mounts before the diff mounts and the diff mounts can't be made until the differential is here, you're looking at a huge number of dependencies on the differential getting there early. Plan accordingly. On the alternate side, make sure

that you have stock before you need to machine your parts. Stock can take up to a week to get in depending on how many layers of bureaucracy you are cutting through. There's nothing worse than going to machine a part and realize that you don't have the stock– and your only options are taking a way-too-large- piece of stock and machining it down to size (wasting both material and time) or waiting a week for the correct piece to get there.

3. **Prepare Your team.** Anyone can machine given enough practice. But there are so many instances of people having no idea what they are doing. The more preparation and practice you can give them before it matters, the more hands you will have when you have to make actual parts. Especially when it comes to tolerancing, how to center-find, stuff like that. These are fundamental skills that will benefit you tremendously when your members make the parts right on the first try.

4. **Prepare your sponsors.** Your sponsors are one of your greatest assets– able to create the parts that you can't make in house. Even while they do this work professionally, it is important to prepare drawings highlighting critical dimensions with tolerances, have a conversation on the function of your part, have a discussion on the manufacturing process, and most importantly agree on a schedule. Note that this schedule should be far in advance of your own– sponsors are often late, or sometimes flaky, and you need time to recover if things go amiss. One thing we did wrong this last year was waiting too long for a sponsor to finish. We should have started working on sending it elsewhere earlier, as that delay ended up costing us several hundred dollars while also putting more stress on our sponsors.

5.4 Assembly and Testing Management

1. **Test early and often.** More testing time is obviously better, as it serves both as validation for designs, reliability testing, as well allows for fine-tuning. If you can get 10 weeks of testing in, that would be ideal. The first 4 weeks should be focused on tuning, and the final 6 focused on testing, not to say we are ever going to be exclusively doing one or the other. But the first weeks should be dedicated to adjusting the car to its optimal state, while the last weeks should be focused on pushing the car to its limits at this state. The final 4 weeks should represent a taper, with the amount of stress on the car overall decreasing, until by the week before competition it is merely shaking down the car.

2. **Don't be afraid to break the car.** Failure in this sense isn't really a bad thing at all. As students, our primary goal is to learn, both about engineering and the car. Breaking

things is the most definitive evidence of a design that needs to be changed or a process that needs to be updated. If you're not pushing your car to its limits during testing, then you are setting yourself up for failure at competition. Obviously as competition comes up, you don't want to break your car before you get to competition– so this goes with the first point of testing early and often. There becomes a time where you want to be tapering wear– its not conducive to break your car before competition. In general, don't push your car past what you can remake- if it takes 4 weeks to CNC a new differential mount, don't abuse the diff mounts less than 4 weeks before competition.

3. **Always Debrief.** After every testing session, always hold a debrief session with your drivers, your leads, anyone present. By the next day, everyone will have forgotten half the things that occurred. What was the tire pressure? How did the car feel after making x adjustment? The next day all the adjustments are going to blur together.

4. **Pass tech.** The most important thing a team can do to improve performance is to maximize their time at comp spent working on making their car fast– not making their car mechanically sound. Tech, re-tech and re-tech your car until you are 90% sure your car will pass first try. Every time you have to re-tech at competition will delay you by at least an hour at minimum, sometimes closer to 3 or 4 hours.

5.5 Competition Management

1. **You're the boss.** In competition, there is no room for indecision and discussions over tea. What you say goes. Sure you can take the opinions of others, but don't be afraid to overrule people. Time is precious, if you have to yell to get people to move, then do it. Speak up– if you're looking for something theres a good chance that someone else will know where it is, like Ben finding the ECU in the driver's gear in Lincoln.

2. **Time is limited.** Two minutes saved at competition is worth the 5 minutes it costs organizing your tools beforehand. At competition, there should be no major modifications made to the car, unless it will drastically increase performance. On the Friday Dynamic Day, even starting at 8AM, it is nearly impossible to get all your runs in if you are also working on your car. In addition to design feedback and practice track time, its likely that you will be waiting before runs for up to 2 hours or more total (counting warm-up time). The car has to be in its ready state before you reach competition, not during competition. Any modifications at competition should be reactionary, not something you knew you would have to do ahead of time.

3. **Don't skimp on the static events** We've done fairly well at these, and they actually

are worth a decent amount of points. Points here are a solid foundation for points elsewhere, and the best part is they are slightly less luck based.

4. **Build something that works.** If you are having to make modifications at competition, focus on function not form. Wasting time making things look good, or perfectly sizing your bolts is something to be done ahead of time. At competition the primary focus needs to be on competing, not on making the car perfect. That time was for a month ago.

5. **Learn from competition.** In what other setting do you get to see 80 different test cases for the same ultimate goal? And you didn't even have to do the R and D yourself.

6 How to Design and Build a Car

Coming into Formula SAE, I had very little idea how cars worked. Even through my first two years, I focused on such a small project that I still had no idea how the rest of the car worked. It was only through the my experience on data acquisition, and work on Powertrain that I started to learn about what makes a car work. Cars are actually pretty simple. Sure they involve a lot of different parts, but each piece is fairly self-explanatory once you have a good basis. The following sections will be broken down into general advice for engineering projects, specific advice for Formula SAE, and specific advise for the UCLA Formula SAE program.

6.1 How to Design and Build Anything

Before going onwards, I recommend taking another look at Section 5.2, where I discuss the management side of things. Establishing those steps are critical so that when design occurs, it occurs within the scope of the project and also stays on track in terms of goals. Always keep these in mind as you are designing. If you start off designing for your suspension to be as light as possible, but then add Anti-roll bars, are you really meeting those goals? Here are some considerations that should be taken for all designs.

1. **Research ahead of time.** You don't have to reinvent the wheel, when thousands of papers have already been written on wheel mechanics. Not only do you get to live vicariously through other's successes and failures, these papers are the cheapest real-world testing you can do. (hint: it's usually free.) How much force do we need to press our bearings with? Well there's certainly a calculation for that that you could look up. Knowing ahead of time, you can avoid the pitfalls of others and also have a clear idea of what you need to accomplish.

2. **Achieve your goals.** Don't let other bells and whistles distract you from your goals. At the beginning of the year, you're going to outline a set list of goals. Now obviously those goals can change over the course of the year, but don't end up with a huge rear-wing when the primary goal was to minimize drag on the vehicle.

3. **Packaging is important.** Subsystems cannot only be focused on themselves– the car is one unified system, and all have to work together. Packaging is often left behind. Work on packaging in the full vehicle assembly. Use an exploded view to plan how you are assembling and disassembling your system.

4. **Manufacturing/cost is important.** These two are lumped together because they often operate under the same resources. Effort and money are often interchangeable.

Sure we could hand miter every tube by hand to save some money, but is that worth it? This is where budgeting is crucial to determining what we have resources for, as well as figuring out where to best spend our limited money. Do we really need a $450 bias bar? Do we really get $200 extra of performance out of it? These are the types of justifications you have to make.

5. **Tolerancing and repeatability saves lives.** Discuss which pieces are going to be made in house; manufacturability is a key towards streamlining production. If you design a welding jig which involves having to take the piece out and flip it (as with this years A-arm jig) you are going to be exponentially making your life more difficult as to complete each part you essentially have to set your part up twice. Same thing applies to manual machining parts. If you can make it so that your entire part can be made without taking the part out of the vise, you save a lot of time needed to align and indicate your parts. Keep in mind especially how easy it is to make your part, and how critical tolerancing is. If you have an insanely tight tolerance part that also has 6 different indications that need to happen, you should anticipate making it 2 or 3 times. Nobody ever plans to make extra parts, but in reality its likely that if you ask for 8 a-arm plugs, you probably will end up needing 10 as 2 will be wrong. Related to that, setup often occupies a majority of machining time. If you can design your parts such that you can make all your pieces at once (or at least the critical dimension) then you can save that setup operation.

6. **Know the hand you're dealt.** Sure, other teams have access to a wind tunnel. That doesn't mean you get to complain the entire time you design about your lack of resources. Another example, other teams can CNC every single part of their car. An effective designer plays to the strengths of their organization, especially in terms of manufacturign capabilities. Sure, you can design every part on the car to have weird 3D cutouts to maximize weight savings, but then you're going to need every part to be CNC'd on a 3 axis CNC. Likewise, make sure the leadtimes follow both your own schedule as well as everyone else's.

7. **Keep it simple, stupid** The simplest car that works is often the best car. The less pieces to manufacture, the less pieces that could potentially fail. Don't complicate designs more than they have to be. The simplest cars are also the lightest cars.

8. **Ask for help.** There are hundreds of other Formula SAE teams. There are dozens of former Formula SAE members at UCLA. There are thousands of industry professionals who build cars for a living. There are over 50 faculty members at UCLA who could probably help you. At least one of all these people have probably encountered a similar

scenario, and most would be happy to help. What you are doing isn't innovative– its all been done before. So don't be afraid to seek advise from those more knowledgeable than you.

9. **Perfection is impossible.** Know when to stop designing. There are always going to be ways to make your design better. Save it for next year though.

6.2 How to Design and Build a Formula SAE car

1. **Weight is king.** The easiest way to get more performance out of your car is by decreasing your weight. Better handling, better acceleration, you name it. Second, be mindful of where the weight is. A car with most of its mass close to the center of mass has better inertial properties than one with the mass distributed towards the edges. That's one reason why the exhaust is routed towards the front of the vehicle.

2. **Triangulate everywhere, except where you don't.** Good engineering practice involves triangulating all tubes, all loads. Analyzing the load cases can help determine which tubes need to be which thicknesses. In some cases it is ok to not triangulate tubes **if** you can show that the tube is sufficiently strong, and the benefit is significant.

3. **Tubes are superior to sheet.** Tubes are the most effective way to transmit a load in pure tension or compression, and most of loads are often close to this. A tube can just be so much thinner than an equivalent sheet metal part.

4. **Understand your load scenarios.** Good design starts from knowing your problem. If you can't explain the forces on the suspension, how can your decision to make each tube a certain thickness? The better you understand your load scenarios, the lower your factor of safety can be. Factor of safety is correlated directly with weight– if you have a part and one has a 1.3 FOS and one has a 1.7 FOS, the 1.3 FOS part (everything else remaining the same) will be lighter. Before you plunge headfirst into design, it's critical to know how you are planning on running your FEA, and especially also if you're able to put strain gauges or other sensors on the car.

5. **Fasteners are heavy.** Size your bolts properly. That includes making sure you have proper length ones, but also making sure you don't oversize your fasteners. Never in the history of UCLA's Formula SAE program have we broken a fastener. If anything, your fasteners should be weaker than your parts– they sure are a lot cheaper to replace. We mostly guess on what bolts are good– we should be choosing bolts based on strength not based on what size hole seems about right. A corollary to this is, standardize your

fasteners to coarse. This will help you down the line when it's competition and you just lost the nut in the undertray.

6. **Assemble once.** Do it right the first time. Every time you have to assemble and disassemble a) theres a chance you will lose or break something b) you will waste at minimum an hour of time c) You will be likely taking down the entire car's ability to drive.

7. **Reliability is the most important trait you can have.** Would you rather have a car that drove great 50% of the time, or a car that drove well 100% of the time? Focus on reliability and durability over all else. In this vein, don't change too many things at once.

8. **Money solves all problems.** Wouldn't it be cool if we just brought a spare car to competition in case something screwed up with the first one? Money can solve all problems. Having spares, having parts machined by professionals, paying for better software, these are all steps towards creating a better car. So while this is a design competition, it is also a fundraising competition. Shoutout to Connie for helping tremendously on this front during my senior year.

6.3 How to Design and Build UCLA's Formula SAE car

1. **Waterjetting is the best.** We're a 2D design team. Anything that can be waterjet saves a boatload of time compared to manual machining. General tolerance is about 0.003", which is good enough for almost everything. Undersize critical holes and drill them out later.

2. **CNCing is a luxury.** Yes, we have pretty good sponsors, but regardless the leadtime is exponentially more than if were to do it in house. If it doesn't need to be CNC'd, avoid it at all costs.

3. **Start manufacturing as early as possible.** We always get stuck with the machine shop being closed, 183A having projects, and more. Start manufacturing as early as possible, thats where the car is made or broken. Delaying manufacturing causes less testing which in turn generally creates a worse car. For example, unless suspension is radically changed, there are a bunch of plugs that have to be made. Those don't have to wait until everything else is ready.

4. **Make the team as cohesive as possible.** The more multidisciplinary the team is, the more hands you will have when something needs more help. It's highly unlikely

that all teams will magically be on the same timeline. The more flexibility you have in terms of allocation of resources (especially people), the easier it will be to help catch up the subteam that is behind.

5. **Reliability.** I already wrote this in the previous section, but we have a particular issue with it. The first step to building a high performance car that works is building a car that works. The high performance can come later, probably 2 or 3 more years down the line.

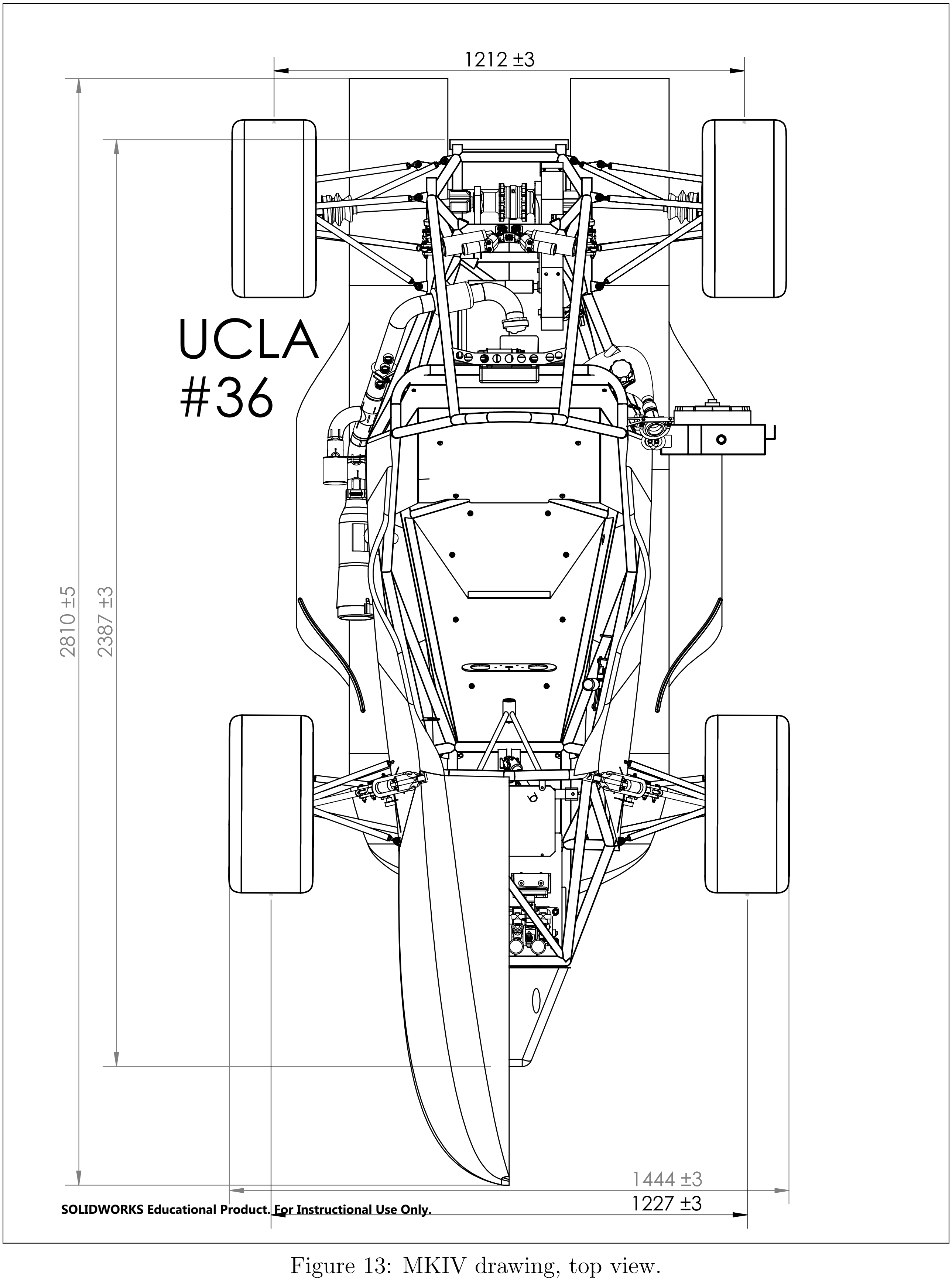

Figure 13: MKIV drawing, top view.

7 How to Grow as a Person While Staying Sane

A lot of people ask me how I managed to commit so much of my life while not breaking down or burning out. In truth, I think that a lot of this depends on the person, and each person has their own methods. For me, I think what kept me going was a strong sense of responsibility and pride. One of the first things to realize is the need for tradeoffs. Nobody can fulfill everything, so prioritizing (both between Formula specific goals and in terms of overall personal goals) is critical. Balancing time spent in and out of the shop is the first step to make sure that a) you fulfill your Formula duties while b) making sure that you don't fail all of your classes as a result. Firstly, knowing how spending "an hour" at the Formula shop can spill into a 5 hour marathon, I tried to pick certain days to come in as opposed to certain times. This allowed me to have some guaranteed personal time, to relax and do that thing called school. The other thing I did was start to make Formula a social experience. My first two years, I got in, did my work, and got out. It was only when I started hanging out in the shop did I start to feel more excited about coming to the shop. Even just studying in the shop, its a lot easier to feel connected to the team, while also being able to help out with small tasks throughout the day. Eventually, you realize that its not as productive in the shop, but still just being able to hang out, work on homework (with the added bonus that there are usually people working on the same homeworks as you), and see whats going on with the car was a really nice thing to be able to do.

The tremendous friendships and brotherhood also were critical in keeping me going. This is the part where I also thank everyone else who has served with me. Those who came before me, I looked up to as the legends, a constant source of design knowledge and also general management advice–I took comfort in knowing they had been in the same shoes as me. Those younger than me, I sought to inspire and drive towards excellence, in addition to creating a lasting warm and friendly culture. Their energy and fresh insights were a welcome break from the monotony and cynicism that emerges as time on the team passes. Those who filled in roles beside me (namely, those in the same graduating class as well as fellow leads)–they are the ones who suffered alongside me and my sense of responsibility and duty to them also kept me sharp.

I think part of staying sane in this club is knowing that what you get out is what you put in. Sure you gave up your entire weekend to try to fix the engine, but in the end when that engine hums back to life, you feel enormous pride and joy. In a sense, the lows amplify the highs. If an entire Formula car was handed to you on a silver plate, sure it'd be pretty cool but it's much more meaningful to know that you personally built it, it was your blood, sweat and tears. This point is about keeping things in perspective. Both with an eye towards school and realizing that one bad grade won't kill you, as well as knowing that what you're doing is really actually super cool. The late night taco runs, watching the car drive at midnight– theres so many unique experiences that you will never experience elsewhere.

8 Next Steps For the Club: A personal opinion on Bruin Formula Racing's next moves

Some advice I have for the team, in no particular order. Firstly the technical goals:

1. **Hang the diff.** Super cool weight savings yeah! And should be pretty manageable to do, the hardest part should be with suspension.
2. **Reduce weight in suspension mounting.** Eliminate the front tubes, decrease the size of the bell cranks and mounting tabs. Related to this is make the bellcranks a lot smaller.
3. **Redo the a-arms.** Can probably make them smaller.
4. **Flat bottom chassis.** This is nice cause it simplifies aero, lowers the CG of the vehicle. Mostly a suspension thing (possibly wheels as well) and based on how you do your design cycle. Involves bringing the front and rear of the car closer to the height of the tube under the main roll hoop.
5. **Consider routing the undertray around the chassis.** Then you don't have to raise the chassis bottom.
6. **Make the chassis skinnier.** Jon and I looked at this, and it seems like our chassis is a lot wider than it has to be.
7. **Learn how to ECU.** Yeah. We still don't really know much about engine tuning.
8. **Redo the wheel assembly.** We can totally shave a lot of weight off our wheel assemblies, and we also need to address the bearing issues we learned at comp.
9. **Improve steering assembly.** Reduce slop by moving away from double u-joint. Decrease the size of the steering pinion and rack.
10. **Actually do DAQ.** You probably will have to allocate some resources for this from other subteams, instead of complaining about how it wasn't done.
11. **Reduce your fastener sizes.** I bet we could knock off 5 pounds by choosing fasteners more carefully.
12. **Custom Impact Attenuator.** Not only can you make the car look cooler, you can save significant weight by decreasing the size of the front bulkhead, which reduces the size of the IA plate as well as needing less tubing in the front.

13. **Make a robust chain tensioner.** This is one of the most delicate pieces on the car. Make your FEA robust.

And now for the non-technical goals:

1. **Improve training and new member retention.** Get your new members up to speed with more hands-on projects. Teach more advanced courses for your vets to learn CNCing, waterjetting, etc.
2. **Train your drivers.** Get your drivers way more seat time, and pick them at least a month or two in advance.
3. **Get way more sponsors.** We're at a good point but theres so much more we can do. Especially stock, welding, CNCing (including foam), and the big one, money. They are out there, you just have to find them.
4. **Keep your sponsors happy.** We're at a good point but theres so much more we can do. Newsletters, more swag, signed posters, theres so much stuff that can be done to make your sponsors excited about helping you out.
5. **Finish earlier.** We could have used way more testing time. Don't be too ambitious, the main goal still needs to be reliability, which mainly happens with testing.

9 Conclusion

In the end was it worth it? That's a question I always wonder. I know I gave up 4 years of friendships I could have grown, every single Saturday for a good part of two years, and perhaps a bit of my GPA as well. But looking back, I am always amazed that I built this car (with help of course!), and am thankful for the friendships I forged. They say the best friendships are forged with mutual suffering, and we certainly had the mutual suffering part down. Not many people can say they built race cars in their free time, and I'm really proud to point to this car and know that I created something awe-inspiring. A real car that not only drives but drives fast, and keeps my head pushed against the headrest when I push the throttle. While certainly there were many lows, perhaps more than any should come from a voluntary club where nobody is even paid, these really served to amplify the highs, the moments of pure joy at seeing your hard work pay off. Hearing the engine roar to life, an immense sense of pride comes from within, knowing that I helped build this magnificent beast. Seeing the car zip around the track, and sharing a great big cheer with my team, my friends–that's when I know that my time was well spent.

Figure 14: 2017-2018 Formula SAE team with MKIV at Lincoln, Nebraska competition

10 Acknowledgements

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