I, Ashley Alexander II, hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

It is entitled:
Analysis of Using Electronic Fuel Injection In Restricted FSAE Competition Engines

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Analysis of Using Electronic Fuel Injection In Restricted FSAE Competition Engines

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Abstract

The Formula SAE competition is a collegiate competition in which students are tasked to design, build, and race an open wheeled race car. This task is not a simple one as there is no true correct answer for any decision which is made. Engine selection and tuning is just one small aspect of the car which must be examined for a great deal of time and with thoughtful consideration if the engine is to perform at a competitive level and be reliable.

The Formula SAE engine is very simple in many terms, but very difficult in one main aspect: restriction. Depending on the fuel type used, an air inlet restrictor of either 19 or 20 millimeters must be in place through which all air for the engine passes. If it were not for this item, the engines utilized by the students could be off the shelf engines from a number of on- and off-road vehicles and would therefore likely be much more powerful than those currently utilized for competition. As it stands today, the engines used must be modified in order to incorporate and optimize the engine performance around this restriction in a number of ways including fuel delivery.

The majority of engines which fit the 610 cubic centimeter displacement requirement in the past were from 4-cylinder motorcycles which were manufactured as 600 cc class on-road sport motorcycles. Today, there are a number of classes of off-road racing previously dominated by 2-stroke 250 cc engines which now allow for 450 cc 4-stroke engines. In order to be competitive from a cost standpoint, these engines have historically been carbureted. More recently though, the price of electronics has fallen to the point where electronic fuel injection can be offered in a cost effective manner and seen by the consumer as a “premium” feature. The consumers have not needed a great deal of research to see that fuel injected engines have more torque, have better response, better tolerance for atmospheric changes, and are more efficient. While these things tend to be taken as fact by the casual rider, this thesis looks to examine the advantages and disadvantages of electronic fuel injection as it applies to a single cylinder Yamaha 450 cc off-road sport quad engine which is intended to be used as the engine for the 2012 University of Cincinnati Formula SAE competition car. For this examination, cost, torque characteristics, manufacturability, and efficiency will all be discussed from a theoretical standpoint, and these points will be discussed as they relate back to the goals of the Formula SAE student competition.
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Chapter 1. Motivation and Introduction

The motivation for this thesis is to provide future teams participating in the Formula student competition of the Society of Automotive Engineers (Formula SAE or FSAE) at the University of Cincinnati with insight into one of the major decisions that have been made for them. Each year, students cycle through the University of Cincinnati Automotive Design courses which are the courses which deal with the design, fabrication, and testing of the Formula SAE student car. The majority of these students are well aware of the car which is built each year, but due to the cooperative education program at UC, many of them do not have any significant investment or understanding of the program until their senior year. In fact, this year, there are no mechanical engineering undergraduates except for seniors which help on a weekly basis. This provides a very unique team dynamic in which the team is formed based on what people perceive as their level of commitment and wanted responsibility rather than knowledge level or seniority. One major problem is that the students are now expected to put forth time doing work towards a project that they only slightly understand and with some guidance intentionally withheld in order to promote independent learning and problem solving. This is then compounded by the infinite answers that now exist to their design problems, which contrasts most undergraduate work which results in a single answer to every problem. This leads to some very steep learning curves as they design, build, and test the parts which they feel meet the engineering requirements of the car. Advisors, graduate assistants, and alumni often struggle with the method that should be used to bridge the gap in understanding quickly so that the design ideas can be created with proper consideration for the relevant design criteria. One method which has been used is summed up in the first sentence: provide insight into major decisions which have already been made for them. Specifically, the decision has already been made to
utilize a 450 cubic centimeter Yamaha engine which has been converted to electronic fuel injection for the 2012 University of Cincinnati Formula SAE student car. This method has been discussed ad nauseum as to whether or not it is the best direction, but there is just not enough time to carefully review and optimize each major design on the car in the team’s 9 month design, fabricate, and test cycle. This leads to a situation where it is only reasonable to select 4 to 5 major design changes to occur in any given season. So, with this in mind, the information regarding the decision to run fuel injection as opposed to carburetion has been collected in this document with the intent to inform future teams of the monumental consideration which can be taken in order to make a key design decision.
Chapter 2. Fuel Systems: Theory and Background

2.1. Carburetion

The most basic consideration for modern fuel delivery systems for FSAE student engines is the carburetor. The reason for this is that it requires little to no electronics in order to function. The carburetor functions most basically by connecting a fuel supply tube to an intake tube with a variable air supply (Walker, p. 30). Also in accordance with FSAE rules (2011 FSAE Rules, p. 47), each intake, no matter what type of fuel delivery is used, must have a mechanically actuated air throttle. This air throttle is then placed upstream of a venturi type restriction which accelerates air to a higher velocity and therefore lower pressure which is used to draw fuel out of the supply tube and is then mixed by the movement of the air. A simplified drawing of this process is shown in Figure 2.1 below. This is an extremely simple concept, and thus why it has been nearly perfected by many companies over nearly a century of development.

![Figure 2.1: Cross sectioned view of the venturi in relation to a carburetor jet. Air flows in from the right where it is necked into a smaller diameter tube to accelerate air speed and decrease pressure to suck fuel into the air and mix it.](image)

A more in depth look at carburetion shows that there are several arrangements for single or multiple variable air restrictions, multiple fuel supply jets, and multiple venturi arrangements.
Each one has specific pros and cons which will not be discussed here in this thesis but should be noted by anyone who seriously considers this as a form of fuel delivery system for their engine.

The only realistic carbureted arrangement for the FSAE competition engine is the use of a carburetor which has already been fitted to a factory motorcycle or scooter. The most common variable air restrictor in these carburetors is known as a butterfly. The butterfly is a disc connected to a shaft which rotates inside the air path so that it blocks nearly all air when closed and becomes a restriction only as wide as the shaft when open. Therefore, the butterfly meters all airflow through a travel of generally less than ninety degrees. See Figure 2.2 for a diagram of the closed and open positions of an intake butterfly.

![Butterfly Fully Closed](image1.png) ![Butterfly Fully Open](image2.png)

**Figure 2.2: Cross sectional view of butterfly valve in operation from fully closed to open.**

In addition to air metering, fuel must be metered somewhat appropriately at all of the throttle positions. It must be understood that engines do not have an infinite air supply and therefore do not run better and better with additions of more and more fuel. Therefore, fuel and air delivery must be tailored to be a nearly stoichiometric mixture at all times in order for there not to be excess heat or fuel in the cylinder which can cause problems which will be discussed later in this thesis. Appropriate fuel delivery is usually accomplished through the use of multiple
jets, which are actually fuel restrictors, located at various locations in the air path around the butterfly. In theory, all the fuel could be supplied by what is usually referred to as the main or primary jet. However, the reality is that air speed cannot be controlled close enough to provide adequate mixing at multiple throttle positions and also provide enough fuel at full throttle with just a single jet. According to Walker, the air speed at the jet caused by the orifice or venturi in this area is called 'signal'. Higher air speed at the jet causes fuel to be picked up more efficiently and therefore there is good 'signal.' Lower air speeds near the jet causes fuel to be picked up less efficiently if at all and this is called bad 'signal.' Therefore, multiple jets end up being used. Figure 2.3 shows an example of a Weber DCOE carburetor at low throttle and Figure 2.4 shows the same carburetor at higher throttle positions.

Figure 2.3: Weber DCOE carburetor at idle and slightly off idle conditions. (Walker, p. 35)
The carburetor shown has 3 different locations for fuel to enter which helps to provide the proper signal level at nearly all throttle openings to provide close to stoichiometric mixtures at all throttle values. By increasing and decreasing jet or drilling sizes one can fine tune the amount of fuel which is put in for any given amount of air flow with a trade off in the mixture quality. Larger jets usually have a tendency to create larger droplets which take longer to evaporate or atomize and mix with the air entering the engine. Not all fuel needs to be atomized in order to be used by the engine, but poor mixture quality has implications which are discussed more fully later in this thesis. There is a very fine art to jetting a carburetor and requires carefully observing the air fuel ratio at each throttle position and engine speed in order to correctly dial in all of the jets which exist in any specific carburetor.
2.2. **Electronic Fuel Injection**

The most widely used fuel supply system in production engines as well as FSAE engines today is a low pressure indirect (or port) electronic fuel injection system. This seems like a lot of fancy terminology but it is mainly for clarification purposes as there are so many different types of fuel injection systems. The common denominator which is present in all electronic fuel injection systems is the injector. The electronic fuel injector is a simple solenoid valve that, when activated, allows the fuel from a pressurized fuel line to be pushed through the nozzle and into the air of the engine utilizing the pressure differential as the driver. Stating that a system is low pressure can mean a lot of different things depending on the sanctioning body of a race, but according to the 2011 FSAE Rules, "Low pressure fuel injection systems are those functioning at a pressure below 10 Bar (145 psi)." (p. 48) Indirect injection simply refers to the fuel being placed into the air at any point before the combustion chamber. Most gasoline indirect injection systems inject the fuel into the intake ports which lead to the cylinder head and are therefore known as port fuel injection. This is in contrast to direct injection in which fuel is squirted directly into the combustion chamber.

The design considerations for indirect electronic fuel injection are much the same as those for carburetion. There still needs to be some form of air throttle in the system to control airflow to the cylinder(s) and most of these are still butterfly valve type throttles. Again, multiple air throttles can be used as well as multiple venturis and multiple fuel injectors with varying injector sizes. For FSAE competition, the rules governing placement of throttles and restrictions make the use of multiple throttles or venturis unlikely and unbeneficial, however, the use of multiple fuel injectors may still be used with benefits.
Unlike carburetion, the fuel mixture is no longer primarily influenced by signal strength. In fact, the most important aspect in port fuel injection becomes the fuel injector size, placement, and pressure. The smaller the injector and the higher the operating pressure, the finer the mist which is created, and, therefore, the quicker the fuel may evaporate and mix with the air. This becomes more important when one must also consider the added versatility of placement of the fuel injector. Injectors placed closer to the valves can provide better response but must also have a finer mist in order to properly mix in the shorter amount of time it takes to reach the cylinder.

Finding an optimum solution can take lots of trial and error and simulation since there are several additional variables involved over carburetion such as injector incidence angle (angle of the injector body relative to the port), tip protrusion (distance the injector sticks into the air stream), and firing angle (angle of engine rotation that the injector fires prior to top dead center). Injectors can be fired every 720 degrees or every 360 degrees of crankshaft rotation depending on the engine sensor setup (often referred to as batch fire and sequential fueling in multi-cylinder engines). Fuel can be injected at nearly any incidence angle between zero and one hundred and eighty degrees from the runner (one hundred and eighty degrees being straight up the runner away from the cylinder head, ninety degrees being perpendicular to the runner). Fuel can be injected at times where airflow is positive, negative, or zero within a port which means that fuel can be injected even when the engine is off. Also, multiple injectors can be used on an individual port which is known as staged injection. This allows for smaller injectors to be used as each injector need only supply part of the fuel for each cylinder. With so many variables, not only is it hard to find an optimum solution, but it is equally easy to tune correct any shortfalls in the basic setup through tuning.
The requirement of being electronically controlled also means that most aftermarket fuel injection setups also include the ability to modify fueling based on any number of inputs including barometric pressure, intake air temperature, coolant temperature, battery voltage, manifold pressure, fuel pressure, or even trim individual cylinders based on airflow inequalities. Tuning any given fuel system is a long process which requires lots of time and dedication to understanding exactly what the conditions the engine is seeing and how to tune for them correctly.
Chapter 3.  FSAE Rules

In order to understand the impact these two different fuel systems can have on a design, one must also understand the rules which govern the design of the engine and the air intake system. The most important of all of these rules is the air restriction rules. These rules state:

**B8.6.1** In order to limit the power capability from the engine, a single circular restrictor must be placed in the intake system between the throttle and the engine and all engine airflow must pass through the restrictor.

**B8.6.2** Any device that has the ability to throttle the engine downstream of the restrictor is prohibited.

**B8.6.3** The maximum restrictor diameters are:
- Gasoline fueled cars - 20.0 mm (0.7874 inch)
- E-85 fueled cars – 19.0 mm (0.7480 inch)

**B8.6.4** The restrictor must be located to facilitate measurement during the inspection process.

**B8.6.5** The circular restricting cross section may NOT be movable or flexible in any way, e.g. the restrictor may not be part of the movable portion of a barrel throttle body.

**B8.6.6** If more than one engine is used, the intake air for all engines must pass through the one restrictor. (2011 FSAE Rules, p. 46)

While a simple, circular intake restriction doesn't seem like it would complicate matters very much, the truth is that this is the most important design consideration for an FSAE engine. The intake restriction is meant as a power limiting device because the amount of air that can be pulled through such a circular restrictor is limited only by the size of the restrictor and the speed of sound. Speed through such a restrictor can only practically go up to the speed of sound (sonic) and therefore it very effectively limits the maximum amount of air which can enter the engine under steady state conditions. In addition to this effect, the rules surrounding this restriction dictate several additional conditions which further regulate the way in which air is fed to the engine. The restrictor, since it is such an important part of the engine design criteria, must
always be in a place where its size can easily be checked. This somewhat limits the restrictor's positioning and affects overall packaging. Additionally, the restrictor must be stationary and therefore cannot be a movable part in certain types of throttle bodies. Lastly, and most relevant to the purpose of this thesis, the restrictor cannot have any form of air throttle located downstream. This means that any intake air throttling must be done between the atmosphere and the restrictor instead of between the restrictor and the cylinder head. This will become relevant later in discussion as it relates to the engine response characteristics.

In addition to the restriction requirements, there are rules which govern the methods of attachment of the intake manifold and low pressure fuel rail to the cylinder head. (2011 FSAE Rules, p. 48) Essentially, for safety reasons, these items must be fastened to the cylinder head using mechanical fasteners. This basically means that the pieces may be connected using sections of hoses but they cannot have the ability to pull away from the cylinder head in the event of a crash. Furthermore, there are a couple of rules which govern the throttle's operation. The throttle must be cable or rod operated as opposed to drive by wire, or electronic control. The throttle must have two return springs not including any internal springs within the throttle position sensor, to ensure that the throttle closes in the event of a mechanical failure. (2011 FSAE Rules, p. 47) Again, these items essentially limit the hazardous conditions which would occur if a throttle were to stick while out on the track. These rules may not seem to have far reaching implications with respect to the intake, but some of the most difficult design considerations deal with how to correctly fasten the intake to the cylinder head and how to incorporate the twin return springs into throttles which are nearly always designed for use with only one return spring. In fact, if these rules are not considered in the initial design, they could
take hours to correct while at competition and could even prevent a team from competing if they are unable to be corrected in a timely manner.
Chapter 4.  Manufacturability and Cost Considerations

Manufacturing any given fuel system is closely tied to the cost of that fuel system. The FSAE competition has to follow some of these rules, but not all of them. In order to level the playing field, a new set of cost formulas were implemented beginning in the 2009 competitions. These formulas essentially standardize the cost for given common use items as well as common machining tasks. What this means is that, if two teams create the same item, it should cost them the same amount as it relates to the cost competition. While this is a great way to standardize the competition, the truth is that there are teams which can afford to design, prototype, modify, and then iterate to a final design and others which can only afford and only have the time to create and use one design regardless of its drawbacks. Not to mention, the actual way in which something is manufactured does not necessarily have to be the way it is placed in the cost report. A great example of this is selective laser sintering or SLS for short. This process is the successive layering of metal or plastic utilizing a laser to melt and build the layers one on another in a highly accurate manner which rarely requires further machining (Protocam). Several teams utilize this or similar rapid prototyping processes for pieces which they run on their car at competition, including the University of Cincinnati. The problem is that this is generally a process meant for rapid prototyping. These parts do have some drawbacks, but generally retain the functionality of equivalent machined or cast parts. The only difference is cost. A part which is created using rapid prototyping techniques likely costs ten times as much as a part which is created through typical machining processes. Even further complicating the issue is that most people will put such parts into their cost reports as an injection molded plastic or a cast metal part. These two processes would be even more expensive than rapid prototyping to create just a single part, however, for the purposes of cost reporting the teams are allowed to
cost as though thousands of parts were being created which makes the part show up as exceptionally cheap.

What does all of this convoluted cost reporting have to do with carburetion and fuel injection then? Well, several of these ambiguities are very applicable to the fuel system. For example, the 2011 Materials Cost spreadsheet lists any carburetor as fifty dollars no matter what the design. Similarly, fuel pumps, injectors, regulators, filters, hoses, and check valves are all predetermined cost when it comes to the cost report. However, the throttle body and restrictor as well as the remainder of the intake must be cost "as made." This means that you must then follow a completely different set of rules which cost out the materials and processes in order to determine the "value" of the part. Now, you can see that the fuel injection system will end up costing more in the eyes of the cost judges since a throttle body must be "manufactured" in order to use electronic fuel injection at competition. The reality is somewhat different though. The process to purchase and create a fuel injection system as opposed to a carburetion system is not all that different. Yes, a throttle must be created for an electronic fuel injection system. However, considering that a restrictor, an intake plenum, and the intake runners must be manufactured anyway, there is not a significant overall cost or manufacturing time savings in having to manufacture one system instead of the other. In fact, a simple butterfly air throttle with similar flow characteristics to the carburetor butterflies can be manufactured very quickly and easily using parts which are typically sold along with the engines typically used for competition.

None of this takes into account the cost of the microcontroller which is meant to control the fuel injection system, though. All cars are required to run some form of electrical system as they are all required to have an electrical timing beacon and each and every engine in the race
uses some form of spark plug and electrical ignition to fire their engine. So, it is not a question of whether or not the car will have an electrical system of some sort, it is a question of how far a team is going to go. The cheapest controllers available for the use as stand-alone engine management are around five hundred dollars according to the 2011 Materials Cost spreadsheet. With any one of these you can control such items as fueling, ignition, water pumps, fans, any number of dash warning lights and provide some sort of data logging capability. These items are critical from a tuning and design competition perspective and you will rarely see a team which forgoes a microcontroller. In fact, most are constantly trying to create or purchase a controller with more capabilities such as traction control and the ability to actuate stepper motors and shifting systems. With this continuing pursuit for more and more computer control, it is almost a guarantee that a microcontroller will already be on board which will have the ability of controlling a fuel injection system and therefore should be considered a wash from a cost standpoint.

The difference in the remaining costs is very dependent on the engine used. Several engines typically used for competition start as electronically fuel injected engines and therefore would require the purchase of a carburetor in order to use them as such, but would require very little additional investment in order to compete as an electronically fuel injected engine. As a counterpoint, engines which begin being carbureted tend to be cheaper upon initial purchase but can require extensive modifications in order to be able to run with electronic fuel injection. However, this too is very dependent on the engine in question. As part of the research for this thesis, a single cylinder, Yamaha 450 cc engine which began as a carbureted engine was converted to fuel injection utilizing parts off of an electronically fuel injected version of the same engine. The cost for the conversion was only about three hundred dollars and took about four
hours of machining time in order to complete the conversion. Even with a relatively small engine team budget, this is miniscule.

It is easy to see rather quickly that the manufacturing time and the overall cost for an electronic fuel injection system on an FSAE engine is going to be greater than that for a carbureted fuel system. The degree to which this is true will greatly depend on the engines used and the pieces which are already available from the team in question. With respect to the University of Cincinnati team, nearly all of the components used for a fuel injected engine are already available as their cars have been running fuel injection for a minimum of ten years. The items which would have to be manufactured are going to be nearly equal for each system as each would require a unique intake and exhaust based on the chassis packaging design considerations and each team's specific goals for the engine in any given year. Actual purchase cost should be within about five hundred dollars of one another and the difference in price for competition purposes based on the new cost guidelines will likely appear to be much less than the real cost difference. With so little difference in cost and manufacturing time linked with the relatively low weight of the cost event in the overall score (one hundred points possible out of a total one thousand points), it is very unlikely that one should consider points in the cost event as the reason in order to choose one system over the other. However, if a choice has to be made due to cost and manufacturing considerations, carburetion should be considered the better choice.
Chapter 5. Torque Characteristics

5.1. Defining Horsepower and Torque

When discussing an engine, inevitably the power that an engine makes will come up. Generally what is being discussed is brake horsepower. The term brake horsepower comes from the fact that the horsepower is measured by using a brake to hold the engine at a given RPM and simultaneously measuring the torque the brake must put into the shaft in order to hold the RPM constant. This torque is then known as brake torque. Since horsepower is simply a derived term, the brake horsepower can then be quickly determined.

Adding to the confusion are the terms "flywheel horsepower" and "wheel horsepower." When dynamometers measure torque, there are seldom instances where the engine is removed from a chassis in order to measure the torque output. So, companies have come up with ways of measuring the torque output at the rear wheel. Some behave like a brake and hold RPM constant and others simply allow the car to accelerate a roller with a known inertia and measure the acceleration. In any case, they are attempting to measure wheel horsepower. Out of all measurements, this should be the lowest horsepower figure as wheel horsepower also takes into account drivetrain losses and rolling resistance losses from the tires. If the instance did arise where an engine could be removed and linked directly to a brake by the flywheel, such as what is done during engine development by OEMs, the resulting power figures would be flywheel horsepower. Flywheel horsepower is usually equal to OEM quoted brake horsepower as most manufacturers test the engine with accessories but no drivetrain in accordance with the relevant SAE standards.
In the case of the University of Cincinnati, neither of these terms is entirely accurate. Due to the engines which are utilized by the team, flywheel horsepower can never be directly measured. This is due to the fact that all of the engines used by UC FSAE always have a transmission integrated into the same basic structure as the engine. This means that in order to measure true flywheel horsepower, major work would have to be done to separate the engine and transmission and then one would finally be able to measure what is really coming off of the flywheel. What is actually done by the team is measure torque directly from the transmission output shaft. On the motorcycles and quad bikes that these engines are usually in, this is the location of the front sprocket which leads to a chain which turns a rear sprocket that will turn the rear wheels. What this means is that the power measured is usually somewhat lower than that of flywheel horsepower and somewhat higher than that of rear wheel horsepower. This introduces some interesting math into the process, in that the transmission output shaft is usually spinning at a different rate than the engine crankshaft. Primary reduction and transmission gearing determine the ratio of the transmission output shaft rotating speed and the engine rotating speed. Either way, the torque at the transmission output shaft, engine RPM, and transmission shaft RPM are measured by the computer controlling the dynamometer. These numbers are then used to calculate the torque and horsepower that the engine is making at each engine speed.

This fact is confusing to some because it is not realized that if it were not for the system losses, horsepower would be the same at each location in the system while torque can be multiplied or divided depending on the gear ratios involved. For example, one ft-lb of torque at the crankshaft can go through the transmission and become five ft-lb of torque at the transmission output shaft. However, the output shaft would be spinning five times slower in
order for this to be true. Meanwhile, the horsepower at the crankshaft and the transmission output shaft would be nearly identical.

The actual definition of one horsepower is the ability to move 33000 pounds the distance of one foot in one minute. To put it in terms of the previous paragraph, technically the same horsepower is being made by an engine which moves a 33000 pound block a distance of one foot in one minute as one that moves a single one pound block a distance of 33000 feet in one minute. This definition, in the case of engines, needs to be translated from linear movement to rotational movement. This is done by understanding that one revolution is equal to two times pi in radians. So by understanding that 33000 ft-lbf/min is equal to one horsepower you can create the equation:

\[
\text{Horsepower} = \frac{2 \times \pi \times \text{Torque (ft} \cdot \text{lbf)} \times \text{RPM}}{33000}
\]

\[
\text{Horsepower} = \frac{\text{Torque(ft} \cdot \text{lbf)} \times \text{RPM}}{5252}
\]

The latter is the equation most are familiar with and why the first thing that should be checked when looking for the validity of dynamometer curves is that the horsepower and torque curves cross at exactly 5252 RPM. Once these basic concepts are understood, one can begin to think about what the dynamometer readings mean from a practical standpoint.

5.2. Maximum Horsepower and Torque

When it comes to producing maximum horsepower, there are more than just a few factors which have major influences. When it comes to comparing carburetion to electronic fuel injection the answer is actually very surprising to most as carburetion usually has the ability to
deliver a slightly higher maximum horsepower number than electronic fuel injection. This is counter intuitive to nearly everything that gets stated about the so called advantages of electronic fuel injection. The answer lies simply in fuel atomization. Since a carburetor uses a large pressure differential caused by high velocity through a venturi, fuel is atomized more effectively than what can be accomplished by spraying fuel through an orifice as in electronic fuel injectors. Not to mention, single or even dual carburetors are nearly always a greater distance from the intake valves giving the atomization more time to occur. This would be especially true of the FSAE competition engine. Rules mandate that the throttle be placed upstream of the restrictor. Since most carburetors have an integrated air throttle, this means that most would need to be placed ahead of the restrictor. This additional 10-20 inches of distance and turbulence would provide extreme atomization to the fuel by the time it reached the cylinder. All of this leads to a situation where, even with the same amount of air and fuel, the carburetor will actually outperform an electronic fuel injection system in maximum power output.

Being capable of and doing are two entirely different scenarios though. One very important factor in making maximum power is providing the proper amount of fuel. In production fuel systems they must operate at or very close to a stoichiometric fuel and air mixture at all times in order to ensure the most efficient operation of the three way catalytic converter which is used to control emissions. (Turns, p. 569-571) In competition engines, running at a stoichiometric mixture often provides significantly less power than what can be obtained by utilizing a slightly rich mixture. Richer mixtures provide more fuel than what the chemical equations would say can be fully burned with the air available in the cylinder. This usually leads to higher unburned hydrocarbons in the exhaust, but ensures that every bit of the air in the cylinder is used up by providing it with easier access to hydrocarbons. In addition,
running an engine on the rich or strong side leads to lower combustion temperatures. This makes combustion much less hazardous since it eliminates some of the worry of detonation due to in-cylinder hot spots. With carburetion, the amount of fuel provided is governed by the amount of pressure delta acting on the fuel jet and the size of the jet. This means that the nonlinearity in Bernoulli’s principle only allows the main jet to appropriately work over a relatively small velocity window. So, the engine can be optimized to run better than fuel injection, but the optimization will be over a comparatively small RPM band.

This is further compounded by the fact that FSAE competition engines can only practically run one carburetor due to the rule stipulating a single restrictor. It is generally accepted that airflow to each cylinder is almost always different based on the bends and curves that exist within an intake manifold. This is not only true for air, but even more so for fuel as it has an even greater propensity to not want to turn corners due to its higher molecular weight. This leads to a situation where you have not only different amounts of air for each cylinder, but different amounts of fuel for each cylinder. If there was a good correlation between the flow characteristics of the two substances, there would at least be a similar air fuel mixture in each cylinder. However, this is not the case. So, not only is there an unequal quantity of air at each cylinder but that air is likely to have a very different fuel mixture than the cylinder next to it. This can cause any number of issues depending on the severity of the condition but none of the outcomes have a positive effect on overall power. The fewer cylinders there are, the less problematic this situation becomes. In fact, with a single cylinder engine this problem with air and fuel distribution is non-existent. But, this phenomenon cannot be forgotten when planning for multi-cylinder engines like those which have been historically used for FSAE competition.
These issues with carburetion make it nearly impossible to realize the theoretical maximum power benefits which exist while working within the confines of FSAE rules. Many times the solution to the problems given above is by utilizing multiple carburetors, even up to using a single carburetor per cylinder in order to prevent uneven distribution between cylinders. This is a completely impossible solution due to both complexity and the fact that it violates FSAE rules for everything but the single cylinder engine. With that in mind, using individual or even multiple fuel injectors per cylinder is perfectly legal and simply requires the addition of a proper bung, fuel supply, and electrical connection in order to be utilized. This means that in most practical applications, the system which ends up making the highest peak power is an electronic fuel injection system because it can supply a more accurate fuel and air mixture to each cylinder independent of RPM or uneven airflow.

5.3. Power Delivery

More important than nearly every other power characteristic is accurate power delivery. If a driver puts their foot on the throttle they are in essence demanding a torque value. More "pedal" should equate to more torque in a somewhat linear fashion independent of RPM. This means that the ideal torque curve would be flat from zero RPM all the way to redline. In addition to this, ten percent throttle would equate to ten percent of the maximum torque the engine could provide, twenty percent throttle would give twenty percent of maximum torque, etc. With an intake restrictor, this issue is severely complicated. Maximum airflow is completely limited by the inlet restrictor. In order to achieve the highest average power for a given engine the restrictor would need to be choked essentially at all times.

When you place a flow restriction in front of the mandatory intake restriction such as a butterfly air throttle, you are introducing two things to the system. One, you are adding an air
restriction which is hindering airflow more than even the mandatory intake restrictor. Two, you are adding a flow disturbance ahead of the intake restrictor. Neither of these are a problem until you begin to demand enough airflow to choke the restrictor. Then they can become a significant problem. With regard to restriction, the air throttle needs to be large enough (usually ~25% larger than the restriction) to make sure that at wide open throttle, the intake restrictor is the only major restriction in the system. This means that nearly the entire pressure drop of the system is occurring across the restrictor. In the case of the University of Cincinnati, the restrictor behaves essentially as a nozzle. Since the nozzle choking at a given pressure delta, the higher the pressure on the front of the nozzle, the higher the pressure can be inside the intake manifold and still choke the nozzle. This means that the nozzle will choke for a greater percentage of time and therefore power will be maximized. With regard to flow disturbance, this disturbance placed in front of the nozzle essentially reduces the flow area of the restrictor because the disruption essentially creates a thicker velocity boundary layer, or layer of close to zero velocity.

The reason that the flow characteristics of a butterfly valve are important is primarily because most carburetors in existence utilize a butterfly valve as the air throttle. The butterfly valve is a great and simple solution to creating an air throttle, but they have one severe downside: airflow nonlinearity. If airflow was being controlled only with a butterfly valve, at a given pressure differential, moving the valve from zero to ten percent open does not provide the same change in flow as moving the valve from ten percent to twenty percent open. This nonlinearity continues throughout the valve's operation. The fact that carburetors almost exclusively utilize butterfly valves means that even an appropriately sized butterfly valve would cause the driver to have a difficult time knowing precisely the amount of torque the engine will produce when they adjust the pedal from one point to another. This is then amplified by placing the intake
restriction behind the butterfly. A butterfly large enough to not cause significant flow restriction or turbulence upon entry into the throat of the nozzle would be large enough that the throttle would be too touchy at low throttle positions but with very little resolution at higher throttle positions. This is due to the effective flow area of the valve quickly exceeding the total flow area provided by the restrictor. The solutions to this are to use a butterfly valve which compromises some of the linearity and overall flow, or to use a larger butterfly valve with either a cammed or drive by wire actuation. The drive by wire would allow you to input a valve position which does not have to be related to the driver's foot which would correct all these problems, however, this is not allowed in FSAE competition. Therefore a cammed throttle would be the most appropriate solution, but would require proper design to correctly link throttle position to airflow with smooth operation. Fuel injection on the other hand does not specify the type or position of the throttle body. This allows such elaborate pieces as ball, barrel, or slide throttles which will not be discussed here other than to say that these can alleviate the specific problems seen by the butterfly valve by providing no flow restriction at wide open positions even when their overall size is on the correct order as to provide good throttle resolution.

Additional complications of the carburetor from its location out beyond the restriction are throttle response and uneven distribution. Typically when the throttle is snapped open in a carbureted vehicle there is a moment where the fuel air mixture turns lean as the fuel has not yet begun to start flowing correctly from the correct jet. This makes for a momentary power lag until the carburetor can react and correct for the instantaneous throttle change. As alluded to earlier, even once the carburetor has caught up, there tends to be a slight air and fuel distribution difference from cylinder to cylinder. This can manifest itself in a worst case scenario as misfires, backfires, or detonation all of which cause interruption in the power of the engine. Any of these
occurring at exactly the correct time can not only cause precious seconds, but can actually be hazardous as it causes the driver to lose control or grip.

Lastly, and probably most importantly, are situation based corrections. When a carburetor is used, the most advanced adjustment that can be done on the fly is a choke. The choke is usually used to choke off airflow into the carburetor. This creates enough vacuum within the manifold to pull additional fuel from the main jet to create the slightly rich conditions needed due to the reduced fuel volatility while the engine is cold. The colder engine is unable to properly atomize the fuel to create a homogeneous mixture in the cylinder, so more fuel must be used to try to burn the air available. But, what about when the engine begins to run hot? Or when the car is driven on a colder day or at a higher elevation? Well, instead of automatic corrections in the fueling based on such factors, the carburetor will only supply the fuel that is dictated by the airflow which is dependent on the pressure differential and jet size. This can cause any number of conditions from extremely lean to extremely rich. Each situation would require the carburetor to be adjusted or even rejetted in order to correctly compensate for the changes in conditions that could even occur during a race. To this end, electronic fuel injection is the only reasonable choice. It allows each condition to be tuned for without ever turning a single wrench, and, once a specific situation is tuned for, it should never have to be adjusted again.
Chapter 6. Fuel Efficiency

Fuel efficiency and racing have always gone hand in hand, except for in FSAE. In the past, the car only benefitted from fuel efficiency because it allowed for the use of a smaller fuel tank and therefore a lower amount of weight, and, even more importantly, a lower amount of weight transfer due to fuel sloshing. In the most recent of competitions, fuel efficiency is being counted as part of the overall score. For 2011 competition, it counts for one hundred points out of a total of one thousand. While one hundred points out of one thousand may not seem like much, this event will likely continue to carry more weight in future events as it continues to carry more weight in passenger car design.

The primary drivers for fuel economy can be broken down into two categories: mixture quality and mixture maldistribution. Both of these subjects have been discussed in this thesis already, but must now be looked at from a slightly different perspective as they imply slightly different things when it comes to fuel economy. It has already been said that theoretically a carburetor could supply a more homogeneous mixture than what can theoretically be supplied by an electronic fuel injection system. If the mixture becomes more homogeneous, an engine becomes increasingly able to run on leaner mixtures. If this could be realized fully, the actual power of the engine could be modulated more with fuel input than with air input. This is very similar to the way diesel engines operate. Unfortunately, in order to achieve mixtures homogeneous enough for this to be done requires elaborate mixing techniques which are often reserved for laboratory tests. As it stands, the only relevant comparison is between the mixture qualities given by a carburetor ahead of a restrictor.
as compared to port electronic fuel injection. The reality is that there is very little if any appreciable difference between the mixture qualities which can have any effect on fuel economy.

So, that leaves fuel mixture maldistribution as the leading cause of reduced fuel economy. The reason why this can have such a profound effect on fuel economy has to do with transient operation. As was discussed earlier, when the throttle is applied on a carbureted engine, this typically results in a temporary lean condition which is actually the most pronounced immediately following a snap closed throttle. The reason for this is that the thin fuel film which usually exists on the manifold walls is completely burnt off during these overruns which means that when the throttle is opened again, these films require additional fuel to be sprayed in order to be reestablished. (Blackmore, p.91-93) In order for there to be enough fuel for this and to make sure the cylinder doesn't misfire from a lean condition, carburetors and electronic fuel injection systems must employ some form of transient enrichment or continuously be run much richer than is optimum for fuel economy. A carburetor must supply enough excess fuel to all the cylinders to ensure that the cylinder which runs leanest does not misfire during this time. Port fuel injection, due to individual injectors per cylinder and the allowed cylinder trimming, allows for each cylinder to be supplied exactly the right amount of additional fuel to prevent misfire during these transient operations with very little waste.

As a whole, the ability for adjustment due to unusual operating conditions, as well as the basic ability to adjust fueling appropriately cylinder to cylinder, outweighs any potential mixture benefits seen from any theoretical advantage in fuel mixture quality. In addition, electronic fuel injection allows for leaner mixtures to be used for parts of the engine’s operation where maximum power is not necessary which allows for much greater fuel savings overall compared to what any carburetor would allow.
Chapter 7. Conclusions and Future Work

7.1. Conclusions

Nearly every team in FSAE competition runs some form of indirect electronic fuel injection system. A deeper investigation of the pros and cons of each of the primary choices for fuel system quickly sorts out what most teams end up selecting without even considering the alternatives. This is disappointing since the competition should be all about being able to make good engineering decisions based on the benefits and drawbacks as they relate back to team goals. The University of Cincinnati is particularly vulnerable to this type of action since the team tends to be only seniors whom have little to no exposure to racing, much less this specific competition and rule set.

From the investigation presented, it can be seen that carburetion carries several inherent benefits. More homogeneous fuel mixtures are nearly guaranteed with a carburetor in the mandatory FSAE configuration in front of the restrictor. Also, with the use of the single cylinder being heavily considered for 2012 competition, there is no worry of fuel maldistribution which tends to be a predominant shortfall of carburetion. Lastly, carburetion will always be easier to implement as there are no complicated timing adjustments or modifications to a specific engine to get it to work. In fact, in most cases, it simply requires the adjustment of a few jets in order to run well enough to get out on the racetrack. Getting the car running well enough to get out on the racetrack should be any team's number one team goal regardless of what their design decisions are. This gives the team a proper chance to evaluate the decisions that have been made and when the true reasons for the success of a design is understood it provides every future team with better knowledge with which to make decisions. That is exactly how this thesis should be
used. Hopefully, despite the focus on fuel systems, it contains enough information for those incoming seniors to begin to understand the complex nature of combustion which they nearly always take for granted. With this knowledge, the team fuel system decision should never be limited to just electronic fuel injection.

All of this simplicity also comes at a substantially lower cost compared to a well designed and implemented electronic fuel injection system. During this investigation, it became apparent early on that a bare minimum of one thousand dollars must be invested in order to make an engine originally designed for carburetion to work with a modern electronic fuel injection system. There are pieces which need to be modified, sensors which are needed as inputs, controllers which need to be purchased, and a significant amount of wiring which needs to be done. With proper sponsorship, this cost can be mitigated though, and the difference in the price between fuel injected and carbureted engines makes it a cost effective proposal for FSAE teams which have machine shops and sponsorships at their disposal.

While the carburetor does carry the key benefits of cost and simplicity, the improvements which can be achieved with an electronic fuel injection system are almost always worth the additional cost and work. The ideal powerband for an FSAE engine is extremely wide and the operating conditions are so varied from one track to another that using electronic fuel injection becomes almost mandatory for those teams that wish to focus on the factors which are overall more important to good racing. Having a consistent engine with predictable characteristics makes chassis tuning and driver development easy. An engine which puts down inconsistent power day to day, or even on the same day, usually ends up frustrating even seasoned drivers as they attempt to optimize the car's setup and become comfortable with driving the car at 100% around a track. And, even more importantly, reliability is drastically effected by not having the
engine setup and prepared for varying track conditions. When in a competition scenario, a driver will typically not stop pushing the engine to 100% no matter what types of conditions or problems which are exhibited. The best example of this is when the engine begins to overheat. No driver will slow down because their engine is becoming too warm, and therefore corrections to fueling need to be made to help keep the car cool while the driver continues to push. A carburetor does not offer this form of adjustment and therefore could be the reason why a team does not finish a race. Bottom line, a properly adjusted and well-designed electronic fuel injection system will always be a better choice for an engine which is expected to perform at 100% for the entirety of a race.

7.2. Future Work

When working on this thesis, a single cylinder, 450 cc Yamaha engine out of a 2006-2008 quad bike was investigated as the engine to be used for the 2012 University of Cincinnati Formula SAE team. This engine provides several key benefits from the standpoint of learning about engine design, optimization, and evaluation. The best thing about the engine and dynamometer configuration is that fueling can be controlled by the existing engine control unit or a carburetor could also quickly be put in place without any other hardware modifications. This would allow future teams to quickly determine for themselves if the fuel injection system carries any inherent benefits over a well-tuned carbureted system and would allow them to present their findings to the design judges at competition.

In addition to this benefit, the single cylinder configuration quickly allows for adjustment of intake and exhaust lengths and diameters. The major adjustments available for modifying the torque curve characteristics in FSAE restricted engines are the intake runner length and exhaust
runner length. With a couple pieces of hose and a hacksaw the team can modify and test literally hundreds of combinations for their impact on the interaction between intake and exhaust length as well as torque curve characteristics. In this respect, the single cylinder is heavily endorsed to be used for all future engine teams. If the main benefit to the competition is knowledge, there is no configuration which supplies as much knowledge with as little effort as a single cylinder engine.

Lastly, the single cylinder engine chosen is primarily used in many types of racing in dirt bikes and quad bikes. This usage means that the aftermarket parts available for the engine are produced with enough volume to make them cost effective to implement even on a reasonable budget. The current engine may only be 450 cc, but kits exist which can take this engine well into the 530 cc range of displacement while also increasing compression ratios. This may not seem like a huge bump, but it all goes back to being able to make the most power under all conditions. Higher compression ratios make better use of the air and fuel available by providing a more efficient combustion while the larger displacement would make sure that the restrictor is choked over more of the rpm range where the engine operates. This would need to be carefully considered against reliability concerns as reliability is worth much more than a small bump in torque. But, forced induction is also considerably cheaper and simpler on single cylinder engines.

In the end, the future work which results from this thesis should focus on an attempt to better understand the key points of combustion through the use of the single cylinder engine currently setup at the Center Hill Research Facility. By modifying the intake and exhaust as well as internal aspects of the engine, the future engines should be much more robust to the racing
environment than the current engine choices and prove to make the University of Cincinnati FSAE team more competitive despite the decrease in overall torque and horsepower.
Bibliography


Appendix A: Yamaha Single Cylinder Information

Throughout the process of writing this document, the prime path for the University of Cincinnati Formula SAE team was centered on the conversion of the team to a single cylinder platform for the 2012 competition. This meant that considerable work needed to be done in parallel with the 2011 car development to determine both the engine, controller, and power characteristics of the new engine platform so that the team for next year would have a stable dataset from which to design the remainder of the car. This is where I came into the picture. Having worked on the engine team for a couple of years, I knew many of the intricacies which existed in the development and implementation of a new engine and control system and therefore became the prime candidate to spearhead all the work related to the single cylinder.

The development work started by selecting a specific engine which was felt to meet the needs of the team best. This generally boils down to little more than cost and availability, but due to the gravity that comes with any team engine change, several additional factors were considered. Dustin Lindley, another graduate student from the university, led most of this research and found that the single cylinder Yamaha 450cc engine used on sport quads and dirt bikes were readily available for good prices while being light weight and having more modern light weight designs with nontraditional metals. Additionally, the 5 valve cylinder head incorporated titanium valves which meant that the valvetrain would likely be reliably capable of operation during sustained high speed driving while having highly efficient airflow characteristics. The last, and probably most important, factor was the incorporation of a dry sump oiling system. This type of oiling system incorporates a scavenging pump which draws oil from the bottom of the crankcase to a holding tank where it is then picked up by the high pressure oil pump to be distributed throughout the engine. This design prevents oil aeration and starvation issues which have historically plagued the UC Formula SAE team while competing with 4 cylinder engines with wet sump oiling systems.

From this point, it became a question of whether or not to go forward by purchasing a 2009 model engine or an engine from the 2006-2008 years. The internal differences were relatively small, but involved a shift in the 2009+ model engine to an internal dry sump oil tank as opposed to the externally mounted one on the 2006-2008 year models. While the 2006-2008
model’s remote located tank was thought to provide the team with more mounting options, this
difference was miniscule compared to the addition of fuel injection for the 2009 model year
engines. The UC Formula SAE team has been successfully utilizing fuel injection for many
seasons due to the reasons which have already been hashed out in the main text above.
However, there was no good consensus amongst the team captains, graduate students, and
advisory team about whether purchasing this engine with fuel injection was worth the
substantially added cost associated with it. Not to mention, the relative new release of the engine
limited our ability to find the engine at all.

In the mean time, Performance Electronics had approached the team through the advisor
about the possibility of incorporating their new ECU called “The Edge.” This controller was
specifically targeted toward the 2009+ Yamaha sport quads and dirt bikes. In fact, it was a direct
plug and play swap between the factory ECU and their new unit. This further complicated the
conversation as our relationship with Performance Electronics is generally good and their
product support for the UC team has been very good but until this point the general consensus
was that the team was going to purchase a 2006-2008 model engine and test it using carburetion
to try to understand its performance. Talks with Performance Electronics, however, led us to
believe that a compromise could be reached with mutual benefits for both PE and UC FSAE.
This led to the decision to utilize the Performance Electronics ECU on a 2006-2008 model
engine and together the mechanical and electrical problems of such a swap could be figured out.
In the end, UC would likely have the information that they needed about the performance
characteristics of the engine while Performance Electronics would gain valuable knowledge and
tuning time on a different engine with lots of different inputs and outputs than what the ECU was
originally designed for, and, in the end, could use this information to their benefit to sell the new
ECU to the new market of Formula SAE teams.

This specific direction led to the need for our team to find an appropriate size fuel
injector for the engine and a couple additional sensors in order to make the engine work with the
controller. Fuel injectors are usually sized based on wanting to be able to supply a given amount
of fuel at a given pressure. The amount of fuel needed is based on the amount of power it is
presumed an engine will make (usually based on an assumed volumetric efficiency) and then
further modified by assumed brake specific fuel consumption. This then gets worked further
down into the maximum speed of the engine or more specifically the duration of which the injector will have in order to spray the fuel amount needed. Then utilizing some safety factor or time allowance for injector cooling, usually 15-20%, an injector is selected. In the case of the single cylinder though, the work had already been done by the engineers at Yamaha, and so utilizing a contact from PE (GT Thunder), the factory fuel injector, fuel rail, wiring harness, and some additional sensors were purchased off of a 2009 factory sport quad.

Once the engine itself and the fuel injection pieces were available, the main portion of the intake pieces could begin to be made. In the images below, you can see the intake bellmouth designed based on the paper “Best Bell” written by Gordon P. Blair and W. Melvin Cahoon.

![Machined bellmouth located inside the intake plenum.](image)

The inside diameter was matched to the diameter of the inlet on the cylinder head of the engine and the rest of the dimensions were created based on that base diameter. This was then placed inside of an intake plenum which was sized based on the previous starting point for designs which is based upon the plenum being four times the volume of a single cylinder of the engine it was being attached to. This has been found by the team, through simulations to provide a good starting point for the engine testing as it gives good performance without sacrificing a great deal of throttle response. It should be noted that all of the testing done on the engine thus far has simply been steady state testing where this specific attribute would not be tested,
however, a similar design could likely be carried forward to the first iteration of the car’s plenum without significant consequences. This plenum was fitted with a machined aluminum ring with which to attach the intake restrictor which has been used by cars for several generations to allow the quick usage of available intake throttles from several cars. The assembled plenum is shown below.

![Figure A.2: Nearly completed intake plenum with 2.4L of volume.](image)

Once the intake plenum was completed, the fuel injection system needed to be added to the intake system. Since a Yamaha injection system was to be used, measurements simply needed to be taken of the injector in order to design and machine the appropriate bung to hold and appropriately seal the injector. From there the bung needed to be “fish mouthed” at the correct angle and then welded to an intake runner. The angle with which it was attached was mostly dictated by the way that the fuel rail mounted to the intake runner. In the picture below,
you can see that the fuel rail had two tabs which are meant to attach the rail to the intake system. This dictated the angle of incidence for the injector which was an acceptable 35 degrees.

![Intake runner with fuel injector and rail properly located.](image)

**Figure A.3: Intake runner with fuel injector and rail properly located.**

The runner was created by taking the inner and outer diameters of the intake port of the cylinder head and then simply finding the appropriate size tubing to match the inner diameter and then machining a ring which was press fit on this tube in order to closely match the outside diameter. This piece was made separately from the plenum for several reasons. The first of these reasons is the ability to add and remove length from the intake runner in order to optimize the power characteristics of the engine. The second of these reasons is the ability to quickly swap the intake plenum out if a newer or better design is created. When utilized on the dyno, large diameter steel wire reinforced tubing was utilized as the connection between these two pieces to minimize the amount of deflection that occurred due to vacuum created by the engine. The minimum length of the intake runner from the cylinder head to the plenum was dictated based calculations of the speed of sound in air at standard temperature and pressure. The ideal length for a tuned wave intake runner was calculated to be somewhere in the 12-15 inch range.
for the RPM range which the single cylinder was designed to make peak power (8-10 kRPM) and so the minimum length was set to the lower limit of 12 inches.

Once the intake tract had been created, the exhaust was created with a similar design philosophy. Since the engine would likely need to be tested with varying length exhaust primary lengths for modifying and optimizing the engine’s power characteristics, a minimum length was chosen based on similar speed of sound calculations for gas at elevated temperatures compared to the intake runner tuning. The minimum length corresponded fairly closely with the length of the factory exhaust header of approximately twenty inches. For simplicities sake, the factory stainless steel exhaust header was purchased and a mild steel extension pipe was added in order to make it easier to weld in the appropriate EGT and O2 bungs for testing purposes. This extension pipe could either be shortened or removed altogether as the team works to optimize the engine’s power characteristics.

The last and most important piece that needed to be created or modified was the engine’s flywheel. The factory engine utilizes a carburetor and a capacitive discharge ignition system which is common to most factory single cylinder off road motorcycle and sport quad engines. This ignition system does not provide enough trigger signals to allow for complete control of fuel and spark timing tables the way that is required when utilizing electronic fuel injection systems. In capacitive discharge ignition systems, a single large tooth is attached to the engine in a manner so that it spins at a one to one ratio to the crankshaft of the engine. On the Yamaha engine, this is on the outside of the flywheel. This single tooth is part of a circuit which charges a large capacitor. When the tooth is seen by the sensor pickup, the capacitor is discharged and when it is not in a triggered state, the capacitor is charged. This is a simple and inexpensive ignition system for engines which have a single cylinder and run at high RPM. Specifically, the Yamaha uses a variable reluctance sensor as the pickup to this tooth. Without going into details of sensors and their operation, this sensor essentially outputs an analog signal as opposed to a typical Hall Effect sensor which produces a digital square wave. This is important to note as the ECU must be able to read this type of signal and interpret it appropriately if the sensor is to be used. Luckily, the Performance Electronics ECU was capable of post processing an analog signal, so the factory sensor could be utilized.
Once the sensors have been verified to be compatible, the tooth arrangement must be considered. The options for tooth arrangement for the Yamaha 450 were fairly straightforward. Because a cam position sensor was not intended to be utilized, the flywheel had to go with a “missing tooth” arrangement. This means that the teeth which are placed on the flywheel are generally positioned an equal distance apart, but that distance is chosen as if there were an additional tooth. After discussing the issue with Performance Electronics, it was decided that a 12-1 tooth arrangement would be best suited to the needs of the team. This meant that each of 11 teeth were placed 30 degrees apart around the flywheel with a single tooth missing. This missing tooth was originally placed in a randomly chosen location, however, it was later discovered that certain locations behave better than others as the speeding up and slowing down of the engine caused by compression can create a situation where, during cranking, the missing tooth is not seen as missing. This occurs when the tooth is placed shortly after top dead center. Placing it far away from the top dead center of the engine typically provides a smoother engine speed near the position of this missing tooth when cranking and allows for much easier starting and running. It should also be noted that the tooth width should be taken into consideration specifically in the case of the variable reluctance sensor. Due to the nature of the sensor, the tooth which is seen needs to be of similar width to the sensor’s pickup in order to obtain accurate timing of the “zero crossing” of the magnetic flux. The final design for the flywheel and teeth is shown below.

![Figure A.4: Flywheel machined to accept timing teeth and timing teeth attached.](image)
Once these items are all completed, it is simply a matter of properly wiring the engine and controller, attaching the engine to the dyno, and starting the tuning process. The engine dynamometer setup is shown in the image below.

Figure A.5: Center Hill Research Facility dynamometer test setup.

Following the work on this specific engine, a plot of torque and horsepower were obtained. The plot is shown below.
Figure A.6: Torque and Horsepower curves for the tested Yamaha 450cc single cylinder with electronic fuel injection.