Development of a Port Fuel Injection System Utilizing 3D Printed Components

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Abstract

Prior to the 1990s, spark-ignition engines relied heavily on carburetors to deliver the proper mixture of fuel and air into the combustion chamber at a variety of engine speeds and load levels. Carburetors however do not have the capability to supply continuously variable fuel and air amounts which are required to optimize combustion completeness and therefore fuel efficiency. Electronic port injection however utilizes a multitude of precision sensors to determine variables such as the crankshaft position and compute the optimal injection time and fuel quantity for a desired performance goal e.g. maximum horsepower or efficiency. This project consisted of designing a retrofit port injection system as well as implementing a control system to demonstrate the greater efficiency and variability that fuel injection can achieve. This will be particularly useful for Prof. Littman's Freshman Seminar: The Art and Science of Motorcycle Design, where he demonstrates the function of carburetors on the Triumph Tiger Cub. Consequently, the implementation of the injection system will be on one of the Tiger Cub engines.

Acknowledgements

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To my advisor Professor Littman, thank you for giving me the opportunity to work on this project and be a small part of your freshman seminar. Your expertise during the project's many quandaries was indispensable. I can only hope to pursue my future work with the same passion you demonstrated everyday while working with your students.

To Jon Prevost, thank you for guiding me through this humbling learning experience. During my time at Princeton you were always working to create the best learning experience for your students. Your dedication to this cause was especially visible during this project. I feel extremely fortunate to have been able to bring my time at Princeton to a close learning about engines from you.

To Nick O'Donnell, thank you for always reminding me that nothing will ever replace a cold morning drive to break a hole in the ice and watch the birds come in.

To Bobby, Karl, Pranav, Ritika, Caroline, Nate, Will, and Demetra, it remains a mystery how we all ended up together on Guyot Ave. I only hope all nine of us can make it for another salmon dinner sometime.

To the small army which my siblings make up, I love y'all. The next siblings Braums run is on me.

To Mom and Dad, thank you for shaping me into the person I am today. Mom, despite your concerns, thank you for you letting me walk the line between outright dangerous activities and formative experiences. Dad, thank you for instilling in me a love for work well done. I am who I am because of the hours turning wrenches with you in the garage.

To Jeremy Clarkson, James May, and Richard Hammond

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Chapter 1

Introduction

1.1 Fuel Metering Techniques

Fuel injection is the process by which liquid fuel is metered, mixed with air, and vaporized prior to combustion. Today, the internal combustion engines used in most consumer vehicles employ two types of fuel injection: direct and port injection. While this project focuses solely on port injection, the widespread adoption of direct injection compels a brief discussion of its operating principles. Fundamentally a more complex method of fuel-air mixing, understanding its features will clarify the main advantages underlying mechanical mixing via carburetors as well as the more refined process of port injection.

Opening the hood of any new vehicle in the United States or Europe will inevitably present the average motorist with a mass of plastic covers and caps which preclude any view of fuel lines or injectors alike. Once a key has turned in the ignition however, a less obvious sign sounds from the rear of the vehicle. Unbeknownst to most, this high pitch whine which reliably precedes ignition is perhaps the most distinguishing feature between a daily driver and the standard push mower. The sound originates from a high pressure fuel pump which is required for direct injection of fuel into the combustion chamber. Timed to utilize the compression stroke to mix fuel and air, operating pressures for direct injection are in excess of 2000 pounds per square inch (psi) [1]. Unfortunately, this requires mechanically complex and expensive high pressure fuel pumps. In addition, for an injector to be able to survive the harsh conditions inside the combustion chamber presents, temperature resistant materials are required which further increase costs. These factors combine to create an injection system which, while widely adapted by consumer vehicle engines, is far too expensive and complicated for smaller displacement engines.

Currently, the main method for fuel-air mixing in low cost and power applications is carburation. The carburetor relies primarily on the venturi effect to mobilize and mix fuel with the oncoming stream of air which has been regulated through a throttle body or similar orifice.

$$p_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = p_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \tag{1.1.1}$$

The gravitational potential in a carburetor can be ignored thus reducing the equation to:

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2 \tag{1.1.2}$$

Finally, rearranging the equation depicts the venturi effect:

$$p_1 - p_2 = \frac{\rho}{2}(v_2^2 - v_1^2) \tag{1.1.3}$$

Derived from Bernoulli's principle, the venturi effect simply states that as the velocity inside the carburetor v_2 increases due to the restrictions in area, the pressure then decreases. The differential in pressure between the atmosphere and inside the carburetor's throat then draws fuel up and into the airflow. The greater the velocity of air, the lower the pressure, and the more fuel that is metered into the intake manifold of the engine. Often, carburetors must rely on multiple passageways or needles which are calibrated for different engine conditions to draw fuel up from a small reservoir and ensure proper starting and throttling performance. While this system requires no electronics or expensive fuel pumps, the small orifices required are prone to clogging when exposed to impurities. The most important downside to carburetion however is that, as previously mentioned, carburetors are only calibrated to a single fuel-air mixture for the given environmental conditions which they were tuned in. Consequently, fuel economy and performance are greatly affected when the environment changes. Lower levels of fuel vaporization also impacts fuel economy. Fuel droplets from a carburetor are generally much larger than injection methods and have less direct contact with the heated intake valve. All of the factors combine to demand a more effective fuel mixing method.

Small displacement applications which have historically been dominated by carburetion stand to benefit greatly from the introduction of low cost electronic fuel injection upstream of the cylinder head. Henceforth this method will be referred to as port injection (PI). In the simplest settings, PI consists of a throttle similar to that used in all other methods of fuel mixing, and an electronic solenoid which is pulsed to provide the correct amount of fuel for the engine. What sets PI apart from all other types of fuel mixing is the fact that in most higher performance applications, the injector is positioned downstream from the throttle, aimed directly at the intake valve. The intake valve, which absorbs large amounts of heat from the combustion process, vaporizes any injected fuel which contacts it and produces a more complete combustion as a result. In addition, the cooling effect of greater fuel vaporization increase the engine's charge when in turn increases its power output and fuel economy.

1.2 Project Description

With all of these concepts and considerations in mind, this project aims to provide a technical demonstration of how modern injection techniques are not only technologically feasible for low power applications, but also cost effective and environmentally beneficial. The Environmental Protection Agency (EPA) defines a similar low-power segment of engines as gasoline-fueled non-road equipment (GNRE). This category can be further divided into gasoline-powered lawn and garden equipment (GLGE) lawn and maintenance equipment (GLME). While data on this section of internal combustion engines is relatively sparse compared to passenger vehicles, GLGE accounted for between 25-45% of all non-road emission in 2011 [2]. The use of 2-stroke engines in this sector contributes significantly to the overall emissions, however, a significant portion of GLGE equipment utilize 4-stroke carbureted engines as seen in Table 1.1. Importantly, most of these engines lie in the 1-3 horsepower (hp) range while lawnmowers, which are also included in GLGE, range from 4-40 hp. Consequently, this project's engine was deemed comparable.

Table 1.1: GLGE Equipment Configurations [2]

GLME	Engine Configuration
Leaf Blowers	2 stroke, 4 stroke
Trimmers/Edgers/Cutters	2 stroke, 4 stroke
Mowers	4 stroke
Other GLGE	**Engine Configuration**
Chain Saws	2 stroke, 4 stroke
Rotary Tillers	2 stroke, 4 stroke
Snowblowers	2 stroke, 4 stroke
Turf Equipment	2 stroke, 4 stroke
Chippers/stump grinders	4 stroke
Tractors	4 stroke
Shredders	4 stroke
Other	4 stroke

The engine in question is a 199 cubic centimeter (cc), single cylinder, 4-stroke from a Triumph Tiger Cub. It produces around 14 hp at maximum output [3]. Preliminary testing was conducted to determine baseline data before implementation of an electronic fuel injection (EFI) system on the motorcycle engine. Afterwards, a cost-effective EFI system was developed and integrated onto the engine with the goals of improving peak power output, fuel economy, throttle response, and starting ability.

Chapter 2

Methods

2.1 Fuel Management Models

There are three fuel delivery models which are widely used in electronic fuel injection calculations. Each requires its own specific array of sensors and has drawbacks which should be taken into account when considering a retrofit application. In this section, these methods will be explained and the considerations specific to this application will be discussed.

2.1.1 Mass Airflow Model

The mass airflow model (MAF) relies on a sensor to determine the velocity of air inside the engine intake. While there are several types of sensors which can be used for this model such as moving van meters and membrane sensors, modern engines usually employ a hot wire device [4]. As the speed of the flow increases, the hot wire decreases temperature which also decreases the resistance. By ohms laws the resulting current will be higher and the velocity can then be calculated internally. Adding a temperature measurement then allows volumetric flow rate to be converted to mass flow rate for fuel injection.

There are several downsides to MAF sensors which are relevant to this application. This first is the large size of these sensors compared to pressure sensors. On the Tiger Cub, there is no virtually no space between the rear of the carburetor or throttle body for a cylindrical MAF sensor. The second is the importance of accurate calibration of the velocity-current relationship which the ECU relies on when using a MAF sensor. Without an accurate calculation of the King's law constant through testing, the volumetric flow rate will not be accurate. Finally, MAF sensors are sensitive to contamination from particulate in the air and corrosion from harsh environmental conditions such as salinity. While MAF sensors are preferable for a custom designed throttle body, their size prohibits use on this application.

2.1.2 Speed-Density Model

The main advantage to the speed density model is that only two, small, easily retrofitted sensors are required for its use: manifold air pressure (MAP) and ambient temperature. In practice, ambient temperature can even be assumed to be a constant and the only one sensor is necessary. MAP sensors do not measure the speed or volume of the air flowing through the intake directly. Instead these use the ideal gas law to derive a volumetric flow rate from the speed of the engine and the manifold air pressure.

$$P\dot{V} = \dot{n}RT \tag{2.1.1}$$

$$\dot{V} = \frac{V_{dis}RPM}{CPR} \tag{2.1.2}$$

$$\dot{m} = \frac{PV_{dis}RPM}{2R_{air}T} \tag{2.1.3}$$

The primary downside to the speed-density model is that most engines are not 100% volumetrically efficient. Leaks around different sections of the intake tract will cause the vacuum to be lower than expected for a given displacement. This factor is especially important for a retrofit application like this project. Single cylinder "thumpers" like the Tiger cub have additional pressure instabilities which result from having one cylinder. Even though pressure changes travel at the speed of sound, there is not a distinct separation between when the intake valve of the engine closes and when compression begins [5]. In addition, the intake manifold does not always see a constant flow rate because the engine spends $\frac{3}{4}$ of a cycle with the intake valve closed or partially closed. This causes erratic pressure values in the intake section which are extremely problematic for the ECU at low rpm. In a multi-cylinder engine, there is greater percentage of time when any given cylinder is on the intake stroke thus creating more uniform flow through the intake manifold where the MAP sensor is usually placed.

2.1.3 Alpha-N

Alpha-N tuning operates off of only two variables as well: engine load as measured by the throttle position, and engine speed via an rpm signal. The difference with Alpha-N is that it does not calculate the required fuel through any direct measurements of the engines conditions. Instead, it works purely off of an estimate of the engine's volumetric flow rate at a given load. The primary advantage to Alpha-N is that the only additional sensor needed besides the tachometer input is a throttle position signal (TPS) on the throttle body itself. This method is also far less sensitive to flow instabilities in the intake tract. For idling and other low rpm zones on the Tiger Cub, Alpha-N is extremely effective. Once the throttle has been applied however, the speed-density model becomes superior for this application.

2.2 Experimental Setup

2.2.1 Injector Integration

The first and most critical step when implementing an EFI system is selecting a fuel injector. In order to accomplish this, an understanding of their simple mechanics is necessary properly fulfill the requirements of a given application. The fuel injector is responsible for providing the correct amount of fuel for a given amount of air which is entering the combustion chamber. For a single cylinder engine, calculating the correct amount of fuel is relatively simple but critical to injector sizing. The governing equation is the reaction of gasoline (approximated as octane) with air. To completely react one mole of octane requires 12.5 moles of oxygen. By weight, taking into account the average makeup of air (oxygen = 21.2%), this equates to a stoichiometric AFR of 14.7:1.

$$C_8H_{18} + 12.5O_2 \rightarrow 8CO_2 + 9H_2O \tag{2.2.1}$$

The Tiger Cub's engine has a displacement of 199 cc which will be approximated to 200 cc. This amount of air weighs in at 0.257 grams at STP [6]. The amount of fuel needed to react with this amount of air, which corresponds to one intake stroke of the engine, is 0.0175 grams. This number is important as it will help determine the baseline injector setting for idling. For selection of the injector however, a maximum fuel flow quantity is necessary. To find this, the maximum engine rpm of 6000 is used. Because this is a 4-stroke engine, there is combustion once every two revolutions. Consequently, a maximum fuel flow of 52.5 $\frac{g}{min}$ is determined.

2.2.2 Injector Sizing

Injectors are usually sized in terms of $\frac{lb}{hr}$ which for our application means around $7\frac{lb}{hr}$. Critically, if a $7\frac{lb}{hr}$ injector was used for this application, running at as little as 80% power for an extended period of time could potentially damage the injector. This is due to the way in which injectors meter fuel. Consisting of essentially just a solenoid valve, fuel injectors exhibit several characteristics which must be taken into account for combustion applications. The two main considerations are response time and duty cycle. Response time refers to the amount of time a solenoid takes to fully open or close and is usually on the order of 1ms for fuel injectors. If a fuel injector is too large for a given application, at low engine speeds the injector will be operating at a very low duty cycle where the amount of fuel needed is so small that the amount of open time is within the response time of the injector. This is not ideal because the solenoid will be only be partially opening and closing and not given a consistent or accurate amount of fuel. In some cases, the injector may not even be able to meter to such a low fuel level and the engine will therefore run lean at ideal. On the other side of the spectrum is running too small of an injector. Here there are two possible issues. The first is in the case where an injector's wide open fuel flow is not enough for the engine at maximum rpm thus limiting power production. The second is when an injector must run at a high duty cycle (85-100%) to achieve the engine's max power output. This would result in overheating and seizure after prolonged operation. Consequently, injectors are usually sized to meet an engine's maximum fuel flow needs at an 80% duty cycle. For our application this increases our injector size from $7\frac{lb}{hr}$ to $9\frac{lb}{hr}$.

2.2.3 Fuel Delivery System

While sophisticated fuel injectors meter with great precision, this method is predicated on a constant supply of high pressure fuel. Three components are necessary to achieve this: a high pressure-low displacement pump, pressure regulator, and tank. While the Tiger Cub already has a fuel tank, its carburetor was gravity fed so no high pressure supply is available. Fortunately, fuel pumps of all displacements and operating pressures are available because using larger injectors is a cheapest and fast way to get more power out of an engine. For this project, an in tank fuel pump and regulator was sourced from a 2015 Honda PCX 150. The PCX 150 is a similar displacement engine at around 150 cc and produces exactly the same rated horsepower at 14 hp. Consequently, it fuel supply system should be adequate to deliver fuel to the injector.

2.2.4 Crank Position Sensing

While there are a variety of engine cycles which can utilize fuel injection, the one investigated in this project is Otto cycle [7]. Comprised of four distinct strokes, the Otto cycle tracks the position of the piston from top dead center (TDC) to bottom dead center (BDC). Moving from TDC to BDC is considered a single stroke and accounts for half a rotation of the crankshaft. To begin the cycle, the piston begins a movement from TDC to BDC while the camshaft forces a push-rod to open the intake valve on the cylinder head. As the piston moves away from the intake port, it draws in a mixture of fuel and air. After the piston reaches BDC, its return begins the compression stroke when the fuel-air mixture is compressed 7:1 in preparation for combustion. Sometime before the piston reaches TDC, the ignition system will initiate combustion using a spark plug. The amount of time or degrees before TDC (BTDC) at which the spark is initiated is called timing advance and for the Tiger Cub is roughly 4° BTDC [6]. Timing advance is critical because it takes time for the flame front to propagate towards the cylinder walls and complete combustion. In addition, as the engine picks up speed, the combustion process will have less time to finish before the crank is at the best position for the power stroke after TDC. Consequently, the timing must be advanced proportionally to engine speed. The final stroke also utilizes the camshaft to open the exhaust valve and expel the combustion products before the cycle repeats.

The two events from the descriptions above which are important to this project are the intake stroke and ignition event. More specifically, the timing of these events relative to crankshaft position is critical to ensure smooth and efficient operation. In order to accomplish this, the position or velocity of the crankshaft must be known at all times. in practice, there are a variety of ways in which the crank position can be tracked with suitable accuracy including inductive, hall effect, optical, and magnetic sensors. Most commonly, these are used in conjunction with a toothed reluctor wheel [8].

For ignition, the Tiger Cub utilizes a mechanical technique which is emblematic of most carbureted systems. As previously mentioned, the fuel side of the problem is controlled passively by employing a camshaft to open and close the intake valve which draws in air and fuel using the carburetor. The ignition side on the other hand uses a spark distributor which is connected to the crankshaft using a distributor drive gear as shown in Figure 2.1. This connection is not a direct drive however. Because a spark event is only required for every two revolutions of the crankshaft, the distributor drive is geared down by a ratio of 1:2. This particular connection to the crankshaft is critical because it enables access from outside the engine's case.

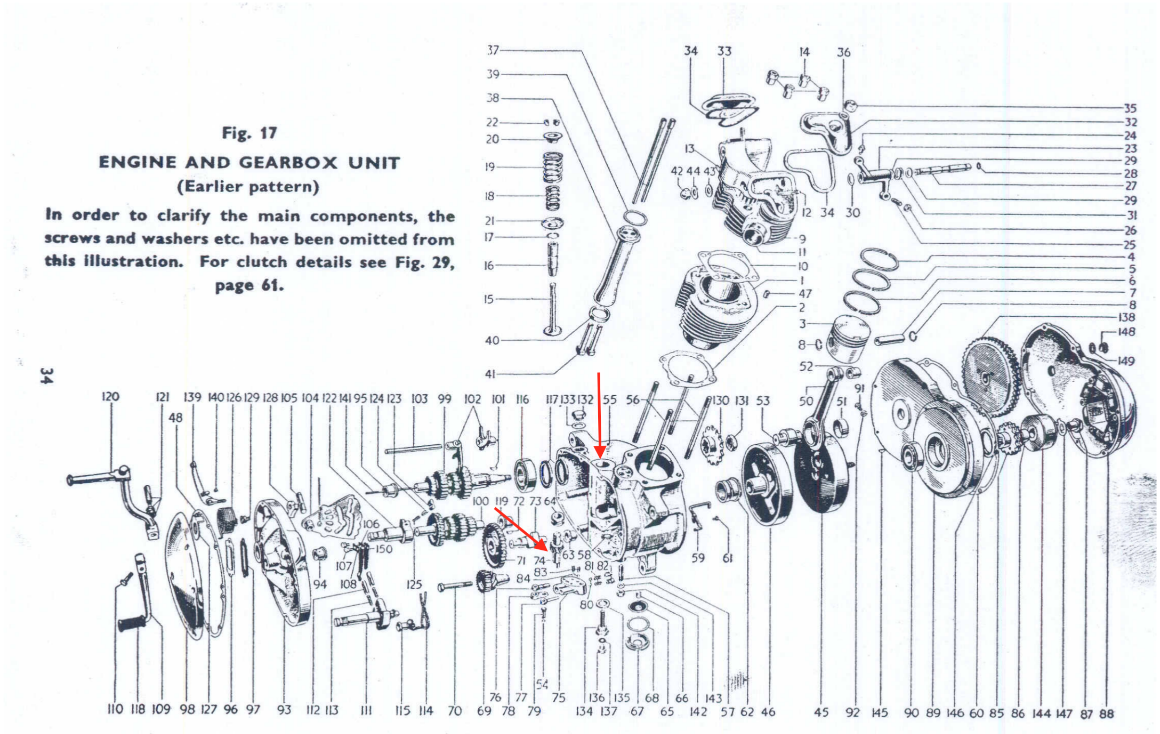


Figure 2.1: Illustration of Distributor Drive Gear and Mounting Point

2.2.5 Encoder Selection and Implementation

While many traditional forms of crank position sensing could have been used for this project, they all have major drawbacks for this particular application- the primary being invasive modifications. While most of the systems necessary for proper fuel injection and ignition timing on the Tiger Cub have to be added, this project sought to keep permanent modification to original parts to a minimum. For the crank sensor, this meant that any traditional method, which would require drilling into the crankcase or attaching devices such as magnets to the flywheel, were out of the question. The external distributor provided an excellent opportunity for a direct connection to an incremental magnetic encoder. Another reason for selecting an encoder over other methods of rotational sensing was the impact of engine heat on magnets and the poor quality of analog signals. The specific encoder considered for this application was a three channel quadrature encoder which employs two directional channels (A and B), and one position or homing channel Z. By reading the priority of the digital output of the directional channels, a micro-controller can first determining the direction which the encoder shaft is spinning. Next, the angular velocity of the shaft can be found using the frequency of this signal. Finally, the Z channel, which goes high once per revolution, can be used to determine to position. Each of theses channels also has a complimentary signal which can be used to improve noise resistant when signals are being passed over long distances or in areas of high interference. While this was not a concern for this application, the encoder is robust enough for use in future project in the department.

It is worth mentioning that encoders have several drawbacks which usually preclude them from this type of application. The most difficult being mechanical constraints such as maximum angular velocity and vibration restrictions. Because encoders use precision bearings to keep a constant gap between their encoded disk and the sensor, high rpm and the resulting vibration can cause inconsistent signals and eventually destroy the device altogether. Consequently, it was imperative to select an encoder which could withstand a moderate amount of vibration load and operate well beyond the maximum distributor speed of 3000 rpm. In addition, while a very high encoder resolution on the order of 1000 pulse per revolution (ppr) could have been selected, a more conservative 360 ppr was chosen to decrease the possibility of missing a count due to the low processing power of a available micro controllers and the high speed of the engine. Even with only 360 ppr, this degree of accuracy could only be maintained after designing a precision mounting system to hold the encoder in place above the distributor shaft. This process is outlined in a later design section.

Coil Signal

Given the difficulties with mounting an encoder described in the next chapter, another method was utilized to determine the engine's speed. By connecting the ECU directly to the engine's ignition coil, the rotational speed of the engine was determined using the frequency of ignition events. After using frequency rejection to filter this signal, it provided a clean input to be used by an ECU performing fuel injection.

2.2.6 Manifold Air Pressure Sensor

The MAP sensor is usually placed just after the throttle mechanism prior to the engine intake. Its purpose is to determine the amount of vacuum being drawn by the engine for use in the speed-density model described in the previous section. The only consideration when selecting a MAP sensor is whether or not your engine is naturally aspirated. Only about 1-2 bar is drawn from a naturally aspirated engine while 3-4 bar can be drawn from a turbo charged or other type of forced induction engine. The pressure range of the sensor must match the range of vacuum which the engine will produce.

Single cylinder engines like the Tiger Cub's have a unique behavior which can make the use of a MAP sensor complicated and sometimes altogether impossible. Due to their short intake tracks and single cylinder nature, the pressure inside of the intake is quite dynamic and often erratic. While a single cylinder only has one open intake valve per engine revolution, a twin cylinder has two, and a four cylinder engine has virtual one open intake valve at any point during a revolution. Consequently, the more cylinders an engine has, the more stable the airflow is through the intake manifold. An additional challenge from this behavior is called valve overlap. While intuitively one would think that the closing of the exhaust valve and the opening of the intake would be distinct events, in reality, they overlap considerably to assist the engine in maximizing charge at higher speeds [5]. This leads to even more unstable pressure readings in the intake as the exhaust and intake flows mix with one another. On the Tiger Cub, while this behavior was initially thought to warrant the use of another fuel management method, a MAP sensor was eventually implemented successfully.

2.3 Microsquirt Engine Control Unit

All the sensors and their data would be of little use without an engine control unit. The Microsquirt controller is a low-cost engine control unit which can be integrated with common automotive sensors to run fuel injection and electronic ignition. Because this kind of product has never been used in senior independent work before,

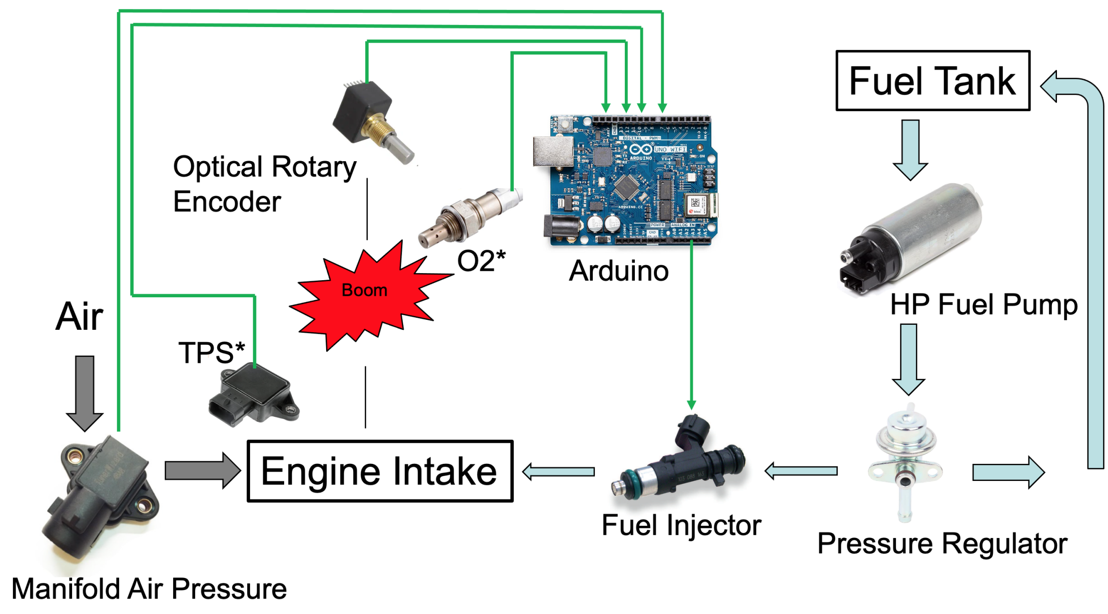


Figure 2.2: Illustration of Engine Management System

great effort expended to work through the capabilities and constraints of the ECU. Figure 2.2 illustrates the information flow from the ECU.

Chapter 3

Design

3.1 Design Philosophy

Over the course of projects such as this one, the designer faces a choice of whether or not to sacrifice the features and aesthetics of the original design. While more difficult to implement, retaining as much of the stock look as possible is often the more desirable path. For this project the rational behind this is quite obvious. The Tiger Cub serves as a demonstration piece for FRS 106: *The Art and Science of Motorcycle Design*. Fortunately, the course attracts students with varying levels of exposure to engineering. Consequently, there are some students who know what a carburetor is and how it works, other however do not have the slightest clue. As the Tiger Cub's technology becomes more obsolete, it will be important for students in the course to have a side by side comparison between carburation, a technique they will likely never see on any mode of transportation in their lifetimes and fuel injection. Consequently, allowing students to focus primarily on the distinctive elements between the two techniques will be extremely beneficial. In summary, while the fuel injection system looks distinctly different from a carburetor, any components which could be replicated or maintained between the carbureted bike and the fuel injected version were incorporated into the design to retain the motorcycle's simplicity and aesthetic appeal.

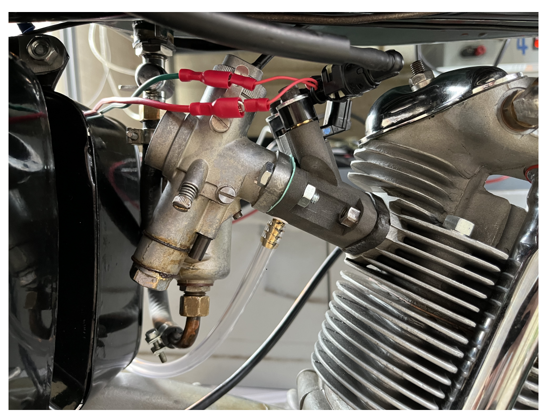
3.2 Throttle Body and Injector Housing

3.2.1 Injector Housing

The design of the throttle bottle/injector housing consisted of three distinct versions which have their advantages and disadvantages. Originally, the design consisted of two separate sections. The first was an injector spacer which would connect directly to the engine. The second was a throttle body attached directly being the spacer. Together these two components would completely replace the carburetor. Due to the complex geometries which a traditional throttle body consists of, this part was sourced from a similar displacement engine and adapted to the intake flange on the Tiger Cub. The injector housing however was originally planned to be machined from aluminum. During the early design stages however, this part was prototyped on a Creality Ender 3 FDM 3D printer. The benefit of this type of rapid prototyping throughout the design process can not be overstated. This and the recent addition of Formlabs Nylon Printers to the MAE shop eventually lead to an investigation into 3D printing as the main manufacturing method for this project. This process is detailed in the following sections.

Once the decision to 3D print the entire injection system had been made, more complex geometries were possible and the designed shifted to a single piece replacement for the carburetor which would function as a true throttle body. Throttle body

(a) Without injector housing



(b) With injector housing

Figure 3.1: Triumph Tiger Cub intake area

in this case refers to a module which housing the injector and controls the flow of air into the engine. The justifications for this design switch include the limited available build space and the aforementioned concept of retaining the motorcycle's stock look for educational purposes. While important sections of the throttle body such as the intake tract diameter and flange bolt pattern were easily to replicated with FDM printing, some aspects of a well functioning throttle were difficulty to produce. The throttle design relied on a similar valve technique as the carburetor's throttle. It consists of a cylinder which slides vertically to open up and close off the flow of air inside the intake passage. While this design is very simple, it relies the manufacturing method being able to produce parts with tight tolerances and exceptionally smooth surfaces on the cylinder and the passageway to keep the throttle from sticking in any given position and moving smoothly across the rpm range. Unfortunately, FDM and SLS printers are not able to print a perfectly smooth circular shape without extensive post processing. Consequently, the decision was made to retain the original carburetor body for use as a throttle while spacing it off of the intake with an injector housing.

It is worth reiterating that injector spray angle is one the primary benefits of fuel injection. In order to take advantage of this, mounting position of the fuel injector must be carefully considered. More specifically, being able to direct fuel onto the intake valve can lead to improved power production and fuel economy. Consequently, the main design goal with the final iteration of the injector housing was to position the injector as close to the intake as possible. In addition, it was critical to optimize the angle of the injector in its housing to get as much of the spray onto the valve itself. Because the valve is located below the actual intake opening, the only way to maximize the benefits from the injector was to mount it on the top side facing down. The issue here is that the Tiger Cub's engine is air-cooled, so it has large cooling fins which extend past the intake flange. This issue is illustrated in Figure 3.1a. As a result, the injector had to be positioned 0.6 in back from its optimal location and the angle of attack was adjusted accordingly. This offset prevented the design from fully realizing the injector's potential but still directs the majority of the fuel spray onto the intake valve.

3.2.2 3D Printing PETG and Nylon 12

3D printing engine components which will be exposed to high temperatures and corrosive fuel presented a unique but fascinating set of obstacles. With the FDM printers available, only a small subset of possible materials could be printed. Selection from the list of options was relatively simple. PETG's combination of high maximum operating temperature, resistance to gasoline, and FDM printing ability made it the first natural choice. Nylon also has a strong resistance to gasoline and an even higher operating temperature than PETG. In its current state, the Ender 3 printer unfortunately cannot print nylon filaments due to its high melting temperature. However, with a few small modifications, including an all metal extruder, it could easily print in nylon and other more versatile filaments. Fortunately, the recent addition of SLS nylon printers to the MAE shop allowed for the produced and testing of a nylon version for comparison with PETG.

3.2.3 Thermal Analysis

Due to the high heat loads coming from the combustion chamber to the cylinder head where the throttle body was attached, a thorough thermal analysis was conducted.

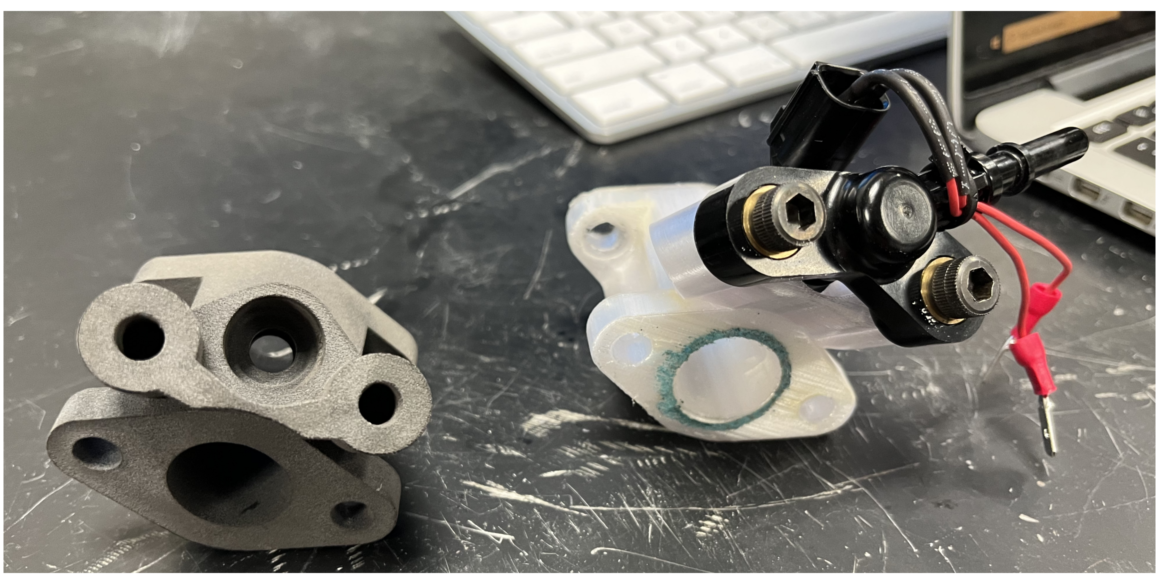
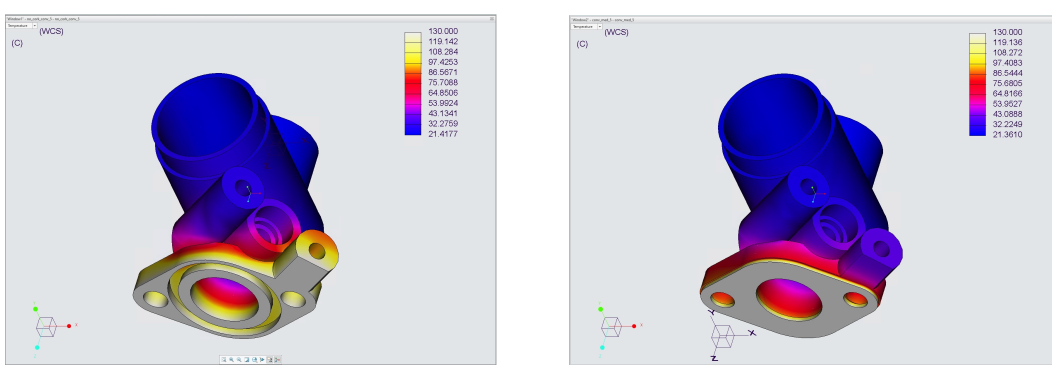


Figure 3.2: Nylon (Black) and PETG (Clear) Injector Housings

This was done using both empirical temperature data from the cylinder head while running with a carburetor and with an estimated heat flux derived from a usual percentage loss of total engine power as waste heat. Because there is no listed operating temperature for the Tiger Cub, a constant steady state value was found through testing with an infrared thermometer. The intake flange of the cylinder head was observed to reach surface temperatures at or below 120 °C. Because this testing occurred with the bike at a standstill under a load of 50% throttle, the conditions are representative of the average heat load from the bike while moving at all throttle ranges with greater convective heat transfer due to increase airflow over the engine while moving. With the 120 °C maximum exterior cylinder head temperature in mind, an 8% safety margin was instituted and consequently the CREO thermal analysis was run with an intake port surface temperature of 120-130 °C.

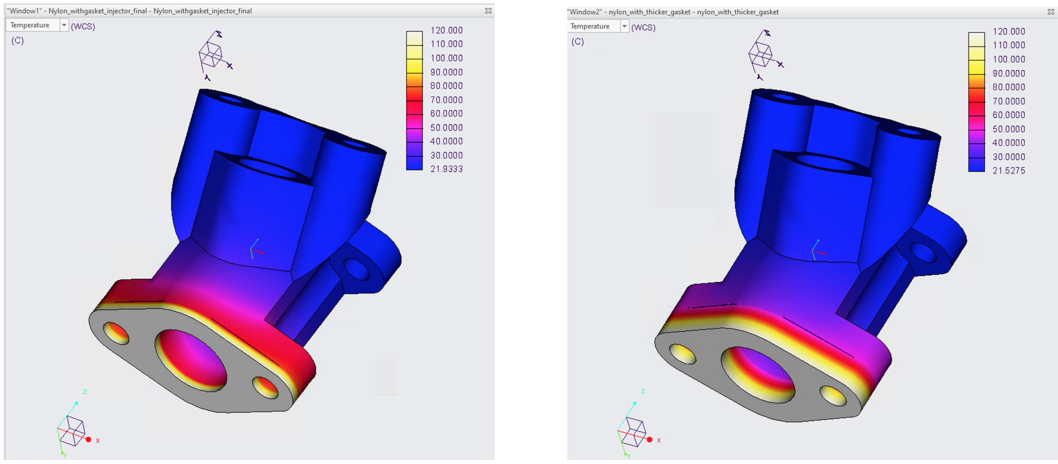
CREO's default thermal conductivity and specific heat capacity values for nylon and PETG were used for each simulation respectively. For simulations involving a gasket, cork was used as simulation material. In later testing, the cork gasket was replaced with a phenolic spacer as seen in Figure 3.4. To simulate the effects of heat convection off of the part while the bike was not in motion, conservative estimates for natural heat convection were used varying from 5-25 $\frac{W}{m^2K}$ [15]. Focusing on the lower end of the convection spectrum at 5 $\frac{W}{m^2K}$, it is clear from Figure 3.3 that without a protective gasket, the injector housing will reach temperatures far



(a) without gasket

(b) with gasket

Figure 3.3: Temperature distribution for contact temperature of 130°C and convection rate of $5\frac{W}{m^2K}$ on the throttle body



(a) 2.5 mm cork gasket on nylon

(b) 7.5 mm phenol spacer on nylon

Figure 3.4: Temperature distribution for contact temperature of 120°C and convection rate of $5\frac{W}{m^2K}$ on the injector spacer

exceeding the maximum operating temperature of PETG or Nylon 12 which are 67.3 °C and 121 °C respectively [10]. Consequently, the same simulation was run with a 2.5 mm gasket. With this addition, the PETG injector housing will be reaching the maximum of its continuous operating temperature given a reasonable safety factor so some deformation is expected over longer engine run times. The nylon version however was well within its operating range and should perform well over extended run times with no discernible defects.

While more accurate simulations of the temperature ranges in the middle section of the injector housing could have been found by taking into account the thermally conductive mass of the carburetor which is connected at the rear, the rear flange temperature was found in preliminary simulations to not be high enough for substantial heat transfer to have occurred. In addition, the thermal conductivity of both materials is low enough were appreciable conduction to the carburetor would not occur.

The last result from the thermal analysis which is extremely important in understanding the behavior of this part while thermal load is temperature gradient. For thermoplastics whose physical properties change dramatically depending on the temperature the material is at, it is critical to analyze where the maximum temperature gradients occur. For 3D printed parts, this is even more important because the part

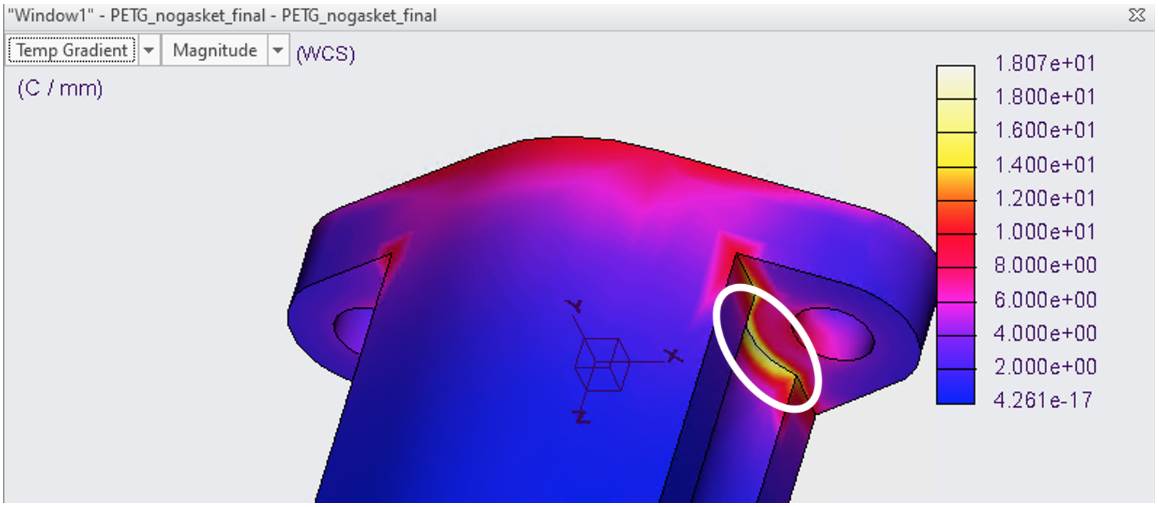


Figure 3.5: Temperature Gradient

is not homogeneous. The layers which results from the FDM printing process create obvious failure zones at the layers. This is especially true for areas with a high temperature gradient where one layer will expand due to a high temperature and another close layer will have a much lower temperature, not expand as much, and therefore break away from the expansion layer. By analyzing the areas were the maximum temperature gradients occur, failures sites can be predicted, observed, and reinforced to prevent a catastrophic event.

3.3 Encoder Mount

While the encoder was not implemented in the final system, a design was iterated for the purpose of mounting an encoder above the distributor shaft. The benefit of this method was that the crankshaft position could be measured from within the tight void between the engine intake and the seat. Unfortunately, implementing the encoder mount proved to not be feasible due to the difficulty in aligning the two shafts. Because encoders are only meant to support a certain amount of lateral force, if two connected shafts are not perfectly aligned, rotation will induce a force perpendicular to the shaft direction which in turn increasing wear on the high speed bearings within the encoder. Eventually, these forces would result in the encoder failing.

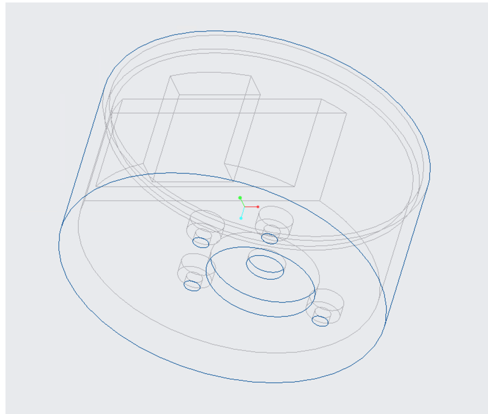


Figure 3.6: Encoder Mount

In an attempt to resolve this issue, the design of the encoder mount included two homing tabs which intercepted known extrusions on the distributor. This method, illustrated in Figure 3.6 was extremely effective with regards to locating the outer diameter of the encoder with the distributor casing. However, because the distributor shaft is not concentric with the outer diameter of the housing, the distributor and encoder axle did not align. At this point the encoder was replaced with a negative coil signal but remains an option for future work with the Tiger Cub.

Chapter 4

Analysis

4.1 Overview

The goals for this project were to develop a fuel injection system which could demonstrate the operating principles and benefits of fuel injection in comparison with carberhetion. In order to accomplish this, several types of data were taken and analyzed to illustrate increased fuel economy, improved starting performance, better throttle response, and increase peak power output. Peak horsepower can be measured using data taken from the MAE chassis dynamometer. The increase in fuel economy was measured via an oxygen sensor in the Tiger Cub's exhaust. Finally, starting performance was timed and described qualitatively over the duration of project.

4.2 Results

4.2.1 Dynamometer

One of the MAE dynamometers was planned to be employed in order to determine the maximum horsepower which the Tiger Cub can produce when running with a carburetor and when fuel injected. Comprised of a rotating drum of known mass, the dynamometer utilizes a very simply formula to calculate horsepower. Because power is just the product of torque and angular velocity, it can be calculated with

Figure 4.1: Dynamometer Setup

one pickup on the drum to determine the rpm and another formula for torque.

$$Torque = I_{drum}\alpha \tag{4.2.1}$$

$$Horsepower = I\frac{d\omega_{drum}}{dt} * rpm \text{ where } I = \frac{1}{2}mr^2 \tag{4.2.2}$$

The procedure for taking data from a run on the dynamometer is unfortunately significantly more involved than the calculations which it relies on. As previously stated, the MAE department dynamometer is a chassis dynamometer. This means that the Tiger Cub must be rolled up and onto the machine. It must then be secured by placing two racket straps from anchors points on the dynamometer frame to secure points on the bike such as the frame section which the seat attaches to. Importantly, the anchor points should be placed near the center of mass of the bike when a rider is on it. This keeps the chassis from moving vertically or side to side during a run. One final strap should is then placed from the front wheel holder through the spokes and back to the return hook to keep the bike from lurching off its mount during throttle off. The front wheel holder can also be adjusted to move the bike forwards and backwards on the stand. This feature allows the same stand to accept bikes of various lengths while still keeping the rear wheel centered on the measurement drum. This is critical because it mimics the interaction between the wheel and the road. If the bike's tire is tangent to any point on the drum besides directly on top, the torque exerted by the bike on the "road", and conversely the "road" on the bike, will not replicate real driving conditions. This fact is also important because it emphasizes that the chassis dynamometer is not designed to accurately characterise the engine's performance on it own. Instead, it is concerned with power generation at the wheel otherwise known as wheel horsepower (WHP).

Once the bike is in place and running, the dynamometer can be remotely triggered by the rider to begin processing and plotting either horsepower/rpm or torque/rpm. The maximum horsepower values are obtained with the bike in its highest gear while increasing engine speed from the beginning of the range up to red line.

Dynamometer Data Processing

Due to the age of the chassis dynamometer and its associated software, it is not currently possible to output raw data in any useful form. Instead, it is only able to display low resolution plots or output print files utilizing HPGL printer control language. Unlike other printer languages at the time, HPGL utilizes a coordinate system to direct the print head. Consequently, it would be possible for a script to be written to decode the printer language and scale the coordinates into raw data for processing and comparison in MATLAB. After this however, it would still be necessary to utilize either a floppy disk or ethernet file share to retrieve data from the dynamometer computer. For this project, while runs were conducted with the carbureted Tiger Cub on the dynamometer, the data was not found to be suitable for further analysis.

4.2.2 Oxygen Sensor

Data from the oxygen sensor gave the most precise and noteworthy results from the fuel injection system. In general, there are two main types of sensors, wide-band and narrow-band. While narrow-band sensors can only be used to determine whether the engine's AFR is rich or lean, wide-band sensor output a different voltage across the AFR range and can be used for much more accurate tuning [11].

While the operating principles of a wide-band oxygen sensor are quite involved, there are a few facts which are of importance to this project. The sensor itself relies on a "Nernst Cell" which is exposed to both the exhaust flow through a diffusion hole, and the outside environment. If there is a difference in oxygen concentration across the cell, a voltage is produced which can then be measured an converted to an AFR value. Crucially, these sensors really on a constant temperature inside the Nernst cell. This is achieved using a separate heating element which keeps the sensor above the exhaust gas temperature. The sensor cell is also susceptible to contamination from other combustion products such as NO_x and other pollutants including phosphorus from burnt oil or silicon resulting from a blown head gasket [12]. It should be noted that the Tiger Cub's engine was observed to be burning a small amount of oil during testing. This could have had a slight impact on the O_2 results.

O2 Data Filtering

The preliminary data taken by the oxygen sensor on the Tiger Cub clearly illustrated noise in the form of high frequency oscillations. Because these oscillations increased in magnitude as testing went on and the engine heated up, exhaust leakage most likely caused this trend to appear. While any observed leakage in the exhaust was addressed as soon as it was observed, the raw AFR data was filtered in an attempt to reduce noise contamination and better depict the effects of engine load and fuel mixing. To accomplish this, a low-pass filter was first applied to the raw data utilizing a factor of the session's mean sample rate for frequency rejection. The effects of this post processing are illustrated by the blue curve in Figure 4.2. While this curve

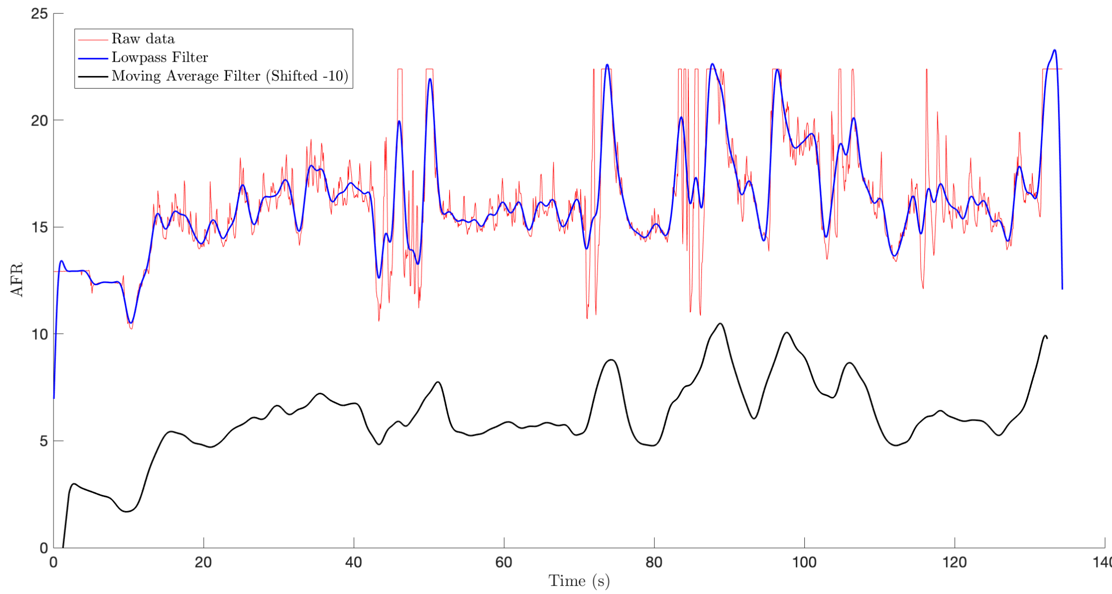
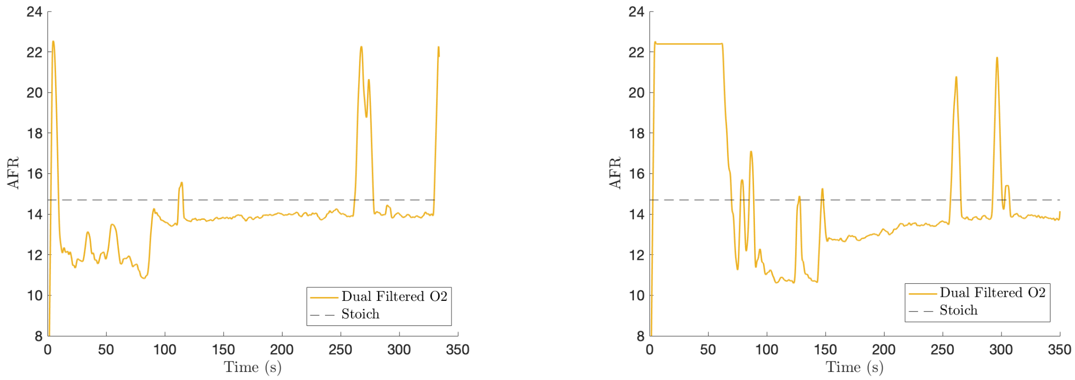


Figure 4.2: Carbureted Engine Oxygen Data Filtering

is useful in identifying the actual magnitude of smoothed AFR values, it is still difficult to determine whether the engine is at idle, under load, or moving closer to the stoichiometric ratio via the Microsquirt's closed loop control. To depict these trends, a moving average filter was applied to the filtered curve. The black curve in Figure 4.2, which had been shifted down -10 on the AFR y-axis, clearly depicts when the engine is at idle (horizontal curve) and where the engine is being throttled up (spikes towards a higher AFR under).

Closed Loop AFR Control

After the initial data from the carbureted engine had been taken, the O2 sensor was used to measure the effeteness of the Microsquirt's closed loop AFR control on the Tiger Cub. These test yielded impressive results as the controller was able to begin moving towards the correct stoichiometric ration within 100-150 seconds after after starting. While the settings can be adjusted to begin applying closed loop control more quickly after engine start, it is beneficial to wait for the engine temperature to begin to rise and the engine speed to reach a stable level. As the fuel injection system usually started on the richer side around AFR = 12, the controller reliably closed to



(a) Test 1 (b) Test 2

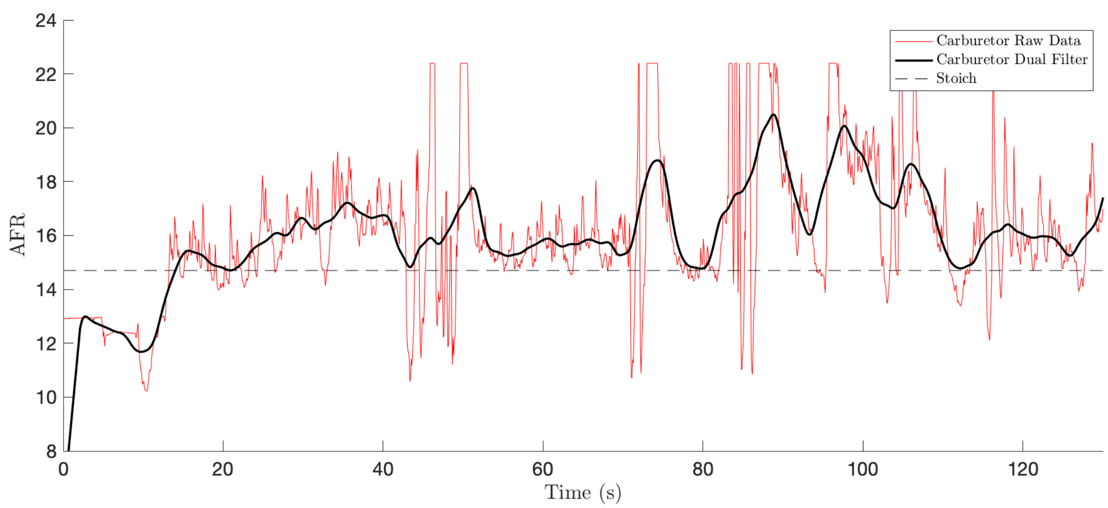
Figure 4.3: Closed Loop AFR Control at Idle

within 2% of the desired AFR within a reasonable time frame. Again, the controller is capable of tracking much closer to a desired AFR but was programmed to run rich while the engine was still moving towards operating temperature.

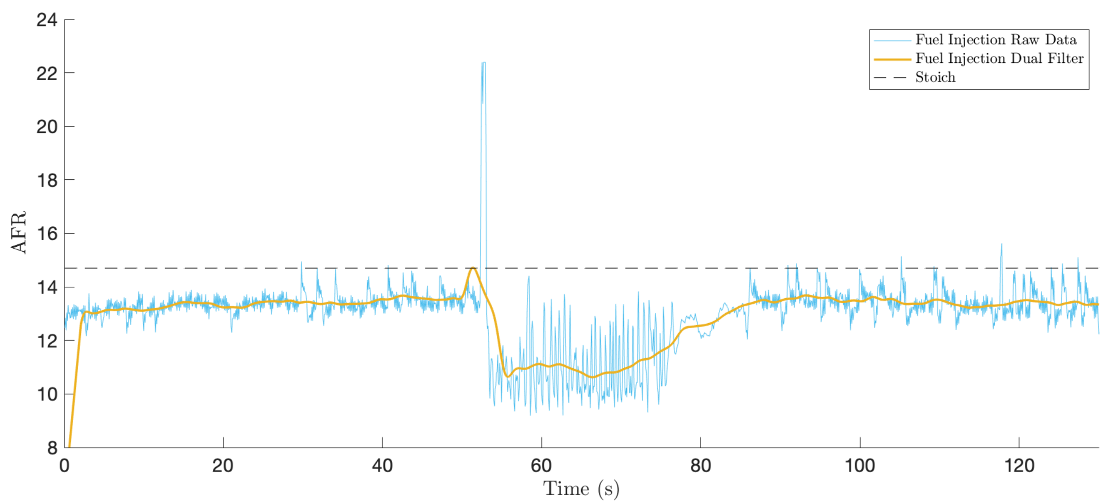
Carburetor and Fuel Injection Comparison

The last testing conducted with the oxygen sensor measured the performance of each system under load. To simulate this, both systems were run up to the same rpm and then back to idle in order to see how the mixture from each reacted and recovered. In the case of the carburetor, the mixture at idle was lean and became even leaner when the throttle was applied. Figure 4.4a depicts several separates instances when the throttle was applied. The reaction of the system was to run more lean at an AFR of around 20-22. While intuitively, this may seem like a good result because the engine is burning less fuel under load, it could actually cause the engine to be damaged. Fuel vaporization is a major source of heat loss in an engine so running lean under load can eventually cause the engine to overheat. While this carburetor was tuned prior to testing, this result just illustrates the potential consequences and drawbacks of not having a perfectly tuned carburetor for a given set of environmental conditions.

The fuel injected system on the other hand performed quite well under load. As illustrated in Figure 4.4b, the fuel injected system began the test tracking very close to the optimal AFR. Upon application of the throttle, the mixture was enriched to reduce lagging during engine acceleration. After the load was released, the system quickly move back to its optimal AFR. Consequently, fuel injection system produces a more advantageous AFR ratio under load and recovers more quickly when the throttle is released, thus saving fuel. These characteristics are by no means an coincidental. Fuel injection systems like the Microsquirt are completely programmable which means this behavior or any of those discussed so far can be manipulated or changed depending on the desired outcome for the system. AFR control and throttle response are just a few examples of the flexibility and precision of such systems.



(a) Carburetor



(b) Fuel Injection

Figure 4.4: AFR under throttle up load

4.2.3 Starting Performance

Over the course of this project, the Triumph Tiger Cub was started a multitude a times utilizing a variety of methods. Very early on, when the bike had not been run for sometime, the carbureted engine was difficult to start reliably. Starting fluid was frequently employed to give an initial inertial boost and wet the cylinder walls. Without the assistance of starting fluid, dozens of attempts had to be made in succession to wet the cylinder walls with fuel and place the engine in an advantageous condition to start. Because the bike does not have an electric starting system, the process of starting the motorcycle could often be physically demanding and delay any experimentation or analysis the user was wishing to perform. In winter months this was even more of a problem as the engine started from colder conditions which made more fuel condense on the intake walls instead of making it into the combustion chamber. Consequently the air-fuel ratio would be off until the walls were sufficiently dampened.

Getting the Triumph Tiger Cub to start reliably was one of the main goals and greatest successes of this project. As previously mentioned, with a carburetor starting from cold engine conditions, this particular Tiger engine often took dozens of attempts to start. While this changes to one or two attempts when the engine is warm, it still causes logistical problems if the engine is being used for research. With fuel injection, the engine now starts reliably with one generous starting kick. The Microsquirt controller is aware of whatever environmental conditions the engine is in when starting due to the suite of sensors which has been fitted to the bike. Consequently, the motorcycle will continue to have excellent starting performance baring any major mechanical change or damage. Not only was the beneficial for this project's attempt to characterize the performance of the fuel injection system, it also created a reliable and easily controllable engine platform for future student work which was not previously available.

4.2.4 Thermal Stress

As previously stated, Tiger Cub engine was put through many thermal cycles from cold engine temperature all the way up to the stationary steady state engine temperature of 120 °C. Consequently, the results from the CREO thermal analysis were compared to the real world results after using PETG and nylon as engine intake components. Unfortunately, after only three thermal cycles, the PETG injector housing was inspected and found to have significantly deteriorated. As illustrated in Figure 4.5, the inner diameter of the injector housing had become brittle and prone to cracking. Several networks of cracks had begun to propagate from the middle section of the passageway out towards exterior walls. At this point in the testing, the PETG part was replaced with a Nylon version in order to prevent a catastrophic failure.

While the preliminary thermal analysis did not predict the failures during testing, there are two possible explanations for why the PETG showed sings of deterioration sooner than expected. The first is due to the stresses causes by repeatedly cycling through different temperatures. While this would certainly have a negative effect on a thermoplastics mechanical properties, due to the relatively low number of cycles the part underwent, and the cracking nature of the defects, this is likely not the best explanation. Another aspect of the physical testing which was not including in the thermal analysis was mechanical load. Not only does the 3D printed part support the suspended carburetor, it is also connected directly to the engine and vibrates constantly. It is likely that as the PETG reached its maximum operating temperature, vibration caused layer separation at the surface of the part where defects

Figure 4.5: PETG Deterioration

already existed, and then crack propagation. One piece of evidence supporting this notion is that the nylon part, which has a much high layer resolution, showed no signs of cracking.

While PETG is certainly an effective material for rapid prototyping of engine components which must be exposed to gasoline and higher temperatures than most thermoplastics can withstand, it is not well suited for extended use in the engine intake. There are other plastics such as Nylon which are easily printed on both FDM and SLS machines that have far higher operating temperatures. If PETG is to be used around an engine however, improving the surface finish of FDM printed parts would increase there service life considerable by removing surface defects cause by layer separation at which cracking originates.

4.2.5 Throttle Response

One of the more difficult aspects of this project was achieving smooth throttle performance on the Tiger Cub. A throttle position sensor is necessary to give the ECU an indication of the user's desired power output for a given load. While the Tiger Cub can currently go through the rpm range with just a MAP sensor, the controller is hesitant to inject more fuel into the engine because it is not given any indication of an increase in desire power output by the user. If a TPS sensor was added, this problem would be completely resolved and the system would behave as expected. Several possible methods for accomplishing this are discussed in the next section.

Chapter 5

Conclusion

5.1 Summary

Over the course of the academic year, the aim of this project was to create a minimally invasive fuel injection system for a Triumph Tiger Cub motorcycle. Because the chosen platform was produced from 1954 and 1968, its design was not optimal for retrofitting a fuel injection system. In fact, factors such as the bike's lack of a crankshaft position sensor and the challenges associated with easily adapting one to the engine forced ignition control out of the scope of this work. With that being said, the implementation of a fuel only electronic engine control was extremely successful. Utilizing the Microsquirt platform, existing components such as the ignition coil were adapted to give the controller the necessary engine information for fuel injection. After researching the key concepts regarding the fuel delivery system for EFI, off the shelf components such as the injector, fuel pump, and MAP sensor were selected to complete the system.

In order to integrate the fuel injection components to the Tiger Cub, several designs were developed and 3D printed including an encoder mount which, while not ultimately used in the final system, presents a great path for future work discussed in the next section. Additionally, the fuel injector mount and throttle body were developed over several iterations in order to accomplish as many of the projects goals as possible. Finally, the fuel system of the Tiger was adapted to house a fuel pump, pressure regulator, and high pressure fuel lines. Throughout this stage, several thermoplastics were researched, analyzed, and prototyped for us on the Tiger Cub.

After bench testing the system, confirming the proper operation of all components, and installing them on the Tiger Cub, work began tuning the Microsquirt for this specific application. Quite a capable controller, there are dozens of sources and thousands of options for configuring the controller for a given application's specific needs. While this is one of the greatest advantages to fuel injection, it was critical at this stage of the project to ensure all calculations for the engine's fuel requirements were correct and the corresponding settings in the Microsquirt's TunerStudio software were selected. After rpm signal tuning and fuel adjustments were made, the Tiger Cub starting reliably and running for any desired amount of time.

The final stages of this project consisted of tuning the Tiger Cub's fuel map by utilizing the oxygen sensor, installing the MAP sensor and changing the Tiger Cub's fuel calculations from alpha-N to speed density. Additionally, data was gathered to determine the performance of the fuel injection system compared to the carburetor. Testing over the course of project demonstrated the EFI system's superior fuel metering ability compared to the carburetor during starting and when maintaining a consistent idle. RPM and oxygen data taken during testing also demonstrated the fuel injection system's superior fuel economy and response to engine load.

5.2 Future Work

While many of this project's goals were successfully accomplished, several potential avenues for further work opened as a result. In particular, in order to truly reap the benefits of electronic fuel injection, an accurate method of crankshaft position sensing should be implemented. Hall effect sensors or encoders such as the one investigated during this project are excellent tools for implementing a full ignition timing system in conjunction with electronic fuel injection. Additionally, the fuel injection system could benefit from a well designed throttle position sensing system for smooth operation of the engine. Finally, the fuel injected and carbureted Tiger Cubs maximum power outputs could be compared following a thorough service of and development of a data transfer system for the MAE dynamometer.

While the above are simply ways to improve the existing system, its current reliability and robustness opens up many possible research opportunities. Various intake designs, injector spray geometries, fuel pressures, fuel types, etc. could now be compared on the same platform. Finally, further analysis with rapid prototyping materials such as PEEK and other advanced plastics also pose interesting potential projects. Once the engine is running, there's no telling how far it can take you.

Appendix A

Appendix

A.1 MATLAB Code

Contents

- Data Importing
- Data Filtering
- Closed Loop AFR Control
- FI and Carb Comparison

Data Importing

```
clear all
close all

%Carb idle and throttle up
CarbData = csvread("O2 Data/carbheretor.csv",4,0);
carbtime = CarbData(:,1);
carbO_2 = CarbData(:,2);

fuel_injection_first_test =
csvread("O2 Data/first test-Session 1.csv",4,0);
```

```
fift_time = fuel_injection_first_test(:,1);
fift_O2 = fuel_injection_first_test(:,2);

%Early cutoff
%fuel_injection_second_test = csvread("O2 Data/test 2.csv",4,0,
[4,0,712,1]);
%fift_2_time = fuel_injection_second_test(:,1);
%fift_2_O2 = fuel_injection_second_test(:,2);

fuel_injection_second_test_2 = csvread("O2 Data/test 2.csv",720,0);
fift_2_time_2 = fuel_injection_second_test_2(:,1);
fift_2_O2_2 = fuel_injection_second_test_2(:,2);

fuel_injection_third_test = csvread("O2 Data/test 3.csv",4,0);
fift_3_time = fuel_injection_third_test(:,1);
fift_3_O2 = fuel_injection_third_test(:,2);

%Closed loop idle illustration under FI
MAPData1 = csvread("O2 Data/throttle installed.csv",4,0);
MAPtime_1 = MAPData1(:,1);
MAPO_2_1 = MAPData1(:,2);

%Closed loop idle illustration under FI
MAPData2 = csvread("O2 Data/map take 2.csv",4,0);
MAPtime_2 = MAPData2(:,1);
MAPO_2_2 = MAPData2(:,2);

%Single throttle up goes rich under FI
Throttling_w_MAP = csvread("O2 Data/throttle up.csv",4,0);
Throttling_w_MAP_time = Throttling_w_MAP(:,1);
```

```
Throttling_w_MAP_O2 = Throttling_w_MAP(:,2);
```

Data Filtering

```
%Low Pass Filter
fs = 1/mean(diff(carbtime));
y = lowpass(carbO_2,0.0001,fs);

%Moving Average Filter
windowSize = 50;
b = (1/windowSize)*ones(1,windowSize);
a = 1;
y2 = filter(b,a,y);

stoich = ones(size(carbtime))*14.7;

figure(1)
hold on
plot(carbtime,carbO_2,'r')
plot(carbtime,y,'b',LineWidth=1.5)
plot(carbtime-2,y2-10,'k',LineWidth=1.5)
plot(carbtime,stoich)
xlabel('Time (s)')
ylabel('AFR')
legend('Raw data','Lowpass Filter','Moving Average Filter
(Shifted -10)')
axis([0 140 0 25])
hold off

% figure(2)
% hold on
```

```
% plot(carbtime-2,y2,'k',LineWidth=1.5)
% xlabel('Time (s)')
% ylabel('AFR')
% legend('Moving Average Filter onto Lowpass')
%
%axis([0 140 0 25])
%
% hold off

%All 3 on 1 axis
% figure(2)
% plot(carbtime,y)
% hold on
% plot(carbtime-2,y2)
% plot(carbtime,carbO_2)
% legend('Low Pass','Moving Average','Input Data')
```

Closed Loop AFR Control

```
%Low Pass Filter
fs_MAP1 = 1/mean(diff(MAPtime_1));
y_MAP1 = lowpass(MAPO_2_1,0.0001,fs_MAP1);

%Moving Average Filter
windowSize = 50;
b = (1/windowSize)*ones(1,windowSize);
a = 1;
y2_MAP1 = filter(b,a,y_MAP1);

stoich_MAP_1 = ones(size(MAPtime_1))*14.7;
figure(2)
```

```
hold on
%plot(MAPtime_1,MAPO_2_1)
%plot(MAPtime_1,y_MAP1)
plot(MAPtime_1,y2_MAP1,color='#EDB120',LineWidth=1.5)
plot(MAPtime_1,stoich_MAP_1,linestyle='--',color='k')
xlabel('Time (s)')
ylabel('AFR')
legend('Dual Filtered O2', 'Stoich')
axis([0 350 8 24])
hold off

%Low Pass Filter
fs_MAP2 = 1/mean(diff(MAPtime_2));
y_MAP2 = lowpass(MAPO_2_2,0.0001,fs_MAP2);

%Moving Average Filter
windowSize = 50;
b = (1/windowSize)*ones(1,windowSize);
a = 1;
y2_MAP2 = filter(b,a,y_MAP2);

stoich_MAP_2 = ones(size(MAPtime_2))*14.7;
figure(3)
hold on
%plot(MAPtime_2,MAPO_2_2)
%plot(MAPtime_2,y_MAP2)
plot(MAPtime_2,y2_MAP2,color='#EDB120',LineWidth=1.5)
plot(MAPtime_2,stoich_MAP_2,linestyle='--',color='k')
xlabel('Time (s)')
ylabel('AFR')
```

```
legend('Dual Filtered O2', 'Stoich')
axis([0 350 8 24])
hold off
```

FI and Carb Comparison

```
%Low Pass Filter
fs_comp = 1/mean(diff(Throttling_w_MAP_time));
y_comp = lowpass(Throttling_w_MAP_O2,0.0001,fs_comp);

%Moving Average Filter
windowSize = 50;
b = (1/windowSize)*ones(1,windowSize);
a = 1;
y2_comp = filter(b,a,y_comp);

stoich_comp = ones(size(Throttling_w_MAP_time))*14.7;

% Fuel Injection
figure(4)
hold on
plot(Throttling_w_MAP_time,Throttling_w_MAP_O2,color='#4DBEEE',
LineWidth=0.15)
%plot(Throttling_w_MAP_time,y_comp,color='#EDB120',LineWidth=1.75)
plot(Throttling_w_MAP_time-2,y2_comp,color='#EDB120',LineWidth=1.75)
plot(Throttling_w_MAP_time,stoich_comp,linestyle='--',color='k')
xlabel('Time (s)')
ylabel('AFR')
%legend('Fuel Injection', 'Carburetor')
axis([0 130 8 24])
legend('Fuel Injection Raw Data','Fuel Injection Dual Filter',
```

```
'Stoich')
hold off

%Carburetor
figure(5)
hold on
%plot(Throttling_w_MAP_time,Throttling_w_MAP_O2)
%plot(Throttling_w_MAP_time,y_comp)
%plot(Throttling_w_MAP_time,y2_comp)
plot(carbtime,carbO_2,'r',LineWidth=0.15)
%plot(carbtime,y,color='k',LineWidth=1.75)
plot(carbtime-2,y2,color='k',LineWidth=1.75)
plot(Throttling_w_MAP_time,stoich_comp,linestyle='--',color='k')
xlabel('Time (s)')
ylabel('AFR')
%legend('Fuel Injection', 'Carburetor')
axis([0 130 8 24])
legend('Carburetor Raw Data','Carburetor Dual Filter', 'Stoich')
hold off
```

A.2 TunerStudio User Interface

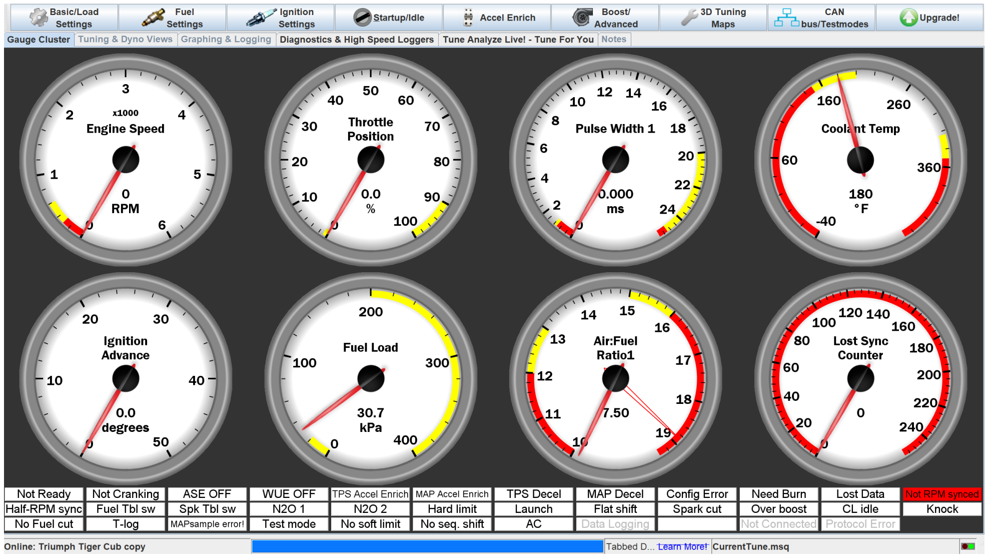


Figure A.1: TunerStudio readout screen

A.3 O_2 Sensor Software

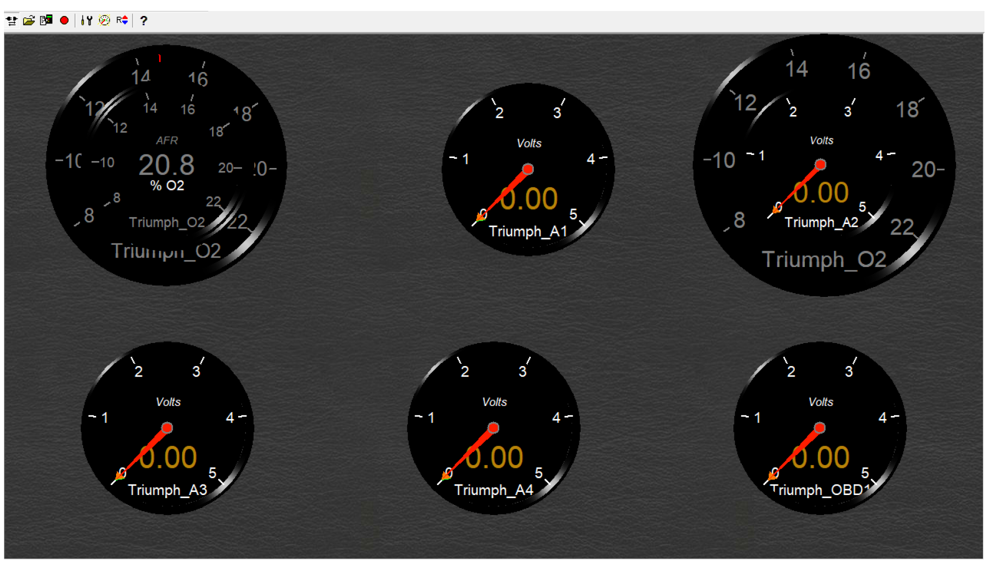


Figure A.2: O_2 sensor readout screen

A.4 Injector Spacers

Figure A.3: Throttle body iterations

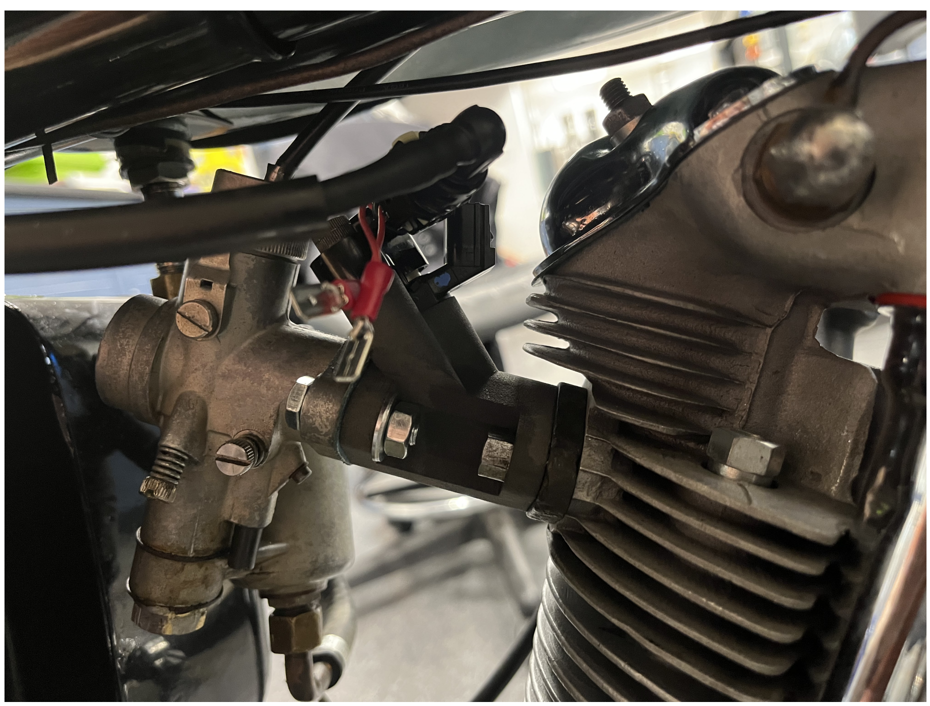


Figure A.4: Nylon injector mount

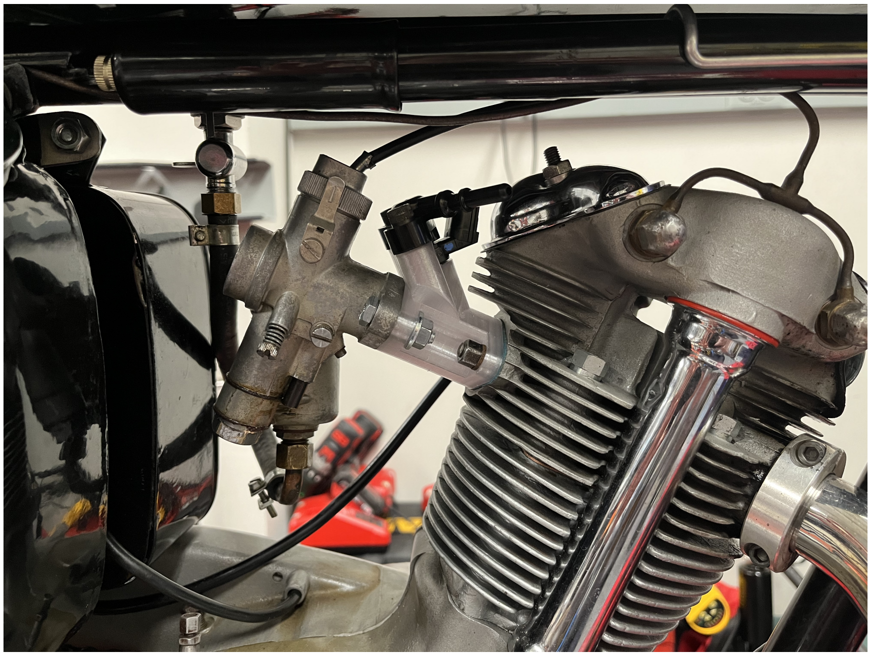


Figure A.5: PETG injector mount

A.5 Experimental Setup

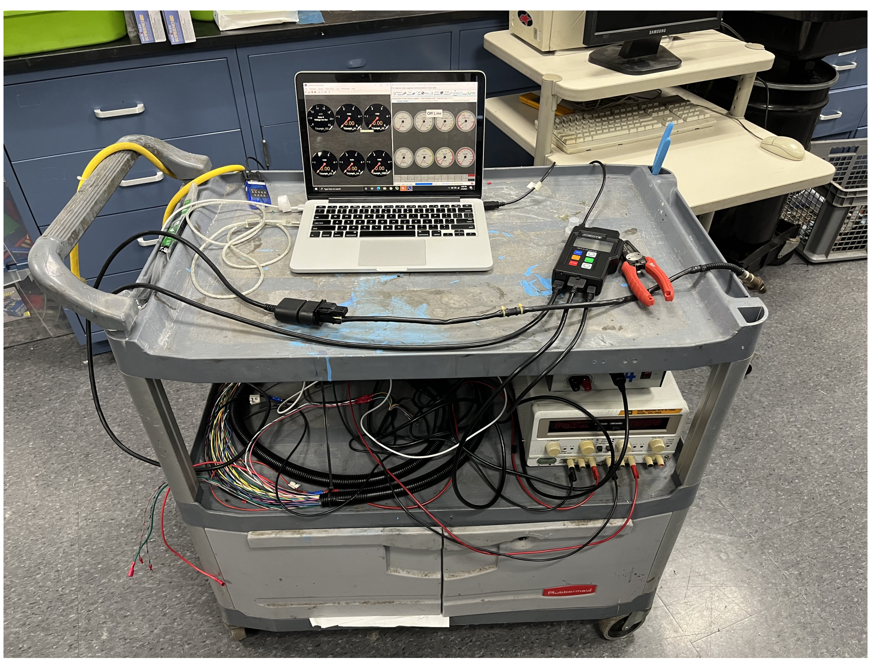


Figure A.6: Test stand

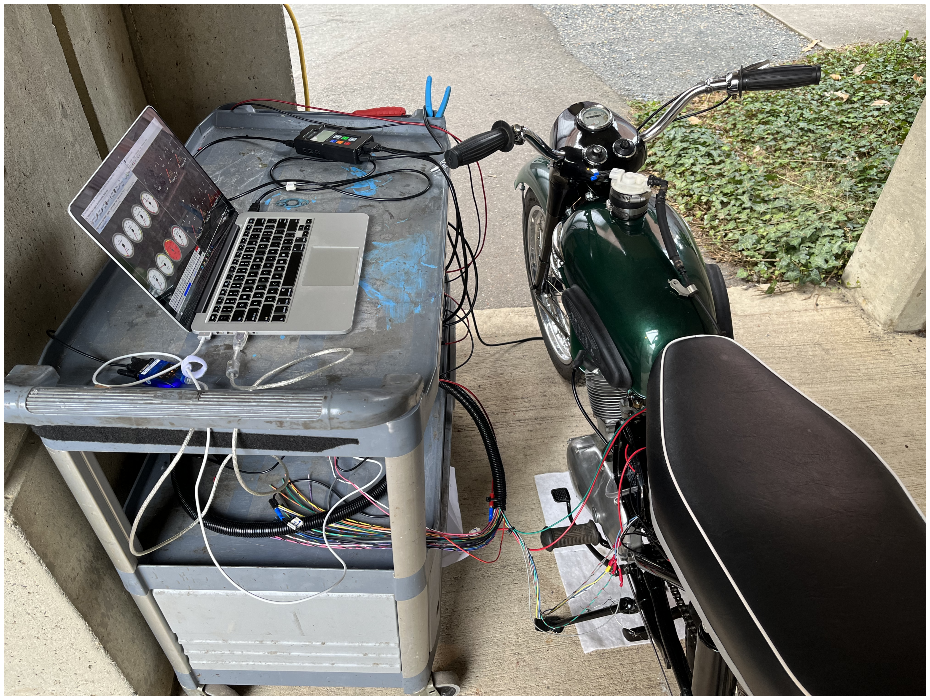


Figure A.7: Testing setup

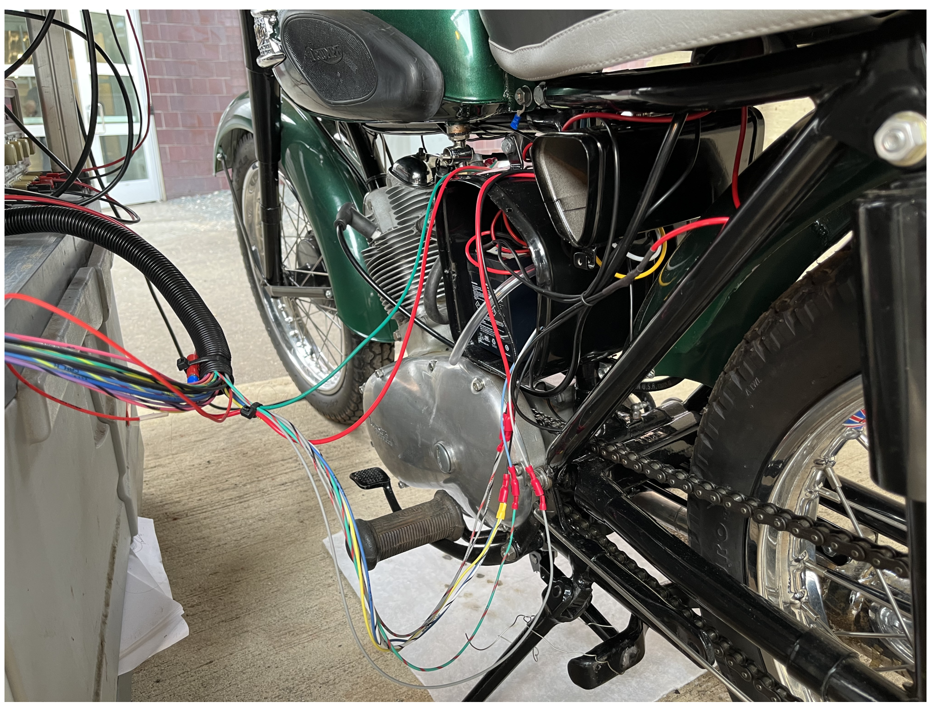


Figure A.8: Engine wiring

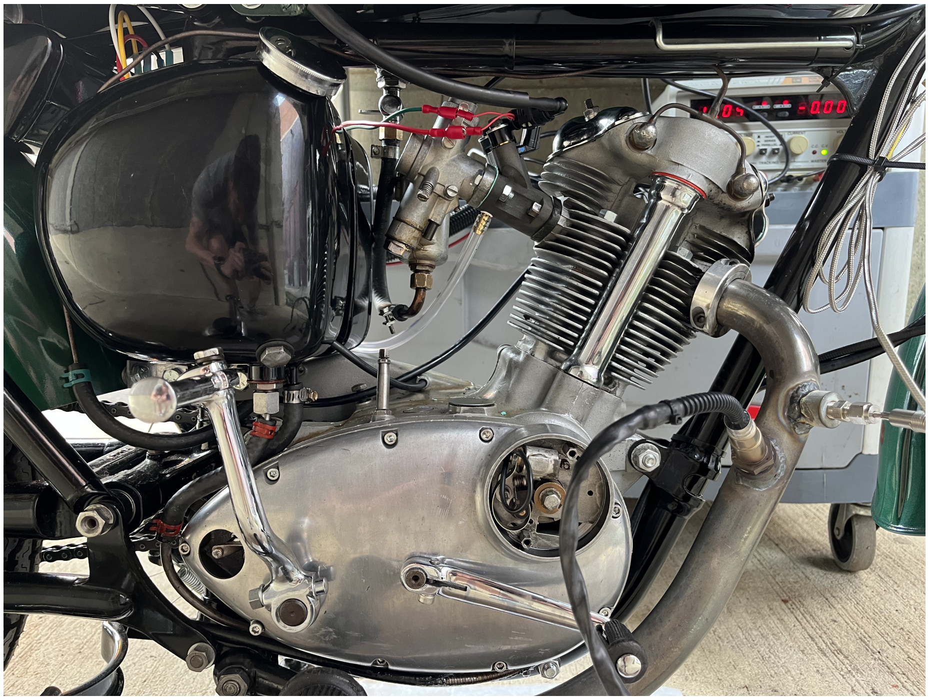


Figure A.9: Engine components

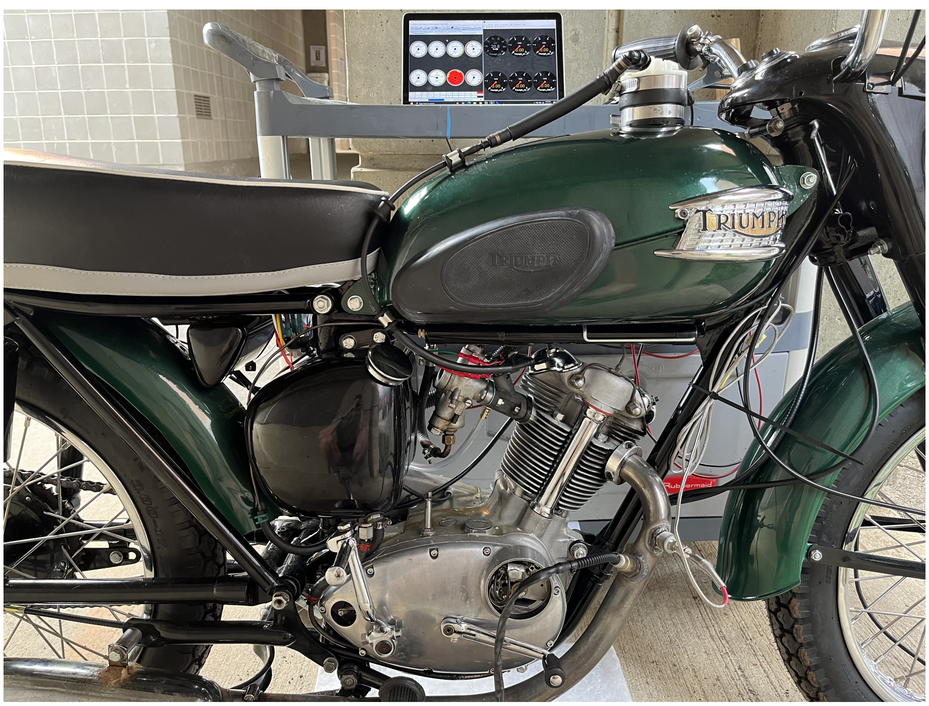


Figure A.10: Tiger Cub side view

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