TWO-STROKE ENGINE TEST PROCEDURES FOR PERFORMANCE AND EMISSIONS BASED CALIBRATIONS

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AUTHORIZATION TO SUBMIT THESIS

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ABSTRACT

Students involved in collegiate design series (CDS) competitions and engine lab research need to configure engine test equipment and implement protocols for meeting competition rules and/or graduate research. In this process students will modify fuel and ignition parameters across an operational band. This thesis inventories and details test procedures for medium scale two and four-stroke engine calibration and testing strategies. Procedures include lab specific set ups, society of automotive engineers (SAE) standard tests, and an strategies for calibration. These resources coupled with proper use of equipment allows the user to produce data regarding brake specific emissions, fuel consumption, power, and environmental protection agency (EPA) E-score.

ACKNOWLEDGEMENTS

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DEFINITION OF TERMS

CDS	Collegiate Design Series
SmERF	Small Engines Research Facility
EU	European Union
CSC	Clean Snowmobile Challenge
EV	Electric Vehicle
ICE	Internal Combustion Engine
DI	Direct Injection
CAFE	Corporate Average Fuel Economy
HC	Hydrocarbons
CO	Carbon Monoxide
NO_x	Oxides of Nitrogen
PN	Particulate Number
SAE	Society of Automotive Engineers
EPA	Environmental Protection Agency
NPS	National Park Service
DOE	Department of Energy
PCM	Powertrain Control Module
SDS	Safety Data Sheet
TDC	Top Dead Center
BDC	Bottom Dead Center
EO	Exhaust Port Open
TO	Transfer Port Open
TC	Transfer Port Close
EO	Exhaust Port Close
UHC	Unburnt Hydrocarbons
RAVE	Rotax Adjustable Variable Exhaust
FSAE	Formula SAE
FHSAE	Formula Hybrid SAE
EGR	Exhaust Gas Recirculation
LNT	Lean NO_x Trap

MAF	Mass Air Flow
VVT	Variable Valve Timing
PFI	Port Fuel Injection
TBI	Throttle Body Injection
BMEP	Brake Mean Effective Pressure
CVT	Continuously Variable Transmission
GA	Genetic Algorithm
BSFC	Brake Specific Fuel Consumption
SWRI	Southwest Research Institute
ECU	Engine Control Unit
RSM	Response Surface Methodology
UQ	Uncertainty quantification
AFR	Air-to-Fuel Ratio
SOF	Standard Optimum Form
NA	Naturally Aspirated
MAP	Manifold Air Pressure

1. INTRODUCTION

This section describes the philosophies and motivation for developing useful strategies for use of the research lab for small engines. Included is a basic guide for calibrating engines from the standpoint of Collegiate Design Series (CDS) teams. The environmental and legislative motivations will also be discussed. The goals of this research will be described to shed some light on a potential future for the power-sports industry.

There exists a need at the University of Idaho to mitigate "tribal knowledge" specifically in engine development. In addition to this the Small Engines Research Facility (SmERF), is unique to the University. As such, the organization of the equipment needs to be described both for maintenance and general use. As an addition to the sample data will be shown and described to aid in interpretation. Many common equations will be included that should be used in testing.

1.1. BACKGROUND AND MOTIVATION

As the global dependence on fossil fuels increases, the need for improved efficiencies, alternative fuels, and advancement in engine technology is an urgent concern. The European Union (EU) and the United States are implementing stricter emissions and fuel economy standards in the automotive industry to reduce the environmental impact of motor vehicles. The most common power plant in the United States is the four-stroke engine. In the recreation and utility market the two-stroke engine is extremely popular due to its high power to weight ratio and mechanical simplicity. However, four-stroke engines are gaining popularity for these markets as well. The power density of a four-stroke engine is approaching their two-stroke counterparts due to better turbocharger technology.

Advanced emissions standards have not yet been adopted in many parts of the world, and as such two-stroke technology is very common in parts of Asia. This unfortunately means that the vehicles in use in these places have a high fuel consumption rate, and worse noise and exhaust emissions. Due to the two-stroke's mechanical simplicity the manufacturing costs are low, making it a popular powerplant choice in impoverished countries.

More to the point of ever more stringent emissions standards, a CDS exists to push the industry toward more advanced technology. This is the Clean Snowmobile Challenge (CSC) which the University of Idaho has been involved in since its inception in 2000.

The use of petroleum derived hydrocarbons in combustion devices has negative impacts on the environment. Moreover, there exists only finite reserves of fossil fuels, and engineers need to develop technology that utilizes these resources more effectively. Sustainability needs to be made a priority in the auto and power sports industry. Everything mentioned in this section largely means one important thing, students receiving university training in engine calibration will be expected to be more advanced than in the past.

1.2. RESEARCH GOALS

The presented research's first goal is to add value back into the university and the CSC. More importantly it is meant to be used as a quick training course for new calibration engineers at the university. Second, academically the pursuit of using optimization as a calibration tool is explored [1]. The third goal is to provide recommendations on future upgrades to the lab as well as documents that support the training of students in the lab environment. The majority of this research will be conducted from the viewpoint of the CSC team due to the author's experience here. More specifically, the two-stroke engine will be focus of much of the descriptions for the same reason.

1.3. POTENTIAL APPLICATIONS

Beside the application in the recreation market, two-stroke technology could easily be applied to other applications. A few will be discussed here. In the automotive industry both hybrid and all-electric vehicles (EV) utilize electrical energy to reduce their environmental impact and to increase vehicle efficiency. One major drawback to these vehicles are the batteries that power the motors. They have very limited volumetric energy density compared to a tank of fuel for an internal combustion engine (ICE). Battery and battery charging technology have not reached a point to fully meet the needs of a long-range vehicle. Therefore, other technology options must be pursued. One useful application of two-stroke engines is using them as a range extender. This is essentially an ICE used as a generator to charge the accumulator or battery pack. One such example is the MAHLE Powertrain Range

Extender Vehicle. [2]. A study by Mattarelli discussed of the use of the platform being explored as a range extender. The necessary technology to make this viable include, being direct injected (DI), externally scavenged or turbo/supercharged, and low speed. [3]

As discussed above, the potential to use this technology as a generator in a vehicle can be adapted and extended as a prime-mover in a motor-generator set as well. This would be a popular choice among many people as the high power-to-weight ratio of a two-stroke engine would make it easy to transport and store. Since four-strokes are more commonplace than two-strokes in most consumer markets the potential applications are well known and utilized.

1.4. RELEVANT LEGISLATION

As emissions standards for the power-sports and recreation industry are relatively lenient, at least by automotive standards, the increased EU and US standards will be described as they seem to foretell what the recreation industry may have to deal with. The corporate average fuel economy (CAFE) standards dictate that required fuel economies must almost double by 2025 [4]. There are also standards that require reduction in hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and a relatively new standard dictating particulate number (PN). PN is a measurement of soot in the exhaust stream. In the past, particulate size has been dictated by PM_{10} [5].

1.5. CLEAN SNOWMOBILE CHALLENGE

The Clean Snowmobile Challenge was started in 2000 with the intention of overcoming legislation that would, in effect, ban snowmobiles from national parks like Yellowstone [6]. This was accomplished through the support of the Society of Automotive Engineers (SAE), the Montana Department of Environmental Quality, the Environmental Protection Agency (EPA), National Park Service (NPS), and the Department of Energy (DOE). In addition, the competition was developed to push industry standards. One major change since the inception of this competition is that manufacturers now produce NPS certified trail snowmobiles, which allow the vehicles to be used in environmentally sensitive areas. As such, the UICSC team recognizes that the bigger issue in this industry is land access, especially in the Midwest where public land is much scarcer than in the West. This has shifted the design efforts of the UICSC to be more in line with developing technologies

that are easily applied to vehicles that do not meet the strict NPS requirements. It is important to develop these technologies without hindering power, or adding weight and maintenance.

1.6.   CHAPTER OUTLINE

The remainder of the text will achieve all the goals presented in section 1.2. Chapter 2 is an introduction to many of the university specific information including involvement in the CSC, available test equipment, and some engine basics. The third chapter represents many basics of engine design. Chapter 4 outlines how to achieve a calibration. Discussion of dyno control and experiment design is included here. Chapter 5 discusses basic testing procedures and how to represent data for a customer. Case studies of various capabilities of the lab are presented in chapter 6 which also presents conclusions and recommendations for future work/ improvements in the lab.

2. UNIVERSITY OF IDAHO TESTING AND DEVELOPMENT

Over the past 20 years the University of Idaho has explored small engine development based around power or motorsports engines. This has ranged from calibrations to bottom end designs. This section is meant to act as a brief introduction to much of what has been tested in recent years at the University.

2.1. IDAHO'S INVOLVEMENT

It is worth describing the history of Idaho's involvement in the CSC. This is meant to be used as a justification for use by the UICSC team. Idaho has been attending the CSC since its inception in 2000, although they did not compete that year. Through 2003 the team utilized a four-stroke platform, winning the competition twice. In 2004 the team began development of the two-stroke engine that has been utilized since then.

The competition revolves around powertrain developments rather than chassis redesigns. This means modifying components around the engine as well as recalibration are main focus of the competition. The utilization of bio-fuels is also a major component. This is where the research that will be discussed in this thesis comes into play. The University of Idaho platform is already set-up to be flex-fueled, and has been recalibrated for improved efficiency and emissions. The University of Idaho strategy for this is to reduce the overall operating speed of the engine. This lowers engine noise and allows for longer burn times in cylinder which reduce engine out emissions. The lowered operating speed of the engine dictated the need for a redesign of the exhaust, which will be described below. The intake has also been modified for increased efficiency and reduced noise.

The UI team has focused primarily on intake and exhaust modifications since the initial research into fitting the Ficht outboard injectors to a snowmobile platform. The extent of these modifications has nearly been reached at the conclusion of the 2017 CSC. This means that another, drastic design should be pursued. There is great potential in doing a cylinder/head redesign while using the same injectors and crank from the 2017 CSC.

2.2. STANDARD TEST CELL EQUIPMENT

The following information is a brief overview of equipment that may be used in a dyno test cell. Although a familiarity with the equipment is not necessary, it would be beneficial to

know the capabilities of the equipment. All the equipment needs to be respected; although some equipment may be inexpensive or seem menial it deserves to be treated well. Most equipment in use is extremely expensive and complex. Other equipment can be dangerous if it is not handled properly. The test cells are not a dangerous place to work, if the proper procedures are followed. This portion describes much of the equipment that will be found in many industry level cells.

Engine Dynamometer: this is probably the most obvious piece of equipment in the cell. This tool is coupled to an engine's crankshaft via a flange. The dyno can motor (spin) the engine, or apply load (regulate speed). During this the dyno measures applied torque and current speed.

Data Acquisition Box: allows the dyno cell to record many different variables in the cell, including but not limited to, exhaust, engine, and air temps, pressures, locations, etc. Any sensor that outputs an analog signal can easily be interfaced with the dyno data acquisition box. Some digital PWM signals can too, although they are much more difficult and should be avoided if possible.

Exhaust System: the engine typically has an exhaust system representative of what will be seen on vehicle. This will get extremely hot under testing. Also, combustion produces chemicals that can be detrimental to your health so pay attention to the emissions alarms located above the door. There is an exhaust fan installed that does a good job of evacuating the cell of emissions. If you are working in the cell soon after the engine was running and start to get a headache go step outside and get some fresh air.

Intake System: the engine needs controlled intake conditions to be more repeatable day to day. As such a combustion air system is used to control air relative humidity and temperature that is fed to the engine. Unfortunately, this is a point source of air which does not do much to cool the cell overall so it can get quite warm in the cell.

Cooling System: combustion creates a lot of heat that must be dissipated from the engine. There are 3 primary ways to cool the engine forced convection, engine water through a heat exchanger, and engine oil through a heat exchanger. Engine temperature can influence performance so it should be regulated. Before operating the engine water and oil need to be

"warmed up" to normal operating temperatures, unless cold testing is being done. These values need to be checked as they can cause a significant change in friction. See motoring friction tests for more information.

Instrumentation: this should go without saying, but watch your step. A fully instrumented engine has many I/O's and other cables for basic operation. Do not step on these cables if possible as a broken wire is very hard to track down and could cost a lot of money in time even for an inexpensive fix. First the equipment and hazards will be described.

Emissions: all emissions equipment is quite expensive. It is often fragile as well. Be mindful when you are working around it. Its purpose is to measure engine or tailpipe out emissions. It does this with the utilization of O2 sensors, NOx sensors, non-dispersive infrared sensors, etc. These are a key to any engine calibration and can be indicative of many different things in the engine.

Combustion Analysis System: CAS utilizes very expensive and fragile pressure transducers produced by a company named Kistler. This system is used to produce pressure traces of the engine and can be vital to performing proper calibrations. They show early indication of knock, poor combustion, and are used to determine indicated measurements. The system is able to give the user combustion information on the order on 10ths of degrees' crank angle because it utilizes an encoder wheel and a spark trace (essentially a current clamp).

ECU/PCM: The ECU controls all the engine parameters and houses all the engine maps. It is the brain of the engine and controls throttle, fueling, ignition, and sometimes cam values. It is important, but hard to master as there are so many different engine controllers on the market. There are also PCM's that do all the above and control shift points and some auxiliary systems.

2.3. SAFETEY PRECAUTIONS

With anything there should be some safety protocols. These will describe the personal protective equipment that should be worn while in the cell if the engine is on. The correct proper protective equipment is described in the following.

Hearing Protection: the engine is very loud. The noise your car produces is very misleading. A lot of engineering work goes into quieting this down. Be sure to utilize ear plugs, muffs, or both when entering the cell. At the levels of noise the engine produces it does not take much time to cause permanent hearing damage.

Safety Glasses: safety glasses should be worn as there are many spinning parts. A single driveshaft bolt exiting at 6000 RPM will be traveling at about 150 mph, and has a similar weight and size of a .50 caliber bullet. DO NOT STAND IN THIS PATH. There is the potential for much smaller particles to be thrown around as well, which can easily damage your eyes. Even if the cell is not running and maintenance is being performed it is recommended to wear glasses as there are many fluids and springs internal to the engine.

Hard toed shoes: although not required it is a good idea to wear safety shoes because many of the engine components are very heavy and will break bones if dropped on your feet.

Dress: close toed shoes, long pants, no loose-fitting clothing, no jewelry (rings, necklaces, bracelets) should be worn. If a top with long sleeves is worn the sleeves should buttoned or be rolled up to the elbows. Long hair should be tied back and up.

Hands: latex or nitrile gloves should be worn. They help keep finger oils off the parts as well as keep chemicals off your skin.

Chemicals: if chemicals are being used the user needs to be aware of the safety data sheets (SDS). If two chemicals will be used near the sheets should be referenced to see if the chemicals will react together.

2.4.   INFRASTRUCTURE UPGRADES

The SmERF is a constantly changing facility where upgrades are made each year. These are largely pushed by the users and proposed annually. The scope of these upgrades is typically small. They are small in the sense that they can be completed short term in a month or two at most. A focus of the work being accomplished is not only to test an engine, but to integrate much of the equipment used in testing. This is coupled with the development of small how-to sheets that should allow new users to get up to speed relatively quickly.

Since the SmERF moved to its new location in 2012 there have been many upgrades to the system that was used in the previous location. The biggest change is in the control room being moved closer to the engine so it can be more properly observed under test. It is important to view the engine to monitor for exhaust leaks, dropped bolts, or burning and melting components. In much of industry a large window is often forsaken for the use of multiple cameras placed at strategic locations. Moving the engine closer to the control room is also extremely convenient because in instrumenting the engine or transferring data the amount of signal wire necessary is reduced drastically. Heavily filtered water is also accessible from the steam plant which had been previously unavailable. The benefit of this is all the cooling components will be able to last longer. When using the water from the steam plant a small amount of automotive grade coolant should be added to the water for diluting it so it won't eat away at the bare metal components in the flow path. Using the filtered water will increase the life of the components, specifically the radiators. The narrow tubes internal to the radiators tend to become covered in scale which results in the loss of heat transfer through the system and eventually plugging the entire system.

There have also been upgrades in the calibration equipment. This is in software and hardware. It is important in any calibration that the data be collected and reported. The CSC team was able to garner the use of Uniplot which is plotting software that was designed specifically for engine data. This in conjunction with WinDyn and SuperFlow allows the user to determine most operating parameters of an engine. Most recently the calibration software was upgraded to Inca by Etas. This is automotive standard software. It also allows for high speed data acquisition through the CAN parameters internal to the ECU. Figure 1 shows the new SmERF bay installed without a test engine.
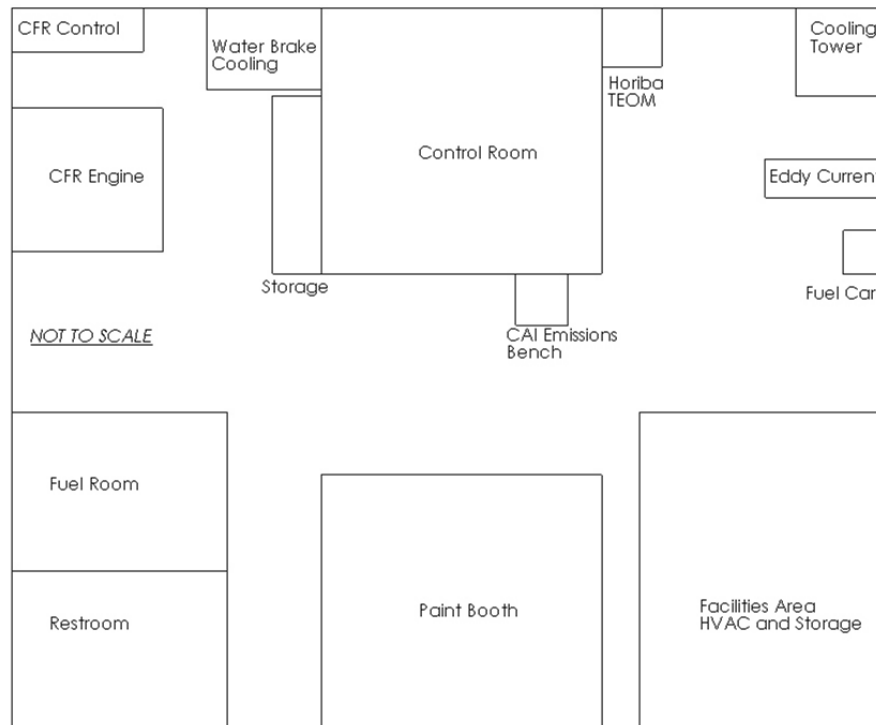
Figure 1: SmERF floor plan, not to scale.

2.5.   CURRENT TEST EQUIPMENT, MAINTENANCE, AND DIAGRAMS

The current test equipment available in the lab is straightforward and simple to use. This is ideal for the learning environment. Conversely, the equipment is high quality and allows for consistent, correct data acquisition. This has been proven by comparing data acquired in the SmERF to data that was collected using top-of-the line AVL equipment. The manuals for the majority of the equipment is located in the SmERF. The equipment utilized in the test cell are:

- Innovate lambda meter [7]
- Borghi and Saveri eddy current dynamometer [8]
- Horiba 5-gas emissions analyzer [9]
- Land & Sea water brake absorber [10]
- SuperFlow data acquisition [11]
- CAI emissions bench
- Max machinery fuel measurement system

- SuperFlow fuel metering and conditioning system
- Cooperative Fuels Research variable compression ratio engine
- TEOM soot measurement system
- Dilution tunnel
- Cooling systems (engine (thermostat controlled), eddy-current, water brake cooling loop
- Large exhaust evacuation fans, 3000 cubic feet per minute if only one fan on rear or front is used
- Small exhaust evacuation fan 450 cubic feet per minute

The equipment has been relatively well maintained throughout the years, but it would be worthwhile to have the bearing on the eddy current dyno checked. The maintenance cost would be quite small compared to the cost of replacing the dyno. Thoroughly cleaning the entire system should also be done every few years. The last time the cooling system was cleaned was in 2012-13.

Over the span of this research much was learned about the use of the facilities. First and foremost, the dyno needs to be maintained regularly. This means monitoring the cooling system, changing driveline bolts, greasing the driveline, and maintaining electronics. Each of these will be discussed as well as recommendations on how to increase the longevity and proper steps to achieve this.

The cooling systems, displayed as component diagrams, shown in Figure 2 and Figure 3 need checked annually. Figure 3 shows the electrical control. It displays that the pumps and fan are each on their own circuit, with two circuit breakers for safety. This entails the radiators being cleaned. Cleaning them should be as easy as using a small pump loop to push descale fluid through them. The pumps should also be cleaned in the same way, as well as checked for leaks. Users should also only refill the cooling components with feed water from the steam plant. This water has been filtered many times to be very pure, which will help to increase the longevity of the plumbing. Due to the water being so soft it is necessary to add some glycol (coolant) to the water so it does not degrade the metal components it touches.
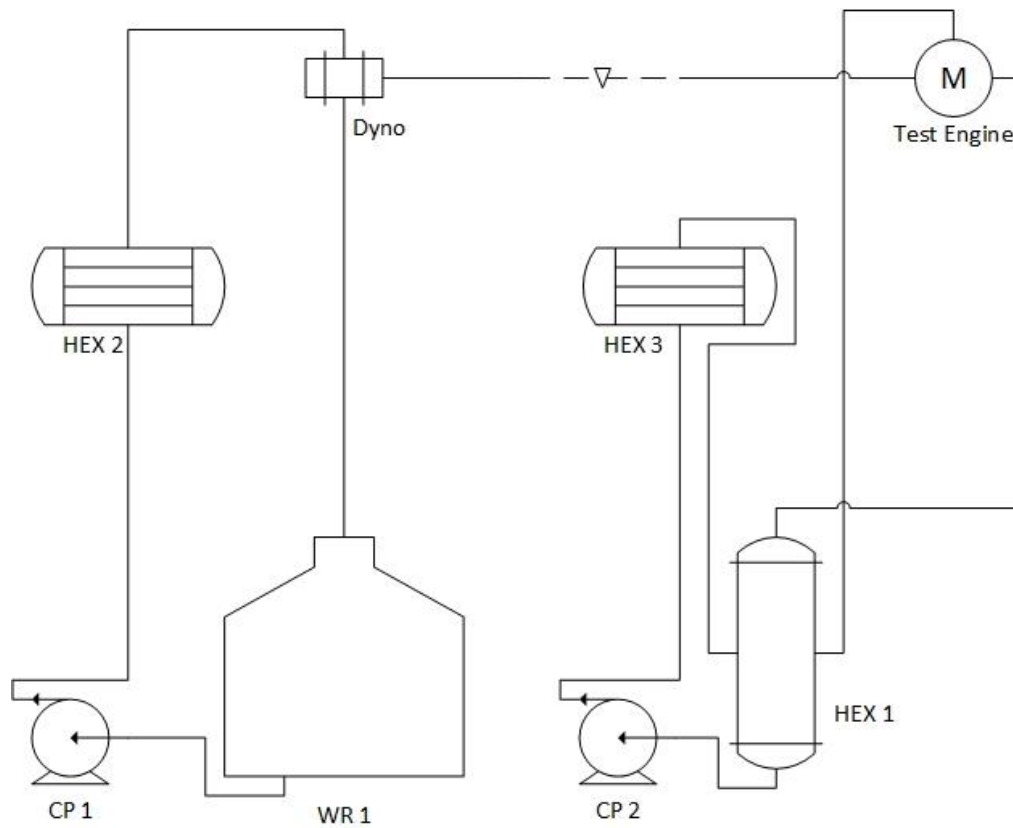
Equipment List			
Displayed Text	**Description**	**Model**	**Manufacturer**
CP 1	Centrifugal Pump	S39520	Berkley
CP 2	Centrifugal Pump	S39521	Berkley
Dyno	Eddy Current Dyno	FE260S	Superflow
HEX 1	Tube and Shell	AB-1204-D4FP	Superflow
HEX 2	Double Pass Radiator	80126N	Afco
HEX 3	Double Pass Radiator	80126N	Afco
WR 1	200 Gallon Tank	NA	NA

Figure 2: Schematic of cooling loop in SmERF.
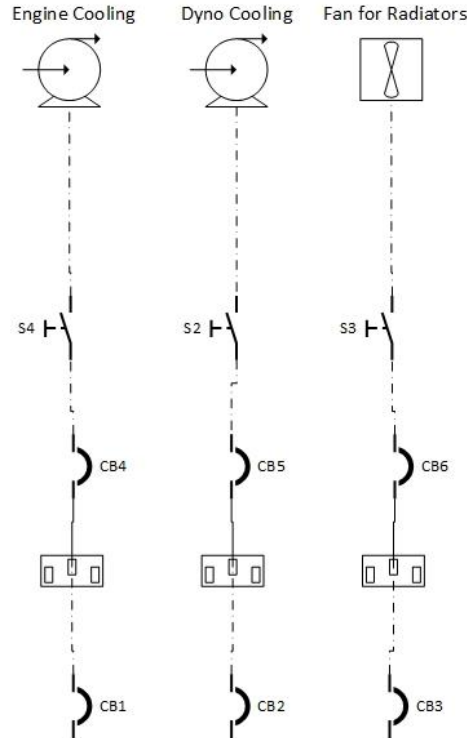
Equipment List		
Displayed Text	**Description**	**Location**
CB 1	Main Breaker	West Wall Circuit Box
CB 2	Main Breaker	West Wall Circuit Box
CB 3	Main Breaker	West Wall Circuit Box
CB 4	GFI Outlet	South Wall
CB 5	GFI Outlet	South Wall
CB 6	GFI Outlet	West Wall
S 1	Manual Switch	South Wall
S 2	Manual Switch	South Wall
S 3	Manual Switch	Fan Stand

Figure 3: Cooling loop electrical system.

The driveline bolts should be replaced annually and should never be reused. It is recommended that a grade 8 minimum be used for the bolts. Whatever bolts are chosen should be torqued to their specification for dry threads. It is also worth noting that in coupling the engine to the dyno there is a mix of both standard and metric screws used. If these screws are not torqued properly they tend to shear and cause a lot of damage. This is along the same lines of what can happen if the driveline is not greased properly. There are grease zerks on the driveline that should be filled every couple of months. If they are not, the roller bearings in the yokes could go dry and fail the driveline.

As far as electronics go, there is very little maintenance to do, but there are a few things that can be done to help reduce the risk of failures. The dyno has a SuperFlow control board that is mounted at its base. To maintain this, it is recommended that the breakers on the wall for the dyno are turned off as well as unplugging the data acquisition box from the wall. Moscow has a lot of power surges that will fry the board and it is expensive to repair. Also, it is important to turn off the X-console in the control room. The backlight can go out on it. This is an easy repair, but it will be a few weeks out and cost quite a bit. Another unfortunate fact is that the wireless controller that is used is no longer manufactured by SuperFlow, so replacement parts are hard to find.

Not much in these areas specifically were upgraded, but the radiators were replaced in early 2016 so they could cool much more efficiently. The control board was replaced last in 2015 due to the electrical overload. The driveline was also replaced in 2015 due to a failure.

2.6. FUEL METERING AND MONITORING

Being able to accurately deliver, measure, and monitor fuel is important. An important aspect of this is regulating the temperature. If the fuel varies greatly in temperature it will also have significant variation in density. In most injectors, which are based upon length of time open, this can have some variation in fuel metering at this point. Moreover, most fuel measurement devices need to monitor the fuel density. In many SAE standards, this temperature is required to be held nearly constant. Before the implementation of the new fuel system in the SmERF the fuel temperature had to be monitored closely as in a test cycle it could vary by more than 30° F in a day. With the new system, graphically shown in Figure 4, there are heat exchangers to keep the fuel ideally at room temperature. Unfortunately, in the SmERF there is significant variation in room temperature day-to-day, as well as throughout testing. This is largely due to the inability to cool the SmERF. The ability to heat is present though. The roof of the SmERF is not insulated at all, so during the summer the temperatures can be greater than 90° F. What this means is even though there is the ability to cool fuel in the bay, if the ambient air is too hot then the fuel won't cool. It does not make testing impossible by any means, but it should be a consideration for swinging lambdas or knock issues.

Figure 4: Schematic of fuel system.
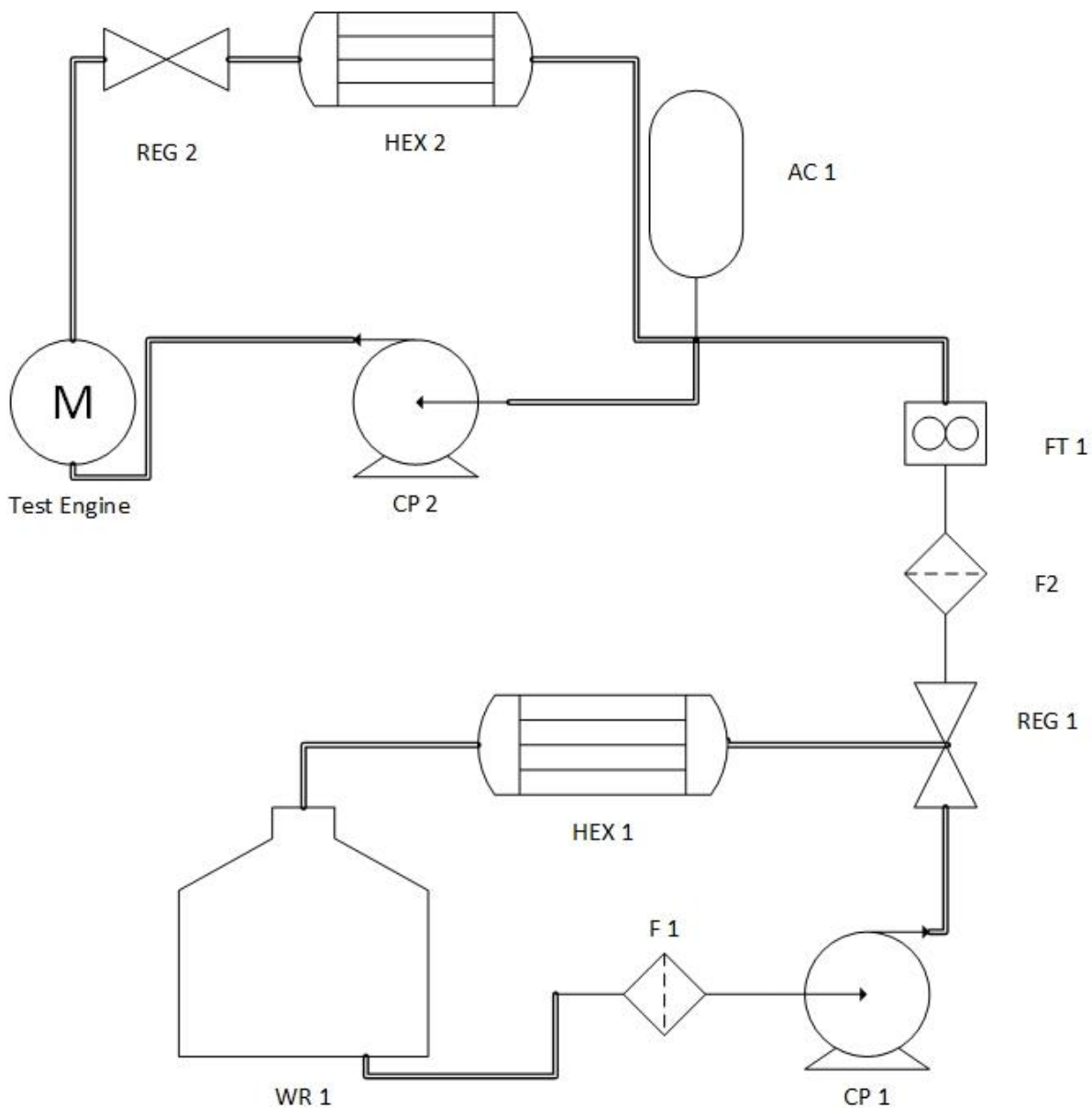
Equipment List			
Displayed Text	**Description**	**Model**	**Manufacturer**
CP 1	Fuel Pump	SUM-G3138	Summit
CP 2	Fuel Pump	Aeromotive 11209	Summit
HEX 1	Fuel Cooler	Derale Electra Cool	Summit
HEX 2	Fuel Cooler	Derale Electra Cool	Summit
WR 1	Fuel Tank	NA	NA

2.7. EQUIPMENT SETUP

In the test lab there is a reasonable amount of data acquisition that occurs. To properly test an engine there is much that needs to be recorded to understand what is occurring. Figure 5 represents a basic testing configuration. This shows the basic layout of the minimum sensors that should be included in a two cylinder engine being tested in the SmERF. A description of the variables is provided in Table 1.
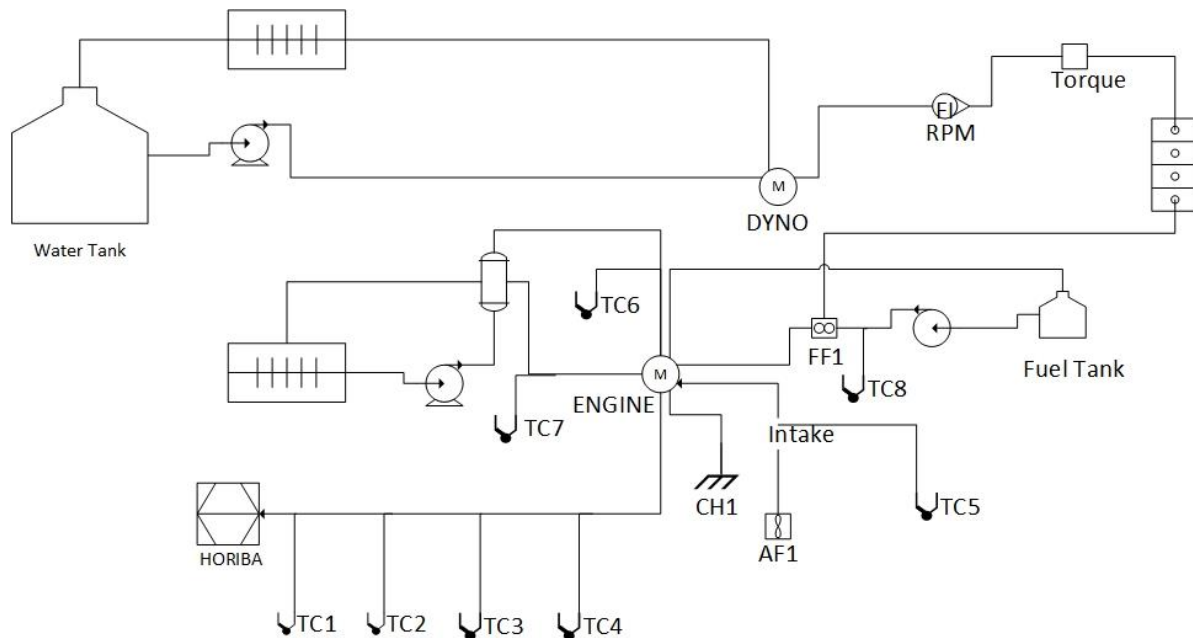
Figure 5: General testing layout in the SmERF.

Table 1: Description of acquired data.

Sensor Name	Name in Figure	Description	Location
EGT 1	TC 1	PTO side thermocouple	76 mm (3 in) from exhaust port
EGT 2	TC 2	Magneto side thermocouple	76 mm (3 in) from exhaust port
EGT 3	TC 3	Pre-catalyst thermocouple	Within 76 mm (3 in) of catalyst inlet
EGT 4	TC 4	Post-catalyst thermocouple	Within 76 mm (3 in) of catalyst outlet
Coolin	TC6	Coolant inlet temperature	Within 760 mm (30 in) of coolant inlet
Coolot	TC7	Coolant outlet temperature	Within 760 mm (30 in) of coolant outlet
Lamvt1	Not Shown	Oxygen sensor	460 mm (18 in) from exhaust port
Volair	AF1	Air turbine to measure airflow	At plenum attached to intake air box
Volful	FF1	Fuel turbine to measure fuel consumption	In fuel system designed to regulate flow
Dyntmp	Not Shown	Monitors temperature of the dyno	At the dyno head

Every variable that is described in the table is coupled with a recommended location of measurement on the physical location around the engine. These are not absolute, but they will give good useful data. The most important part is to not change the relative location between tests if possible. For instance, the catalyst inlet temperature should be measured at the same distance before the catalyst regardless of the length of the exhaust. There are many other types of measurements that can be taken as well, but they will be more specialized and should be chosen on a case-by-case basis.

2.8.   INTEGRATION OF TEST EQUIPMENT

Much of how testing was done at the UI prior to this year was several independent pieces that were manually brought together at the end to analyze them. The SuperFlow dataq is

reasonably powerful, as such it can take most of the data taken in the cell and print and record it all in one fell swoop. In the past fuel, emissions, lambda, and general engine data were all taken separately. In the current state, only emissions are taken separately from the rest of the data. This means that the post processing necessary to get useful data is significantly reduced. More importantly everything is time aligned and stamped so it will be easier to see what is happening and when. It also allows the dyno operator to focus on what matters rather than trying to look at several screens to see what is happening. Table 2 explains many of the measurements currently being recorded in the SuperFlow.

Table 2: SuperFlow recorded measurements.

Parameter	Description	Unit
Engine speed	Rotational speed of the crankshaft	RPM
Torque	Torque at power take off shaft	N-m
Engine Temperature	Head temperature	C
Exhaust gas temperatures (left and right)	Temperature at manifold	C
Hydrocarbons	Unburned Hydrocarbons in exhaust stream	PPM
Carbon dioxide	CO2 in exhaust stream	PPM
Carbon monoxide	CO in exhaust stream	%
Fuel Consumption	Fuel used by engine for combustion	kg/hr
Lambda	Lambda in the exhaust	NA
Coolant Temperatures	Coolant in and out temperature	C
Intake air Temperature	Temperature of ambient air being fed to the engine	C
Humidity	The humidity of ambient air	%
Pressure	Ambient air pressure	Pa

Exhaust Back Pressure	Pressure measured before the muffler in the exhaust	Pa
Throttle Position	Position of the throttle	%
Air Flow	Air moving into the air box	kg/hr

Even with all the listed equipment added to the system there is room for much more. The SuperFlow system allows for CAN inputs as well as several other analog inputs. For the testing that is conducted at the UI there is little need for any more inputs, although being aware of the possibility of expansion is important. There is potential to incorporate the Horiba emissions analyzer into the SuperFlow as well. This would be achieved by identifying how the Horiba outputs data. This is likely through either serial or CAN. Once that is determined it would be possible to assign a channel(s) to take in this information and interpret it. This might require an additional panel be purchased that can interpret the signals. This is not a very intuitive process, but an ambitious group of students could probably achieve this in a couple of months.

3. ENGINE BASICS

This section is intended to provide a basic introduction to two- and four-stroke engines. In much of testing it is necessary to understand the basic differences in power plant choices as well as transmissions. In addition to this, the basics of emission mitigation.

3.1.   THE TWO-STROKE ENGINE

Two-strokes are common in implements and recreation vehicles. A two-stroke, in short, consists of a crankcase scavenged engine that utilizes fuel mixed with lubrication oil. In addition to this it utilizes intake reed valves and a tuned exhaust pipe for increased fluid control. Modern two-strokes typically will utilize direct-injection or port injection rather than carburetion as well as point-of-use electronic oiling. This helps to reduce the overuse of hydrocarbons in the combustion cycle. A two-stroke engine is known for its high power-to-weight ratio. This is partly due to the mechanical simplicity coupled with having a power stroke on every cycle.

The mechanical simplicity of the two-stroke engine comes at a cost. That cost is a reduced control of fluid flow through the engine. A two-stroke engine's intake and exhaust process, overlap and happen simultaneously. The cycle will be discussed from top dead center (TDC) through bottom dead center (BDC) and back to TDC. The power stroke moves from TDC until exhaust port opening (EO). The exhaust port remains open while the transfer ports open (TO). As the piston travels toward BDC fresh fuel-air charge enters through the transfer ports. The flow of the charges helps force out the trapped exhaust gasses through the exhaust port. Through the function of swirl and tumble the fuel and air undergo mixing. Intake and exhaust (simultaneously occurring) continue through BDC. As the cycle begins its upward travel the transfer ports close (TC) first, 180 degrees from where they opened. This is soon followed by the exhaust port closure (EC). Now that all the ports are closed, the fresh charge is compressed, followed by the ignition event, leading to combustion which concludes the cycle. Figure 6 clearly shows the overlap of exhaust and intake [12].
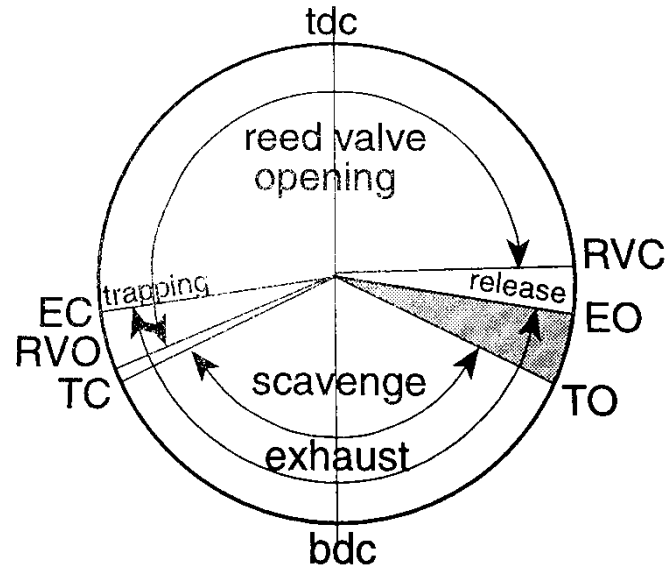
Figure 6: An example of port timing in a two-stroke engine.

3.2. THE TWO-STROKE EXHAUST

Because of the overlap of the exhaust and intake ports, and the lack of valves in the two-stroke, the fluid flow in the cylinder cannot work properly without auxiliary components. A major difference between the two and four stroke engines is the tuned exhaust pipe. The tuned pipe creates two exhaust pulses one positive and one negative. These are referred to as the trapping and scavenging pulses respectively. Scavenging is the process of pulling fresh air fuel mixture into the cylinder through the crankcase. When this occurs, fresh charge can be short circuited through the cylinder introducing unburned hydrocarbons (UHC) into the exhaust stream, wasting the fuel air mixture [13].This also increases the engine out emissions which makes meeting EPA standards more difficult. This is mitigated slightly by the utilization of DI technologies. The purpose of the trapping pulses is to mitigate the amount of short circuited fuel by forcing part of the charge back into the cylinder. The problem with this is the tuned pipe is only effective over a small operational band of the engine. This means that at some places the engine does a great job of utilizing the fuel that is injected, but over much of the operational range of the engine this is not done well.
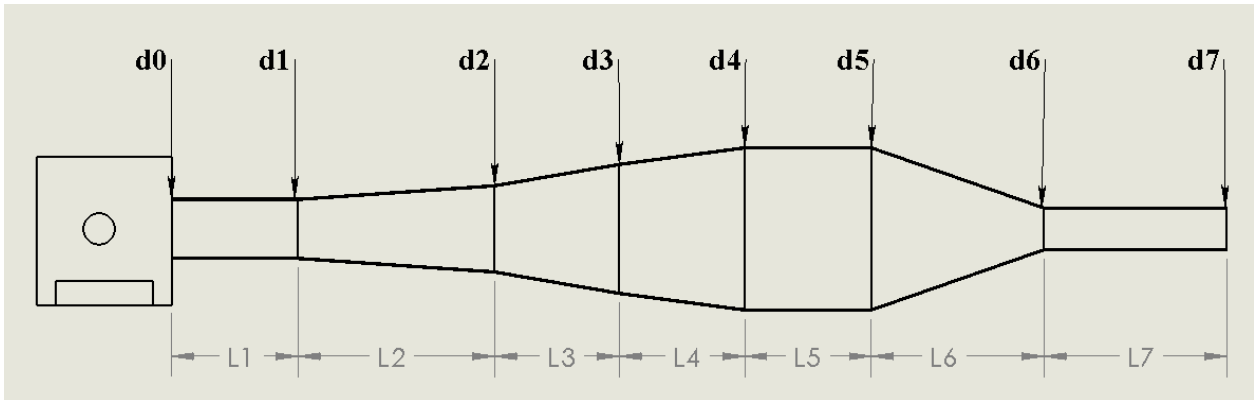
Figure 7: General layout of a two-stroke tuned pipe.

The tuned pipe is comprised of 7 sections. The first is the y-pipe header directly from the engine (L1). The next three are the diverging cones which create the scavenging pulse in the exhaust (L2, L3, L4). Next is the dwell which acts as an expansion chamber (L5). This is followed by the converging cone which creates the trapping pulse (L6). The last is the stinger which is the entrance to the muffler (L7). The pulsations in the tuned pipe are vital for engine performance, as such there cannot be any obstructions in this portion of the pipe. All modifications must be done after the stinger. As an aside to this, it is worth mentioning that tuned pipe design has scope for improvement. It is a difficult task to achieve as all the research for designing these was performed on single cylinder engines and those conditions do not directly apply to multi-cylinder engines. Figure 7 shows a typical layout of a tuned pipe. [14]

The Ski-doo E-TEC engine uses the Rotax Adjustable Variable Exhaust (RAVE) valve system to improve the emissions characteristics. These valves change the exhaust port height. This means that the port stays open for a shorter amount of time, reducing the amount of short circuited fuel. There are three possible positions; low, mid, and high. Each position is used through approximately 30% of the operating span of the engine. These valves should be thought about like a variable valve timing in a four-stroke. The changing port heights aim to optimize the volumetric efficiency at each point. If these are calibrated poorly then the power curve can "surge" meaning that there is either a large gain in power or a loss. This leads to rough transitions during empirical testing. An example of poorly versus correctly calibrated RAVE valves is shown in Figure 8.
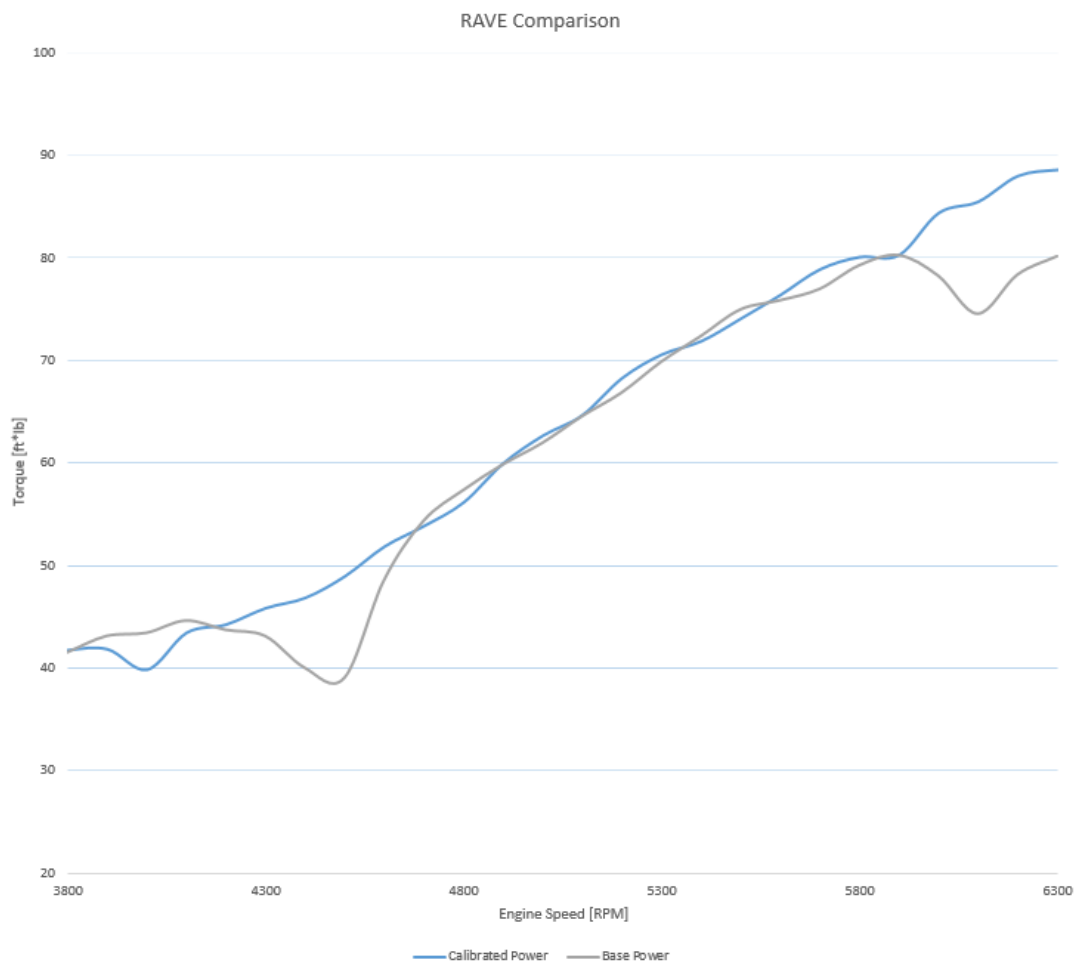
Figure 8: RAVEs pre-and post-calibration.

3.3. DIRECT FUEL INJECTION

A common way to reduce engine out emissions is through the utilization of direct injection. This involves a specially designed injection system that allows fuel to be injected directly into the cylinder at a precise time and in a precise quantity. This allows, especially in a two-stroke engine, for the amount of short circuited fuel to be reduced. DI is still a new technology in the power-sports industry and is rarely used. The only major drawbacks to DI are the added cost and complexity coupled with increased particulate production. A typical two-stroke, which is port injected or carbureted, operates under homogeneous combustion. One benefit to the use of DI is the capability of stratified combustion. This consists of a rich combustion around the spark plug, typically injected after the exhaust and transfer ports are closed, while the cylinder is globally lean under low speed and load conditions. This operation produces low power due to the low mixing time. As engine speed/load increases

toward mid loads and speeds combustion shifts to a more traditional homogenous, or fully mixed fuel air mixture, which produces high power. As the engine approaches full load mixing time is reduced, which can reduce combustion efficiency. Figure 9 provides a visual representation of the differences between these combustion types. Further details on these combustion modes can be found in the theses of Johnson and Bradury [15] [16].
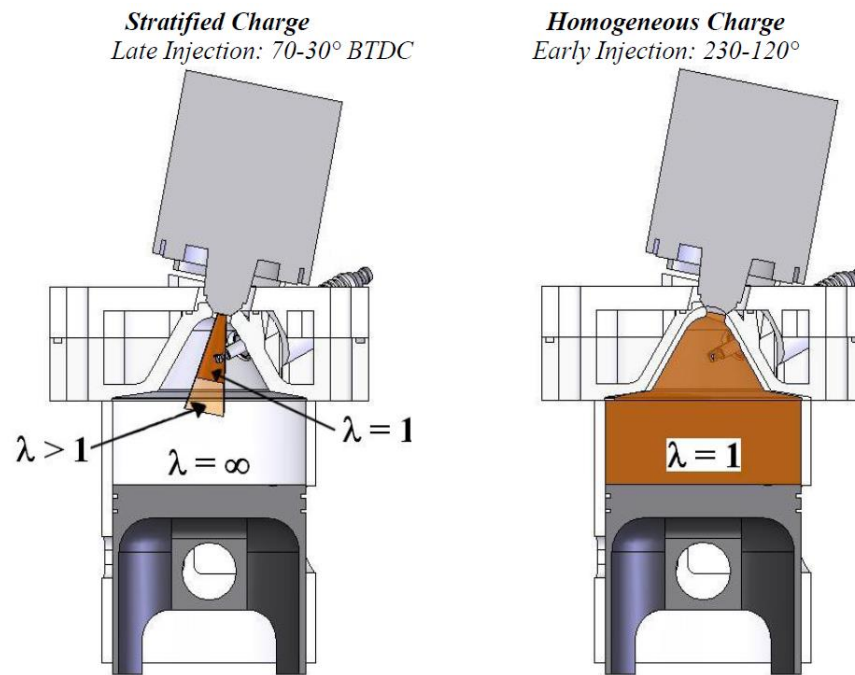
Figure 9: Difference between stratified and homgeneous charge [17].

3.4. THE FOUR-STROKE ENGINE

Four-stroke engines are fairly different from the two-stroke engines physically, although the combustion is modeled the same using an Otto cycle, assuming it is a simple four-stroke engine. The main difference between the two power plants is the four-stroke uses valves to allow for relatively precise fluid control during a combustion cycle. Another defining characteristic of the engine is the power stroke of the engine occurring only every other rotation. This, in general causes a naturally aspirated (NA) four-stroke to make half as much power as the NA two-stroke. The four-stroke engine has much higher mechanical losses than the two-stroke due largely to the valve train.

Despite higher mechanical losses the four-stroke engine is typically more efficient in their use of fuel. This is mostly due to the more advanced technology and research that has gone into this platform coupled with improved fluid flow through the engine. At the UI, a four-stroke engine has been used in the Formula SAE (FSAE) and Formula Hybrid SAE (FHSAE) competitions. Although there has been desire by student leads in the past to make the switch to two-stroke, the competition rules forbid the powerplant. If the UI pursues these competitions again a four-stroke will likely be the engine of choice.

3.5.   ENGINES COUPLED WITH GEARBOX

When testing engines in the powersports world many powerplants come coupled with a power transmission system i.e. a gear box or equivalent. There are limits associated with the dyno for torque and engine speed. For instance, the FHSAE engine has a peak engine speed of 12,500 RPM [18]. This is very near the limits of the dyno so it is recommended to reduce that speed. In conjunction with this the amount of torque the engine produces is relatively small, which means that the instability of running the engine causes a large amount of error. The easy solution to this problem is to shift the engine into a different gear, thus changing the ratio. Shifting gears reduces the RPM at the dyno shaft and increases the torque. This will allow the user to more appropriately monitor the torque. The WinDyn software allows for the input of the gear ratio as the parameter OVRRAT. With this put in correctly the SAE torque, power, and engine speed take this into account.

3.6.   EMISSIONS BASICS

Emissions are a concern as the world's climate changes. Consideration to pollutants needs to be a priority in most development. There are two common ways to refer to emissions: engine-out and tailpipe-out. These refer to non-conditioned exhaust gasses and exhaust gasses that get released to the environment, respectively.

Aftertreatment is most commonly achieved using a three-way catalyst. It is easiest to think of a catalyst as an oxygen storage device, which then uses the stored oxygen to convert harmful emissions that the engine produces. In short, a catalyst requires oxygen and heat to work effectively which is difficult to achieve. This difficulty stems from the basics of combustion. Excess air is produced from lean operation. Lean operation results in lower

combustion temperatures. Now a discussion on how two- and four-stroke engines utilize catalysts [19].

In the four-stroke engine it is possible to use a lean-burn principle to reduce engine-out emissions and improve fuel economy, resulting in poor catalyst light-off [19]. So, the nature of the four-stroke is to sacrifice fuel efficiency for emissions performance after the addition of aftertreatment. This is due to what is commonly referred to as "dithering" which is swinging the lambda values in the exhaust from rich to lean. This effectively regenerates the oxygen necessary for the catalyst to function while keeping combustion temperatures high enough to maintain light-off. The two-stroke is much simpler to mitigate emissions for two reasons. The first is due to the pipe. The nature of the two-stroke pipe is to over-scavenge air into the exhaust at low load and speed operation. This results in an excess of oxygen in the exhaust to load the catalyst. The second is the two-stroke has difficulty operation in lean situations so the combustion is largely rich or stoichiometric meaning that combustion temperatures are high enough to allow for light-off. Unfortunately, over-scavenging of air typically includes short-circuited fuel which means poor engine out emissions [14].

A strategy common in DI four-strokes and diesel engines for emissions reduction is to implement an exhaust gas recirculation (EGR) valve. This is primarily done to reduce the production of NO_x, but it has the added benefit of improving knock characteristics of the engine. There are two types of exhaust gas residuals (also commonly referred to as EGR, but will not be in this writing to avoid confusion), internal and external. Internal refers to any residual gasses that remain due to the scavenging of the engine. External residuals refer to any gasses that are introduced using a valve [20]. A down-side to the EGR system is that it can increase the intake temperatures. Due to this it is becoming much more common to use cooled EGR systems. A well designed four-stroke has relatively low levels of internal exhaust gas residuals due to its efficiency at evacuating the cylinder. In a two-stroke engine there are varying levels of residuals. This is due to the nature of the pipe. At certain loads and speeds the pipe may under-scavenge leaving exhaust in the cylinder or it could trap effectively forcing evacuated gasses back into the engine. Another NO_x reduction strategy is common in diesel engines only. This is the use of urea and a lean NO_x trap (LNT) to reduce emissions.

LNT's are beginning to find their way into gasoline applications, but they are still quite rare [19].

Soot reduction is becoming increasingly important as well. In diesels, soot has been heavily regulated in the past. These particulates are controlled based on both size and quantity. In the past, gasoline engines largely did not have to be controlled for particulates. Due to the increasing popularity and need for DI in automotive applications the particulate production has increased. This is due to the poorer mixing associated with DI. If the cylinder were to be frozen just before ignition and the contents analyzed, it would be evident that there are both fuel rich and fuel lean pockets. This results in partially combusted fuel in the rich pockets resulting in higher levels of soot. So, a technology common in diesels, particulate filters, may soon become common place in DI gasoline engines.

4. CALIBRATION

In short calibration is a physical, small scope optimization of the operation of the engine. Engine calibration, or tuning as it is commonly called, is an important aspect of engine design, development, and testing. As such, it is important to know the basic strategies that are involved. The two main forms of engine control are open and closed loop fueling. Closed loop fueling is created using a control scheme in the ECU. Essentially the end user pushes the throttle and the ECU changes variables actively during operation to achieve a calibrated target. Open loop fueling is the opposite where the ECU will operate based strictly off the input from the user. This will be discussed in more detail in subsequent sections.

Calibration is delineated by the type of powertrain that is being used i.e. electric, CI, SI or hybrid. The relative difficulty of calibration would be least complex to most complex from left to right respectively. Table 3 represents a basic list of calibratable variables that should be available in most types of engine controllers. This does not encompass all the variables that are available, but should allow the calibrator to get the engine running properly.

Table 3: Basic calibration variables for spark ignited, internal combustion engine control.

Name	Description	Units
Injection Timing	Alters crank angle at which fuel is injected from the injector, can be described as start of injection and end of injection. Can also be a crank angle or time duration of injection	Degrees BTDC/ ATDC
Injection Quantity	Volume of fuel injected into the system from the injector	mm^3
Ignition Timing	Crank angle at which the spark plug fires to ignite the fuel/ air mixture in cylinder	Degrees BTDC/ ATDC
Spark Dwell	Length of time that current is running through the primary windings of the ignition coil	ms
Rev Limiter	Cuts off fueling at a specific engine speed to restrict over-revving	RPM

4.1. CALIBRATION STRATEGIES

Calibration should follow the same basic strategy regardless of being open or closed loop. There are two basic control schemes for calibration in both open and closed loop. They are N-alpha and speed density. N-alpha calibration utilizes maps that control based off engine speed (N) and throttle blade angle (alpha). Speed density uses engine speed and manifold air pressure (MAP). N-alpha is rarely used in closed loop fueling.

N-alpha calibration is relatively simple. On an engine or chassis dynamometer the engine is taken to a chosen throttle position and engine speed that should correlate to cell in the engine map. For all calibration there is a relatively straight forward strategy that is used. The calibrator performs "fish hook", or "J-hook" sweeps. Calibration is achieved using a three-step method. The objective of the calibration changes depending on the location in the operating range. It can vary from minimum BSFC, max brake torque, or some balance of the two using an objective function. Each step described below should be repeated individually until a minimum is reached at each cell in the operating range. The entire process should be repeated to ensure a global minimum at each point rather than a local.

1. Injection timing: change the fuel injection timing while adjusting the injection quantity to replicate the equivalence ratio ϕ from the initial point. This will obtain the optimal injection timing for that equivalence ratio.

2. Injection quantity: change the equivalence ratio by adjusting the injection quantity while using the same injection timing found in step one. To achieve the optimal setting, multiple iterations must be completed.

3. Ignition timing: after tuning steps one and two, ignition must also be adjusted. It is typical that the objective for this step is max brake torque without excessive knock. A revalidation of steps one and two should be completed to validate that no major changes occurred due to the spark quantities.

Prior to completing each of the 3 steps above on chassis data acquisition should be used to identify the points that are operated in the most. These points should be the focus for the calibration. Beypnd these points an equal distribution of points should be selected to build a coarse map. In parallel to optimizing these points an interpolation should be performed in between the tested points. This can be done mathematically or using a plotting tool to back out a map from the known data. These points should be tested to ensure there are no runability issues. This step is done to reduce the overall time necessary to fully calibrate the engine. Time permitting the three step process should be repeated at each cell in the engine map, this is often not realistic because there can be greater than 1,000 cells. A rough estimate is 10-15 minutes per cell to do a full calibration.

Next the user must repeat this process until the engine is running smoothly and is fully calibrated. This is considered three-dimensional mapping. When the engine becomes more advanced and things like VVT are added into the mix and the calibration becomes more complicated. A four-dimensional map would require several sweeps at each point to ensure that the best point is chosen. Figure 10 shows an example of step one of calibration where air-to fuel ratio is held constant. In this sweep minimizing BSFC is the goal. Each point in the plots below represent one iteration of one step. The entire plot shows a completion of each step. These plots with numerous points will exist for each cell in the operating range, requiring a large amount of time to complete a calibration.
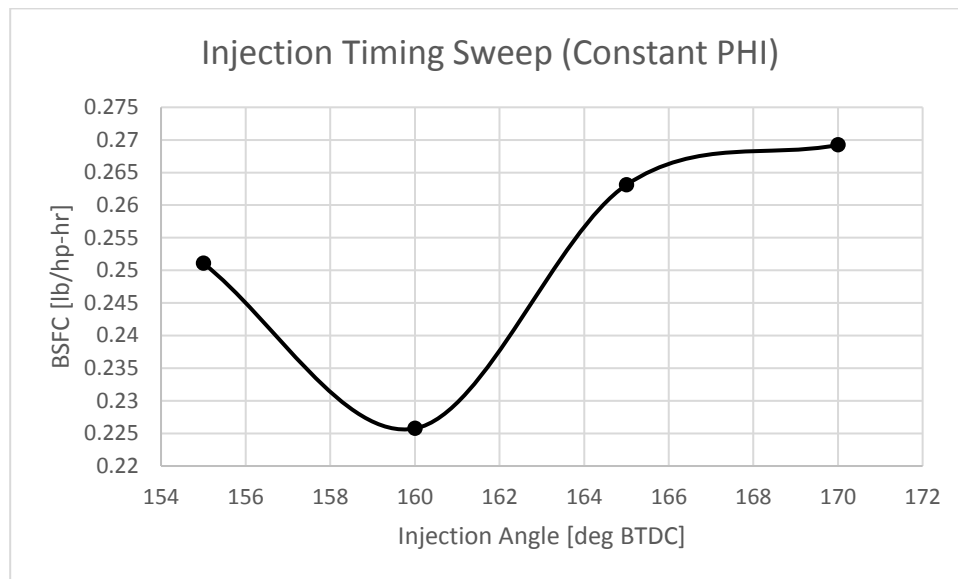
Figure 10: Injection timing sweep.

Figure 11 represents step two of calibration, injection quantity sweep where minimum BSFC is the objective.
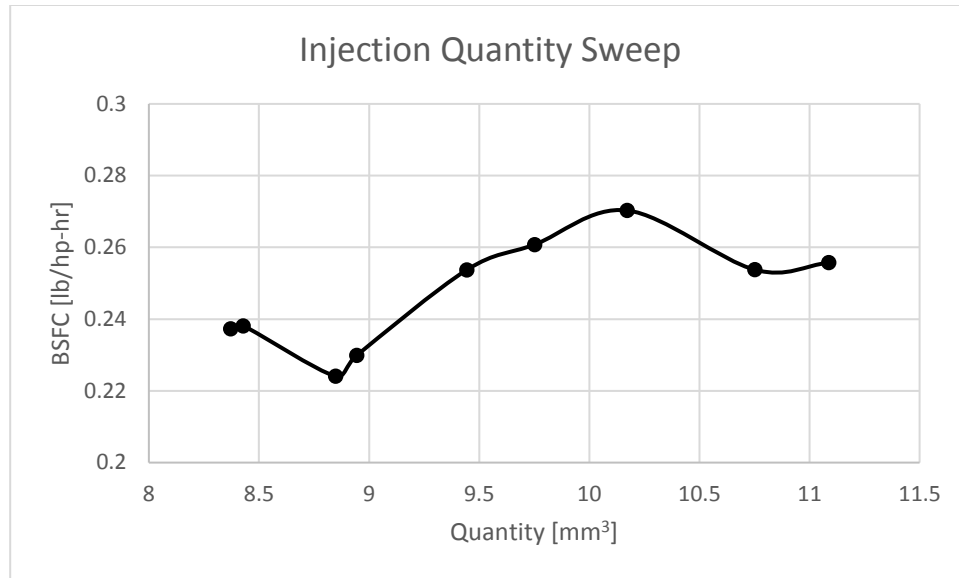
Figure 11: Injection quantity sweep.

Figure 12 represents step three of the calibration where max brake torque is the target. The dip in torque as the spark goes lower is due to the tendency to knock as spark is advanced.
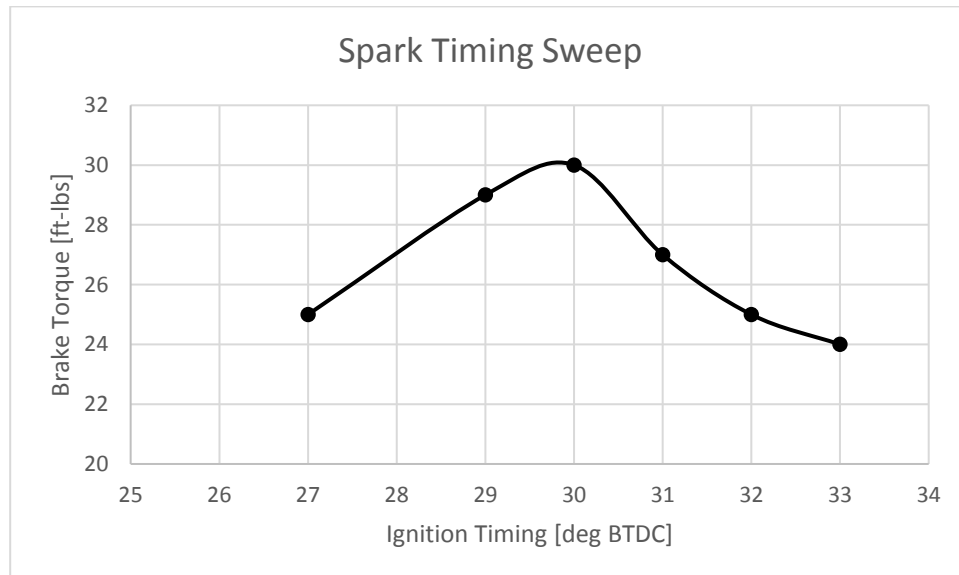
Figure 12: Spark timing sweep.

There are several different injection strategies common in engines and these will be discussed here. In a port fuel injected (PFI) or throttle body injected (TBI) four-stroke without VVT the calibration is completed using the 3-D strategy described above. In a PFI or TBI system the injection timing can be significantly different without affecting the runability of

the engine much, but it can have a significant effect on the emissions of the engine. It still needs to be addressed, but it is by no means the largest contributing factor to the effectiveness of the engine. Conversely it will have a large effect on smoothness of idle. In a DI system the injection timing makes a significant difference. To put this into perspective, in a TBI system once a point is found that works the calibrator can shift this number by +/- 20 degrees and probably not see a huge change, but in a DI system 3 degrees can be enough to cause knock and runability issues.

During calibration it is advantageous to develop an objective function. Depending on the objective of the calibration this function can change drastically. For instance, in the CSC an objective function was created to achieve the best results of the 5-mode test used at competition. In short, this equation balances power and emissions production. The function was built using numerical methods, common in optimization, by a CSC graduate student in 2011 [21]. It is recommended that if FSAE of FHSAE returns to the UI a function should be developed to balance BSFC and torque. Ideally these points should be similar, but at certain operating loads they may not be. The CSC objective is given in Equation 1. In this function W_m the mode weight from the 5-mode test, UHC, CO, and NO_x are the percentages of each emission, while P is the brake power of the engine.

$$F = W_m * \frac{\left(\frac{6 * UHC + NO_x}{150} + \frac{CO}{400}\right)}{P}$$

Equation 1: Calibration objective function.

It would be a good decision, especially with the capabilities of Motec, to explore closed loop fueling for any future four-stroke research the UI pursues at CDS competitions. In the realm of four-stroke engines closed loop fueling is considered common practice. Implementing this control would be worthwhile.

The question has come up many times as to whether closed loop fueling can be used in the CSC two-stroke. While being physically possible to implement closed loop control the level of complexity is much greater than that in a four-stroke and the current controller does not have this capability. This is due to the tuned exhaust pipe and variable exhaust ports. The performance of the pipe, as described above, is greatly affected by temperature and pressure.

As the pipe heats and cools there will be different expected oxygen amounts in the exhaust. This changes dynamically over a day of riding. Due to this the engine, must be calibrated to meet emissions at every possible operating condition. This can be roughly characterized as cold pipe, warm pipe, and hot pipe in conjunction with valve low, mid, and high. Beyond this there should also be consideration to elevation. There is potential for this to all be accomplished with compensations or corrections.

4.2.   CALIBRATION BASICS

When calibrating the user is changing are values in what is essentially a spreadsheet that is used by the ECU as a look-up table that is then interpolated as needed. N-alpha will be used as the example throughout this description. Each of these maps will have two axes, engine speed and throttle position. The resolution for these maps typically varies throughout the operating range of the engine. Some ECUs allow for a variance in this resolution, the Motec is a good example of this. Figure 13 shows an example of an engine map, the values are not from a working calibration, the trend is consistent with what would be expected after calibrating. The axes were truncated for ease of reading, typically there is more resolution than what was included in the figure.

Fueling Quantity [mm^3]							
	Engine Speed [RPM]						
		750	1250	2500	3500	4500	5500	6500
	0	25	25	30	32	35	60	66
	5	25	30	32	35	42	62	68
	10	30	33	37	42	50	64	70
Load [TPS %]	15	33	35	40	47	60	68	72
	20	40	42	48	52	65	70	74
	30	44	45	50	61	70	74	78
	40	47	49	55	65	72	80	82
	50	60	60	65	70	76	81	84
	60	63	64	70	74	78	84	86
	70	66	68	74	78	80	86	90
	80	70	74	77	80	81	83	92
	90	75	79	84	87	90	92	95
	100	90	91	91	92	93	94	97

Figure 13: N-alpha calibration map example.

During calibration there are often different objectives. This can vary from vehicle to vehicle or even point to point. For example, in a single calibration some areas might use emissions as the objective, while others might be power or fuel economy. Due to this, the calibrator must have a clear definition of what they wish to achieve at every given point. Moreover, the calibrator should have an idea of the expected value at a point as well as an expected engine output. Once again, this will change based on the objective.

It is critical to calibrate with hardware that, if possible, exactly mimics the vehicle configuration. This includes, but is not limited to, exhausts, intakes, injection systems, cams, bearings, and cooling system. This is not limited to hardware; any wrapping or auxiliary cooling systems should also be included. If any of these hardware changes are made without calibrations being performed specifically for the prescribed change it can cause many issues on chassis. For example, in the 2016 CSC the team calibrated the engine with an unwrapped tuned exhaust. The calibration worked well and ran flawlessly on dyno before competition. In-chassis, a tuned pipe that had been wrapped with insulation was used. This had the effect of increasing the operational temperature inside the tuned pipe, which resulted in scavenging that was different from the pipe used for dynamometer calibration. This mismatch between calibration and components resulted in the scavenging pulses were occurring at different times and intensities than what was calibrated for. In practice this caused dips and rises in torque and trapped AFR which resulted in cooling and knock issues.

4.3.   SHUT DOWN OF THE TEST CELL

The testing in the SmERF is contingent upon being able to properly control the engine. This includes controlling load and speed. This portion of testing is rather simple, and all the procedures for control are found in the manuals. Recommendations for control will be provided here for ways to keep consistent conditions. Discussion will begin from the end of testing shut down through running a test.

The SuperFlow dyno is notorious at the UI for load control board failures. This is indicated by the engine "running away", or not maintaining a specified speed. Over the last few years several procedures have been developed to increase the longevity of the board. On shut down the steps should be followed **in order**, as follows:

1. Save test data & calibrations: ensures that nothing is lost after testing.
2. Turn off ECU: removing auxiliary power from the ECU reduces the risk of component failure internal to the computer.
3. Turn off wireless handheld console: the backlight can fail and this part is discontinued so repairs have long lead times.
4. Close WinDyn software: this prevents the desktop computer from freezing.
5. Switch off power supply: Halts 12-volt power to SuperFlow box that is used for auxiliary power.
6. Turn off SuperFlow DATAQ: halts power output from box.
7. Unplug DATAQ box: saves control board from power fluctuations from storms.
8. Power off starter: no long-term benefits, but good practice.
9. Power off fuel cart: increases longevity of pumps, filters, and regulators.
10. Power down water pumps (2) and fan: reduces noise and prolongs life switches located on South wall and fan tower respectively.
11. Shut down Horiba: increases longevity of consumable components.
12. Check for tripping hazards and shut off lights.

Images of the components that need turned on and off will be included later in this chapter to show where everything is located as well as show the power switches. Following the procedures have increased the life of the control board from 3-6 months to over a year. APPENDIX A: SHUTDOWN AND START-UP OF TEST CELL KAIZEN SHEETS represents the kaizen for start up that should be included online as well as a physical document in the cell.

4.4.   START-UP THE TEST CELL

The start-up procedure for testing is very similar to the shut-down and should be done in a specific order as well. This process is as follows:

1. Check that the engine is bolted to the dyno drive shaft securely and that the engine cart is secured to the dyno frame. For high vibration engines, zip tie or

tape the hooks that secure the cart to the dyno so they don't rattle loose. This should be visually inspected every day that testing occurs.

2. Verify that there are no leaks, no rubbing hoses, and no fatigued components. The drive line should be checked to verify no bolts have loosened and all wiring should be inspected for issues.

3. Check that all coolant and fuel lines are fully connected and that they are routed to avoid heat and rubbing. In addition to this if an engine was recently put on the dyno the cooling system needs checked in 5 locations.

   a. The water reservoir in the SuperFlow cooling tower.

   b. The lower tower needs burped, use a screwdriver down the air release with pumps on.

   c. The engine needs burped this is done initially by holding the top coolant line above the engine and depressing the quick release to allow all the air to leave the engine. In some occasions this will need to be done again with the engine idling.

   d. The Redbull tower needs to be full.

   e. The southernmost radiator may need refilled.

4. Turn on the Super Flow DATAQ box and the 12V power supply.

5. Do not plug more than one pump into each bank of two outlets on the wall as they can only handle 10 amps each. Do not plug a fan and a pump into the same bank of outlets.

6. Turn on fuel system, check for the correct fuel pressure and check that fuel tank is full.

7. Turn on engine exhaust fan, cooling tower fan (switch on tower) and engine fan (black fan on pedestal).

8. The engine exhaust fan inlet should be within less than six inches of the engine tail pipe.

9. Check that the Super Flow hand held controller is on, there are no errors and the engine rpm 'Engspd' is set at least 1000 RPM above your engines' idle speed. Check that the throttle is set to zero.

If using the starter motor on the dyno check that the green light in the lower left of the starter control box labeled 'Marcia/on' is lit, if not press this button. The 'Marcia/On' button should now be lit. Press and hold the green button on the far right to start the engine. The starter uses a compressed air clutch to engage the dyno, check that the air valve on the wall is on and gauge reads about 15psi. APPENDIX A: SHUTDOWN AND START-UP OF TEST CELL KAIZEN SHEETS also includes the kaizen for start-up.

The above should be checked every day. Any one of these suggestions, if not monitored properly, can cause major issues with engine testing. The next step is to set-up WinDyn for the engine being tested.

Figure 14: SuperFlow data acquisition box.

Figure 15: Starter system for SuperFlow.

Figure 16: Improved fuel system through SuperFlow.

Figure 17: Horiba emissions analyzer.

Figure 18: SuperFlow cooling tower for engines.

Figure 19: Red bull cooling tower and radiators.

Figure 20: Starter controls inside control room.

4.5. HANDHELD SET-UP

After completing the hardware set-up it is necessary to get the software ready to go. This process is described in APPENDIX B: STARTING THE SUPERFLOW WINDYN INTERFACE.

The other system that needs to be powered up and set-up properly is the handheld controller. When turned on initially the handheld is useless. It will say "no data from remote". If this error does not go away chances are the SuperFlow control box is turned off. If this is not the case, everything should be in good working order. Once the handheld is turned on the steps listed above should get everything up and running. The options on the right of the screen need to be changed, as the controller defaults to test mode, not manual. To change this option, select the black between text on the far right and the screen will change. Updating the control that the knob affects is done similarly. Select the text of the control that needs to change and the screen shown in Figure 21 appears. The user should select engine speed and medium control is recommended.
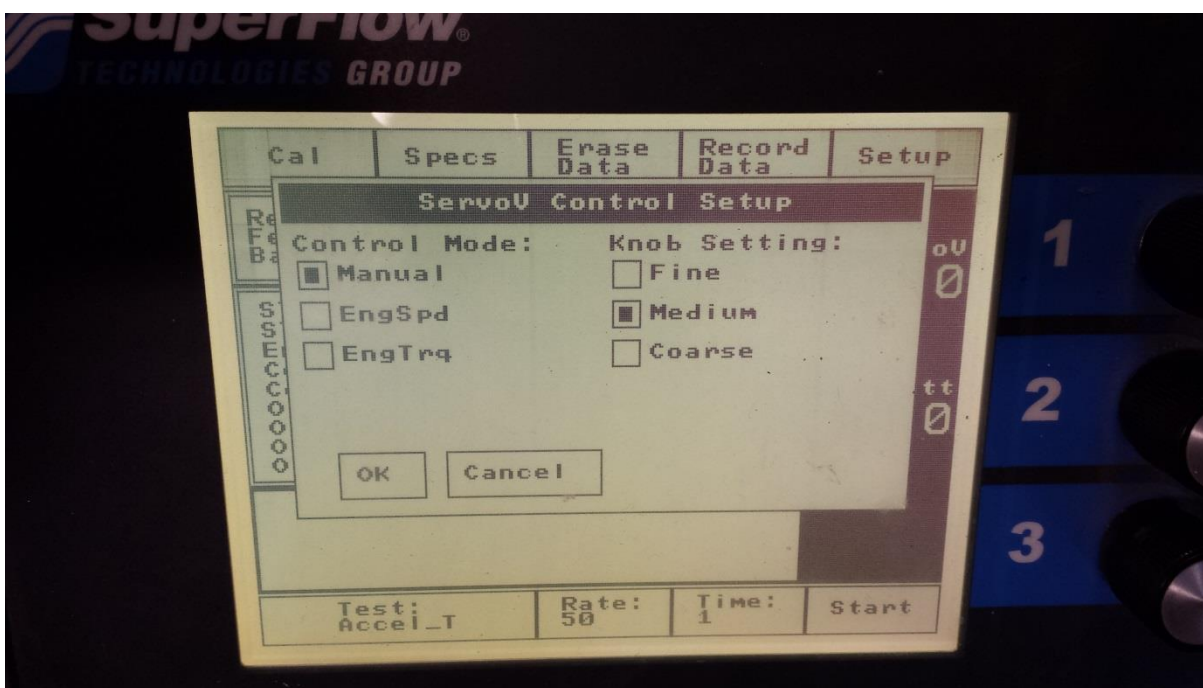
Figure 21: SuperFlow handheld screen.

The specifications described above will be described in more detail below, but only the specifications that should be changed for testing purposes. The specifications of interest that can be changed are shown in Table 4.

Table 4: Adjustable engine specifications.

Channel Number	Channel Name	Units	Description
77	EngBor	mm	Engine Bore
78	EngStr	mm	Engine Stroke
79	EngCyl	[-]	Number of Cylinders
80	EngCyc	[-]	Engine Cycle
81	OvrRat	[-]	Gear Ratio
85	FuelSG	lb/gal	Fuel Specific Gravity
90	4_inch	[-]	Air Turbine Present?
91	6_inch	[-]	Air Turbine Present?
92	9_inch	[-]	Air Turbine Present?

4.6.   PRE-TESTING SOFTWARE SET-UP

While testing the engine, the calibrator may determine that the data that is being exported from SuperFlow does not encompass all the instrumentation they added. The solution for this is relatively simple, but the problem may be in two separate places. The simplest solution is to look in the specifications menu. Near the middle of the screen three tabs appear labeled "Specifications", "Data Printouts", and "Data Analysis" respectively. Select the second tab, inside this tab there are several check boxes that control what data is exported after a test is performed. Figure 22: The data printouts screen in test set-up. Figure 22 shows an example of this.
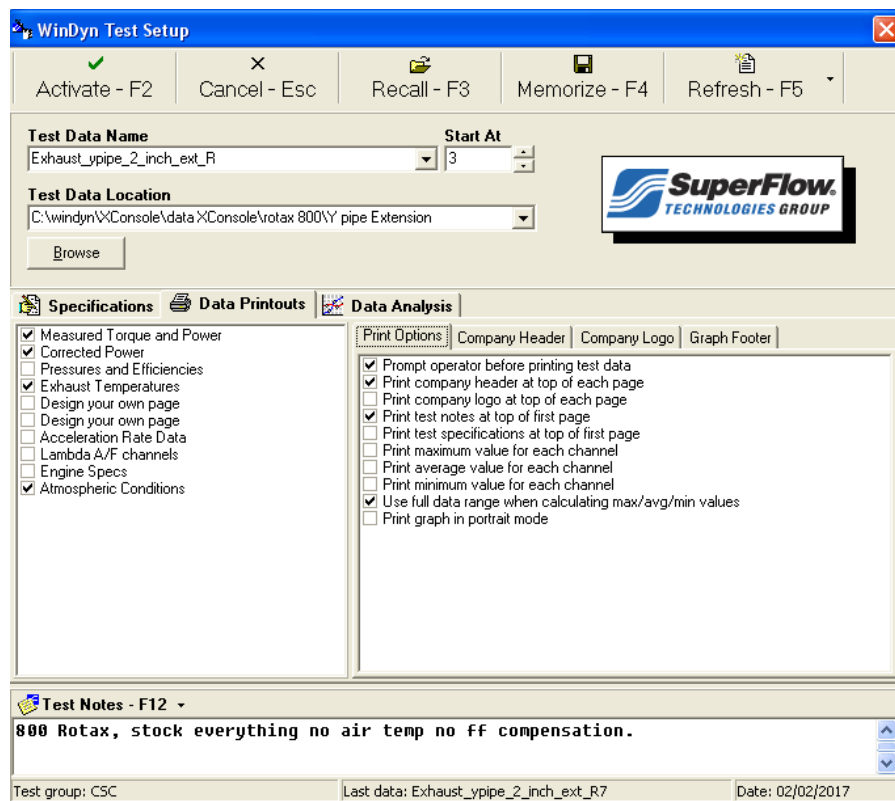
Figure 22: The data printouts screen in test set-up.

The second area that could be causing problems with this is in assigning channels to specific pages. The easiest way to update these lists is by opening a current test using a button in the main ribbon. Once here right clicking into the white space gives the option to adjust channel order. Once here, the engineer has the opportunity to rename the pages, change plot parameters, and select channels for each page that will be printed. Figure 23 demonstrates the screen that the user will use to edit the printed parameters. Although this task may seem menial, it is an important skill to learn before attempting to test an engine.
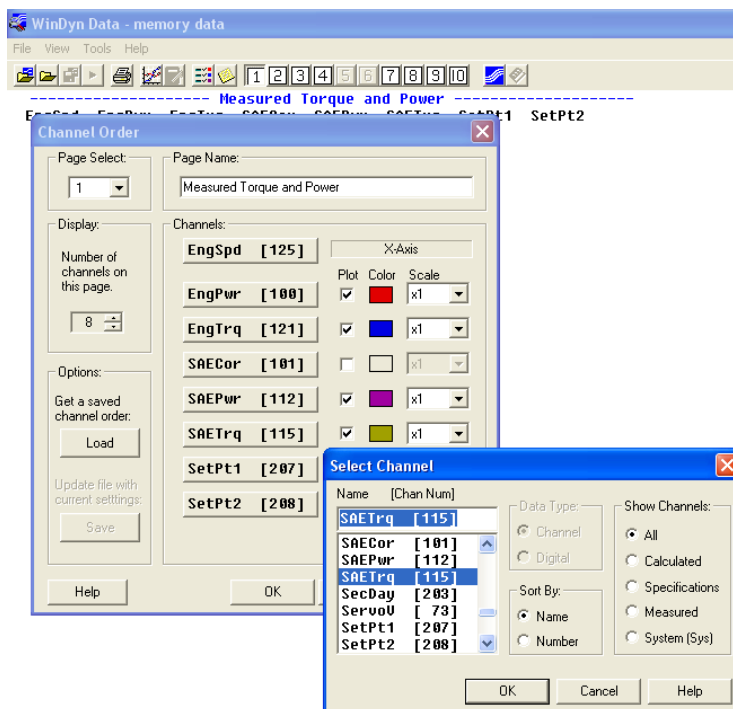
Figure 23: Editing shown channels in channel order screen.

4.7. ADDING OR MODIFYING CHANNELS IN SUPERFLOW

If there is need to change the units displayed on the screen, add sensors, or validate calculations it is necessary to use the configuration editor in WinDyn. This is a blue screen, keystroke navigated interface. To get to this point select design > system configuration. Now the blue screen will open. It is important here to select "Get". This loads the existing interface. The one used at the University is "UIDAHO". To vary the parameters or view any calculations the "EDIT" function is used. If anything is changed then it is necessary to select "KEEP" before exiting the screen through the "QUIT" command.

4.8. COMMON EQUATIONS IN CALIBRATION

While calibrating the engine, it is important to understand what effect the changes are having. There are the obvious effects that are seen in the torque and AFR, but there is much more to understand about the performance of the engine. The first equation that is important is brake mean effective pressure (BMEP) which is a representation of engine load and should typically be used in place of torque in most data. Equation 2 shows how to calculate BMEP.

$$BMEP[bar] = \frac{T[N-m] * 2\pi * 2}{V_D[l] * 100}$$

Equation 2: Torque to BMEP.

Often while testing the calibrator may only have torque as an output. A convenient conversion to determine power from torque is shown in Equation 3.

$$P[kW] = \frac{T[N-m] * rpm}{9549}$$

Equation 3: Torque to power conversion.

It is often necessary to perform acoustic testing while in the dyno. If the calibrator is designing components for the intake or exhaust it is important to know the firing frequency of the engine. This is shown in Equation 4. N_c is the number of cylinders while N_R is the number of power strokes per revolutions

$$f_{E[hz]} = \frac{rpm * N_C}{N_R * 60}$$

Equation 4: Engine firing frequency.

If exhaust gas is being gathered and measured there are 4 more important equations to understand. This is especially true if a catalyst is included in line in the system. Equation 5 shows how to find lambda which is better known as the excess air coefficient. Phi (equivalence ratio) is often used in powersports to determine AFR, while lambda is more common in automotive. This value is found using an AFR or lambda meter. Using lambda is a useful metric to use because it will measure the same regardless of fuel if the calibrator has built in a compensation for the alternative fuel.

$$LAMBDA = \frac{1}{\varphi} = \frac{AFR_{ACTUAL}}{AFR_{STOICH}}$$

Equation 5: Lamda and phi definition.

If the calibrator is not using an AFR meter than the emissions bench will display an AFR as well. The equation for that is significantly more complex and in shown in Equation 6. Table 5 gives the inputs to the formula.

Table 5: Inputs to calculated AFR from emissions.

Name	Representation in Formula
Fuel H:C Ratio (Fuel_H:C_Ratio)	n
Fuel O:C Ratio (Fuel_O:C_Ratio)	m
CO_2 Dry Volume Fraction (dCO2)	$[CO_2]$
CO Dry Volume Fraction (dCO)	$[CO]$
O_2 Dry Volume Fraction (dO2)	$[O_2]$
HC Dry Volume Fraction (dHC)	$[HC]$
NO Dry Volume Fraction (dNO)	$[NO]$
Humidity Ratio (Humidity)	HR
Stoichiometric Dry Air-Fuel Ratio (afr_Stoich)	AFR_{stoic}
Water-Gas Reaction Equilibrium Constant (Kwatergas)	K
Molar Mass of Air (mmAir)	M_{air}
Molar Mass of Water (mmH2O)	M_{H_2O}
Air O_2 Dry Volume Fraction (dO2_Air)	$[O_2]_{Air}$

$$AFR = \frac{[O_2]+[CO_2]+\frac{[CO]}{2}+\frac{[NO]}{2}+\left(\frac{n}{4}\cdot\frac{K\cdot[CO_2]}{K[CO_2]+[CO]}-\frac{k}{2}\right)\cdot([CO_2]+[CO])-\frac{p}{2}\cdot\left(\frac{K\cdot[CO_2]}{K[CO_2]+[CO]}\right)\cdot([CO_2]+[CO]+[HC])}{\left[1+\frac{100}{21}\frac{HR}{2}\frac{M_{Air}}{M_{H_2O}}\left(\frac{K\cdot[CO_2]}{K[CO_2]+[CO]}\right)\right]\cdot\left(1+\frac{n}{4}-\frac{k}{2}\right)\cdot([CO_2]+[CO]+[HC])}\cdot AFR_{stoic}$$

Equation 6: Calculated AFR from emissions.

5. TESTING PROCEDURE

The process for acquiring data on engines is to create a data map. This is accomplished by exploring many throttle positions at several different engine speeds. An example of this is through the snowmobile engine. The snowmobile utilizes a continuously variable transmission (CVT). The CVT allows for some adjustment in clutch engagement, or when engine power begins to transfer to the drivetrain. This typically occurs at around 3000 RPM. This is important because anything below this point runs stratified, and is not an area of interest. The ceiling for engine speed on the stock snowmobile is 8000 RPM. As such, the data map will consist of data in this range.

5.1. ENGINE HEALTH CHECK

A data map should be found by using a rudimentary design of experiment. While this can be performed using software, and often is in industry, an engineer should understand intuitively how to accomplish this. In short, the design should encompass a wide variety of data points that are evenly distributed through the operating range of the engine. It is good practice while calibrating an engine that is relatively unknown to start at low speeds and loads. The author recommends starting just below transmission engagement at low load and calibrating at a specified load for ~2000 RPM. The engineer should then drop to the beginning RPM and increase the load. Repeating these steps up to mid-load result in a reasonably safe calibration initially. This method is roughly how the FHSAE engine was calibrated. This has the ancillary benefit of reducing risk of catastrophic failure of the engine. In motorcycle engines the useful life of the pistons for peak power are on the order of tens of hours. This method of calibration should allow for a reasonable calibration on a single piston without losing performance.

Once a calibration has begun a mid-load point should be chosen as a daily health check for the engine. The purpose of this point is to proactively find issues with the hardware on the engine before there is a failure. This is an important testing step as a failing part can greatly skew a calibration. This means the few moments it takes to check this point every day can save many hours of rework. The daily health point should be operated the same way daily. The engine test conditions should be as follows:

- Throttle locked at a fixed angle

- Intake and exhaust cam locked at a target position

- Ignition timing overridden by the user and locked at a constant setting

- Start of injection timing overridden and locked at a constant setting

- Fuel rail pressure overridden and locked at a constant setting

- Lambda set to closed loop control at $\lambda = 1$

- Waste gate set to a fixed duty cycle

Not all the conditions listed will apply to every engine, but the above conditions should encompass any engine tested. Moreover, if possible, the test cell should be held at the following conditions:

- Combustion air set to achieve a repeatable intake air temperature and humidity settings (+/- 2°C and 5% RH respectively)

- Fuel pressure set to specification and holding constant

- Fuel feed temperature set to specification and holding constant

- Fuel should be consistent, i.e. equivalent RON, ideal to use fuel from same delivery throughout testing if possible

- Oil / coolant temperature stabilized to within +/- 2°C at repeatable settings

- Coolant is purged of all air and is free of bubbles

- Intercooler outlet temperature adjusted to a repeatable setting

- Exhaust backpressure set correctly and exhaust system is completely sealed

Again, not all the above conditions are available in the UI cell, but they are included due to the potential for cell upgrades available in the future. Currently the daily health check is performed at 40% throttle opening as seen in the ECU, and a mid-load point 5000 RPM. This is applicable for both the CSC and FHSAE engine. The process is to warm the engine to 40°C, allow the exhaust temperature to stabilize, and then record data through SuperFlow for 60 seconds. Once this is completed the data that should be interpreted, and recorded are as follows:

- Emissions: Measured using emissions bench. It is important to verify that emissions are consistent. Although, through calibration these will change some they can often act

as indicators of issues in the engine. For example: abnormally high CO can indicate a leak in the head of the engine. Also, since the emissions bench is turned on separately from the rest of the data acquisition equipment it isn't uncommon for the bench to be left off.

- Blow-by: If a blow-by meter is being utilized this may be a check to monitor internal engine component life. If blow-by suddenly increases it could indicate hardware failure such as recessed valve seats.

- Atmospheric (test cell) Conditions: Much of the day to day change can be seen as a change in the test cell conditions. Calibration work should include a correction factor (SAE J1349) that is based off these conditions (barometric pressure, relative humidity, and air temperature). Moreover, many pressures that are measured on the platform are based from absolute which takes into account the barometric pressure. Ideally the humidity and temperature should stay consistent due to the combustion air system. Unfortunately, an engine produces a significant amount of heat which causes the temperature to drift for prolonged testing.

- EGT's: The exhaust temperature probes tend to go out relatively frequently. This is often due to melted/faulty wires, but can sometimes be a sensor failure. The exhaust runner temperatures and collector temperature should be checked for functionality.

- Coolant and Oil Temperature: As coolant and oil temperature rises and falls there may be changes in the output data, primarily emissions and friction. Cold oil will result in higher frictional losses and will show reduced brake power. This is not nearly as important in a two-stroke platform, especially since the oil will roughly be room temperature.

- Engine Hardware: A running list of hardware changes should be kept for traceability. That being said, day-to-day changes should be *representative and explainable.* If they are not, work needs to be done to discover the cause of the changes.

- Fuel: If none of the above are producing a cause for the inconsistencies in operation it may be worthwhile to verify that the fuel parameters are consistent. For example, AFR for pump gas is ~14.7 while indolene (a common test fuel) can be ~14.5 or if the RON's are different i.e. 87 vs 93 the emissions, power, and knock characteristics may change.

In the past at the UI this process has been done, but not to a standard. Any future users of the test cell should follow the above recommendations to ensure consistency. The most important part of this is to show what changes are occurring in the engine. An engineer should say "it's just the nature of it" as little as possible in a test cell. Very few changes are inexplicable. Without a fully instrumented engine it can sometimes be difficult to discover the cause of an engine change. At this point the engineer must use intuition and attempt to recreate the issue in a way that will ascertain the cause. An example of this data is provided in APPENDIX C: CASE STUDY DATA FROM UI SMERF. This represents the minimum data that should be included in the results.

5.2.   USING WINDYN TESTS

Internal to WinDyn are a few customizable tests to gather data. The two most useful are the power sweep and steady state tests. The power sweep requires inputs of a throttle position, beginning speed, ending speed, ramp rate, and sample rate. Recommended values for the above provided in Table 6.

Table 6: Power sweep recommended inputs.

Required Input	Recommended Value
Throttle position	Typically wide open, can be whatever blade opening that is desired.
Lower	Clutch engagement minus 50 RPM
Upper	Max RPM plus 200 RPM
Return	What RPM the dyno will be set to after the test is completed
Ramp rate	50 RPM/sec is common
Sample rate	1 Hertz is adequate

The second test is the steady state test. This test runs the engine at a specified throttle position and engine speed for either a set amount of time or until the user cancels the test. This test is recommended for getting data for the 5-mode emissions. It will allow the user to get an average power, torque, and engine speed which is more representative of what will be

seen at any emissions test facility. The inputs for this test are the same as above, with the exception that the input engine speed should be the desired speed plus 50 RPM.

It is possible to create custom tests in WinDyn it would be worthwhile to create two new tests. The first would be to automate the data mapping. This could be done with a little work in the program. The second would be to build a ramped modal cycle test that is used at the CSC into the programs. The interface is reasonably graphical and straight forward. A more detailed description of this can be found in APPENDIX D: DATA ACQUIZITION IN SUPERFLOW.

5.3. OPTIMIZATION

Development was pursued in the form of a genetic algorithm (GA) to speed up the process of improving engine performance. More specifically the GA used a mutation and crossover process to find the optimum point. This GA could easily have been made more complex by looking at a larger amount of design variables, but for the sake of simplicity this was kept to two: intake pressure and air-to-fuel ratio (AFR). Engine speed was held constant as was ignition timing to find the best point. In practice the calibrator would have to spend time on the dyno to find the rich and lean limits of the engine, as well as find peak spark values. This information will be used to make the penalty functions for the optimization. Using the data mapping process described above the map should give enough resolution to find optimum points at specific points of interest. The program was not automated to move from point to point, but with a little work a new user could add this functionality.

To begin the optimization a response surface needed to be created. This was developed by using a little intuition about how the engine operates, as well as some guess and check. In the end the data had a reasonably good fit and predicted better points well. The minimization function is given in Equation 7. This was determined to be the best fit of the data where A(i, 1) is AFR and A(i, 2) is intake pressure.

$$\min f = [1 \; \frac{A(i, 1)}{A(i, 2)} \; \log\big(A(i, 1)\big) \; \log\big(A(i, 2)\big)] \; * \; [\, \beta_1 \; \beta_2 \; \beta_3 \; \beta_4]^T$$

Equation 7: Minimization function for optimization.

This fit function was valid for empirical data as well. It essentially showed that just under wide open throttle was the peak point from an efficiency standpoint at the target RPMs that

were tested which held true when compared to empirical data. A report that was written with the purpose of duplicating these points is included in APPENDIX E: INTRODUCTION TO OPTIMIZATION OF ENGINE.

First the data that will be gathered is determined. Typically it is important to start with a baseline. This is a vital first step because the difference between a mechanic and an engineer is quantifying data. It is important to understand the operating band of the initial set-up. A standard way of gathering this data is to create the data map described in section 3.1. Several operating speeds and a majority of engine loads are explored, and data gathered. The data is compared by comparing the test points to each other. The x and y axes of these data are typically engine speed and BMEP. BMEP is a representation of engine load that allows many different engine platforms to be compared. For most parameters, brake specific values are calculated then compared. The data of interest in this testing is shown in Table 7. From this information, most engine parameters can be calculated including brake specific emissions, brake specific fuel consumption (BSFC), power, BMEP, and fuel trapping efficiency.

Table 7: Calibratable parameters in engine testing.

Parameter	Description	Unit
Engine speed	Rotational speed of the crankshaft	RPM
Torque	Torque at power take off shaft	N-m
Engine Temperature	Head temperature	C
Exhaust gas temperatures (left and right)	Temperature at manifold	C
Hydrocarbons	Unburned Hydrocarbons in exhaust stream	PPM
Carbon dioxide	CO_2 in exhaust stream	PPM
Carbon monoxide	CO in exhaust stream	%
Fuel Consumption	Fuel used by engine for combustion	kg/hr

The data listed in Table 7 will be collected at several discrete engine speeds ranging from 4500 RPM to the max operating speed of the engine in intervals of 500 RPM. To record a reasonable amount of points at each test speed, from 10-60% throttle the throttle opening will be varied by 10% at a time, and above 60% it will be varied by 5%. This strategy is pursued because near 60% throttle opening the exhaust valves shift to a mid-position. There is also more diversity in the throttle points at high load rather than low. This is in part due to the effect of the tuned pipe. This results in 13 data points per engine speed which is more than enough to interpolate a reasonably accurate map from. A general testing plan is explained in Table 8.

Table 8: Testing plan.

| Configuration Number	Configuration	Description	Purpose
1	Baseline	Stock 600cc hardware and calibration	To attain a baseline to develop
2	Detuned	Reduce the operating speed of the stock engine and hardware	To lower the operating speed for competition rules
3	Tuned Pipe Redesign	Attach redesigned pipe and header	Introduce pipe and calibrate for the modified trapping and scavenging pulses
4	Intake Modifications	Introduce intake resonators	Calibrate with increased intake pressures to quantify efficiency changes as well as acoustic improvements

For each of the configurations, aside from the data map, two standardized tests will be performed to quantify the change in engine operation. The first is a WOT power sweep, taken over 1 minute, increasing from 4000 RPM to max engine speed, collecting data at 10 samples per second. This will be done three times, back-to-back. This helps to normalize for the heat soaking of the engine and exhaust components. Finding peak power and torque this way is an industry standard and very repeatable.

After each data set is gathered, the data will be analyzed to verify that nothing strange is happening. If nothing odd occurs, there is sometimes a desire to gather more data points around certain points of interest to better understand what is happening in the engine. The data analysis should take a few days to accomplish. One day to get the data into a useable form and 1-2 days to interpret the results and make the decision to move forward or to continue acquisition with the current set up. This step is important because during testing if a portion of data needs to be reacquired; it could add a large amount of time to correct if not done at this step. For instance, if the pipe is modified multiple times it often cannot be changed to mimic the previous configuration.

The next test is the EPA 5 mode emissions test which was developed by the Southwest Research Institute (SWRI) to certify snowmobiles as meeting EPA or NPS standards [22]. This test uses the peak power and engine speed found during a power sweep and determines the 5 modes using that information. The modes are based upon data taken over several years to learn how much time an average rider spends at various load points under typical riding conditions. Table 9 shows the breakdown of the 5 modes. The peak speed is taken where peak torque is found. The rest of the points are calculated from this point. Figure 24 shows a power and torque sweep where peak is found at the final data point in the sweep. Knowing that torque and speed affect what points will be tested it is possible to calibrate the peaks such that the other points that are tested are at the most efficient points of the engine.

Table 9: 5-mode points for emissions testing in snowmobiles.

Mode Number	Percent Torque	Percent Speed	Mode Weight
1	100	100	.12
2	51	85	.27
3	33	75	.25
4	19	65	.31
5	Warm Idle	Warm Idle	.05
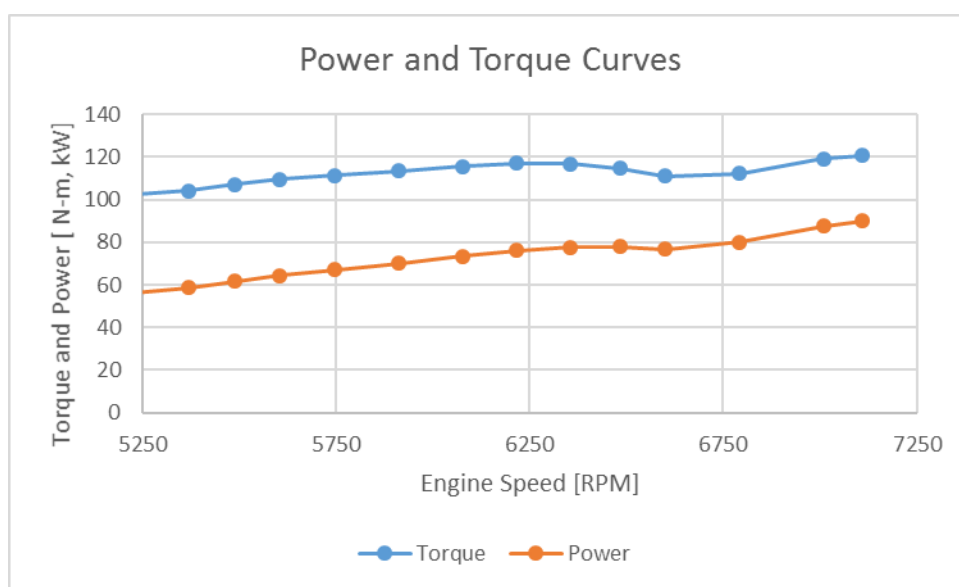
Figure 24: Power and torque sweep curve.

From this test, an emissions or E-score is calculated. This score can vary from 0-210, where a score of 210 implies only water vapor and oxygen are emitted from the engine. A score of 100 is EPA standard and 170 is NPS certified. This score is calculated from Equation 8, where HC, NO_x, and CO are brake specific emissions in g/kw-hr.

$$E = \left[1 - \frac{(HC + NO_x) - 15}{150}\right] * 100 + \left[1 - \left(\frac{CO}{400}\right)\right] * 100$$

Equation 8: EPA E-score formula.

This will all be done while using the SAE J1349 correction factor that takes into account intake charge air temperature, ambient air pressure, and humidity to normalize for

different testing conditions. This is typically kept within certain limits by using a charge air cooler and feeding the engine conditioned air, but that hardware is not available at the University. This allows the results of each experiment to be repeatable anywhere in the world, as long as the correction factor is used. Typically fuel is also cooled, but there is no fuel conditioning system at the UI either. The fuel in the E-TEC engine is used to cool the injectors as well as the engine control unit (ECU). This causes the fuel in the reservoir to heat up during operation, which causes the density to change slightly. This largely does not affect the performance of the engine, but is taken into consideration during testing to keep the temperatures within a reasonable range.

In cylinder pressure trace data can also be collected using Kistler in-cylinder pressure transducers in conjunction with the Kistler charge amp and crank encoder. This will give important information with respect to combustion quality as well show early indications of knock. One risk with the use of these sensors is that they are relatively fragile and if there is a failure there are not funds available to replace the sensor. The best way to use an in cylinder pressure trace for calibration is to look at the burn rates, coefficient of variance, knock thresholds, and indicated values. The burn rates should be pushed to be as fast as possible, getting to a 7-degree crank angle for 50% burn is a good benchmark to aim for. The coefficient of variance is essentially how consistent the combustion is from cycle to cycle and should be minimized. Knock can be seen significantly sooner using pressure transducers and the calibration can be pushed a lot closer to the ragged edge. The indicated values can give good information about the volumetric and mechanical efficiencies. Figure 25 shows what the pressure trace will look like for knock indication as well as different levels of knock. Figure 26 shows a logP logV plot that will show the indicated values. Not shown is ignition that is too retarded.
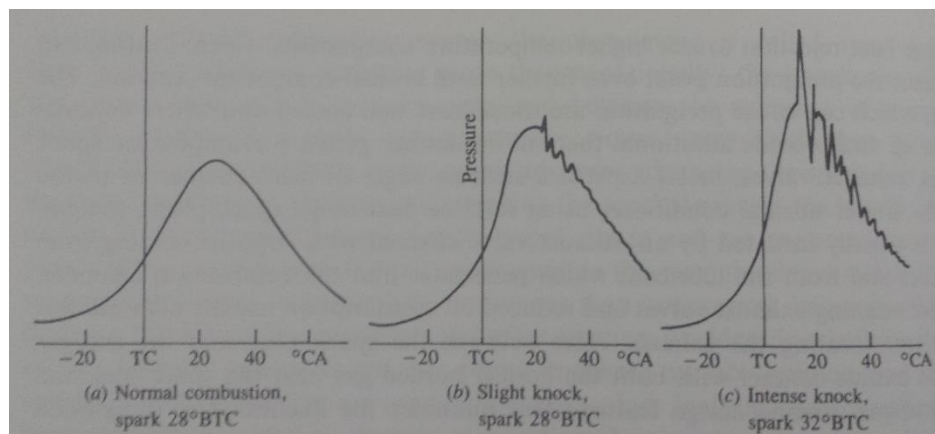
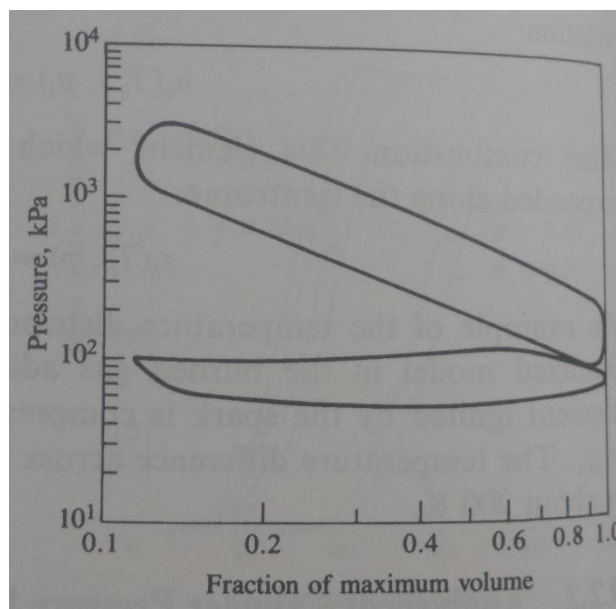**Figure 25: Various knock levels using a pressure trace [20].**

Figure 26: log P log V pressure trace [20].

In addition to recording data from the engine, notes will be taken about other, unquantifiable information. This will include the sound, how smooth the operation is, and vibrations. This is not easy to quantify, but can be used for future areas of focus if the project is pursued.

5.4.   CASE STUDY FOR EXHAUST MODIFICATION

One of the most recent projects completed with extensive data collection involved a redesign and characterization of the tuned pipe. This project needed to be completed because down-speeding the engine required a different tuned length than the stock pipe. Using Blair and Bell, a math model for the tuned pipe was developed [14] [23]. Since designing a tuned pipe is difficult and time intensive, an existing pipe was used and strategically lengthened. Without going into too many of the details of the pipe design, the dwell and header were lengthened by 14% to accommodate the down-speed engine. This project was done in several stages. The first was to lengthen just the header due to the ease of fabrication. It was learned that by extending the header by 5mm the tuned length would be reduced by ~100 RPM. The pipe needed to be lengthened by 50 mm, but that would not be possible to package in chassis. As such a 20 mm extension was tested as well. This was tested in preparation for a full pipe rebuild. Three configurations will be shown to depict the decision-making process in the project. The configurations are described in Table 10.

Table 10: Pipe comparison chart

Pipe Name	Description
Stock	The stock pipe from the 800 cc engine
Aftermarket	A standard aftermarket pipe
Extended Aftermarket	The aftermarket pipe extended by 14%

The stock pipe was used as a baseline to allow for comparison to the modified pipes. An aftermarket, performance focused pipe was selected due to the unknown geometry of the stock pipe. Working with the supplier modifying the aftermarket pipe was much simpler. The final configuration was the extended pipe. The results at several discrete points are shown in Figure 27.
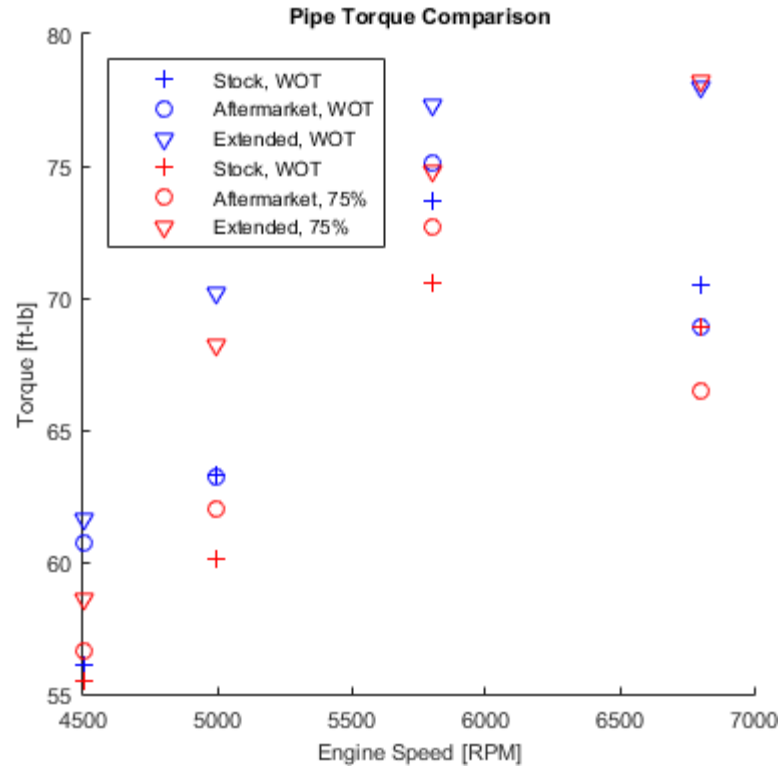
Figure 27: Pipe comparisons.

These pipes were treated as direct replacements with no recalibration at the points. Due to this it is evident that the timing of the pulses is changes. A better indicator of this performance is with BSFC. The peak BSFC for each of the pipes tested is given in Table 11.

Table 11: Comparison of BSFC due to pipe changes.

Pipe Name	Minimum BSFC [g/kW-hr]	Average BSFC [g/kW-hr]
Stock	278	369
Aftermarket	268	359
Extended Aftermarket	261	331

BSFC is essentially a measure of how efficiently fuel is used to create power. That means a lower number is better. In many instances fuel consumption is sacrificed for the sake of emissions. After all the pipes were tested the engine was recalibrated as needed for survivability and peak power while considering emissions.

5.5.   NECESSARY PLOTS TO REPRESENT DATA

There are a few standard ways to present engine performance data. The standard information that an end user would want to visualize are:

- Brake specific values
    - Fuel consumption
    - Emissions (HC, CO, CO_2, NO_x)
    - Air consumption
- Brake power and torque curves (attained at wide-open-throttle)
- Exhaust gas oxygen content using a lambda meter
- Volumetric efficiency curves

The data necessary to create these curves is gathered during normal testing typically. The necessary inputs should be gathered at each data point to ensure the vehicle is running properly.

To properly understand brake specific values, the individual words used should be understood. Any time brake is included it implies that data will be shown on a per-power basis. This will be presented as a per power unit. Specific means that mass will be used. A brake specific value would be mass per power. Finally, consumption requires time to be included. Brake specific consumption is represented as mass per time per power, or in SI units, g/kW-hr. A brake specific output can be represented as a contour plot, analogous to a topographic map, or a single value if a peak or average number is required. A brake specific contour plot has x and y axes of engine speed and BMEP, respectively. The depth, or contours, are typically represented by color with the brake specific values shown. Often BMEP is not an output of the dyno at UI. To convert the brake torque to BMEP equation 2 is used. The easiest way to create these plots is to use a software developed specifically for engine data. The two most common are AVL Concerto and Uniplot. The UICSC team attained a license of Uniplot for non-publishable work. Even though the plots cannot be published a user's guide was created on how to create these plots. It is included as APPENDIX F: UNIPLOT KAIZEN. Strictly from a cost standpoint Uniplot is the obvious choice for academic use over Concerto. Lambda meter and VE data are plotted the same way

as the above. Figure 28shows a BSFC plot for the final exhaust configuration described in section 4.5. The red dots are a representation of the speeds, loads, and weighting of each mode point.
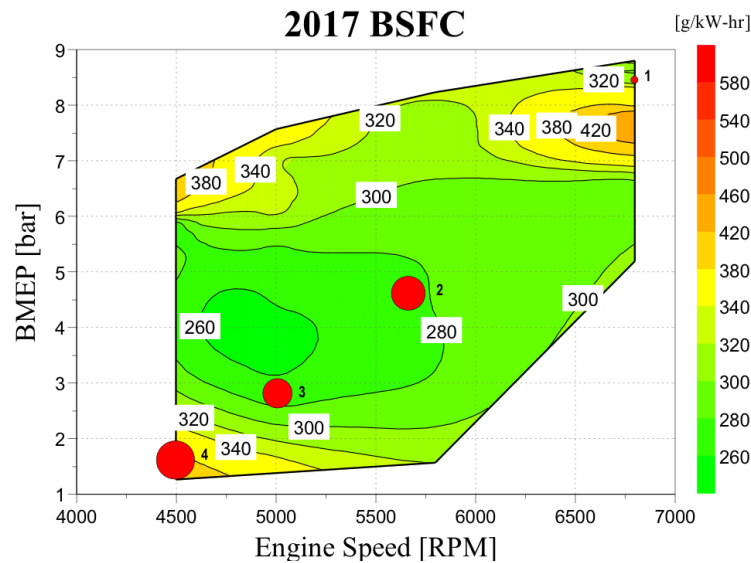
Figure 28: BSFC plot for the 2017 CSC submission.

To understand the performance of the engine and develop transmissions or shift points, it is common to use brake power and torque curves. Brake here means the torque measured at the crank shaft. These plots should be either lines or a scatter plot. The x and y axes are engine speed and horsepower with torque, respectively. If a line plot is used it is imperative to use straight lines to connect the data points rather than curves. This ensures that only known data is presented nothing extrapolated from the measurements. The data shown in APPENDIX is an easy way to plot the power and torque curves, although WinDyn does this automatically after a power sweep is performed.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. VALUE TO STUDENTS

This work at its basest is meant to serve as a calibration/SmERF user's guide for students. The intent is to have created a resource that almost any student can come to, read, and have enough information to use the SmERF for basic engine testing and calibration. This includes basic usage of much of the test equipment. More explicitly the step-by-step guides allow for most users to effectively test many different configurations. This thesis also serves as a repository for much of the "tribal knowledge" that has been passed down year-to-year. From the student's perspective, it allows for consistency in testing. It will allow a student in five years to replicate the conditions that are used today in the lab. In addition to this this study serves as a basic introduction to many engine design concepts. These range from calibration and testing strategies to commonly used aftertreatment devices. As the usage of the SmERF continues the resources available to the students should increase as well.

6.2. SmERF UPGRADES

Although the SmERF works well as a test cell there are a few upgrades that would vastly improve the testing quality. The first would be to replace the SuperFlow WinDyn system with something more substantial that allows for better customer support. In addition to this an AC motoring dyno would allow for accurate measurement of VE of the powerplants. The cost of these upgrades would be immense, but would be well worth it in the long run. The building itself should be upgraded as well. The roof needs to be insulated to allow for better controlled testing. The better choice here would be to make a climate controlled, small, test cell common in industry. For engine and dyno cooling plumbing in chilled water from the steam plant would be incredibly useful. To measure intake air consumption more accurately a laminar flow element should be utilized. Purchasing an improved system for in-cylinder pressure measurements would improve calibration effectiveness as well. A blow-by meter allows for better assessment of engine health allowing for reduced catastrophic failures. A high accuracy crank encoder is necessary for industry grade testing. This allows for data, especially combustion data, to be time aligned with the crank angle of the engine. The final sensor that would be useful is a high-speed exhaust pressure transducer.

6.3.   DESIGN CHALLENGES

In any engine development emissions should always be considered. For the UICSC development has primarily focused on reduced engine-out emissions while using catalysts in the exhaust to reduce tail-pipe out emissions further. Due to the nature of a two-stroke the emissions development has focused mostly on UHC and CO reduction. While using equation 1 for calibration engine out emissions are balanced with power production. This doesn't guarantee that the emissions are minimized. At this point aftertreatment must be considered. The use of a catalyst, or monolith, is the obvious choice. In past years this has been "slapped on" at the end of the exhaust system to reduce emissions. This was done with little to no consideration for back pressure or flow characteristics meaning the catalyst was potentially used ineffectively. To mitigate this, the catalyst should be designed to allow for proper inlet and flow across the face of the substrate. Cones are utilized to maintain laminar flow and ensure uniform flow across the substrate. In addition to this the temperature characteristics of the exhaust system, specifically at the catalyst location should be understood. This is achieved by strategically placed catalysts in the exhaust prior to and immediately after the catalyst. It is common in industry to monitor the mid-brick temperatures of the catalyst as well. The catalyst comparisons at the UI have involved several different coatings and cell densities and are compared using E-score. This is shown in Figure 29. The cell densities vary from 300-400 cells-per-square inch. For a next generation design a full close-coupled system should be explored. This in conjunction with a custom catalyst washcoat could produce some interesting results.
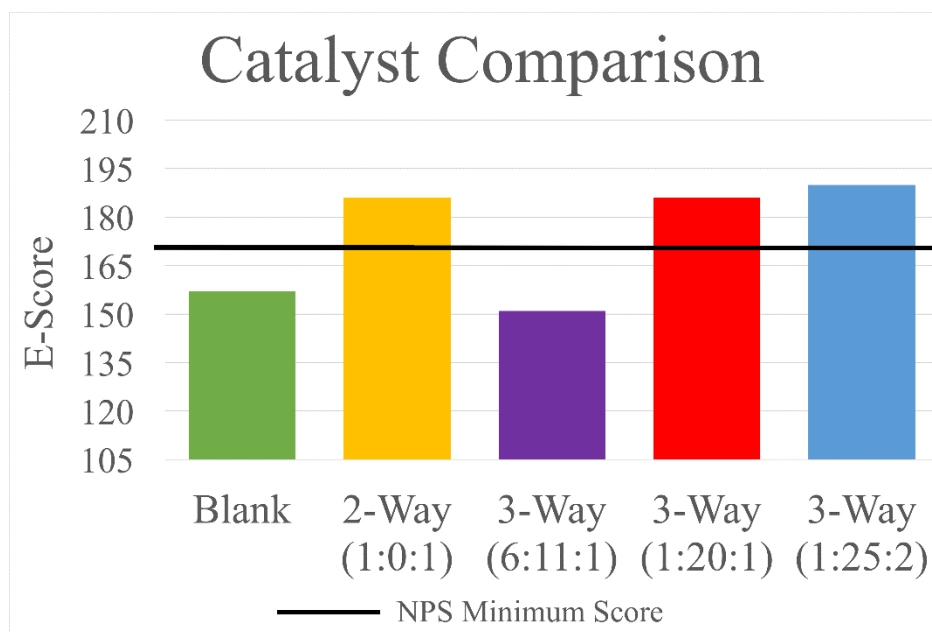
Figure 29: Catalyst comparisons.

When discussing exhaust modifications specifically with regards to acoustics resonators are commonplace. These commonly are either quarter-wave or Helmholtz. Typically, whenever a resonator is used in the exhaust it comes at the cost of back pressure. In much of the testing that was conducted there was little to no increase in backpressure which means there is very little power loss. The development of the resonators was a four-step process. The first was to create a resonator for the second harmonic of the engine. This was manufactured as a straight pipe. The results were positive, so the second design was to bend the tube for chassis fitment. This had no detrimental effects on the acoustics of the pipe. The third was designed to attenuate the first harmonic of the engine. This was difficult to design because it had to be twice as long as the first design. The final iteration was a play on active noise cancellation. A variable length resonator tube was designed using a motor and a custom gear box to drive a plunger based upon engine speed. These were quite effective, but unless the exhaust side of the snowmobile is louder there is no need to add complexity to the exhaust. For more information regarding the active exhaust resonator refer the paper written by Dr. Santora [24]. A next generation design for this would be to explore active Helmholtz as well as coupling either design with a piezo-electric device to broaden the effective range.

In addition to the exhaust, the intake noise is a significant contributor to overall noise. Silencing the intake seemed to be more predictable using the Helmholtz model rather than a

quarter-wave. The initial testing showed not only that noise was attenuated, but due to the increased pressure on the intake torque was increased as well at the design point. In the future, it would be great to design a series of resonators to help keep noise production smooth for the intake. A comparison of sound loss which correlated to a torque increase, for different geometry resonators is shown in Figure 30. For more information on this design refer to the 2016 UICSC paper [25]. A full intake box design should be explored as there are likely large gains available. This would likely be done through the use of software to model the acoustics and fluids.
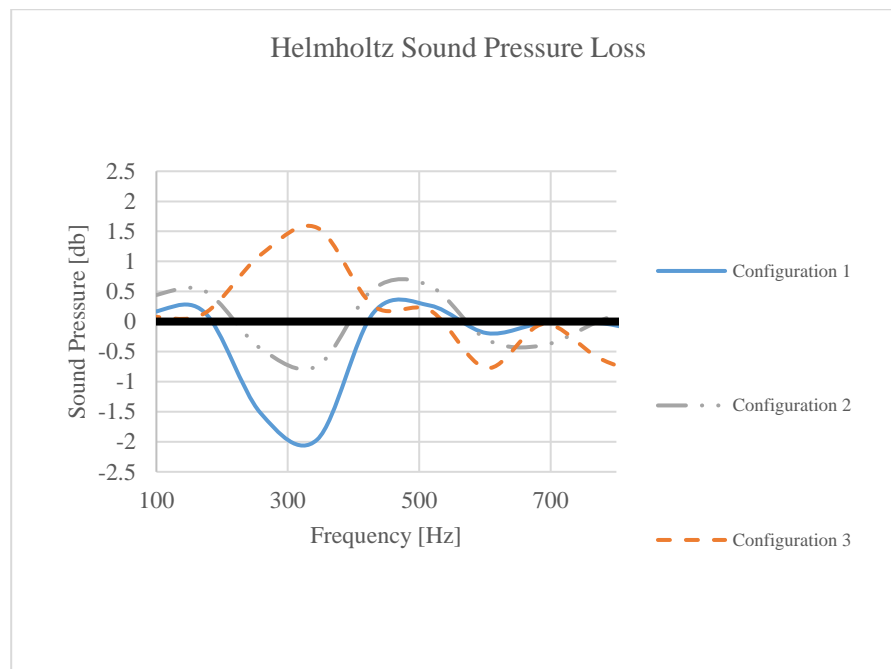
Figure 30: Intake resonator comparison.

Developing an electronic throttle for the two-stroke engine is a relatively new concept. There aren't any commercial two-stroke engines with e-throttles. The initial development of this control was to use a wire driven system. The largest issue with this is a slight lag due to the nature of the system. The next design iteration should include a gear driven system with encoders for precise location of the throttle blade. More importantly in the control scheme for this throttle it should include an intelligent cruise aspect. This control schema would only activate at cruising loads and speeds. At these points, if the user input was "not changing" the sample rate would reduce. This would help to reduce the amount of enrichment due to

acceleration and deceleration compensations. There would be a lot of benefits to on-snow performance.

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APPENDIX A: SHUTDOWN AND START-UP OF TEST CELL KAIZEN SHEETS

SHUTTING DOWN THE TEST CELL

1. Save test data & calibrations: ensures that nothing is lost after testing.
2. Turn off ECU: removing auxiliary power from the ECU reduces the risk of component failure internal to the computer.
3. Turn off wireless handheld console: the backlight can fail and this part is discontinued so repairs have long lead times.
4. Close WinDyn software: this prevents the desktop computer from freezing.
5. Switch off power supply: Halts 12-volt power to SuperFlow box that is used for auxiliary power.
6. Turn off SuperFlow DATAQ: halts power output from box.
7. Unplug DATAQ box: saves control board from power fluctuations from storms.
8. Power off starter: no long-term benefits, but good practice.
9. Power off fuel cart: increases longevity of pumps, filters, and regulators.
10. Power down water pumps (2) and fan: reduces noise and prolongs life switches located on South wall and fan tower respectively.
11. Shut down Horiba: increases longevity of consumable components.
12. Check for tripping hazards and shut off lights.

TURNING ON THE DYNO CELL

1. Check that the engine is bolted to the dyno drive shaft securely and that the engine cart is secured to the dyno frame. For high vibration engines, zip tie or tape the hooks that secure the cart to the dyno so they don't rattle loose. This should be visually inspected every day that testing occurs.

2. Verify that there are no leaks, no rubbing hoses, and no fatigued components. The drive line should be checked to verify no bolts have loosened and all wiring should be inspected for issues.

3. Check that all coolant and fuel lines are fully connected and that they are routed to avoid heat and rubbing. In addition to this if an engine was recently put on the dyno the cooling system needs checked in 5 locations.

   a. The water reservoir in the SuperFlow cooling tower.

   b. The lower tower needs burped, use a screwdriver down the air release with pumps on.

   c. The engine needs burped this is done initially by holding the top coolant line above the engine and depressing the quick release to allow all the air to leave the engine. In some occasions this will need to be done again with the engine idling.

   d. The Redbull tower needs to be full.

   e. The southernmost radiator may need refilled.

4. Turn on the Super Flow DATAQ box and the 12V power supply.

5. Do not plug more than one pump into each bank of two outlets on the wall as they can only handle 10 amps each. Do not plug a fan and a pump into the same bank of outlets.

6. Turn on fuel system, check for the correct fuel pressure and check that fuel tank is full.

7. Turn on engine exhaust fan, cooling tower fan (switch on tower) and engine fan (black fan on pedestal).

8. The engine exhaust fan inlet should be within less than six inches of the engine tail pipe.

9. Check that the Super Flow hand held controller is on, there are no errors and the engine rpm 'Engspd' is set at least 1000 RPM above your engines' idle speed. Check that the throttle is set to zero.

10. If using the starter motor on the dyno check that the green light in the lower left of the starter control box labeled 'Marcia/on' is lit, if not press this button. The 'Marcia/On' button should now be lit. Press and hold the green button on the far right to start the engine. The starter uses a compressed air clutch to engage the dyno, check that the air valve on the wall is on and gauge reads about 15psi.

APPENDIX B: STARTING THE SUPERFLOW WINDYN INTERFACE.

The following steps demonstrate how to start SuperFlow.

Go into the user "Dyno Computer".

Double click the SuperFlow icon on the desktop.

You will see a grey screen after entering the password. Attain password from lab supervisor.

Click the icon indicated followed by your desired test group. i.e. csc.tgp or yz250fx.tgp. Click either okay or install, save exit. This has since been set-up to automatically load an appropriate test group, but changing the group is done through this process.
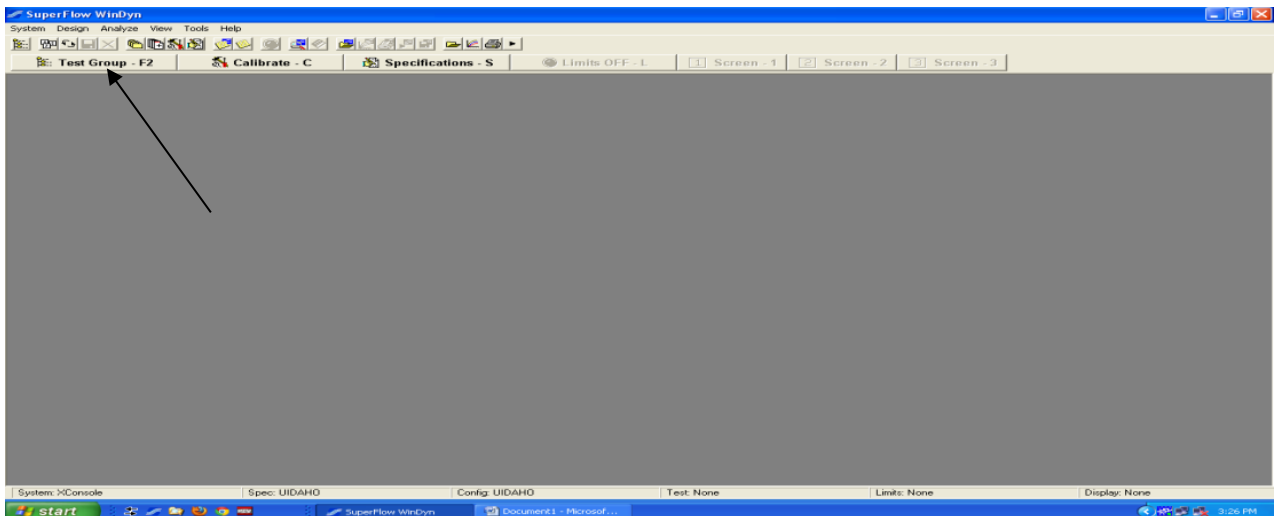
Figure 31: SuperFlow start-up screen.

After installing your test group, you will see a screen that looks like the one below. Each group has a different set up catered to their individual needs. A test group from the University of Idaho is shown as an example throughout this tutorial.
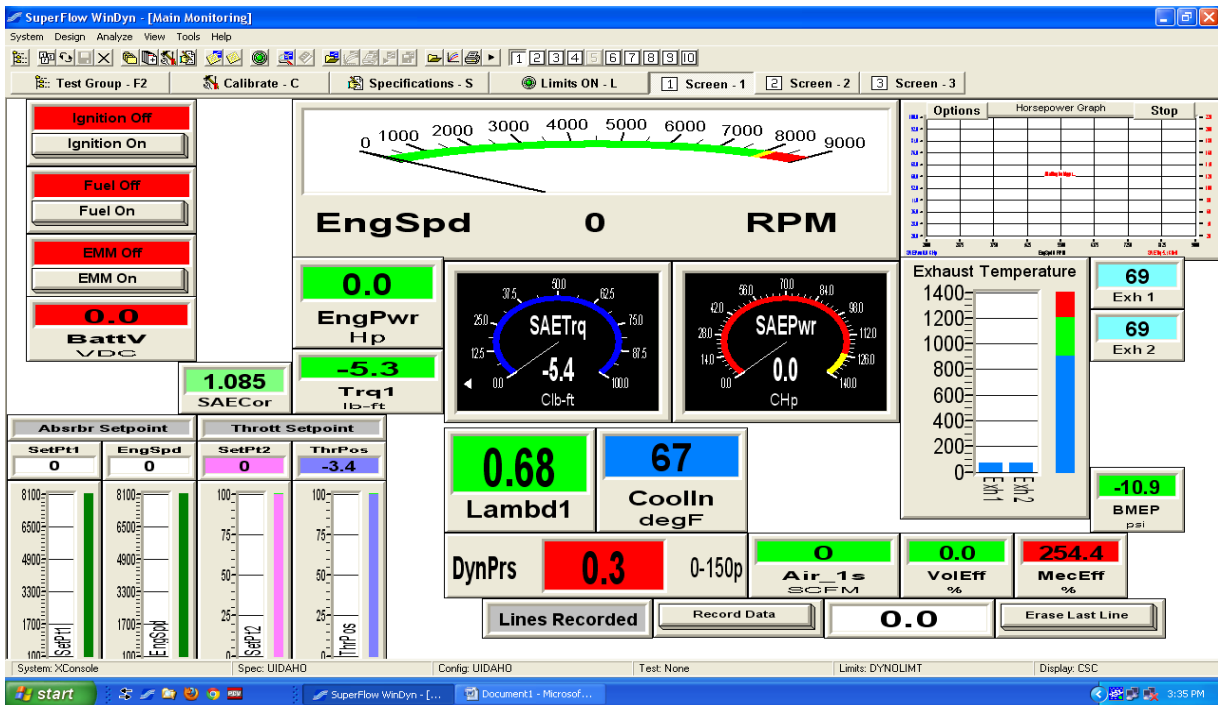
Figure 32: Example test group screen.

The next step is to install the proper specifications file. Each group has a specs file that is specific to their engine.

The steps to get to the right screen are click: Specifications "a screen pops up" > Recall "another screen appears" > Select your given engine > open. IMPORTANT!!! VERIFY ALL ENGINE PARAMETERS IF RUNNING THROUGH A GEAR TRAIN VERIFY OVRRAT WITH GEAR RATIO.
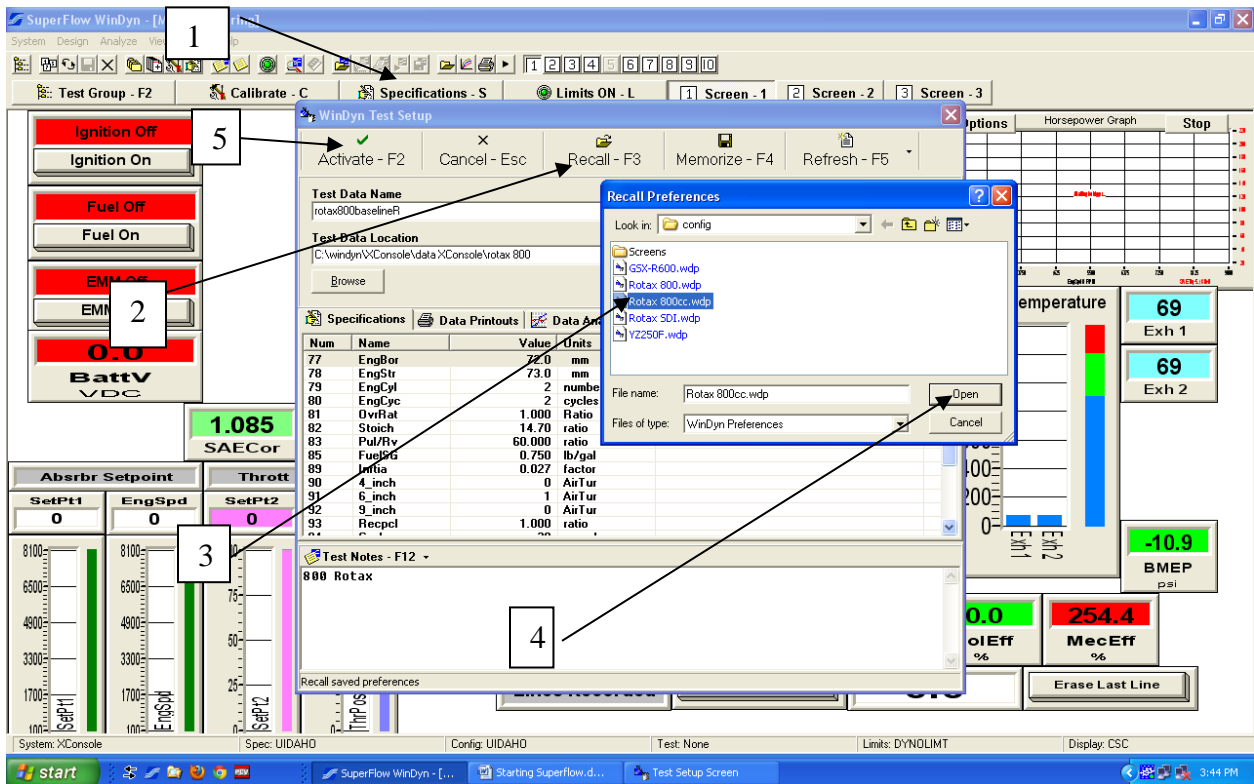
Figure 33: How to install specifications file.

This step ensures that the data that is output by SuperFlow is accurate. These specification values are needed for many equations that the software uses. For this, channels 77-81 are the ones that should be modified internally through the blue screen. If the OVRRAT is wrong the dyno will attempt to hold the engine to a speed that does not match the engine controller.

Now the software should be ready to go. Double check that all appropriate channels are reading a reasonable value i.e. Exh "n" should be 60-75 F. The Dyno torque should be near zero +/- 1 ft-lb. For tuning purposes calibration of the torque arm is not necessary but for data acquisition every system that can be calibrated should be, this includes, but is not limited to the dyno torque and emissions analyzer.

Final note, if the two toolbars are not shown in your screen at start up most actions can be done through the file path. Or you can follow the following key strokes: Click view > toolbars > Check advanced and system.

APPENDIX C: CASE STUDY DATA FROM UI SMERF

This data was gathered on the eddy current dyno on the 800 cc two-stroke with the unmodified aftermarket pipe attached. This data was collected post calibration. This data is not intended to be used as a calibration tool. Colored columns are data to be entered by the tester while the white columns are calculated values.

Rpm	TPS%	Actual TPS	lambda	Torque (ft-lb)	Vol Airflow	Head Temp	Notes	Hp	Fuel (kg)	Time (sec)	Consumption (kg/hr)	BSFC (g/kw-hr)
4500	10	10.4	1.23	18.5	31	42		15.85	0.053	53	3.60	304.85
	20	21.1	1.54	27.4	50	43.9		23.48	0.08	57.8	4.98	284.89
	30	30.7	1.37	40.7	66	46.3		34.87	0.08	40	7.20	277.14
	40	41.6	1.32	49.2	81	48.9		42.16	0.08	32.4	8.89	283.03
	50	50.5	1.19	54.8	91	51		46.95	0.076	23.8	11.50	328.64
	60	60.4	1.13	52.8	94	48.3		45.24	0.08	23.4	12.31	365.17
	65	65.1	1.14	54.5	97	49.5		46.70	0.088	25.1	12.62	362.80
	75	76.4	1.12	56.6	101	50.8		48.50	0.1	25	14.40	398.57
	80	79.5	1.08	57.8	102	52.3		49.52	0.104	25.4	14.74	399.51
	85	85.7	1.09	58.1	103	46.7		49.78	0.11	25.3	15.65	422.04
	90	90.5	1.03	60.2	104	49.2		51.58	0.114	25	16.42	427.20
	95	95.2	1.02	60.8	103	50.5		52.09	0.112	24.7	16.32	420.61
	100	99.1	1	60.7	104	51.6		52.01	0.102	22.6	16.25	419.34
5000	10	11	1.28	19.6	35	37.9		18.66	0.08	68	4.24	304.67
	20	20.4	1.47	29.7	56	41.8		28.27	0.08	51.1	5.64	267.56
	30	30	1.4	41.2	72	45.1		39.22	0.08	36.5	7.89	270.02
	40	40.7	1.18	50.8	87	48.3		48.36	0.081	26.4	11.05	306.56
	50	50.6	1.16	56.5	100	50.2		53.79	0.091	23.9	13.71	342.06
	60	60.2	1.03	58.1	101	51.8		55.31	0.105	25	15.12	366.92
	65	64.7	1.09	61.2	109	45.4		58.26	0.115	26.5	15.62	359.92
	75	74.8	1.03	62	110	48.1		59.03	0.13	27.3	17.14	389.84
	80	81	1	62.7	110	50		59.69	0.12	25	17.28	388.57
	85	84.6	0.99	62.8	111	51.6		59.79	0.122	25	17.57	394.42
	90	89.9	1	64.3	115	46.6		61.21	0.126	25	18.14	397.85
	95	96.3	0.99	64.4	112	48.4		61.31	0.11	22.2	17.84	390.53
	100	98.9	0.99	63.2	113	50		60.17	0.112	22.3	18.08	403.36
5800	10	10.5	1.1	18.3	37	45		20.21	0.075	54.9	4.92	326.65
	20	20.1	1.29	31.4	61	48.3		34.68	0.062	30.5	7.32	283.27
	30	30.5	1.22	42.5	81	50.2		46.93	0.083	30.3	9.86	282.03
	40	39.9	1.01	60.1	103	52.7		66.37	0.088	20.2	15.68	317.18
	50	50.6	1.08	66.7	124	45.2		73.66	0.098	20.1	17.55	319.85
	60	59.9	1.19	69.2	131	48.8		76.42	0.094	19.5	17.35	304.81
	65	65.8	1.2	71.9	136	51.3		79.40	0.104	20.3	18.44	311.78
	75	74.6	1.18	72.7	140	53		80.29	0.092	17.3	19.14	320.07
	80	79.5	1.22	71.8	149	45.2		79.29	0.088	16.1	19.68	333.10
	85	86.4	1.16	74.1	147	48.4		81.83	0.101	18	20.20	331.34
	90	89.4	1.09	74.7	146	50.5		82.49	0.089	15.5	20.67	336.34
	95	93.7	1.14	74.9	148	48		82.72	0.099	17.1	20.84	338.22
	100	98.9	1.09	75.1	146	49.8		82.94	0.114	19.9	20.62	333.78
6800	10	10.4	1.05	6.8	37	38.6		8.80	0.021	13.1	5.77	879.83
	20							0.00			#DIV/0!	
	35	35.9	1.03	47.9	104	45.5		62.02	0.06	14.3	15.10	326.92
	40	40.6	1.03	56.8	112	48.3		73.54	0.063	14.2	15.97	291.52
	50	49.6	1.03	59.6	129	51.4		77.17	0.073	14.9	17.64	306.80
	60	61.9	1.05	65.3	156	47.6		84.55	0.103	15.5	23.92	379.80
	65	66.2	1.04	66.1	155	49.5		85.58	0.094	13.9	24.35	381.83
	75	74.9	1.05	66.5	160	52.2		86.10	0.103	14.8	25.05	390.59
	80	81	1.02	67.1	161	53.9		86.88	0.101	14.4	25.25	390.12
	85	85.4	1.07	68.1	169	47.7		88.17	0.101	13.8	26.35	401.10
	90	91.2	1.04	71	164	50.2		91.93	0.11	15.1	26.23	382.93
	95	95.6	1.06	70.4	168	48.9		91.15	0.102	14	26.23	386.24
	100	98.9	1.02	68.9	164	51.2		89.21	0.112	15.4	26.18	393.95

APPENDIX D: DATA ACQUIZITION IN SUPERFLOW

       Prior to performing a test setting up the save parameters is necessary. This is done from the specifications screen. From the main WinDyn window press "S" and the screen will appear. In this screen, are two sections vital to saving the data properly. The first is the file name. The traditional CSC format is the following year_month_day_mode_run. Numerically this will be: 2017_03_17_M1_R5. The mode number is optional depending on the type of test being performed. In the specifications screen the start at function will automatically increment the run number after each test. The second section is the save location. This is easy to achieve so no detail will be described on how to do this.
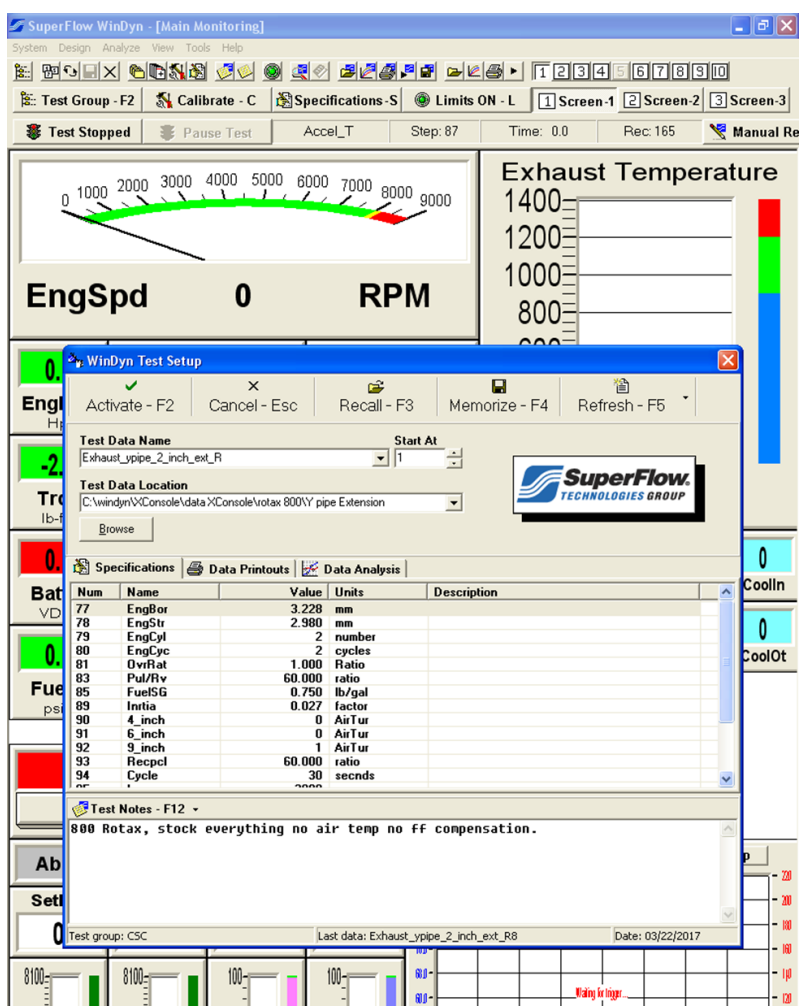
       Performing a test using a program built into WinDyn is simple, effective, and modular. Once the handheld is turned on the steps to run a test are described well on the screen. Normally to start the engine on the dyno the user must switch to the second screen on

the handheld by pressing the touch screen to between the text on the right side. To perform a test this must be done again to return to the original screen. This screen will look like the following figure. The important information is listed along the right side and the bottom. Starting from the top and working clockwise around the screen, the options will be described.

Required Input	Recommended Value
Throttle position	Typically wide open, can be whatever blade opening that is desired.
Lower	Clutch engagement minus 50 RPM
Upper	Max RPM plus 200 RPM
Return	What RPM the dyno will be set to after the test is completed
Ramp rate	50 RPM/sec is common
Sample rate	1 Hertz is adequate

Not every parameter on the screen is used for a test. For example, upper and lower are not used in a steady state test. It should be obvious whether an upper/ lower speed limit is necessary.
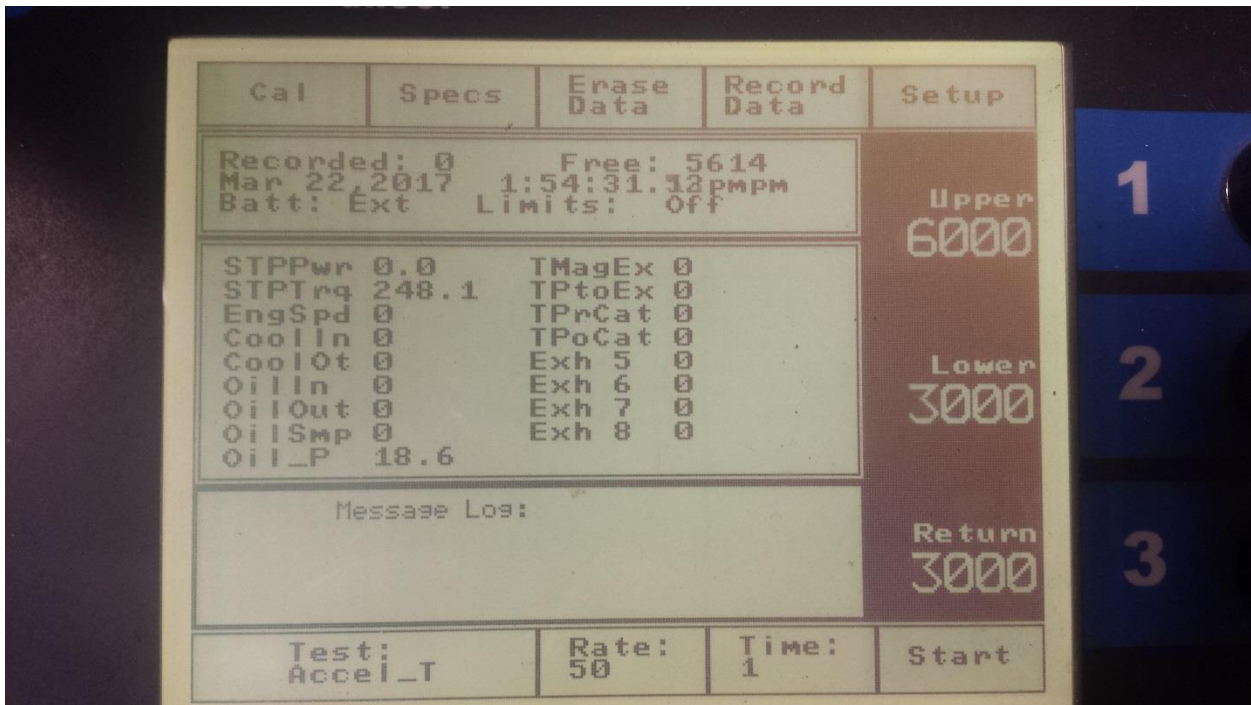
After all the information is selected, press the start key. The handheld will be explicit about what to do from this point. It is prudent to keep a finger above the quit key on the handheld in case anything goes wrong during the test.

Once the test is either aborted or completed the data is saved in the WinDyn data processor. After the test the graph of power and torque will automatically populate. In addition to this, the data is presented in the software. It should look like the following image. There will be 10 pages where the data is saved and presented. In each of these pages by right clicking in the white space and selecting channel order the variables can be selected on a channel-by-channel basis.
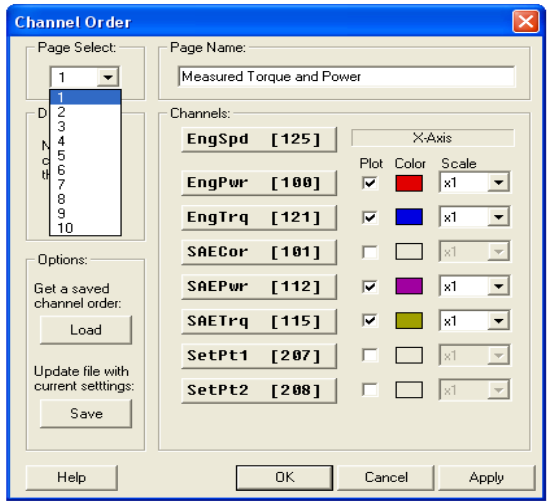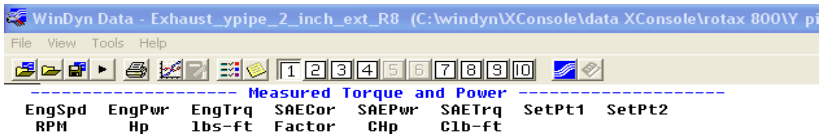
The data can also be averaged in this screen. This is useful for steady state tests to get an average power, torque, and engine speed. This option is found in the following location.
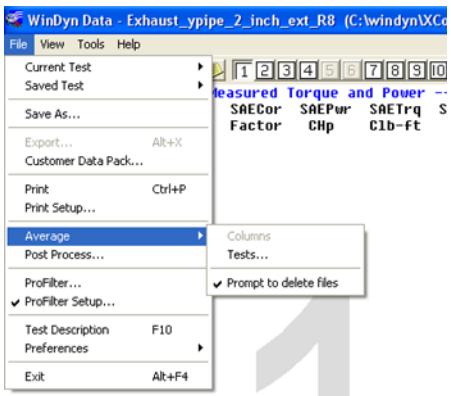
The final step to this is to export the data. The data will export to Excel as a .csv file that exactly mimics the pages and channel order that is selected in the program. The exported data, an example of a power sweep, will be in the following form.

Line no	EngSpd RPM	EngPwr Hp	EngTrq lbs-ft	Fuel2G gpm	Ful1+2 gpm	Exh 1 degF	Exh 2 degF	Exh 3 degF	CoolIn degF	EngSpd RPM	SAEPwr CHp	SAETrq Clb-ft	SAECor Factor
1	5100	55.4	57.1	0	0	888	0	692	80	5100	61	62.8	1.086
2	5200	59.1	59.7	0	0	919	0	703	80	5200	65	65.6	1.085
3	5300	63.1	62.6	0	0	948	0	717	80	5300	69.4	68.8	1.085
4	5400	65.4	63.7	0	0	967	0	726	80	5400	71.9	70	1.085
5	5500	67.9	64.9	0	0	982	0	738	80	5500	74.7	71.3	1.085
6	5600	70.7	66.3	0	0	997	0	752	80	5600	77.7	72.9	1.085
7	5700	72.3	66.6	0	0	1009	0	763	80	5700	79.5	73.2	1.085
8	5800	74.1	67.1	0	0	1013	0	775	80	5800	81.5	73.8	1.085
9	5900	75.8	67.5	0	0	1023	0	786	80	5900	83.4	74.2	1.085
10	6000	66.8	58.5	0	0	1024	0	794	80	6000	73.6	64.4	1.085
11	6100	63.8	55	0	0	1024	0	799	80	6100	70.4	60.6	1.085
12	6200	69.3	58.7	0	0	1055	0	818	80	6200	76.4	64.7	1.085
13	6300	71.5	59.6	0	0	1078	0	832	80	6300	78.7	65.6	1.085
14	6400	72.8	59.7	0	0	1094	0	843	80	6400	80.2	65.8	1.085
15	6500	75.9	61.3	0	0	1117	0	861	80	6500	83.7	67.6	1.085
16	6600	78.4	62.4	0	0	1136	0	878	80	6600	86.4	68.7	1.085
17	6700	79.8	62.5	0	0	1158	0	902	80	6700	87.9	68.9	1.085
18	6800	79.2	61.2	0	0	1175	0	920	80	6800	87.3	67.4	1.085

From here the data can be input into a processor or used from this sheet. It is important to remember that a .csv file can have only one sheet open and is not easy to move between Excel sheets.

To edit a test in SuperFlow is easy as well. It is achieved by the following mouse clicks:

Design > test profile > open > select a test to modify.

Editing a test is mostly graphical. Use the user's manual for a better understanding of the available functions. To load a modified test to the handheld do the following mouse clicks:

System > install > test profile > select test. To find this test on the handheld touch the name and it will cycle through the loaded tests. If the SuperFlow is powered down the test will no longer be loaded to the handheld.

APPENDIX E: INTRODUCTION TO OPTIMIZATION OF ENGINE

The purpose of this optimization is not to fully optimize the engine, but to get a starting point through the use of a simulation software that may take days to fully converge. Several discrete data points will be gathered and a surrogate model will be developed using response surface methodology (RSM). The intention is to fit three surfaces to the data. After the data is fit, basic uncertainty quantification (UQ) will be used to determine the best fit model. Once this is done, an optimization will be performed using one of the methods that was taught during the course. The problem will be greatly simplified, for time constraints on the project. The biggest of these simplifications will be explained later in this report.

I want to create an optimizer for my thesis. The basic problem is that I want to try to develop an eco-boost type engine for the CSC team. This typically involves utilization of a reduced displacement four-stroke engine that is turbocharged to maintain performance. My idea is a little different, instead of downsizing the engine I intend to maintain the displacement, but by detuning the engine and boosting it back up to the performance class for the displacement i.e. stock makes 120 hp, detune to 90 hp then boost back to 120 hp. The end result of this work, I hope, would be to increase the overall efficiency of the engine without sacrificing performance. The long-term goal is to better know what data points I should move toward to get closer to the ideal answer. This will hopefully reduce the time I must spend on empirical validation.

In the interest of keeping this model and simulation simple, I think initially the design variables I would change are: intake (boost) pressure, fuel quantity, and ignition timing. I plan on using a modeling software called ChemKin through Ansys to get my information. This software could possibly take several days to run on the Big Stem computer. The constraints on this problem would likely be 0-3 bar intake pressure, 10-80 mg^3 for fuel quantities, and 10-35 degrees before top dead center for the design variables. There will be thresh holds for knock, temperatures, and compression of the engine as well. The objective function will likely be a derived formula for brake specific fuel consumption. The objective would be developed by me through outputs from the program.

The black box will be ChemKin, which I am currently learning how to use. It is a chemical kinetics software. I will then fit a response surface to the data to try and predict the reactions.

I think I will either use particle swarm or the built-in MATLAB optimizer to decide what the next data sets should be. I will need MATLAB and Ansys' ChemKin. I do not have categorical or integer type variables, if they come up they will be handled by forcing the optimizer to choose from categorical variables, much like in 504 last semester. As I mentioned I'm looking at particle swarm, as it should reach a good optimum, or the built-in MATLAB function because it will be quicker.

Background

The motivation for this project is the graduate research being done with respect to the Clean Snowmobile Engine. The basic idea for the project is the Ford EcoBoost engine. In this four-stroke engine the overall displacement is reduced, then a turbocharger is used to retain the same class power rating. In other words, the stock engine made 200 hp at 20 cubic inches of displacement. The EcoBoost platform would achieve ~200 hp at 15 cubic inches of displacement with increased efficiency.

The platform being explored for this project is a two-stroke engine. A result of this platform being used is a need to approach the problem somewhat counter-intuitively. A smaller displacement two-stroke plus a turbocharger would likely result in less efficiency. This means that this platform should need to be detuned (make less power) then boosted back up to class power with the turbo. The biggest issue with this is there is no published work on this. For lack of better terms, the researcher is largely flying blind using engineering intuition to achieve these goals. Implementing the optimization and black-box engine model should reduce the "blindness" somewhat reasonably.

Black-box Software

ChemKin is a chemical kinetics software, not an engine modeling software. It uses input conditions and some basic information about the engine to predict how the flame will propagate through the cylinder. As the flame propagates, the air-to-fuel ratio (AFR) and compression of the engine is considered to predict the results of combustion. More to that, there are over 100 outputs, this number will be reduced to 5 for simplicities sake.

Design Evaluation

Unfortunately, to empirically validate the design would take a lot of time. A solid engine
modeling software does not exist, but the software being used should be good for ball parking
the results. Once the optimization converges, a 3-part check will be used to confirm validity.
These steps are:

- o look at the data points and see if they are feasible from a basic engine
  designer's perspective
- o input the optimum point into the black-box and analyze results
- o attempt to compare to known data about similar platforms

This can be done several times. The complexity of the model will change the results. One
thing to note is that engines are relatively poorly behaved from a modeling standpoint. The
outputs from them don't fit standard curves very well. This means, the design evaluation will
have a decent amount of error at each evaluation.

Surrogate Modeling

RSM was chosen to develop a model based off the black box evaluations. Gathering many
data points is difficult and each design variable added increases the computation time
significantly. A result of this is having to further increase the simplicity. The amount of
design variables was reduced to two, while looking at one output. The original intent of this
study was to look at power production and efficiency, which can be quantified several ways.
The black box model did not produce power numbers that were usable so efficiency is the
objective. Looking at the output, it can be assumed that peak efficiency will be near peak
power. The data points that are considered are shown in the table below.

Table 1. Shows four variables used in design optimization.

Variable	Description	Units
AFR	Air to fuel ratio	[dim]
Intake Pressure	Pressure at the intake, simulates turbo	PSI

Volume Unburned Zone (output)	How much charge is in the cylinder to be burned. Lower values equate to higher efficiency	mm^3
Burn Rate (output)	How quickly the charge is being burned	mm/s

There are other variables that need to be evaluated to solve the black-box, but these are held constant. It is important to scale the design variables to get them in the same order of magnitude. To ensure the model would weigh the variables similarly, the intake pressure was scaled down by a factor of 10. In the future, these can be expanded to further improve the surrogate model. Within the time constraints of this project this was not included here.

Four separate surrogate models were developed using the 13 points found in the black-box model. These are shown here:

- o Quadratic- [1 A(i,1) A(i,2) A(i,1) ^{2} A(i,2) ^{2}]
- o Linear- [1 A(i,1) A(i,2)]
- o Interactions- [1 A(i,1) A(i,2) A(i,1)/A(i,2)]
- o Logarithmic with interaction- [1 A(i,1)/A(i,2) log(A(i,1)) log(A(i,2))]

Through evaluations on two different outputs it was determined that the least squares error was minimized on the volume in the unburned zone. As such this was chosen to be the objective for the curve fit. The relative errors are shown in table 2.

Table 2. Errors of various response surfaces.

Model	Error VUZ	Error BR
Quadratic	1,579,000	50,450,000
Linear	4,339	44,154,000
Interactions	2,313	41,163,000

Log with interactions	155.97	5,825,200

Clearly logarithmic with interaction terms gives the best fit, being at least an order of magnitude better than the next best fit. With this fit for the initial dataset the Beta matrix produced is as shown in the equation below. In the optimization the Beta values are carried out to higher precision, because it is easy to implement.

$$[\beta\_1 \ \beta\_2 \ \beta\_3 \ \beta\_4] = [0.7296 \ 4.5397 \ -4.5061 \ 4.3210] \tag{1}$$

More time could be spent trying to find a better fitting surface, but this should be good enough especially considering the low amount of points that were collected. It is possible as more points are found, that the other surfaces may overtake the chosen surface and be a better choice.

Standard Optimum Form

When performing an optimization it is imperative to put the problem into standard optimum form (SOF). This can be done before or after the surrogate model is developed, but must be done before performing the optimization. Standard optimum form helps to standardize all the data that includes side bounds, equality constraints and inequality constraints, and shows the function to be minimized. The following equations and inequalities represent the SOF for the problem statement.

$$X_1 = \varphi = AFR \tag{2}$$

$$X_2 = Intake \ Pressure \tag{3}$$

$$-X_1 + .85 \leq 0 \tag{4}$$

$$X_1 - 1.1 \leq 0 \tag{5}$$

$$X_2 - 24 \leq 0 \tag{6}$$

$$3 - X_2 \leq 0 \tag{7}$$

$$\min f = [1 \ \frac{A(i,1)}{A(i,2)} \ \log(A(i,1)) \ \log(A(i,2))] * [\beta_1 \ \beta_2 \ \beta_3 \ \beta_4]^T \tag{8}$$

In the analysis for X2 the values were scaled, before the optimization can run the value should be scaled to match whatever the scale was in the RSM section. The SOF above does not capture this scaling. Equation 8 was developed through RSM, and encapsulates the black-box portion of the project. There is potential in an optimization for a problem to have discrete variables, in this problem all options are continuous.

Solution Path

The optimizer I chose to use was the genetic algorithm (GA). Exterior penalty method could have worked as well. There was also the option of using the built-in optimizers in MATLAB. I was more interested if I could make an optimizer that was robust enough to solve a real problem. Utilization of the RSM inherently is an approximation. The least squared error is shown above, the answer is reasonably close. It is not perfect and with a better surface this has a high likelihood of being driven down to a smaller value. The RSM approximation was chosen through a non-rigorous process of guess and check.

The black-box output data to an excel file, which I think manually input into MATLAB and saved a data set which can easily be modified. The programs were robust, but the input data needed to be scaled. The GA needed to be tuned to solve more efficiently, but this was simple. As a GA was used, any discrete variables are very easy to handle. The parameters that were used in the GA are shown in the table below.

Table 3. Table showing GA parameters

Mutation Likelihood	.20
Crossover Likelihood	.95
Initial Mutation Number	3 places
Number of Discrete Values	2000
Initial Population	1000

Decay of Change of Mutation Location	.95

These numbers were changed until the optimization solved consistently to a similar answer as well as more quickly. The location of the mutation is biased to the left of the binary string and moves toward the right as the problem begins to converge. I don't think it is necessary to further explain what's happening as it is straight forward from here. Now that a better point is found in the optimizer it will be run through the actual software to verify whether it is a better point in the virtual real world as well.

Solution Validity

The initial, unscaled data point for the problem that produced the best results is [1.06 13.3] which gives an output of 5.3175 through the RSM model. The best point is post optimization is [1.09 11.5] with a function evaluation of 5.2464. This corresponds to an improvement of .07 which is significant. This is the average output after running the model several times. The model takes approximately 200,000 iterations to solve. The AFR constraint, X1 is active. This is not too crucial because the limit is estimated based off engineering sense, but can only really be verified through empirical testing. A very small iteration history is shown below as [X1 X2 f].

[1.0999   1.1526   5.2464

 1.0998   1.1568   5.2464

 1.0996   1.1579   5.2465

 1.0993   1.1768   5.2473

 1.0964   1.1390   5.2473

 1.0958   1.1411   5.2473

 1.0948   1.1516   5.2473

 1.0949   1.1463   5.2473

 1.0904   1.1568   5.2482

1.0983　1.1852　5.2482

1.0910　1.1673　5.2486

1.0868　1.1411　5.2486

1.0871　1.1484　5.2486

1.0859　1.1411　5.2488

1.0963　1.1159　5.2492

1.0980　1.1936　5.2492

1.0593　1.1232　5.2536]

The problem did not find a better point after 2000 iterations. This is also evidenced by the problem having a mean, standard deviation, and norm of [5.25 .0012 0]. This shows that the mean was being driven toward the optimum. More runs would likely drive the deviation closer to 0, but it is not necessary.

Engineering Analyses

From an engineering standpoint, I implemented too stringent of convergence criteria. This does not hurt form the engineering view point, but it did take longer to run and didn't get much better for the second half of the iterations. I also had a large enough initial population in my relatively small design space that it got lucky initially. Since there are only two design variables I can check the validity of the solution by graphing it. It can be easily seen that the minimum appears to show up here.
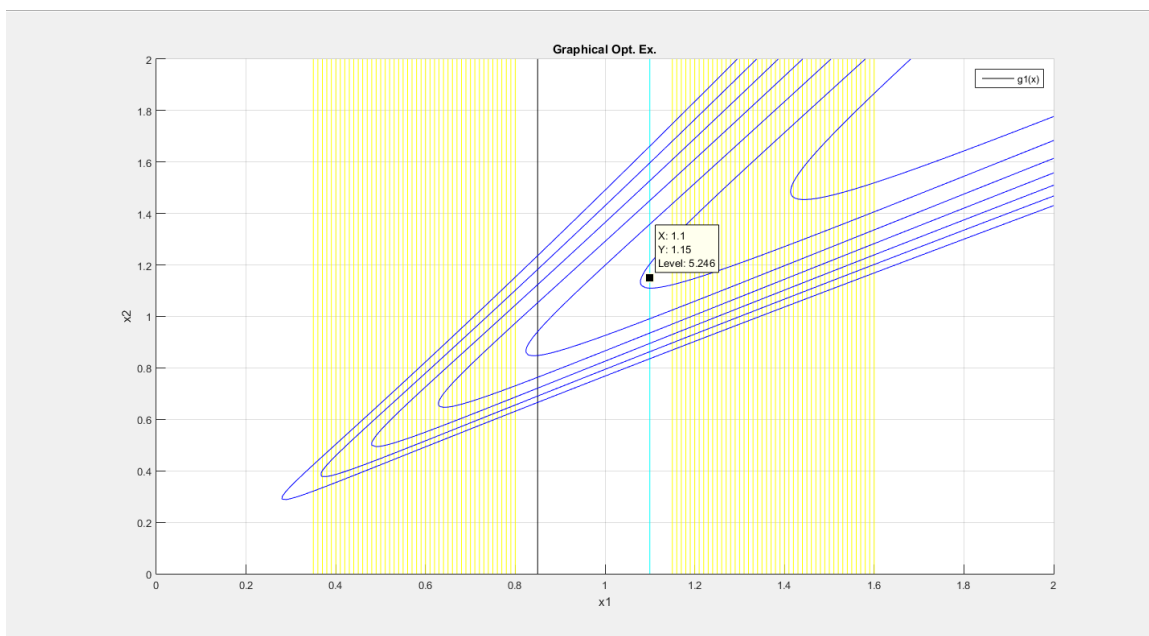
The design makes since intuitively, because at PHI=1.1 the engine makes ~peak power so it seems logical that the data would point to here for a great efficient point. The design shows that at the design point the engine should be on the verge of knocking which is bad, but that is how to develop an engine that runs efficiently is to push it to the limits. Basically, the design says to add some fuel, and intake pressure so that the engine can run more efficiently, but if too much pressure is added engine efficiency will go down, largely due to runability issues. The lower function evaluation means the flame front in the engine is travelling faster which equates to less heat loss, higher power, and more efficiency. The assumption was that in my design space there would be no destructive areas where the engine couldn't run. This is likely untrue but pressure would cause the worst runability issues, and since the design is in the middle of the pressure range it seems very feasible. The assumptions are fine to make here because it will be re validated in software first to lower the risk of catastrophic failure. As more data is intelligently added to the model everything should become more reliable. If I had all the time I needed, I would try to initialize a larger initial dataset as well as validate the results empirically. This would be great for me, because deep down I much prefer experimental work to theory type things like optimization. The black box and empirical

aspects to this problem have a huge cost of time, even when using the resident super computer because the virtual integrator must converge at each design point.
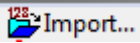
After running the model again with the new parameters, the model output a value of 4.382, which is reduced from the original best point of 4.6192. This means that I can use the optimization algorithm to attempt to decrease the amount of effort I need to put in empirically to calibrate my engine for the research. It is not perfect, but it will get me into the ball park.

APPENDIX F: UNIPLOT KAIZEN

Create an Excel file, 8-10 data points is recommended as it shows functionality well. Include data in Column format, i.e. column one is RPM and has X data points and HP is column two and has X data points. LABEL YOUR SHEETS!!!! When importing data into Uniplot you must select your sheets that you wish to import, because of this it would be prudent to label these for other employee's use. The steps and images below will walk through the import data process and some basic plot manipulations.

First open Uniplot and you will get a screen that looks like this:
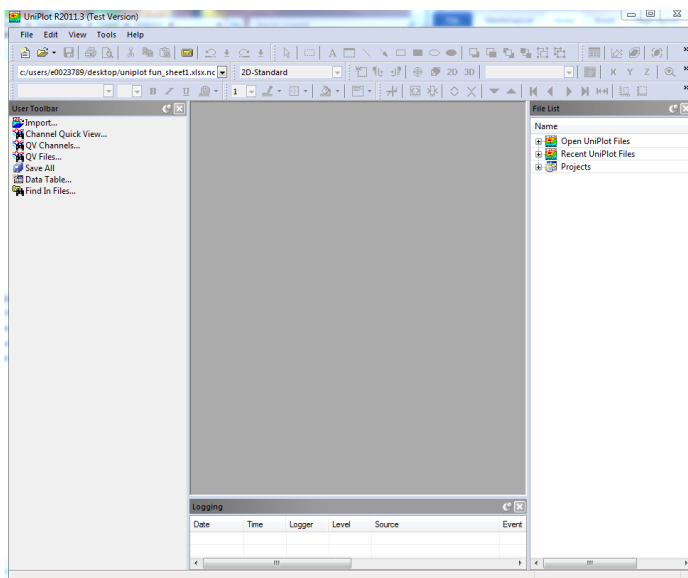
Next, you will click on the Import… button.

You should then see this pop-up.
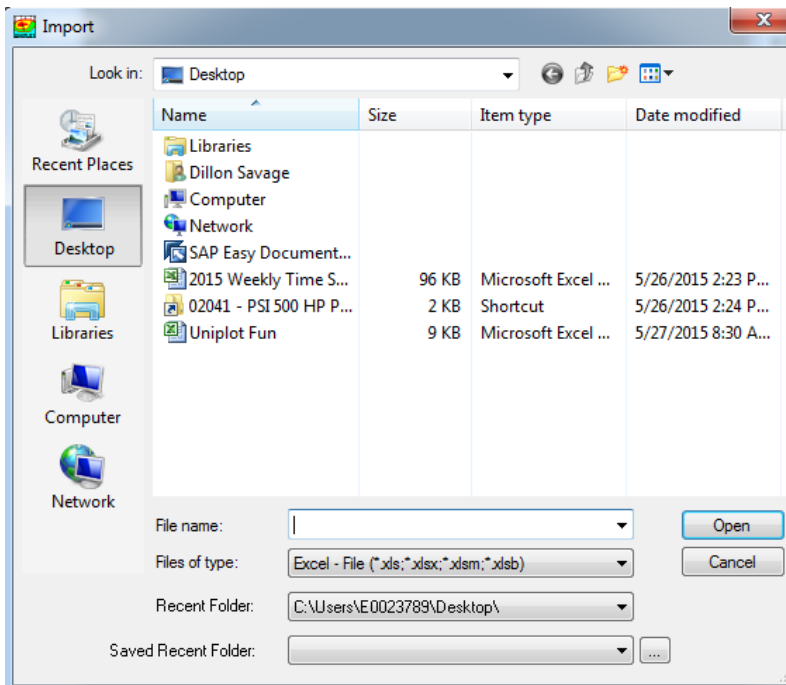
Be sure the FILE TYPE filter (drop-down) is set for Excel files, it usually defaults to Uniplot files. For this example, we will use the file Uniplot Fun. The data layout is shown here. Take note of the labeled sheet at the bottom called Uniplot Data. The image is rotated 90 degrees for packaging in this document.

Select the Excel file and click OPEN. This pop-up will appear and the importance of naming your tabs becomes clear.
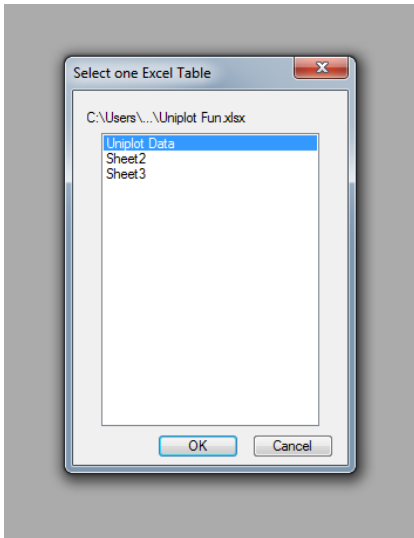
Select OK on the desired sheet. This screen appears.
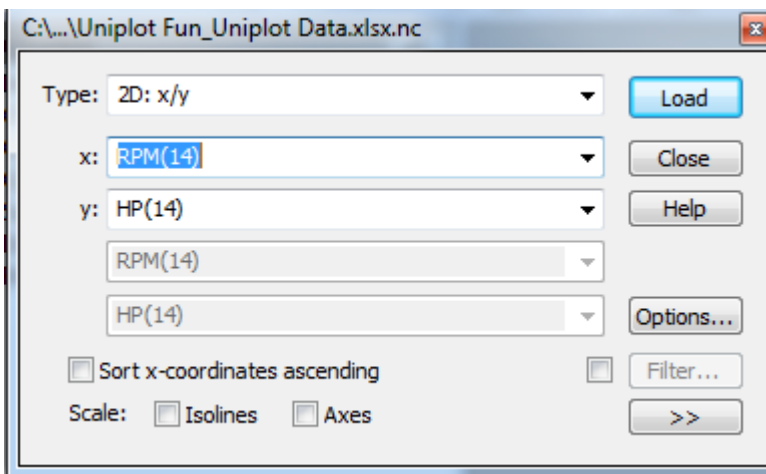
Use the drop-downs to select your desired X and Y axes. Note that the Type is 2D:x/y. The default is not this, so use the drop down to find the proper plot type. Next press Load. When Load is pressed, this happens.
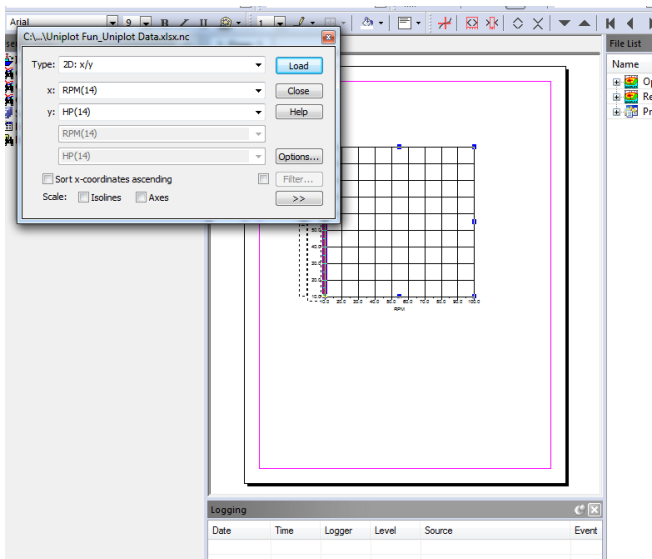
Notice that there is nothing plotted except for grid lines. Next press close on the dialog box. The problem with the plot is that the axes are not scaled properly. To fix this select the X, Y, Z buttons at the top of the screen. They look like one singular button but are three separate. Once X is selected the following pop-up appears.
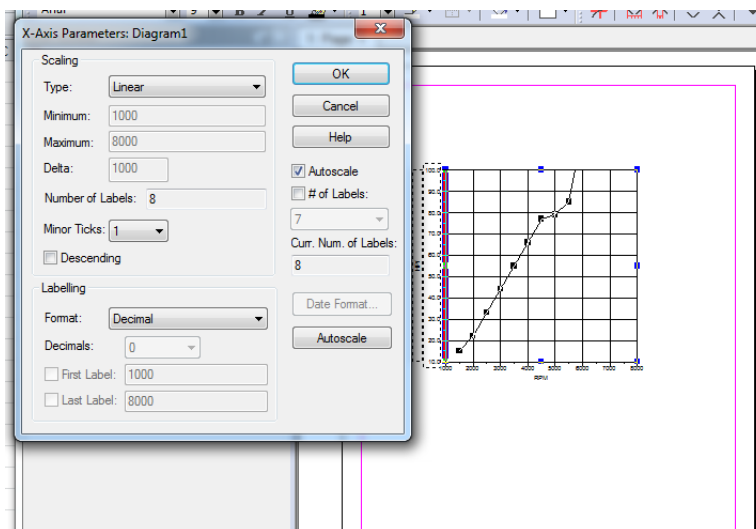
Ensure that you select Autoscale, or set parameters that appropriately set the bounds of your data. Repeat for Y and Z as necessary. Now you have a fully formed, basic plot. Next we will explore how to modify the plot style. Begin by pressing this button Dataset List (CTRL+D). If the button is grayed out, click *inside* the plot area and it should be a functional button. It will open a pop-up menu. Select configuration and you will see this.
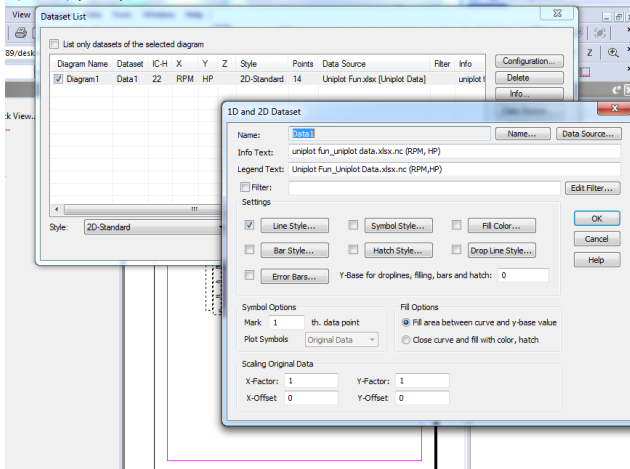
From here many things can be modified. Use this as a basic introduction and attempt to plot useful data, and display it in a thoughtful way. I would recommend attempting to do a 3-D plot possibly BSFC.

Uniplot Kaizen: Novice User's Guide

The purpose of this Kaizen is to help guide a basic user through some of more difficult, yet basic, practices in Uniplot. It will discuss the following commands, in no particular order; editing a legend, adding sheets, copying format to those sheets, editing sheet data, and renaming a page.

Editing Legend: From the **Daily Checkpoint Kaizen,** the user should remember replacing datasets throughout the entire document. In that guide it was necessary to do this to update the displayed data. Sometimes the user will do this to reduce or edit already shown data in an older file for new customer meetings. It is largely the same except when you change the shown data to different data the legend does not automatically update. As such it becomes the user's responsibility to maintain the legend.

Assuming the new data lines are already brought into the document we will start the guide.

The user will begin by selecting the diagram Diagram drop down menu at the top of the screen. Inside this menu, the follow this drop-down… Diagram→More Diagram Options→Create Legend for Active Datasets. This will import a second legend besides the existing.

Once the legend is imported take the file names that are to be kept from the existing legend and copy them in. Be careful to maintain the color aspect of the code which is the bit contained in {}. After this is done delete the old legend and edit the new dataset names to fit the needs of the document. Position the legend where it needs to be placed. Delete all other legends that need to be updated. Then ensure that in each page nothing is high-lighted and paste in the updated legend. Now the user has updated the legends in the document.

Adding a Sheet: This is a simple practice, but worth mentioning. All that the user needs to do is right click on a current sheet tab and the pop-up menu will have a new sheet option; select it. After selection is made you will have the option to pick a sheet size. Typically, a portrait A-4 that is blank will be selected. Click OK and the sheet will open. It should look like the image below.
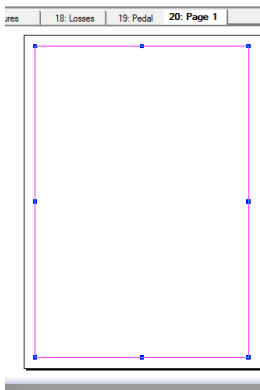
Renaming Page: The user should notice that the page comes in as Page 1. This is not a useful title. To rename the page right click on tab and select the rename page option. Rename to a 1-2 title that is descriptive, yet concise.

Copying Sheet Format: The user will now have a blank sheet that is not particularly useful. The most efficient way to do this is by going to a sheet that is populated with charts. Once here the user will right click and select Copy Page. The user will then go to the blank sheet and right click and select Paste Page. Now the user should have a populated sheet ready to be edited.

Editing Data: After the user has copied the format it will be necessary to show the desired data. A series of dyno runs will be used to perform this example.

Begin by right clicking somewhere on the page. In the pop-up select Page Data Exchange.

Once this is selected you should see something like this menu.
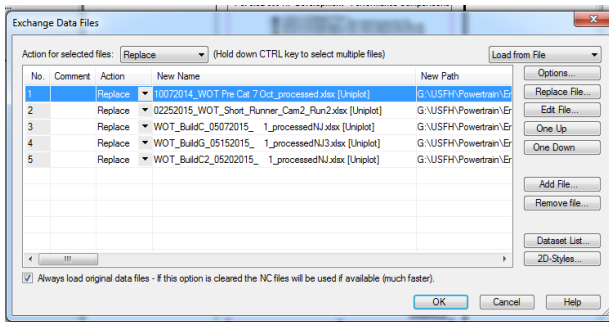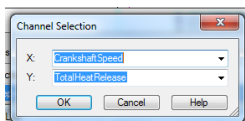

Select dataset list on the bottom right of the window. You will then see this window.
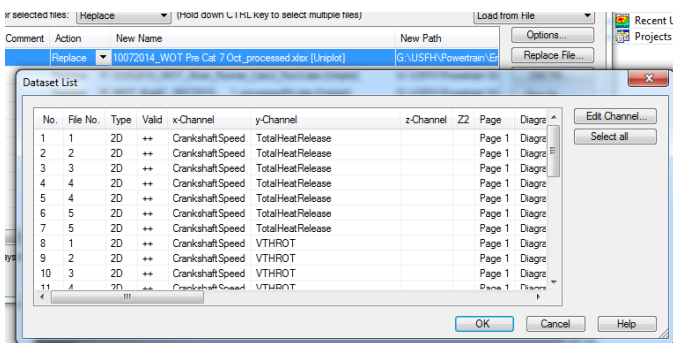
This is the users list of variables used in this sheet. **BE CAREFUL THEY MAY NOT BE IN THE ORDER THEY ARE GRAPHED!** From here the user will highlight *all* the variables for ONE graph.
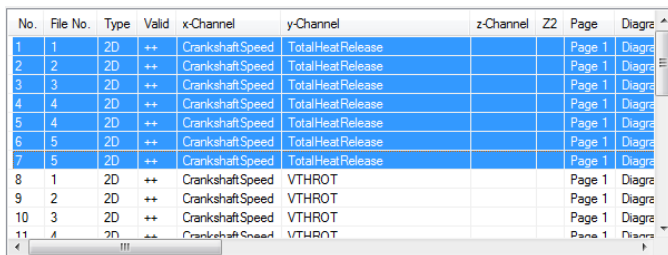

The user will then press Edit Channel. A list of your available variables will appear.

Use the drop downs to edit what is available. It is recommended that the user use the same X axis throughout the document for ease of reading, but it is sometimes necessary to change. Press OK on all open windows and select whatever options needed along the way. The user has now successfully edited their graph.

Plotting 3-D Contour Graphs & Residency (BSFC)

Many aspects of engine performance are demonstrated using contour plots which is a two-dimensional representation data, think of a topographic map where the contours represent elevation. The goal of this is to show common practices in plotting as well as steps to build a contour and residency plot. A residency plot will show an occurrence from empirical data i.e. a drive cycle.

If a dataset is imported with the appropriate data, the steps following this will be shown. Begin with an empty page. Select "import" and find the appropriate Excel file.
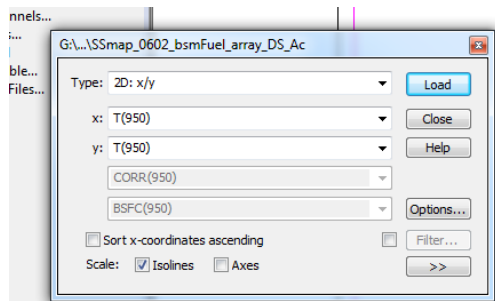
The above menu will appear, select the 3D: x/y/z plot option. Typically, the X axis will be RPM and the Y will be BMEP. I recommend that BMEP should be put into kPa units instead of bar as it is common that customers use kPa. The Z axis should be whatever variable you wish to characterize. BSFC will be used here, but it can be many different things such as efficiencies, time at 50% mass burned, fuel flow, etc.

Once you select load a graph will appear that looks blank. Use the autoscale function on the x&y axes to get the contour. You should see something like the image below.
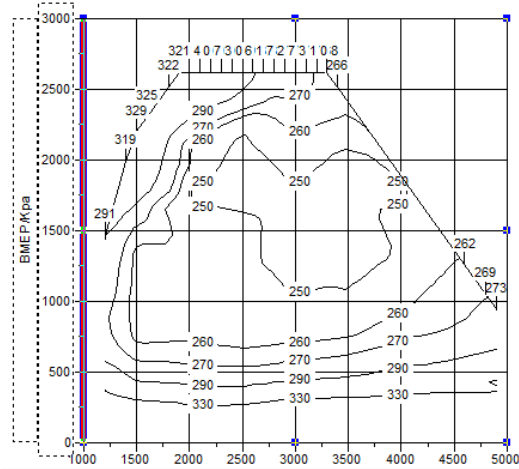
There is some formatting that we will discuss first to make the graph cleaner. We will add color, and remove the numbers from the isolines. Double-click on the plot particularly on an isoline to select the plotted data. A menu will appear. I will use arrows to display the functions that are useful.
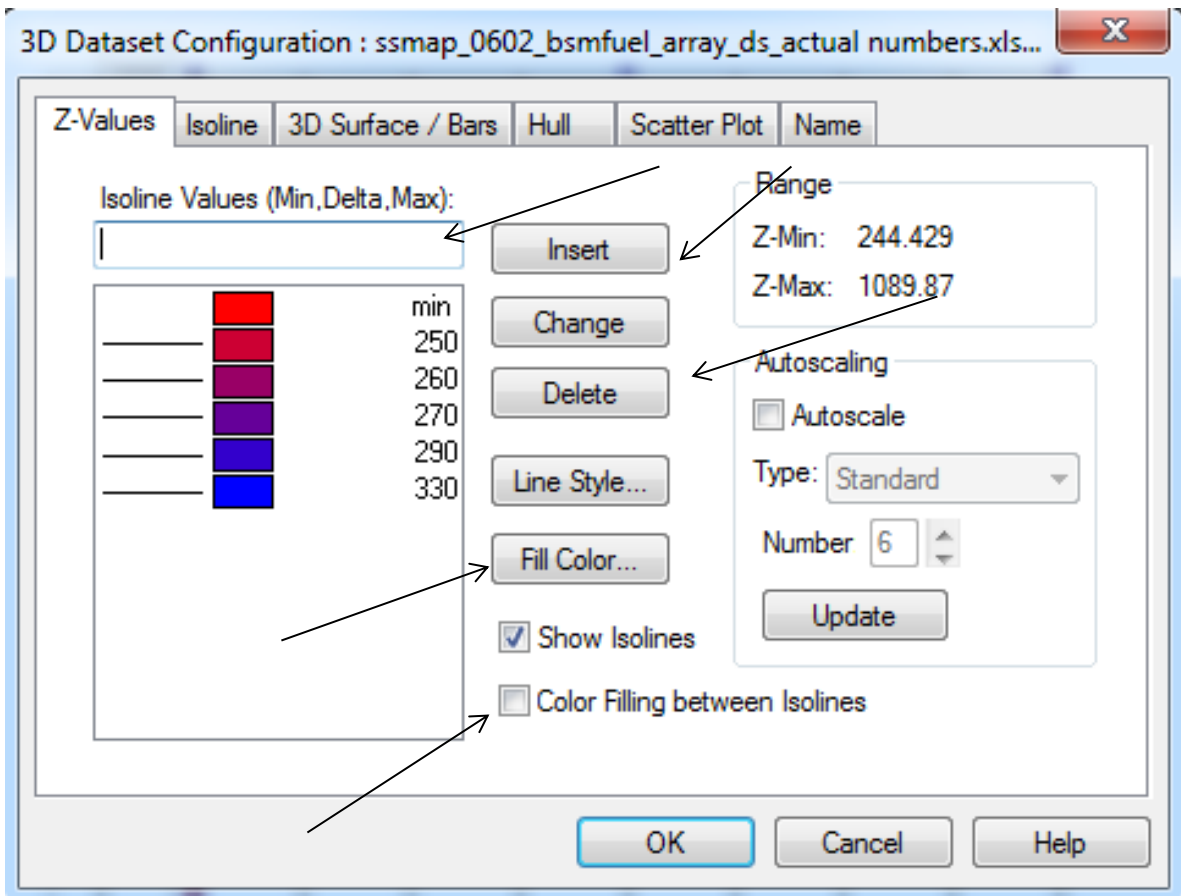
The arrows will be discussed from top to bottom.

1. Allows the user to get a scale that is useful for the project. I.E. the user can go from 200 → 600 at a delta of 50. This will give the user an isoline or band of color every 50 units.

2. Insert must be pressed to insert the lines. If this is pressed while there are still values in the range shown below arrow 1, then it will be added to this range and will not replace these values.

3. Delete is used to remove values from the range. The user must high-light the values that need to be deleted then select delete and the lines will disappear. Min cannot be deleted.

4. Fill Color… allows the user to edit the color range. This will be discussed further later in this tutorial.

5. Color filling applies the selected colors to the graph in-between the isolines.

Now the isoline tab will be discussed.
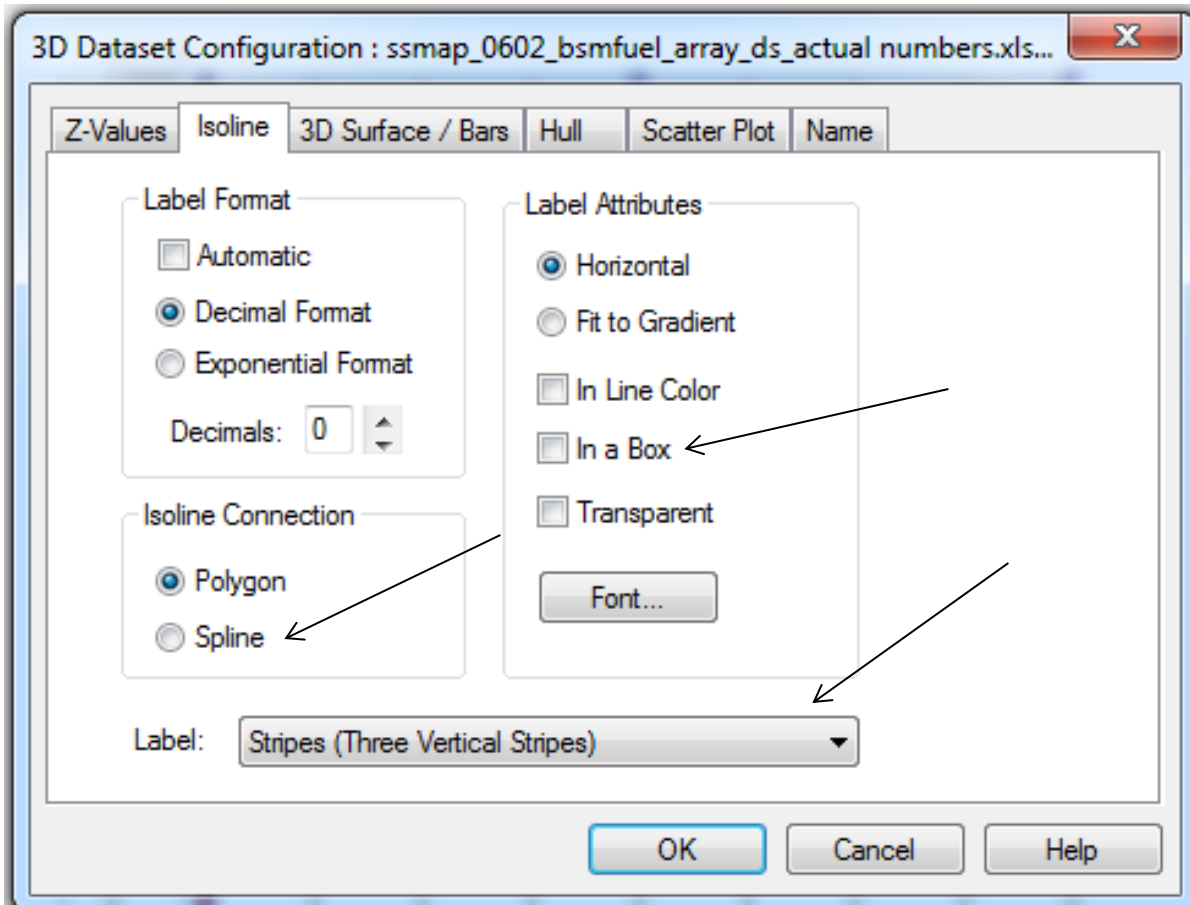
1. In a box deals with the labels on the contour lines. It is common practice to keep the box n plots to aid in reading.

2. Spline is how the isolines connect. Spline helps get rid of the jagged lines between data points. This should be checked for aesthetics.

3. Label should be changed to none and line labels will be added later.

The hull tab will now be discussed.
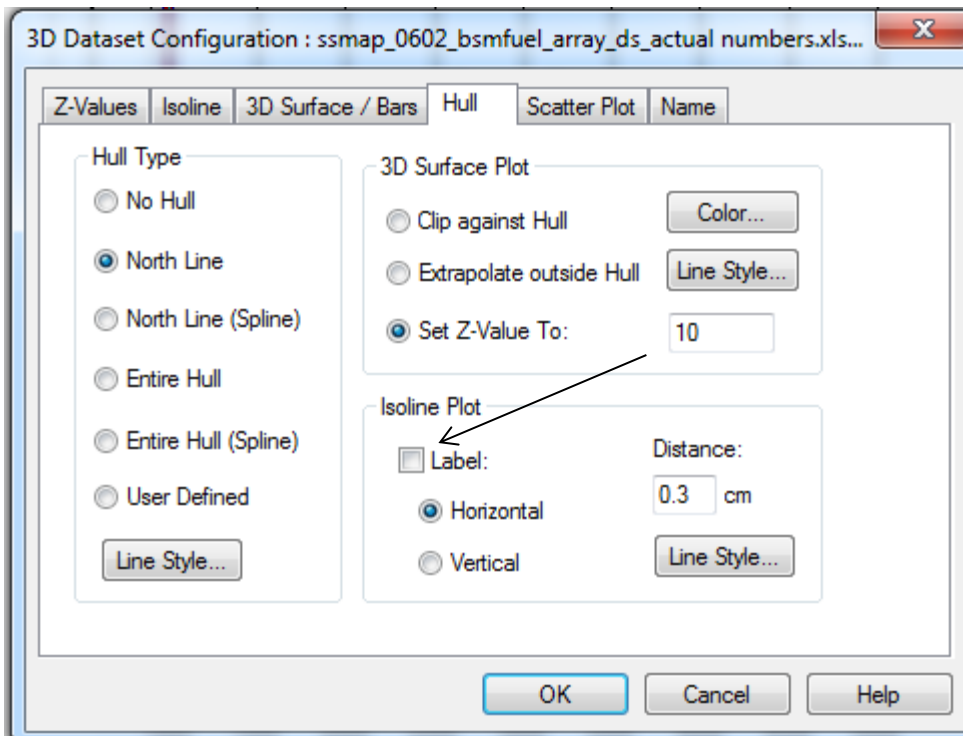
The Hull's purpose is to add bounds to the plot. It may be used, but it's not common.

1. The labels here refer to the numbers on the north side of the plot and should be checked off to clear these from the graph.

Now we will discuss common practices. Color scale should be like this. The minimum will be green and the max red, set this first then move on to the next steps. The middle should be orange which had the RGB code RED 255 and GREEN 140. To edit the color, highlight the first color you wish to change, likely the first green color that is hard to see to approximately the middle of the data. The min will remain the same while the max will be set to orange. Next, select from orange to the max value and select okay. Your range will look something like the image below.
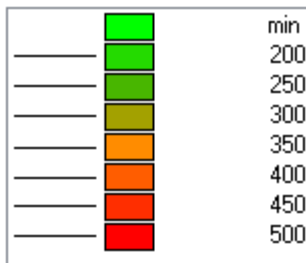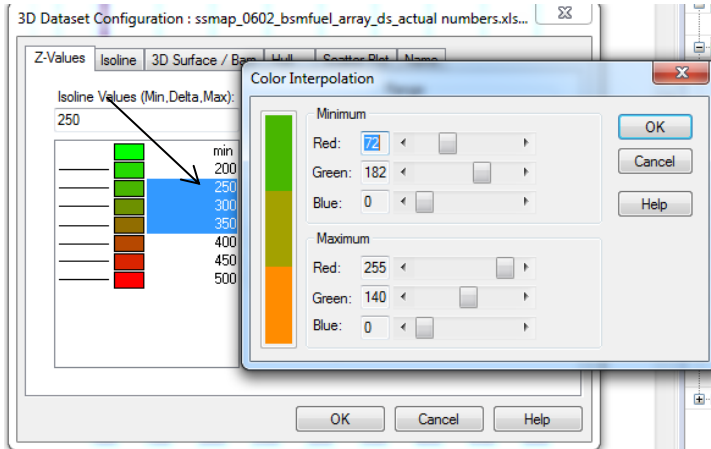
Next labels will be added. Begin by clicking in the graph on and iso or band line. Press [10] near the top right of the page. Next, select iso or band lines to place a label. The labels should be placed in a line and should not overlap. See image.
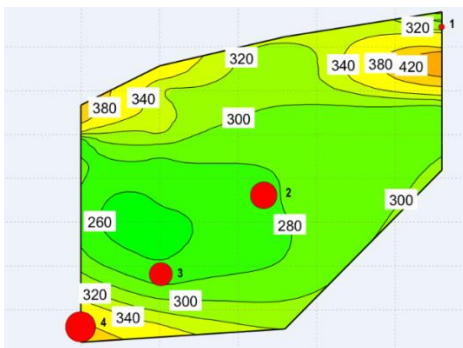
The user might notice some jaggedness to the lines still. This is easily cleaned up by selecting the iso or band lines and right clicking. In the menu a function called interpolation will be selected and in that menu there is a smoothing function. This should clean up the lines further.

Axis titles should be labeled very straight forward. The axis name i.e. BMEP followed by the units in square brackets i.e. [kPa]. To edit this, move your mouse over the title until title is displayed by the cursor then double click. Edit the name accordingly.

To add a color scale, click on the iso/band lines and right click. There will be a function called 3D color legend. Select this to add the legend. It will look like the image below.
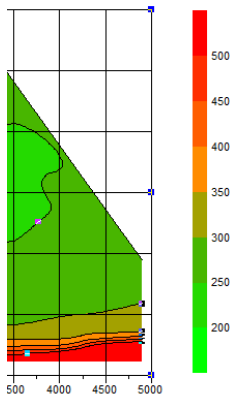

Add a title to the graph. Right click in the white space and select Add Field Function. Select document name→ name. This will insert a textbox in the top right corner of the sheet. Move this to the center of the graph and change the font to BOLD size 14 Arial. Label the graph, be concise and descriptive. Follow this same process to add units to the color legend using default font.

Adding a residency plot is easy. Click on the iso/band lines and then select import. Select the proper dataset and use a 2D: x,y plot. They should match the units and axes chosen for the BSFC plot. A pop-up to replace the current data sill appear. Select no. This is what will appear.
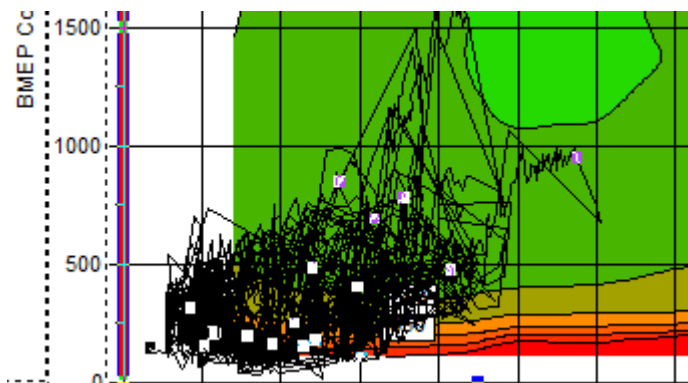
Next, click on the graph of the lines. If the right part is selected the white squares like above will appear. Double click in this space.
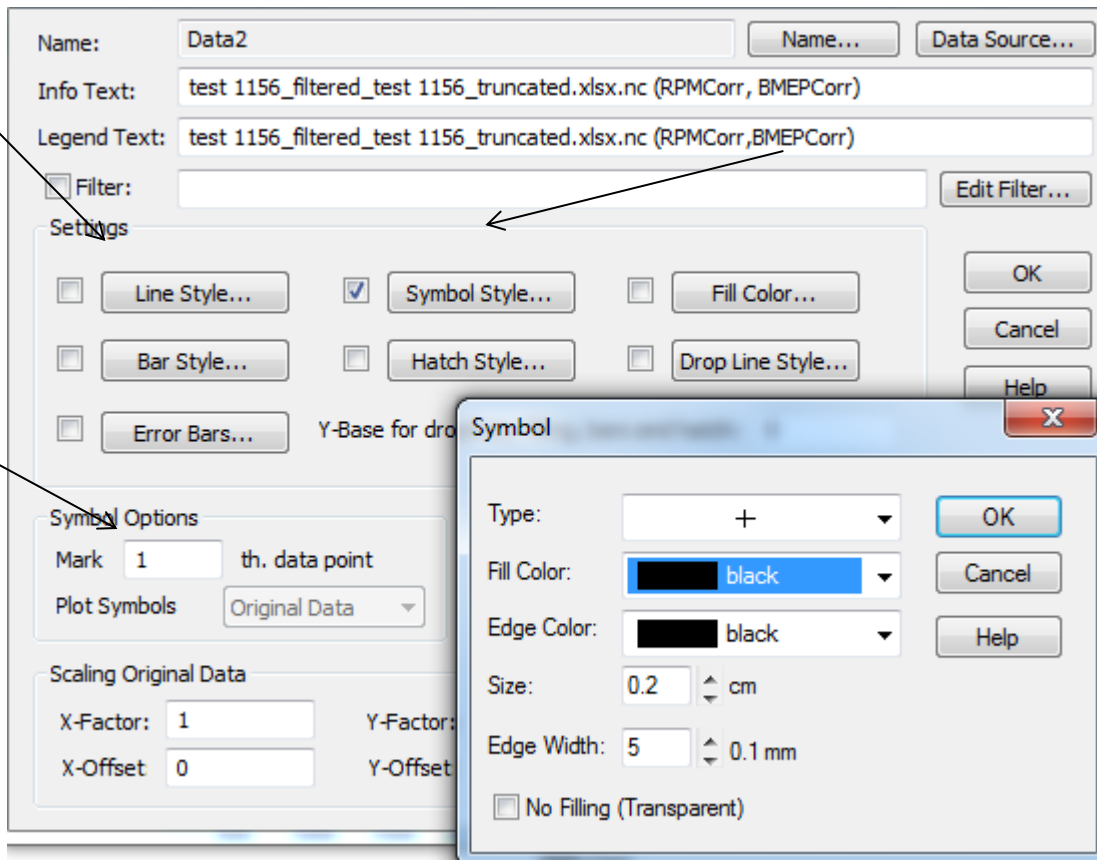
1. When the box is opened line style will be checked. Uncheck this. This also allows the user to edit the line for normal 2D line plots.

2. Check symbol style and click the Symbol Style… button. The Symbol pop-up will appear. I recommend the shown settings. These may change based on use, but these are a good standard.

3. This refers to the amount of data that will be displayed. If 1 is selected every data point will be shown, if 10 every 10th data will be etc. It is common to increase this number for easier visualization.