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Design of a Test Stand for Alternate Fuel and Ignition Systems Testing

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A Thesis Submitted to the
College of Engineering and Mineral Resources
At West Virginia University
In Partial Fulfillment of the Requirements
For the Degree of

Master of Science
in
Mechanical Engineering

Dr. James E. Smith, Committee Chairperson
Dr. Gregory J. Thompson
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Morgantown, WV
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Abstract

Design of a Test Stand for Alternate Fuel and Ignition Systems Testing

Patrick E. Wildfire

There is a growing interest in improving engine versatility through the capacity to run on more than one fuel. To aid in this effort, ongoing research is being conducted to investigate a novel system using microwave plasma ignition designed with the goal of allowing spark ignited engines to run on multiple fuels. To accomplish the testing of this system, it was necessary to design and fabricate a test stand including an engine and instrumentation capable of measuring the performance of the ignition system within the environment of a running engine, and capable of testing this system on multiple fuels. It was also desired to produce data with repeatability within 4% to ensure that results indicated real trends. To achieve this goal it is necessary not only to measure the output of the engine but also to measure several pertinent operation variables as well. With this in mind, a comprehensive test stand and sensor system was designed and fabricated, and repeatability of output data was verified. Output data was also compared to manufacturer-supplied data under similar operating characteristics to validate the accuracy of the measurements. Comparison of this data shows that repeatable data that follows expected trends is produced, and is repeatable to within 1%. A detailed system outline is presented herein, as well as results and conclusions. Recommendations for further research are also suggested.

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Nomenclature

Symbol	Meaning
°C	Degrees Celsius
A	Amps
A/D	Analog to Digital
AC	Alternating Current
ADC	A/D Input Variable
AFR	Air to Fuel Ratio (Mass of Air: Mass of Fuel)
AISI	American Iron and Steel Institute
cc	Cubic Centimeter
CIRA	Center for Industrial Research Applications
Cp	Specific Heat (J/kg°C)
CPU	Central Processing Unit (Processor)
DC	Direct Current
DIN	<i>Deutsches Institut für Normung</i>
F	Force
Fr	Radial Force (towards pivot)
Ft	Tangential Force (perpendicular to pivot)
GHz	Giga-Hertz (1/10 ⁹ seconds)
HP	Horsepower
kg	kilogram
kJ	kilojoules (Joules x 1000)
kW	kilowatt (Watts x 1000)
lb	Pounds
LPG	Liquefied Petroleum Gas
m	Mass
MAP	Manifold Absolute Pressure
MHz	Mega-Hertz (1/10 ⁶ seconds)
MS	MegaSquirt
n	Resolution (bits)
NOx	Oxides of Nitrogen
OEM	Original Equipment Manufacturer
PC	Personal Computer
PSI	Pounds per Square Inch
Q	Heat Added
QWCCR	Quarter Wave Coaxial Cavity Resonator
r	Radius (length)
R	Input Range
RF	Radio Frequency
RPM	Revolutions Per Minute
SAE	Society of Automotive Engineers
SOP	Standard Operating Procedure
sq. ft.	Square Feet
TPS	Throttle Position Sensor
TQ	Torque (ft-lb)
V	Volts
W	Watts (Joules/Second)
Wc	Calibration Weight
Wg	Generator Weight (lbs)
WVU	West Virginia University
ΔT	Change in Temperature
τ	Torque (ft-lb)
Φ	Angle Between Generator Axis and Weight Vector

Chapter 1: Introduction

1.1 Introduction

With oil production nearing its peak and emerging nations consuming increasing amounts of energy, fuel availability and quality are becoming important issues (Hirsch). One way to help prepare for this circumstance is to design new engines that are tolerant of a wider variety of fuels. There are several modifications that facilitate this design, including higher energy ignition systems. The Center for Industrial Research Applications (CIRA) at West Virginia University has suggested the use of a plasma ignition source to initiate combustion in internal combustion engines. This system is based on a spark plug replacement called a Quarter Wave Coaxial Cavity Resonator (QWCCR), and has been investigated by several researchers in an effort to reduce emissions and improve lean burn, and multiple fuel engine, performance. They have analyzed the effects of the QWCCR on gas mixtures in the context of combustion initiation and energy delivery, with encouraging results (Pertl).

The next step in the development of this technology is application of it to an actual engine and testing the performance benefits. To facilitate testing for this application, a test stand was required that included a small engine and all necessary hardware and instrumentation to evaluate the advantages of the QWCCR on various fuels. Accomplishment of this goal required construction of a power measuring and loading device plus measuring of the output and input variables of the engine, as well as a selectable fuel system. This thesis covers the specification, design, fabrication, and authentication of the test platform.

1.2 Objectives

Since microwave plasma ignition is a novel technology that has not previously been successfully adapted to a commercial engine, it is the purpose of this research to produce a test facility capable of evaluating the advantages of this ignition method for use with a wide range of fuel types and in the context of a running engine. Such a facility should produce measurable and repeatable data on engine performance and record the variables that affect this performance. Sources show that performance ignition systems can result in gains of 6-8 percent in brake horsepower, so the precision and repeatability of this test stand must be less than 3-4 percent to accurately measure these types of gains (Jacobs). This research does not seek to evaluate any ignition technology at this time, only to provide the capability to do so.

Chapter 2: Literature Review

2.1 Overview

This section summarizes the history and basics of microwave plasma ignition as well as the pertinent background details on four stroke engines and testing procedures. While this thesis focuses only on the test stand, it is important to understand the motivation for this research, so details of the ignition system are presented. The purpose of this work is to evaluate this technology, and all aspects of the test stand have been designed with this in mind.

2.2 Microwave Plasma Ignition Basics

The ignition system under consideration in this work is a spark plug replacement technology that uses a microwave power source at a frequency of 2 GHz to power a Quarter Wave Coaxial Cavity Resonator (QWCCR). This system differs from a spark plug in that the QWCCR uses a resonant buildup of microwave energy to produce a higher volume, lower temperature plasma discharge that has the potential to deliver an order of magnitude more energy than a conventional spark plug (Wilhelm). The QWCCR works by employing a resonant cavity with a length equal to one fourth the operating wavelength to produce a high electrical potential via resonant buildup, providing a high energy ignition source with moderate input power (Wildfire). Figure 1 shows a QWCCR plasma plug that has been run in an engine.

Figure 1: QWCCR Prototype and CAD Model (J. Smith)

2.3 Microwave Plasma Ignition History and the QWCCR

While there is a vast amount of information pertaining to both microwave plasma production and ignition, this research is only peripherally related as its focus is the integration of a particular system to an engine and the testing of this integrated technology. The background contained herein will therefore omit details that are not directly pertinent to the system as developed by Pertl (Pertl). The history of this technology follows.

Radio frequency (RF) power processing by way of the Quarter Wave Coaxial Cavity Resonator (QWCCR) was first proposed in 1988 by Nash (Nash). His work was purely focused on processing, however, and use of this technology as an ignition source was not considered until 1992, when a pair of papers was presented to the Society of Automotive Engineers (SAE) by Bonazza et al. (Bonazza) and Van Voorhies et al. (Van Voorhies). Bonazza et al. suggests that an adaptation of the QWCCR could be used to replace a spark plug, and theorized that the ability to produce a physically larger discharge over a conventional DC spark would aid in the ignition of leaner fuel-air mixtures. Van Voorhies et al. performed an order-of-magnitude analysis of the QWCCR discharge. His analysis produced an approximate theoretical characterization of the physical manifestation of the plasma production process of the QWCCR, and concluded that experimental verification of the ignition characteristics of the QWCCR should be performed. Such experimentation was in fact conducted by Stiles et al., who constructed working prototypes in the 440 and 900 MHz frequency ranges (Stiles(1997)) (Stiles(1998)). These prototypes were shown to operate in a pressure vessel at pressures up to 7 atmospheres at a power level near 150 W. Experiments in this vein were continued by McIntyre, whose thesis work led to consecutive ignition events in a Briggs and Stratton engine while the engine was motored by a dynamometer (McIntyre). This research was hindered by the fact that the resonator was filled with TeflonTM to keep combustion gases out of the cavity, and this material quickly broke down after a few ignition events. Following up on this issue, Lowery investigated various dielectric filling materials and their effects on quality factor and efficiency using computer simulations and physical experiments (Lowery). In a more comprehensive work, Pertl conducted an analysis of the physical and electrical characteristics and relationships of the QWCCR. He then constructed a microwave source capable of supplying high power levels for a more robust and controllable plasma discharge. He also experimented with ignition of a full range of mixtures of air and liquefied petroleum gas (LPG- more commonly referred to as propane) in a pressure vessel. In this testing, Pertl concluded that the QWCCR had similar capabilities to a conventional spark plug, and theorized that the QWCCR could potentially provide a more robust ignition source, especially for lean mixtures due to its higher energy delivery potential (Pertl).

2.4 Internal Combustion Engine Basics

It is not within the scope of this paper to present a comprehensive description of the characteristics of internal combustion engines, but some basic information is needed. Internal combustion engines are generally divided into two types: compression ignition and spark ignition. Compression ignition engines are often referred to as Diesel engines, as the basic type of engine was invented by Rudolf Diesel in 1892. Spark ignited engines use an electric spark to ignite the air fuel mixture, and are the focus of this research. Another distinction in this case is the difference between 2-stroke engines and 4-stroke engines. The plasma ignition system described in this paper is applicable to both types, but in this case it was applied to a 4-stroke, or Otto cycle, engine as developed by Nikolaus Otto in 1876. This cycle describes the operation of such an engine by dividing it into four distinct phases, or strokes. While this is only an approximate representation of what happens in an actual engine, it serves to help explain and characterize the process. The four strokes are intake, compression, combustion, and exhaust. They are best illustrated graphically, as shown in Figure 2.

Figure 2: 4-Stroke Cycle (AMSOIL)

The significance of this information to the subject of this thesis is in helping to determine what qualities are required to characterize the effects of different fuel and ignition systems on the engine, and what variables need to be measured and controlled. Engine temperature is an example of a variable that is subject to external influences and has a measurable effect on performance. The temperature of the intake air determines its density, and also affects the temperature after compression, which in turn affects the mixture's ease of ignition. The temperature of the cylinder head also affects these same parameters, as it tends to heat or cool the mixture to a large extent, as well as to remove energy from the combustion process (Taylor).

There are several reasons to seek a more effective ignition method in such an engine. First, more effective ignition can mean more complete combustion, which leads to more power, lower hydrocarbon emissions and increased fuel economy. This is due to the fact that not all of the fuel in the cylinder is burned during the combustion process, as mixing and cooling effects within the cylinder hinder the flame propagation. By providing more initial energy to the reaction, the plasma discharge may present the opportunity to combat this effect. Another issue is the tradeoff between lean mixtures and pollutant production. Lean mixtures (mixtures with less than stoichiometric amounts of fuel) can provide increases in fuel economy, but they are more difficult to ignite and tend to produce a higher concentration of harmful exhaust species such as oxides of nitrogen (more commonly referred to as NO_x) (Lieberman). Since formation of these species is not a preferred reaction, it occurs only at high temperatures or in the presence of a catalyst (substance that increases the rate of a reaction). (Thompson) The high temperature of a conventional DC (direct current) spark discharge can combine with the often catalytic nature of its electrode to produce a site for this reaction. Because the plasma plug uses a higher volume, lower temperature discharge it offers the possibility of providing a more powerful ignition source for lean mixtures without production of these pollutants (Pertl).

The combustion environment inside a running engine is subject to many influences and is difficult to characterize. A technology that is expected to perform in this environment can be subjected to analytical analysis and controlled laboratory tests and still may not perform as expected. This problem is the motivation for building a test stand in which the ignition technology can be evaluated with all of the variables involved with a running engine present.

2.5 Engine Testing Procedures

Engines under evaluation are often subject to a wide range of tests, including evaluations of power output, emissions production, mechanical and combustion efficiency as well as reliability, longevity, and robustness (Martyr). In this case the mechanism being evaluated is not the engine itself, but the ignition system. In this situation it is possible to narrow the scope of the actual tests being performed. This study also focuses on the hypotheses and goals of the plasma ignition project- namely ignition of lean mixtures, ignition of multiple fuels, and overall performance improvement. While performance improvement of an as-supplied engine is not a direct goal, it is hypothesized that improved performance will result from higher energy ignitions when operating with mixtures which have adverse ignition properties.

One way to evaluate ignition performance is to evaluate overall engine performance, especially when operating with mixtures which take more energy to ignite. If all other variables are controlled, and if any of the fuel is not being ignited, or is being ignited too late in the cycle, it follows that a more capable ignition system will produce more power output from the engine (Jacobs). In reality, there is always unburnt fuel in the combustion process, so in most circumstances higher energy ignition produces more power (Ceppos) (Emanuel). It is also useful to examine exhaust conditions to gain an indication of the combustion process that is occurring, as higher energy ignition generally has a positive effect on the combustion process (Avallone).

Evaluation of overall engine performance is accomplished by measuring output torque and horsepower using a dynamometer. A dynamometer of this type applies a load to the engine and measures the torque applied by the engine to resist this load, thus measuring the output of the engine (dynamometer). Using this device, the torque the engine produces can be directly measured and used to calculate power using the formula:

$$HP = \tau * RPM / 5252 \quad (1)$$

Where HP is the power in horsepower, τ is the torque in ft-lbs, and RPM is the engine speed in revolutions per minute (Erjavec).

In order to make the data taken from the dynamometer useful, a variety of other variables will need to be measured. The air-to-fuel ratio (AFR) of the intake mixture will have a large effect on the power output, so it must be controlled to a known value (Warner). Ambient environmental conditions such as air temperature and pressure also have an effect on performance and must be accounted for, as well as the temperature of the engine itself (Moran). By operating the engine on various fuels under specific conditions with these variables accounted for and

measuring the power output using different ignition systems, it will be possible to evaluate the advantages of these ignition systems.

Chapter 3: Test Stand Design

3.1 Overview

The test stand consists of a metal table supporting various apparatus as well as the engine which serves as the evaluation platform for the ignition system. A power source and fuel tanks are also included as part of the stand and the ignition system and measurement components are supported and organized as well.

3.2 Engine

To evaluate the performance of the QWCCR ignition system in a running engine, it was necessary to choose an engine that was simple, robust, and reliable. A single cylinder engine was desired so as to reduce complexity of the ignition circuit, as well as to avoid measurement errors due to differences between cylinders. The engine was desired to be relatively small to simplify mounting and torque measurement. A low to mid range compression ratio (8:1 to 9:1) was desired as well. While higher compression ratios are more advantageous to heavy fuel operation, testing on a less suitable engine was expected to better illustrate the advantages gained from different ignition strategies (Taylor). The lower compression ratio was also desired to improve reliability of the engine under lean operation (Dyke). The following is a table of specifications.

Table 1: Engine Specifications

QWCCR Project Desired Engine Specifications	
Specification	Motivation
4 Cycle	Eliminate Lubrication Oil as an Issue
Single Cylinder	Avoid Variation
Low - Medium Compression Ratio (8-9)	Appropriate Test Platform, Reliability
Small Size/Weight (500cc or Less, Under 200lb)	Ease of Mounting, Measuring
Simple Ignition System	Useful Comparison, Baseline
Overhead Valve	Comparable to Modern Engines

The Briggs and Stratton Intek 1450 (Model 205337) was donated for this purpose by the manufacturer. It is 52 pound, 4 stroke, single cylinder, overhead valve engine with a magneto based ignition system and a compression ratio of 8.5:1, which fulfills all the specifications. The engine was observed to run on both gasoline and jet fuel in its original configuration before any modifications were made.

3.3 Table

To house the engine and related equipment, it was necessary to design a table with adequate space and strength. Since some materials were already available as fabrication shop stock, these were incorporated into the design as well. The following specifications were used in the design.

Table 2: Test Stand Requirements

QWCCR Project Test Stand Specifications	
Specification	Explanation
Steel Construction	Strength, cost, and adaptability
Support 200 Lb Equipment load	Engine, Power supply, etc
Support 20 ft-lb torque from engine	Engine operation under load
Rubber mount of engine	Absorb vibration
10+ sq. ft. surface area	Support equipment and work area
Lower shelf or mounting surface	Mount additional equipment
Mount to floor	Remain in place when engine running
12V power supply and distribution	Support engine electronics
120V AC power supply and distribution	Support plasma and data electronics
Factor of safety >5 for basic table	Ensure reliability

Based on these specifications, the table was to be made from 2"x2"x1/8" angle framing, with a lower shelf made from square tubing to hold additional equipment, and an upper deck made from 1/8" steel plate. Figure 3 shows the 3D model of the table as drawn in SolidWorks software, and Figure 4 shows the same table after fabrication before being painted. CAD Drawings are also included in Appendix A.

Figure 3: SolidWorks Table Model

Figure 4: Fabricated table

This model was also subjected to a finite element analysis to ensure its ability to withstand the weight of the apparatus and the torque applied by the running engine. Because the analysis package in SolidWorks has limited functionality, the model was ported to ProEngineer, and the analysis was performed using ProMechanica. The results of this solid analysis show that the table is has a factor of safety twice the required value for the applied stresses of engine weight, 200lb equipment load, and 25 ft-lb engine torque applied cyclically at 3600RPM. Maximum predicted von Mises stress was less than 10% of the yield strength of American Iron & Steel Institute (AISI) 1020 steel, which was used for the majority of the table parts (Oberg). Results are shown in Figure 5. Note that the legs were assumed fixed to the floor, and that the constraints applied by the dynamometer stand described in a later section were not modeled, and the forces applied by the smaller equipment and mounts were assumed to be part of the 100lb distributed load equipment load as seen in the figure.

Figure 5: Table Stress von Mises

This table was also bolted to the concrete floor of the WVU hangar using 3/8" grade 5 steel anchors to eliminate movement. The engine was isolated from the table with rubber engine mounts to absorb vibration. Adjacent to the engine, a mount for an additional fuel tank was added. This mount was fabricated from .5" tubular steel and was designed to hold a 1 gallon plastic fuel tank. Additional mounts were also added to the table as needed for equipment and display stands. A *Deutsches Institut für Normung* (DIN) style rail was mounted to one side of the table to facilitate wire connector blocks. The finished table is shown in Figure 6, followed by a close-up of the auxiliary fuel tank in Figure 7. Note that a complete parts list for the entire project including this section is included in Appendix A.

Figure 6: Engine Test Stand Table

Figure 7: Auxiliary Fuel Tank

3.4 Fuel System

During initial running, the OEM carburetor supplied with the Briggs and Stratton engine was used. Measurements showed that this unit was factory set to a rich air-to-fuel mixture, and was non-adjustable. Since controlled variation of the mixture was a requirement for much of the expected testing, a more suitable fuel system was needed. To meet this requirement, a programmable electronic fuel injection system was used. This type of system provides control over fuel quantity and can be adjusted through a computer interface. Since multiple fuel operation was an objective, the fuel system also needed to be switchable between separate tanks. To accomplish this, a single fuel pump was plumbed from a switching valve to a fuel rail and then a pressure regulator that returned to another switching valve. By switching both valves it was possible to switch between fuels in a matter of seconds, and no mixing of fuels would occur if the engine was off. A diagram of the fuel system is shown in Figure 8.

Figure 8: Fuel System Diagram

In order to apply fuel injection to the engine, a new intake manifold was required. This manifold was fabricated from steel plate and tubing available from the CIRA shop supply. Since a single injector was used, the manifold required only an injector mounting location, a vacuum port, a mounting flange, and a throttle plate. A 3D SolidWorks model of the manifold is shown Figure 9.

Figure 9: Manifold Model

Also shown are a model of the fuel rail (Figure 10), an assembled model (Figure 11), and the finished parts installed on the engine (Figure 12).

Figure 10: Fuel Rail Model

Figure 11: Intake System Model

Figure 12: Intake System

Once these parts were fabricated, the entire fuel system was assembled on the engine and required only the addition of a control system. The control system chosen was the Megasquirt fuel controller, which is described in detail in a later section.

Chapter 4: Dynamometer

4.1 Overview

In order to quantify the performance of an engine, one must measure the power output produced for a given set of inputs. In addition to this, many of the anticipated test plans also required that the engine be loaded to a certain output level for a period of time to simulate real world conditions and to more accurately determine the related performance levels. The accepted way to do this in an experimental environment is with a dynamometer.

4.2 Loading Unit

There are several types of dynamometers available, but all employ the same method, a loading device is used to dissipate power and load the engine, and a load cell is attached to this device via a known lever arm to measure the applied torque (Pulkrabek). Within these parameters, there are two main types: inertial and static dynamometers. Inertial dynamometers couple the load applied with a weight which provides resistance via its inertia. These devices are not capable of applying a constant torque but rather measure the acceleration of the weight and calculate torque and power. Static dynamometers on the other hand are capable of supplying a constant load such that the engine runs at a steady state. This second type is more advantageous for the testing to be performed, and as such, was chosen as the appropriate goal for this facility. The major consideration attached to selecting a dynamometer is the type of device used to apply the load, usually either hydraulic or electric. Hydraulic dynamometers use a pump and an orifice to dissipate power into a fluid, which is then cooled. These systems are generally not well suited to small engines, however, because they require a certain minimum load to operate efficiently. Electric dynamometers come in several forms, from motors to generators to eddy current brakes. Eddy current brakes are generally used for high power levels, so these were not considered. Motor driven models are more common, but require a sophisticated controller to moderate power input or output. With these considerations in mind, the only method left is a generator. Generators can be easily obtained for nearly any power level, and can be more controlled using relatively inexpensive electronics, making them suitable for this application. A brushed generator was desired, but not available in this size range. With this in mind, a 9.5kW generator model AR-100 was procured from VoltMaster. Note that this is a brushless generator, so some additional equipment was required to vary the output load; details of this are described in the next section. Shown in Figure 13 is the generator mounted on its stand.

Figure 13: Generator

Also required for this installation was a driveshaft and safety guard to cover it. The driveshaft was made from .75" steel rod with keyways milled in the ends and was coupled at each end using flexible "spider" couplings that allow for slight ($1-2^\circ$) misalignments and exceed the torque specification (25 ft-lb). The safety cover was made from .5" plexiglass. Note that this material is inadequate but was found in shop supply and thought to be polycarbonate until after installation; a metal shield is being fitted (see recommendations section) These parts are shown in Figure 14.

Figure 14: Drive Shaft and Guard

4.3 Power Dissipation

Another issue is raised by the use of a generator, however, which is the way in which the electricity will be used, since the torque applied by a generator is proportional to the output current. A solution to this issue is found, however, in heating elements. In this case a pair of commercially available heating elements was procured from Lowes which can dissipate up to 4500 watts (roughly 6 hp) of power each at rated voltage (Lowes). Submerging these in a water reservoir of 50 gallons capacity provides more than the 10hp load required for the engine to run at full output. The volume of water will provide some time constraint, as boiling is not permissible, and no heat rejection system is being employed to cool the water. Since the full output of the generator is rated at 9500 watts, the time to heat it from ambient (25°C) to 85°C (as an acceptable upper limit with factor of safety in mind) can be calculated using:

$$Q = mCp\Delta T \quad (2)$$

Where Q is the heat added in kJ, m is the mass of water in kg, c is the specific heat (4.186 kJ/kg), and ΔT is the change in temperature (60°C). Using this in conjunction with the 9.5kW power input and the fact that 1kJ = 1kW*second yields an operation time of 82 minutes, which is enough to complete all anticipated testing. It should be noted that in the case where longer runtimes are required, adding a properly sized radiator and circulation pump would increase the runtime to any desired interval. In keeping with the temperature constraint, a sensor was added to the water reservoir to monitor the temperature and a limit was placed in the engine controller code to shut down the engine automatically at the upper limit of 85°C. The two heating elements were wired in parallel on different circuits (with appropriate circuit breakers for safety) to provide two load ranges: 4500 watts and 9000 watts maximum. In order to vary the load applied to the engine, a variable transformer (variac) was used to adjust the voltage on one of the elements,

while the other element was simply switched on or off to select between load ranges. Also of note is the fact that the generator used is a brushless type which uses an inductor-capacitor resonant circuit to produce the excitation current. Since the resonance is tuned for a specific RPM range (3500-3700 RPM), it was necessary to adjust the capacitance (originally 56.5 microfarads) to produce appropriate voltages at lower speeds. This was accomplished by adding additional capacitors (rated at 30 microfarads each and for 440 VAC) in parallel with the originals – two additional capacitors were used for 2500-3000 RPM tests, while four were added for lower speeds. Figure 15 shows a photo of the capacitor bank, and Figure 16 shows the absorption apparatus. Figure 17 shows a schematic of the electrical output system.

Figure 15: Generator Field Capacitors

Figure 16: Power Absorption System

Figure 17: Output Schematic

4.4 Torque Measurement

The main purpose of a dynamometer is to measure power output of the engine. Since power is directly proportional to torque and engine speed, and engine speed is measured by the engine controller, it remains only to measure the torque being produced. The accepted way to do this is

to mount the loading device such that force perpendicular to the axis of rotation can be measured via a load cell attached to a lever arm of known length using the formula:

$$\tau = F * r \quad (3)$$

Where τ is the torque, F is the force as measured by the load cell, and r is the lever arm length. In this case, the weight of the generator (108 lbs) is a much more substantial load than the maximum torque capability of the engine (15 ft-lb), so a mounting system was designed with a pivot point to carry the weight of the generator without affecting the torque measurement. The pivot point used two block mount ball bearings and was centered under the generator. The following CAD drawing shows a 3-D model of the generator stand. Note: in-depth details of the torque measurement system are included in Appendix C.

Figure 18: Dyno Generator Stand

Since the maximum torque output of the engine is rated at 14.5 ft-lbs, it was assumed that even with possible power enhancements provided by the ignition system and fueling variability, a 25 lb load cell was adequate. CIRA was in possession of four model LC101-25 25 lb S-beam load cells made by Omega, which match this requirement. Since the load cells were readily

available, a second cell was added on the reverse axis of the first to provide a corollary measurement. It should be noted that although these cells can be calibrated to read similar values, a tare value will likely be required. Also of note is the fact that the indicated torque from each cell will be half the applied torque, as the force will be divided between the two cells. Figure 19 shows a close-up of an installed load cell. The output of these cells is configured such that it can be displayed and datalogged by the Megasquirt engine controller; details of this configuration are given in a later section.

Figure 19: Load Cell Installed

Chapter 5: Sensors and Control Systems

5.1 Overview

In order to run the engine under the desired conditions, a controller that could vary the fueling rate based on sensor and user inputs was required. In addition, a range of variables must be measured to validate the source of performance variations as coming from the ignition or fuel system rather than an external input, such as engine block temperature. To meet these requirements, an array of sensor and controllers was integrated into the test stand design. The following sections illustrate these systems.

5.2 Engine Controller

One goal of the control system design was to interpret all of the real-time data through one unit to simplify the data reduction. This was accomplished using the engine controller, as engine controllers have data interpretation and logging functionality built in. This controller interpreted and logged engine related inputs and supplied signals to the fuel system. It was also used in conjunction with a PC to monitor both engine related and external sensor signals in real-time, and to view and edit the data logs.

Since the fuel system described earlier has few components compared with many modern engines, there are a wide range of systems available that are capable of controlling it. In this case, one important issue was configurability. Since engine controllers require a comparatively advanced processor with many inputs and outputs, it was advantageous to select a model that had capability for expansion and reconfiguration such that it could be used to monitor inputs of other sensors specific to this project and supply user-defined outputs if necessary. Of particular importance were input channels for the wideband oxygen sensor used to monitor air to fuel ratios and available channels that could be set up to monitor the torque being produced. The most adaptable choice of a commercially available control system for this application was the MegaSquirt fuel computer. Since the MegaSquirt (hereafter referred to as 'MS') is open source and user assembled, it offers a wider range of configuration options than other controllers in its class. Among these options are two analog-to-digital (A/D) converter input possibilities and a built-in oxygen sensor input channel that can be configured for nearly any oxygen sensor type. The A/D inputs are listed as optional extras and require some modification to the basic unit, but offer channels that can be configured for interpreting the torque measurement from the load cells. More detail on these channels is included in the section on load cell signals.

Once the MS was chosen, it was ordered and wired to the engine. Figure 20 shows the wiring schematic for this system, and Figure 21 shows the installed engine control unit.

Figure 20: Megasquirt Wiring Diagram

Figure 21: Engine Control Unit and Wiring

5.3 Load Cell Signals

Although the MegaSquirt controller is capable of interpreting analog signals as mentioned previously, a conditioning circuit was still required to protect the processor. This comes as three parts: a 10V DC power supply was used to power the cells, a pair of Omega model DRF-LC signal conditioners were used to amplify the output to a 0-10V signal, and a conditioning circuit for protection. Note that the signal conditioners are only capable of reading force in one direction, but this is all that is needed for this installation. Getting the 0-5V input range required by the MS is only a matter of adjusting the gain on the Omega conditioners, but the protective circuit was used to ensure that the allowable voltage was never exceeded so as not to damage the CPU. This simple circuit consisted only of a pair of 5.1V Zener diodes for voltage protection and a low-pass filter with a cutoff frequency of 724 Hz to remove noise as shown in Figure 22. Note that this input circuit is specified by the MegaSquirt manufacturer and was not modified.

Figure 22: MegaSquirt Protection Circuit (Ringwood)

Adding this to the conditioners produced the overall circuit shown in Figure 23, followed by a photograph of the arrangement (Figure 24).

Figure 23: Load Cell Circuit

Figure 24: Load Cell Signal Conditioners

In order to monitor this signal via the Megasquirt software, it was necessary to modify the tuning software configuration file according to the procedure specified by the manual (Ringwood). This procedure hinges around the interpretation of the 0-5V signal at the A/D pin on the CPU as an 8 bit digital character, and converting this to a loggable voltage and display variable using the following formulae:

$$V = ADC * \frac{R}{2^n - 1} = ADC * \frac{5}{2^8 - 1} = ADC * .0196, \quad (4)$$

where V is the voltage, ADC is the input variable (as a digital bit from 0-255,) R is the input range (0-5V), and n is the resolution of the CPU (in bits). By using this formula, it is possible to create a variable that represents either voltage or torque (outputting torque simply requires multiplying the voltage by a calibration factor). Excerpts from the MS tuning program code for the gage display are shown below:

```
; Define Positive Torque Voltage (fuelADC is pin JS5)
TplusVolts      = {fuelADC * 0.0196078}
Torque          = {fuelADC * 0.0196078 * 5}
; Define Negative Torque Voltage (egtADC is pin JS4)
TminVolts       = {egtADC * 0.0196078}
...
; Define +Torque gauge, range 0-5V, Warning 1 4.75V, Warning 2 5V, 2 decimal places
TplusGauge      = TplusVolts,      "TPlus Volts",      "V",      0, 5, 0, 0, 4.75, 5, 2, 2
TorqueGauge     = Torque,          "Torque",           "ft-lb"   0, 25, 0, 0, 15, 20, 2, 2
; Define -Torque gauge, range 0-5V, Warning 1 4.75V, Warning 2 5V, 2 decimal places
```

```

TminGauge    = TminVolts,          "Tminus Volts",          "V",          0,  5,  0,  0,  4.75,  5,  2,  2
...
; Define gauges to display and screen order
; Gauge Setup 0

gauge1 = RpmHiResGauge
gauge2 = cltGauge
gauge3 = matGauge
gauge4 = dutyCycle1Gauge
gauge5 = mapGauge
gauge6 = TplusGauge
gauge7 = TorqueGauge
gauge8 = afrGauge
...
[DataLog]
; Define datalog channel for gages, names, float data style, 3 decimal places
entry = TplusVolts,  "TPlus",      float, "%.3f"
entry = TminVolts,   "Tmin",       float, "%.3f"
entry = Torque       "Torque",     float, "%.2f"

```

This resulted in the displays as shown on the bottom middle gages in Figure 25; note also the modified gages used to show the dynamometer water temperature. As can be seen in this figure only one of the cells is output to the display, this was done so that both voltages and torque could be read in real-time, which helped with zeroing and troubleshooting the cells. The values for both cells are logged, however, so discrepancies can be accounted for if necessary.

Figure 25: Sensor Readouts

Chapter 6: Testing and Results

6.1 Overview

Since the focus of this document is on the construction of a test stand, only basic testing required to validate the data provided by the stand will be presented herein. This data includes a comparison of the power curve generated by the engine under simulated stock conditions to the manufacturer's curve. It also diverges into a power curve with optimized settings available with the more configurable fuel system as well as a power curve while running on plasma ignition. A power curve for jet fuel is also presented for both ignition methods. In addition to these tests, examples of sensor readouts are shown and details of cold start testing are presented.

6.2 Experimental Setup

While the focus of this document has been on the method and mechanics of data production, little emphasis has heretofore been placed on the actual data collection process. This section will expound on that subject. Care has been taken to design this test stand such that most of the data collection is automatically achieved, but a certain amount is also necessarily collected manually. The latter type has been limited to the following variables: ambient air temperature and pressure, plasma power source voltage, plasma controller delay, plasma pulse width, and generator voltage. Items that are automatically logged include block temperature, water barrel temperature, load cell A, load cell B, engine speed, manifold pressure, injector pulse width, air: fuel ratio, and others. Figure 25 on the previous page shows a screenshot of the data gages screen, and Table 3 shows a sample datalog. Note that all channels are logged at a nominal 10Hz sample rate.

Table 3: Sample Datalog

MS1/Extra format 029y3 *****						4000 RPM Ambient P= 95kPa, T=24C									
Time	MAP	O ₂	MAT	CLT	Gego	Gwarm	Gbaro	Gammae	Gve	PW	TPlus	Torque/2	DutyCycle1	RPM	batt V
sec	kPa	V	deg C	deg C						ms	V	ft-lb	%		V
94824.791	89	1.275	24.4	83.3	115	100	100	97	73	13.7	1.725	8.63	44.5	3945	10.7
94824.903	94	1.333	24.4	83.3	115	100	100	97	74	15.2	1.725	8.63	48.1	3950	10.8
94824.99	94	1.176	24.4	83.3	115	100	100	97	70	13.9	1.745	8.73	44	3893	10.7
94825.084	93	1.275	24.4	83.3	115	100	100	97	74	14.8	1.706	8.53	48.1	3840	10.8
94825.188	88	0.98	24.4	83.3	115	100	100	97	73	13.8	1.745	8.73	43.7	3880	10.7
94825.291	96	1.431	24.4	83.3	115	100	100	97	73	15.2	1.725	8.63	49.4	3938	10.8
94825.393	95	1.059	24.4	83.3	115	100	100	97	70	14.3	1.725	8.63	46.5	3888	10.7
94825.479	94	1.235	24.4	83.3	115	100	100	97	74	14.3	1.706	8.53	45.3	3950	10.8
94825.581	96	1.196	24.4	83.3	115	100	100	97	72	14.7	1.725	8.63	46.6	3894	10.8
94825.682	92	1.333	24.4	83.3	115	100	100	97	72	14.7	1.725	8.63	46.6	3891	10.7
94825.76	96	1.059	24.4	84.4	115	100	100	97	72	15.8	1.706	8.53	50	3893	10.8
94825.871	90	1.216	24.4	84.4	115	100	100	97	73	14.2	1.745	8.73	45	3837	10.8
94825.974	94	1.216	24.4	84.4	115	100	100	97	71	14.8	1.725	8.63	46.9	3833	10.8

Defining the variables shown here: Time is the processor clock time, MAP is manifold absolute pressure, O₂ is the oxygen sensor voltage, MAT is the dynamometer temperature, CLT is the engine block temperature, the next four columns are fueling gain values that are monitored but

not used for this testing (they are monitored to ensure the code is not modifying fueling), Gve is the user defined fuel tuning value, PW is the injector pulsewidth, Tplus is the positive torque load cell voltage, Torque/2 is the measured torque from one load cell (half the applied torque), DutyCycle1 is the injector duty cycle, RPM is the engine speed, and battV is the system voltage.

6.3 Testing

In order to validate the quality of data produced by this test stand, a series of tests were performed to acquire a torque and horsepower curve for the engine. These curves were compared to the published curves from the manufacturer. Because of the extensive modifications to the fuel system, a set of data was also taken to evaluate the appropriate air-to-fuel ratio to use for power evaluation. Interestingly, the value which produced peak power was quite different from the value that was measured with the original factory supplied fuel system; this may explain some variation in the data.

To evaluate the horsepower of an engine, it is required only to measure the torque and engine speed, so power results are a mathematical adaptation of torque results. Taking this data required a specific procedure to obtain accurate results, so a standard operating procedure (SOP) was developed, and is shown in Table 4.

Table 4: Testing Procedure

Plasma Test Engine Torque Measurement SOP	
1	Turn on fuel, connect battery power, turn on AC power strip and load cell DC power supply
2	Open MegaSquirt interface program on PC
3	Turn on ignition key, but do not start engine
4	Verify gage readouts, record air temperature and pressure
5	Verify load cell reading using 4-lb weight placed on lever arm directly above load cell
6	Check shaft couplings for endplay or looseness
7	Ensure no loose objects or tools on engine or generator table
8	Turn load control variac all the way down for load 1, turn breaker to on (I) position for load 2
9	Set throttle valve such that orifice is open by appx. 1/8"
10	Start engine
11	Verify normal running condition, appropriate air:fuel ratio (12.5-14) and generator voltage (>100V)
12	Open throttle to wide open position
13	Start datalog, named "desired RPM.number of capacitors" i.e. "3000.4"
14	Increase voltage on load 1 variac until engine is loaded to desired RPM
15	Repeat step 11
16	Take data for at least 30 seconds
17	Turn datalogging off
18	If taking more data points, adjust load to reach next RPM and repeat steps 13-17
19	When finished taking data, close throttle, let engine die
20	Record any changes in air temperature or pressure
21	Turn ignition key to off, turn off fuel, turn off power, disconnect battery power
22	Find datalogs in C:/Program Files/Mega Squirt/car1/
23	Open datalogs and check column S for torque readings, column AD for RPM
24	If readings are present and in range, data is usable and can be reduced, otherwise check equipment and retake data

6.4 Results

When comparing power and torque values, it is customary to adjust these values to a standard level based on atmospheric conditions, so these values are necessarily recorded, but not controlled. The other common variable that has an effect on power is the air-to-fuel ratio, as rich or lean conditions cause loss of output to the point of stalling the engine. There is no correction factor for this variable, so it must be controlled. For gasoline, the stoichiometric value is 14.7:1 (Hollembeak). Many engines actually operate better at a slightly richer ratio, however (Hartman). This is due in part to the incomplete mixing of the fuel with the air, causing an incomplete burn, but is affected by other factors as well. It was originally assumed that the appropriate comparison for this testing would be to measure the mixture produced with the original intake and carburetor and simply duplicate this value for all testing. Upon performing the measurement, however, it was observed that this system produced a rich 11.2:1 mixture. Based on this circumstance, it was decided that an investigation of the engine's optimum mixture was required. To produce this data, the engine was run at wide open throttle with a constant load, and the fuel injector pulsewidth was varied in steps to produce a range of air-to-fuel ratios, allowing 10 seconds to settle to steady state between steps. Horsepower was calculated for each data point, and plotted as a function of the air-to-fuel ratio to determine the peak. This plot is shown in Figure 26.

Figure 26: Effect of AFR on Output

Each point on this plot represents an average of fifteen data points taken after the engine had settled. Both the air-to-fuel ratio and power were averaged, and standard deviation of power output is shown for each point. This shows that the optimum for this engine is in the 12.5-15:1 range, and that the original equipment was causing the engine to run at a reduced power level. Based on this information, it was reasoned that because the air-to-fuel ratio based power curve is steep at the 11.2:1 level and flatter near the peak, running in the 13:1 range would produce much more accurate and repeatable results as small changes in AFR would have less effect on output. Note that the standard deviations are relatively large for some points, especially in the

leaner regions, but represent a maximum coefficient of variation of less than 4%, which is within the goals of this project. It is expected that the reason for this variation is due to the nature of the fuel control strategy used which specified an injector pulsewidth manually and therefore did not adapt to the changes in power output that resulted from small variations in air-to-fuel ratio. This is illustrated in Figure 27 which shows the relationship between air-to-fuel ratio and power as a function of time. This plot shows the variations both before and after a fueling change, but also further illustrates the direct relationship between air-to-fuel ratio and power output. Statistical information for this data is shown in Appendix B along with the datalog.

Figure 27: Time Relation of Power to AFR

With the appropriate air-to-fuel ratio range set to 12.5:1-14:1, it was possible to continue with the torque curve validation testing. This testing was performed as described in the previous section, which produced the following curves representing varying torque output with air-to-fuel ratio and RPM held constant for each data point, and engine temperature and intake air temperature changes verified as negligible for the test intervals.

Figure 28: Torque Curve

Figure 29: Power Curve

In each figure above, the red line is an approximation of the rated power of the engine from the manufacturer (Briggs and Stratton). It should be noted that since Briggs and Stratton no longer

distributes engine ratings, this curve is from a slightly older model of the same engine and therefore may be out of date. The blue diamonds each represent an average of twenty (20) data points of measured data from the test stand. The bars on the charts show the standard deviation of this data, which is discussed in more detail later. As can be seen, the power and torque from this engine are higher than the published value- this is almost certainly due to the rich AFR supplied by the original equipment fuel system as explained for Figure 26. There may also be slight volumetric efficiency advantages caused by the less restrictive intake and exhaust systems fitted to the engine on the test stand. In any case, the trend is steady, averaging 12% higher than expected with a maximum difference of 28%. This difference is well within the range of variation seen in Figure 26, indicating that the air-to-fuel ratio adjustment is responsible for the difference. Also of note is that the sample taken at 3250 RPM was not included in the plots. The reason for this is that a mistake was made in the tune for this data and the ratio is too rich, as can be seen in Table 5. Due to technical difficulties, this data cannot be retaken at this time. Another issue is the comparatively large coefficient of variation for the 2500 RPM data, indicating that there may have been a measurement issue for these samples. Detailed data for all tests is included in Appendix B.

Table 5: Engine Output Data

Compiled Torque and Power Curve Data											
RPM Range	Data File	Engine Speed	AFR	Measured Torque	Measured Power	Manuf. Power	Manuf. Torque	Torque STDEV	HP STDEV	Torque COV	HP COV
		RPM		Ft-lbs	Horsepower	Horsepower	Ft-lbs				
2250	s2250.4 (170-190)	2303	13.45	20.83	9.13	8.10	18.91	0.140	0.192	0.013	0.021
	s2250.4(200-220)	2314	13.28	20.91	9.21	8.10	18.91	0.229	0.229	0.022	0.025
2500	s2500.2(1-20)	2487	13.59	19.09	9.04	8.55	17.96	0.826	0.831	0.087	0.092
	s2500.2(45-65)	2501	13.82	19.06	9.07	8.55	17.96	0.909	0.922	0.095	0.102
2750	s2750.2(50-70)	2699	13.32	19.71	10.13	9.00	17.19	0.289	0.372	0.029	0.037
	s2750.2(1-20)	2730	13.27	19.62	10.20	9.00	17.19	0.200	0.247	0.020	0.024
3000	s3000.4c(500-520)	3091	12.51	17.24	10.15	9.40	16.46	0.151	0.252	0.018	0.025
	s3000.4c(550-570)	3066	12.50	17.29	10.10	9.40	16.46	0.148	0.183	0.017	0.018
3250	s3250.0(1-20)	3275	11.50	14.40	8.98	9.70	15.68	0.146	0.196	0.020	0.022
	s3250.0(50-70)	3270	11.49	14.27	8.88	9.70	15.68	0.195	0.238	0.027	0.027
3500	s500.0(1-20)	3486	13.28	19.34	12.84	10.00	15.01	0.175	0.252	0.018	0.020
	s3500.0(50-70)	3482	13.22	19.06	12.64	10.00	15.01	0.158	0.253	0.017	0.020

Chapter 7: Conclusions and Recommendations

From the data taken in the results section, it is possible to conclude that the test stand does provide useful results that are within the desired precision range. Although the results show discrepancies with the manufacturer's data with differences averaging 12 percent, a reasonable explanation for this variation can be made. Based on the samples taken the data produced is repeatable, as the average difference between samples is less than 1 percent (.62% for the data in Table 5). For the purpose of comparison of different results achieved on this engine with various fuels and ignition systems, the data is expected to be within the <4% range specified in the objectives. An error analysis of the system is included in Appendix C to support these conclusions.

Several recommendations inspired by this research can be used to improve further testing. The first is a safety issue; the guard for the driveshaft was insufficient to contain the shaft upon breakage, and needs to be replaced with a steel grating rather than plexiglass.

The next is the short life span of the load cells: the cells used were rated for 25 lbs, and forces close to this level were reached during periods of rapid deceleration. The vibration of the running engine may also have contributed to the cells' demise. It is recommended that for further research cells rated at 50 lbs be fitted, and mounting systems that isolate the cells from vibration and other loads be investigated. A more robust cell has already been acquired and will be installed once the mounting system is finalized.

Another possible improvement area is additional instrumentation. While the equipment used provides much insight into the performance of the engine, adding some additional temperature monitoring, especially to the exhaust temperature and intake manifold temperature could prove beneficial. Even more important is the need for a cylinder pressure transducer. By examining the pressure curves from inside the cylinder, it would be possible to time the ignition systems more accurately and to have much more insight into the combustion process as it happens. This equipment has already been located and will be installed in the engine before any additional testing is attempted.

Finally, it should be noted that in order to use the data presented here as a basis for comparison against other systems, the 2500 and 3250 RPM tests will need to be retaken to account for measurement and fueling discrepancies present in these data samples.

Chapter 8: References

AMSOIL. "Two-cycle Engine Applications and Lubrication Needs." 2001. AMSOIL News Article. 2009 <http://www.amsoil.com/articlespr/article_2cycleapplications.aspx>.

Avallone, E., Baumeister, T., and Sadegh, A. "Internal Combustion Engines." Mark's Standard Handbook for Mechanical Engineers. New York, NY: McGraw-Hill Professional, 2006. p9.124.

Bonazza, T.J., Van Voorhies, K.L., and Smith, J.E. "RF Plasma Ignition System Concept for Lean Burn Internal Combustion Engines." SAE Paper 929416, 1992.

Bowling, B. and Grippio, A. "Wiring and Sensors." 2008. MegaManual. 7 Accessed 7-12-2009 <<http://www.megamanual.com/v22manual/mwire.htm>>.

Briggs and Stratton. "10 HP INTEK TM I/C Model Series 205400." 2003. Small Engine Suppliers. Accessed 8-15-2009 <<http://www.smallenginesuppliers.com/html/engine-specs/briggs/205400.html>>.

Ceppos, R. "Spark Plugs: How Research is Making Them Last Longer, Perform Better." Popular Science June 1978: 108-109.

Dyke, A. L. Dyke's Automobile and Gasoline Engine Encyclopedia. St Louis, MO: A.L. Dyke, 1920.

"dynamometer." 2009. Encyclopedia Britannica Online. 17 8 2009 <<http://www.britannica.com/EBchecked/topic/175219/dynamometer>>.

Erjavec, J. Automotive technology: A Systems Approach. Florence, KY: Cengage Learning, 1999.

Hartman, J. Nitrous Oxide Performance Handbook. Osceola, WI: MotorBooks/MBI Publishing Company, 2009.

Hibbeler, R.C. Engineering Mechanics Statics, 10th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2004.

Hirsch, R. L., Bezdek, R., and Wendling, R. "Peaking of World Oil Production:Impacts, Mitigation, and Risk Management." NETL Report. 2005.

Hollembeak, B. Classroom Manual for Automotive Fuels and Emissions. Florence, KY: Cengage Learning, 2004.

Innovate Motorsports. "LC-1 Manual." Product Manual. Irvine, CA: Innovate Motorsports, 2007.

Jacobs, C. Performance Ignition Systems: Electronic or Breaker-Point Ignition System Tuning for Maximum Performance, Power, and Economy. New York, NY: Penguin Group, HPBooks, 1999.

Kojima, M. "Air Fuel Meter Shootout: The Ultimate Comparison of Wideband Oxygen Meters." 6 2007. Ford Muscle Magazine. Accessed 8-29-2009
<<http://www.fordmuscle.com/archives/2007/06/WidebandShootout/>>.

Linkenheil, K., Ruoff, H.O., and Heinrich, W. "Design and Evaluation of a Novel Spark-Plug Based on a Microwave Coaxial Resonator." 34th European Microwave Conference. Amsterdam, Netherlands, 2004.

Lowery, A. An Experimental and Computational Investigation of Dielectrics for Use in Quarter Wave Coaxial Cavity Resonators. Masters Thesis. Morgantown, WV: West Virginia University, 2006.

McIntyre, D. The Coaxial Cavity Resonator as a Prototype RF IC Engine Ignition Source. Masters Thesis. Morgantown, WV: West Virginia University, 2000.

Moran, M. and Shapiro, H. Fundamentals of Engineering Thermodynamics, 5 ed. Hoboken, NJ: John Wiley & Sons, Inc., 2004.

Nash, M. A. The Coaxial Cavity Resonator and R. F. Power Processing. Masters Thesis. Morgantown, WV: West Virginia University, 1988.

Oberg, E., Jones, F., Horton, H., and Ryffel, H. Machinery's Handbook, 28th Ed. New York, NY: Industrial Press, 2008.

Pertl, F.A.J. Prospects of Lean Ignition with the Quarter Wave Coaxial Cavity Igniter. Dissertation. Morgantown, WV: West Virginia University, 2008.

Pulkrabek, W. Engineering Fundamentals of the Internal Combustion Engine, 2nd Ed. Upper Saddle River, NJ: Pearson Prentice-Hall, 1997.

Ringwood, P., Murray, J., and Culver, K. "MS1-Extra Quick Guide to Tuning and Using MegaTune." 2008. MegaTune Based Manuals for MS-Extra. Accessed 7-12-2009
<http://www.msextra.com/manuals/MS_Extra_Datalog_Manual.htm#addgauge>.

Smith, J. E., Craven, R. M., VanVoorhies, K. L., and Bonazza, T. J. "Radio Frequency Coaxial Cavity Resonator As An Ignition Source And Associated Method". United States of America: Patent 5,361,737. 8 November 1994.

Smith, J. Integration of Microwave Plasma Ignition into a Multi-Fuel Engine. Research Findings. Morgantown, WV: West Virginia University, 2008.

Stiles(1997), R., Thompson, G., and Smith, J. "Investigation of a Radio Frequency Plasma Ignitor for Possible Internal Combustion Engine Use." SAE Paper 970071, 1997.

Stiles(1998), R. and Smith, J. "Modeling the Radio Frequency Coaxial Cavity Plasma Igniter as an Internal Combustion Engine Ignition System." SAE Paper 980168, 1998.

Taylor, C. F. The Internal-Combustion Engine in Theory and Practice. Cambridge, MA: MIT Press, 1985.

Thompson, G. "Day 03-Combustion." Vehicle Emissions Class Presentations. Morgantown, WV: West Virginia University, 2008.

Van Voorhies, K. L., Bonazza, T. L., and Smith, J. E. "Analysis of RF Corona Discharge Plasma Ignition." 27th Intersociety Energy Conversion Engineering Conference. SAE Paper 929502, 1992.

Von Hagen, J., Venot, Y., Zhang, Y., and Wiesbeck, W. "Microwave-Generated Plasma in Air Under Standard Conditions." IEEE Transactions on Plasma Science, Vol. 29, No. 4 (2001).

Warner, M. Street Rotary, How to Build Maximum Horsepower and Reliability into Mazda's 12A, 13B & RENESIS Engines. New York, NY: Penguin Group, HPBooks, 2009.

Wildfire, P., Nawrocki, A., Pertl, F., and Smith, J. "Investigation of the Cold Start Capability of a Briggs and Stratton Engine Using Jet A Fuel and Microwave Plasma Ignition." 2009 SAE World Congress and Exhibition. Detroit, MI: SAE Paper 09-01-1057, 2009.

Wilhelm, J., Pertl, F., Wildfire, P., and Smith, J. "Ignition Energy Testing of the Quarter Wave Coaxial Cavity Resonator with Air-Liquefied-Petroleum-Gas Mixtures." 26th AIAA Aerodynamic Measurement Technology and Ground Testing Conference. Seattle, WA: AIAA Paper 2008-3775, 2008.

Appendix A : Complete Parts List and Drawings

This section includes information on materials used and specific construction of the test stands and equipment for the project.

A.1 Bill of Materials

This section contains a bill of materials for all sections of the project, as shown in Table A-1.

Table A-1: Parts List

Part Description	Quantity	Part Number	Supplier		
Optima Red Top Battery	1	-	Advance Auto Parts		
EverStart Marine Battery Box	1	-	Advance Auto Parts		
5/16 Fuel Injection Hose (ft)	5	-	Advance Auto Parts		
1/2" hose clamps	8	-	Advance Auto Parts		
2" x 2.5" Exhaust Adapter	1	-	Advance Auto Parts		
SPST 30A Automotive Relay	2	-	Advance Auto Parts		
ATC Fuse Block- 6 position	1	-	Advance Auto Parts		
ATC Fuse Assortment	2	-	Advance Auto Parts		
5/16 hose Fuel filter (high pressure)	1	-	Advance Auto Parts		
14.50 Intek Engine	1	205337	Briggs and Stratton		
Ignition Key Switch	1	092556MA	Briggs and Stratton		
Secondary 1 gallon plastic fuel tank	1	-	Briggs and Stratton		
Innovate LC-1 Oxygen sensor system	1	LC-1	diyautotune.com		
Megasquirt Fuel Injection Controller v2.2	1	MS122-C	diyautotune.com		
GM Closed Element Temperature Sensor w/ pigtail	2	CLTIATwPiggy	diyautotune.com		
Fuel Injector Pigtail	1	InjPiggy-EV1	diyautotune.com		
VoltMaster AR-100 9500w Brushless Generator	1	6HJ90	Grainger		
3/8" NPTF x 5/16" hose barb adapter	2	-	Lowes		
American Water Heater Element (4500w bolt in)	2	6900339	Lowes		
Aluminum Spider Coupling (.75" shaft)	2	9845T603	Mcmaster-Carr		
Polyurethane Coupling Insert (Shore 98A)	1	9845T26	Mcmaster-Carr		
Fiberglass Spider Coupling (.75" Shaft)	1	9939T401	Mcmaster-Carr		
Fiberglass Spider Coupling (1" Shaft)	1	9939T402	Mcmaster-Carr		
Polyurethane Coupling Insert (Shore 64D)	1	9939T22	Mcmaster-Carr		
.75" Base Mount Ball Bearings	2	5913K63	Mcmaster-Carr		
Brass Ball Valve (1")	1	47865K25	Mcmaster-Carr		
2" Metal Flexible Exhaust Hose (ft)	12	5262K27	Mcmaster-Carr		
Exhaust Clamp (2")	1	3042T89	Mcmaster-Carr		
Plastic Electronics Enclosure	3	7593K27	Mcmaster-Carr		
20A 240V Circuit Breakers Panel Mount	2	3931T14	Mcmaster-Carr		
440VAC 30 microfarad Capacitors	4	7602K47	Mcmaster-Carr		
1" Urethane Rod, center drilled, .5"L	4	8695K863	Mcmaster-Carr		
1" Urethane Rod, center drilled, .75"L	4	8695K863	Mcmaster-Carr		
Omega Load Cell Signal Conditioners	2	DRF-LC	omega.com		
Accel 15 lb/hr fuel injector	1	ACCEL-150115	Summit Racing		
Accel Fuel Pressure Regulator (35-70 PSI)	1	ACCEL 74560	Summit Racing		
Summit High Flow Electric Fuel Pump	1	SUM-G3138	Summit Racing		
3-Way Ball Valve	2	-	SWAGELOC		
Wire + Terminals (various)	-	-	CIRA Shop Supply		
Bolts, Nuts, Washers (various)	-	-	CIRA Shop Supply		
.5 "x.065" Wall Tubular Steel 30"L	5	-	CIRA Shop Supply		

.75"x.065" Wall Tubular Steel 60"L	2	-	CIRA Shop Supply		
.75" Steel Round Bar 12"L	1	-	CIRA Shop Supply		
1"x1"x.125" Wall Tubular Steel 6"L	4	-	CIRA Shop Supply		
1.5"x1.5"x.1875" Steel Angle 5"L	1	-	CIRA Shop Supply		
1" Steel Round Bar 31"L	4	-	CIRA Shop Supply		
.5"x16"x16" Steel Plate	2	-	CIRA Shop Supply		
.25"x16"x16" Steel Plate	1	-	CIRA Shop Supply		
2"x2"x.125" Steel Angle 36"L	4	-	WilsonWorks		
2"x2"x.125" Steel Angle 30"L	6	-	WilsonWorks		
2"x2"x.125" Steel Angle 60"L	2	-	WilsonWorks		
.75"x.75" Steel Bar 5"L	2	-	WilsonWorks		

A.2 CAD Drawings of Fabricated Tables

This section contains CAD working drawings of the test stand table and dynamometer stand, as attached on the following pages.

Appendix B : Datalogs

This section contains the data used to produce the curves in the results section. Note that the Torque value here is represented as Torque/2, this is because it is a reading from only one load cell as the other load cell was not used for these tests. In each case the mean, standard deviation, coefficient of variation, and % variation for torque, horsepower, and air to fuel ratio are expressed on the right side of the sheet. Note that in all cases except the 2500 RPM data, the variations are within the objective of four percent. The 2500 RPM data should be retaken as mentioned previously.

Table B-1: 2250 RPM Data

MS1/Extra format 029y3 *****															Standard Deviations										
Time	SecL	MAP	O2	MAT	CLT	Gve	PW	TPlus	Torque/2	DutyCycle1	RPM	batt V	AFR	Hp				EG SPEED	TORQUE	HP	AFR	tqstddev	hpstddev	afrstddev	
s		kPa	V	degC	degC	%	ms	V	ft-lb	%		V	lbair/lbfuel	bhp				sample	RPM	ft-lb	bhp	ma:mf	ft-lb	bhp	ma:mf
6381.802	128	95	1.902	23.9	50	100	13.5	2.059	10.29	25.9	2368	11.5	13.804	9.28				s1 (170-190)	2302.62	20.83	9.13	13.45	0.1403	0.1920	0.2515
6381.879	129	90	1.745	23.9	50	100	13.4	2.137	10.69	24.6	2371	11.8	13.49	9.65				s2(200-220)	2311.72	20.85	9.21	13.27	0.2290	0.2293	0.1758
6381.98	129	90	1.686	23.9	50	100	13	2.118	10.59	24.9	2246	11.6	13.372	9.06											
6382.074	129	95	1.686	23.9	50	100	13.1	2.059	10.29	25.1	2366	11.8	13.372	9.27											
6382.165	129	94	1.725	23.9	50	100	13.1	2.059	10.29	25.1	2306	11.5	13.45	9.04											
6382.242	129	93	1.784	23.9	50	100	13.5	2.118	10.59	25.9	2302	11.8	13.568	9.28											
6382.343	129	94	1.706	23.9	50	100	13.5	2.118	10.59	24.8	2303	11.6	13.412	9.29											
6382.428	129	96	1.667	23.9	50	100	13.6	2.078	10.39	26.1	2304	11.6	13.334	9.12											
6382.529	129	96	1.706	23.9	50	100	13.5	2.059	10.29	25.9	2303	11.5	13.412	9.02											
6382.622	129	97	1.765	23.9	50	100	13.4	2.137	10.69	25.7	2367	11.6	13.53	9.64											
6382.722	129	97	1.588	23.9	50	100	13.5	2.118	10.59	25.9	2367	11.5	13.176	9.55											
6382.818	129	90	1.686	23.9	50	100	13.1	2.137	10.69	25.1	2248	11.5	13.372	9.15											
6382.919	130	90	1.745	23.9	50	100	13.2	2.118	10.59	25.3	2248	11.8	13.49	9.07											
6383.011	130	95	1.569	23.9	50	100	13.1	2.078	10.39	25.1	2306	11.6	13.138	9.12											
6383.112	130	96	1.706	23.9	50	100	13.1	2.078	10.39	24	2249	11.8	13.412	8.90											
6383.197	130	95	1.765	23.9	50	100	13.1	2.118	10.59	25.1	2305	11.6	13.53	9.30											
6383.297	130	95	1.706	23.9	50.6	100	13.1	2.118	10.59	25.1	2369	11.8	13.412	9.55											
6383.375	130	95	1.706	23.9	50.6	100	13.5	2.059	10.29	24.8	2250	11.6	13.412	8.82											
6383.458	130	95	1.51	23.9	50.6	100	13.6	2.098	10.49	24.9	2246	11.6	13.02	8.97											
6383.55	130	95	1.667	23.9	50.6	100	13.4	2.137	10.69	25.7	2306	11.6	13.334	9.39											
6383.644	130	90	1.725	23.9	50.6	100	13.1	2.098	10.49	24	2366	11.8	13.45	9.45											
6383.745	130	90	1.627	23.9	50.6	100	13.1	2.118	10.59	25.1	2247	11.5	13.254	9.06											
6383.838	131	95	1.667	23.9	50.6	100	13.1	2.059	10.29	25.1	2307	11.6	13.334	9.04											
6383.932	131	94	1.824	23.9	50.6	100	13.1	2.078	10.39	25.1	2364	11.6	13.648	9.35											
6384.025	131	94	1.961	23.9	50.6	100	13.1	2.118	10.59	25.1	2308	11.6	13.922	9.31											
6384.11	131	93	1.882	23.9	50.6	100	13.5	2.059	10.29	25.9	2313	11.8	13.764	9.06											
6384.21	131	93	1.961	23.9	50.6	100	13.4	2.078	10.39	25.7	2312	11.6	13.922	9.15											
6384.304	131	95	1.725	23.9	50.6	100	13.4	2.078	10.39	24.6	2255	11.8	13.45	8.92											
6384.389	131	96	1.686	23.9	50.6	100	13.4	2.118	10.59	25.7	2312	11.6	13.372	9.32											
6384.49	131	96	1.765	23.9	50.6	100	13.4	2.118	10.59	24.6	2252	11.6	13.53	9.08											
6384.569	131	95	1.725	23.9	50.6	100	13	2.078	10.39	24.9	2313	11.5	13.45	9.15											
6384.669	131	95	1.725	23.9	50.6	100	13	2.059	10.29	24.9	2314	11.8	13.45	9.07											
6384.744	131	93	1.765	23.9	50.6	100	13.1	2.137	10.69	25.1	2305	11.6	13.53	9.38											
6384.844	132	93	1.686	23.9	50.6	100	13.1	2.118	10.59	25.1	2306	11.8	13.372	9.30											
6384.93	132	96	1.824	23.9	50.6	100	13.6	2.059	10.29	26.1	2303	11.6	13.648	9.02											
6385.031	132	95	1.725	23.9	50.6	100	13.5	2.039	10.2	24.8	2247	11.6	13.45	8.73											
6385.132	132	95	1.608	23.9	50.6	100	13.6	2.059	10.29	26.1	2305	11.6	13.216	9.03											
6385.225	132	96	1.765	23.9	50.6	100	13.5	2.078	10.39	25.9	2310	11.6	13.53	9.14											
6385.329	132	96	1.627	23.9	50.6	100	13.5	2.078	10.39	25.9	2366	11.6	13.254	9.36											
6385.398	132	95	1.412	23.9	50.6	100	13.1	2.059	10.29	25.1	2304	11.6	12.824	9.03											
6385.499	132	95	1.588	23.9	50.6	100	13	2.059	10.29	23.8	2246	11.8	13.176	8.80											
6385.577	132	92	1.686	23.9	50.6	100	13	2.137	10.69	24.9	2304	11.5	13.372	9.38											
6385.677	132	93	1.824	23.9	50.6	100	13	2.118	10.59	24.9	2248	11.8	13.648	9.07											
6385.77	132	92	1.725	23.9	50.6	100	13.5	2.078	10.39	25.9	2307	11.6	13.45	9.13											
6385.872	133	95	1.686	23.9	50.6	100	13.5	2.098	10.49	24.8	2247	11.8	13.372	8.98											
6385.973	133	95	1.686	23.9	50.6	100	13.5	2.059	10.29	25.9	2305	11.6	13.372	9.03											
6386.055	133	96	1.627	23.9	50.6	100	13.5	2.118	10.59	25.9	2367	11.8	13.254	9.55											
6386.148	133	96	1.824	23.9	50.6	100	13.6	2.137	10.69	26.1	2307	11.5	13.648	9.39											
6386.241	133	90	1.804	23.9	50.6	100	13	2.118	10.59	23.8	2368	11.6	13.608	9.55											
6386.342	133	95	1.882	23.9	50.6	100	13	2.078	10.39	24.9	2310	11.8	13.764	9.14											
6386.443	133	95	1.627	23.9	50.6	100	13	2.078	10.39	24.9	2368	11.5	13.254	9.37											
6386.512	133	93	1.667	23.9	51.1	100	13.1	2.137	10.69	25.1	2307	11.6	13.334	9.39											
6386.621	133	93	1.745	23.9	51.1	100	13.1	2.137	10.69	24	2254	11.6	13.49	9.18											
6386.698	133	95	1.451	23.9	51.1	100	13.5	2.059	10.29	25.9	2305	11.8	12.902	9.03											
6386.798	133	94	1.569	23.9	51.1	100	13.6	2.059	10.29	26.1	2304	11.6	13.138	9.03											
6386.884	134	95	1.706	23.9	51.1	100	13.5	2.118	10.59	24.8	2250	11.6	13.412	9.07											
6386.986	134	95	1.627	23.9	51.1	100	13.6	2.118	10.59	26.1	2305	11.6	13.254	9.30											
6387.063	134	95	1.588	23.9	51.1	100	13.1	2.059	10.29	25.1	2366	11.8	13.176	9.27											
6387.156	134	94	1.529	23.9	51.1	100	13	2.235	11.18	24.9	2301	11.6	13.058	9.80											
6387.257	134	94	1.627	23.9	51.1	100	13	2.059	10.29	24.9	2302	11.6	13.254	9.02											
6387.342	134	93	1.745	23.9	51.1	100	13	2.118	10.59	24.9	2365	11.8	13.49	9.54											
6387.435	134	92	1.667	23.9	51.1	100	13.4	2.078	10.39	24.6	2365	11.8	13.334	9.36											

Table B-2: 2500 RPM Data

MS1/Extra format 029y3 *****															Standard Deviations								
Time	Secl	MAP	O2	MAT	CLT	Gve	PW	TPlus	Torque/2	DutyCycle1	RPM	batt V	AFR	HP		EG SPEED	TORQUE	HP	AFR	tqstd	hpstd	afrstd	
s		kPa	V	degC	%	ms	kPa	V	ft-lb	%		V	lbair/lbfuel	bhp		sample	RPM	ft-lb	bhp	ma:mf	ft-lb	bhp	ma:mf
7980.209	153	94	1.804	23.9	63.9	100	12.7	2.039	10.2	26.5	2505	11.6	13.608	9.73		s2500.2(1-20)	2487.48	19.09	9.04	13.59	0.8262	0.8311	0.1783
7980.329	153	95	1.882	23.9	63.9	100	12.7	1.706	8.53	25.4	2441	11.8	13.764	7.93		s2500.2(45-65)	2500.81	19.06	9.08	13.82	0.9087	0.9216	0.2424
7980.432	153	94	1.843	23.9	63.9	100	12.7	1.667	8.33	26.5	2508	11.6	13.686	7.96									
7980.533	153	95	1.706	23.9	63.9	100	12.7	1.667	8.33	26.5	2512	11.6	13.412	7.97									
7980.611	153	95	1.686	23.9	63.9	100	13.1	1.863	9.31	26.2	2445	11.5	13.372	8.67									
7980.704	153	95	1.804	23.9	63.9	100	13.1	2.059	10.29	26.2	2440	11.6	13.608	9.56									
7980.789	153	93	1.922	23.9	63.9	100	13	2.098	10.49	27.1	2509	11.5	13.844	10.02									
7980.89	153	96	1.804	23.9	63.9	100	12.9	2.039	10.2	26.9	2505	11.5	13.608	9.73									
7980.993	153	96	1.667	23.9	63.9	100	13	1.824	9.12	26	2497	11.5	13.334	8.67									
7981.085	153	96	1.725	23.9	63.9	100	12.9	2.059	10.29	26.9	2501	11.6	13.45	9.80									
7981.179	154	96	1.706	23.9	63.9	100	13	2.039	10.2	27.1	2573	11.6	13.412	9.99									
7981.272	154	94	1.824	23.9	63.9	100	13.1	2.118	10.59	26.2	2444	11.5	13.648	9.86									
7981.374	154	96	1.882	23.9	63.9	100	13	2	10	27.1	2504	11.6	13.764	9.54									
7981.474	154	95	1.902	23.9	63.9	100	13.1	1.804	9.02	26.2	2440	11.6	13.804	8.38									
7981.575	154	95	1.902	23.9	63.9	100	13	1.804	9.02	27.1	2569	11.6	13.804	8.82									
7981.642	154	89	1.804	23.9	63.9	100	13.1	2	10	27.3	2441	11.5	13.608	9.30									
7981.743	154	89	1.804	23.9	63.9	100	13.1	2.039	10.2	27.3	2569	11.8	13.608	9.98									
7981.817	154	95	1.667	23.9	63.9	100	13.1	1.647	8.24	26.2	2444	11.5	13.334	7.67									
7981.919	154	94	1.627	23.9	63.9	100	13.1	1.647	8.24	26.2	2442	11.6	13.254	7.66									
7981.996	154	94	1.804	23.9	63.9	100	13.2	1.98	9.9	27.5	2503	11.5	13.608	9.44									
7982.088	154	96	1.882	23.9	63.9	100	13.2	1.98	9.9	26.4	2445	11.6	13.764	9.22									
7982.174	155	90	1.843	23.9	63.9	100	13.2	1.98	9.9	27.5	2510	11.5	13.686	9.46									
7982.259	155	95	1.824	23.9	63.9	100	13.1	1.686	8.43	27.3	2573	11.6	13.648	8.26									
7982.36	155	95	1.882	23.9	63.9	100	13.2	1.843	9.22	26.4	2505	11.5	13.764	8.80									
7982.453	155	95	1.745	23.9	63.9	100	13	1.843	9.22	27.1	2500	11.6	13.49	8.78									
7982.531	155	95	1.627	23.9	63.9	100	13.1	1.725	8.63	26.2	2499	11.5	13.254	8.21									
7982.624	155	94	1.588	23.9	63.9	100	13	1.922	9.61	26	2495	11.5	13.176	9.13									
7982.724	155	95	1.549	23.9	63.9	100	13	1.686	8.43	27.1	2500	11.6	13.098	8.03									
7982.827	155	95	1.569	23.9	63.9	100	13	1.647	8.24	27.1	2504	11.6	13.138	7.86									
7982.913	155	93	1.588	23.9	63.9	100	12.9	1.725	8.63	25.8	2435	11.6	13.176	8.00									
7983.013	155	95	1.451	23.9	63.9	100	13	1.706	8.53	27.1	2500	11.6	12.902	8.12									
7983.115	155	95	1.588	23.9	63.9	100	12.9	1.627	8.14	25.8	2442	11.6	13.176	7.57									
7983.208	156	95	1.686	23.9	63.9	100	12.9	1.706	8.53	26.9	2507	11.6	13.372	8.14									
7983.301	156	94	1.588	23.9	63.9	100	12.7	1.627	8.14	26.5	2503	11.6	13.176	7.76									
7983.404	156	95	1.627	23.9	63.9	100	12.7	1.608	8.04	25.4	2499	11.6	13.254	7.65									
7983.504	156	95	1.706	23.9	63.9	100	12.7	1.608	8.04	25.4	2434	11.6	13.412	7.45									
7983.574	156	92	1.882	23.9	63.9	100	12.7	2.059	10.29	25.4	2440	11.6	13.764	9.56									
7983.668	156	92	2	23.9	63.9	100	12.7	2.039	10.2	26.5	2567	11.5	14	9.97									
7983.76	156	92	1.902	23.9	63.9	100	12.7	2.059	10.29	26.5	2500	11.6	13.804	9.80									
7983.845	156	94	1.843	23.9	63.9	100	12.7	1.824	9.12	25.4	2439	11.8	13.686	8.47									
7983.947	156	92	1.843	23.9	63.9	100	12.7	2.039	10.2	26.5	2502	11.8	13.686	9.72									
7984.037	156	94	1.824	23.9	63.9	100	12.7	1.863	9.31	25.4	2565	11.6	13.648	9.09									
7984.138	156	92	1.922	23.9	63.9	100	12.7	2.059	10.29	25.4	2570	11.8	13.844	10.07									
7984.232	157	93	2	23.9	63.9	100	12.7	1.922	9.61	26.5	2507	11.6	14	9.17									
7984.333	157	92	2.078	23.9	63.9	100	12.7	2.098	10.49	26.5	2500	11.6	14.156	9.99									
7984.425	157	93	2.176	23.9	63.9	100	12.7	2.118	10.59	25.4	2498	11.6	14.352	10.07									
7984.526	157	92	2.039	23.9	63.9	100	12.7	2.098	10.49	26.5	2567	11.6	14.078	10.25									
7984.629	157	92	1.843	23.9	63.9	100	12.8	2.059	10.29	26.7	2571	11.5	13.686	10.07									
7984.722	157	93	1.725	23.9	63.9	100	13	2.039	10.2	27.1	2503	11.5	13.45	9.72									
7984.823	157	93	1.784	23.9	63.9	100	12.7	2.039	10.2	26.5	2561	11.6	13.568	9.95									
7984.9	157	92	1.804	23.9	63.9	100	12.9	1.863	9.31	25.8	2494	11.5	13.608	8.84									
7985.001	157	92	1.725	23.9	63.9	100	13	1.902	9.51	26	2496	11.6	13.45	9.04									
7985.095	157	92	1.863	23.9	63.9	100	12.8	1.922	9.61	26.7	2433	11.5	13.726	8.90									
7985.189	158	92	2.039	23.9	63.9	100	12.7	1.922	9.61	26.5	2434	11.6	14.078	8.91									
7985.266	158	95	1.902	23.9	63.9	100	13	1.627	8.14	27.1	2567	11.5	13.804	7.96									
7985.369	158	95	1.941	23.9	63.9	100	12.9	1.608	8.04	25.8	2436	11.6	13.882	7.46									
7985.462	158	95	1.941	23.9	63.9	100	13	1.608	8.04	27.1	2566	11.5	13.882	7.86									
7985.53	158	92	1.902	23.9	63.9	100	13	2.098	10.49	27.1	2440	11.5	13.804	9.75									
7985.624	158	92	1.902	23.9	63.9	100	13	1.941	9.71	27.1	2501	11.5	13.804	9.25									
7985.698	158	95	1.863	23.9	63.9	100	12.9	1.706	8.53	25.8	2499	11.6	13.726	8.12									
7985.798	158	95	1.961	23.9	63.9	100	13.1	1.686	8.43	26.2	2440	11.5	13.922	7.83									
7985.891	158	96	1.961	23.9	63.9	100	13.1	1.667	8.33	26.2	2438	11.5	13.922	7.73									
7985.974	158	95	1.706	23.9	63.9	100	13	2.039	10.2	26	2496	11.5	13.412	9.70					</				

Table B-3: 2750 RPM Data

MS1/Extra format 029y3 *****																						Standard Deviations		
Time	SecL	MAP	O2	MAT	CLT	Gve	PW	Tplus	Torque/2	DutyCycle1	RPM	AFR	HP			EG SPEED	TORQUE	HP	AFR	tgstd	hpstd	afstddev		
s	kPa	V	degC	degC	%	ms	V	V	ft-lb	%		lbair/lbfuel	bhp		sample	RPM	ft-lb	bhp	ma:mf	ft-lb	bhp	ma:mf		
6470.373	19	95	1.627	23.9	62.8	100	13.1	1.902	9.51	29.5	2781	13.254	10.07		s1	2730.48	19.62	10.20	13.27	0.2894	0.3723	0.2093		
6470.465	20	94	1.431	23.9	62.8	100	13.2	1.863	9.31	29.7	2710	12.862	9.61		s2(50-70)	2698.95	19.71	10.13	13.32	0.2001	0.2474	0.2555		
6470.567	20	93	1.608	23.9	62.8	100	12.7	1.922	9.61	27.5	2646	13.216	9.68											
6470.668	20	96	1.686	23.9	62.8	100	12.9	2.02	10.1	29	2791	13.372	10.73											
6470.769	20	95	1.706	23.9	62.8	100	12.9	1.961	9.8	29	2720	13.412	10.15											
6470.862	20	95	1.608	23.9	62.8	100	12.7	1.922	9.61	28.6	2723	13.216	9.96											
6470.955	20	91	1.706	23.9	62.8	100	12.9	1.902	9.51	29	2712	13.412	9.82											
6471.056	20	95	1.667	23.9	62.8	100	13.1	1.941	9.71	29.5	2709	13.334	10.02											
6471.157	20	94	1.51	23.9	62.8	100	13	2.039	10.2	29.3	2716	13.02	10.55											
6471.257	20	96	1.686	23.9	62.8	100	13	1.902	9.51	28.2	2651	13.372	9.60											
6471.358	20	90	1.667	23.9	62.8	100	13.1	1.922	9.61	29.5	2794	13.334	10.22											
6471.459	21	94	1.824	23.9	62.8	100	13.2	2.02	10.1	29.7	2721	13.648	10.47											
6471.56	21	96	1.686	23.9	62.8	100	13.1	1.98	9.9	28.4	2651	13.372	9.99											
6471.662	21	94	1.843	23.9	62.8	100	13.2	1.922	9.61	29.7	2722	13.686	9.96											
6471.762	21	96	1.588	23.9	62.8	100	12.9	2.039	10.2	29	2720	13.176	10.57											
6471.863	21	96	1.667	23.9	62.8	100	12.9	2.039	10.2	29	2797	13.334	10.86											
6471.932	21	93	1.627	23.9	62.8	100	12.9	1.941	9.71	29	2788	13.254	10.31											
6472.026	21	93	1.647	23.9	62.8	100	12.9	2.02	10.1	29	2707	13.294	10.41											
6472.111	21	93	1.608	23.9	62.8	100	12.7	1.902	9.51	28.6	2780	13.216	10.07											
6472.206	21	93	1.51	23.9	62.8	100	12.9	2.02	10.1	29	2719	13.02	10.46											
6472.299	21	95	1.431	23.9	62.8	100	12.7	2.02	10.1	28.6	2782	12.862	10.70											
6472.383	22	93	1.706	23.9	62.8	100	12.9	2	10	29	2709	13.412	10.32											
6472.484	22	94	1.549	23.9	62.8	100	13	1.98	9.9	29.3	2709	13.098	10.21											
6472.585	22	95	1.529	23.9	62.8	100	13.1	1.941	9.71	29.5	2783	13.058	10.29											
6472.685	22	93	1.686	23.9	62.8	100	13	1.941	9.71	29.3	2710	13.372	10.02											
6472.771	22	93	1.784	23.9	62.8	100	12.9	1.941	9.71	29	2719	13.568	10.05											
6472.848	22	94	1.647	23.9	62.8	100	13.2	1.941	9.71	29.7	2784	13.294	10.29											
6472.934	22	95	1.588	23.9	62.8	100	13.1	1.922	9.61	29.5	2715	13.176	9.94											
6473.035	22	93	1.706	23.9	62.8	100	13.1	1.922	9.61	29.5	2718	13.412	9.95											
6473.112	22	96	1.667	23.9	62.8	100	13.1	1.961	9.8	29.5	2715	13.334	10.13											
6473.205	22	96	1.804	23.9	62.8	100	13.1	1.882	9.41	29.5	2721	13.608	9.75											
6473.291	22	96	1.843	23.9	62.8	100	13	1.902	9.51	28.2	2655	13.686	9.62											
6473.383	23	95	1.725	23.9	62.8	100	13.2	1.882	9.41	28.6	2790	13.45	10.00											
6473.484	23	93	1.843	23.9	62.8	100	12.9	2	10	29	2793	13.686	10.64											
6473.585	23	94	1.804	23.9	63.9	100	13	2.039	10.2	29.3	2717	13.608	10.55											
6473.693	23	92	1.725	23.9	63.9	100	13	1.922	9.61	29.3	2787	13.45	10.20											
6473.787	23	94	1.725	23.9	63.9	100	13	1.941	9.71	28.2	2713	13.45	10.03											
6473.877	23	93	1.706	23.9	63.9	100	13	1.941	9.71	29.3	2712	13.412	10.03											
6473.962	23	94	1.686	23.9	63.9	100	12.9	1.941	9.71	29	2710	13.372	10.02											
6474.047	23	95	1.686	23.9	63.9	100	13.2	1.863	9.31	28.6	2712	13.372	9.61											
6474.138	23	96	1.588	23.9	63.9	100	13.2	1.882	9.41	29.7	2709	13.176	9.71											
6474.239	23	92	1.627	23.9	63.9	100	12.7	1.98	9.9	28.6	2709	13.254	10.21											
6474.333	23	96	1.804	23.9	63.9	100	12.9	2	10	29	2714	13.608	10.34											
6474.433	24	94	1.529	23.9	63.9	100	13	1.961	9.8	29.3	2789	13.058	10.41											
6474.534	24	92	1.824	23.9	63.9	100	12.9	1.882	9.41	27.9	2712	13.648	9.72											
6474.636	24	97	1.451	23.9	63.9	100	13	2.02	10.1	29.3	2776	12.902	10.68											
6474.737	24	96	1.588	23.9	63.9	100	13	2.039	10.2	29.3	2783	13.176	10.81											
6474.83	24	96	1.549	23.9	63.9	100	12.9	2	10	27.9	2649	13.098	10.09											
6474.923	24	95	1.49	23.9	63.9	100	13.1	1.882	9.41	29.5	2788	12.98	9.99											
6475.024	24	89	1.784	23.9	63.9	100	13.2	1.922	9.61	29.7	2717	13.568	9.94											
6475.125	24	95	1.843	23.9	63.9	100	13.2	2.02	10.1	29.7	2712	13.686	10.43											
6475.219	24	96	1.451	23.9	63.9	100	13.1	2.02	10.1	28.4	2643	12.902	10.17											
6475.304	24	98	1.608	23.9	63.9	100	13.2	2.039	10.2	29.7	2712	13.216	10.53											
6475.406	25	96	1.608	23.9	63.9	100	13	1.941	9.71	29.3	2714	13.216	10.04											
6475.496	25	95	1.804	23.9	63.9	100	13.2	1.961	9.8	29.7	2718	13.608	10.14											
6475.596	25	90	1.745	23.9	63.9	100	13	1.941	9.71	29.3	2713	13.49	10.03											
6475.698	25	95	1.627	23.9	63.9	100	13.1	2	10	29.5	2708	13.254	10.31											
6475.798	25	96	1.647	23.9	63.9	100	13.2	2	10	29.7	2704	13.294	10.30											
6475.883	25	95	1.529	23.9	63.9	100	13.2	2	10	28.6	2641	13.058	10.06											
6475.969	25	96	1.863	23.9	63.9	100	13.2	2.02	10.1	29.7	2785	13.726	10.71											
6476.07	25	96	1.706	23.9	63.9	100	13.1	1.941	9.71	29.5	2786	13.412	10.30											
6476.163	25	96	1.706	23.9	63.9	100	13.2	1.961	9.8	29.7	2712	13.412	10.12											
6476.245	25	96	1.706	23.9	63.9	100	13.1	1.961	9.8	28.4	2646	13.412	9.87											
6476.312	25	94	1.824	23.9	63.9	100	13.1	1.941	9.71	29.5	2710	13.648	10.02											
6476.415	26	96	1.608	23.9	63.9	100	13.1	2	10	29.5	2702	13.216	10.29											
6476.507	26	96	1.706	23.9	63.9	100	13	1.941	9.71	28.2	2637	13.412	9.75											
6476.601	26	94	1.412	23.9	63.9	100	12.7	1.941	9.71	27.5	2636	12.824	9.75											
6476.686	26	94	1.647	23.9	63.9	100	12.7	1.961	9.8	27.5	2645	13.294	9.87											
6476.772	26	95	1.686	23.9	63.9	100	12.9	1.961	9.8	27.9	2699	13.372	10.07											
6476.857	26	94	1.608	23.9	63.9	100	13	2	10	29.3	2770	13.216	10.55											
6476.958	26	95	1.373	23.9	64.4	100	13.1	1.902	9.51	29.5	2773	12.746	10.04											
6477.068	26	92	1.																					

Table B-4: 3000 RPM Data

MS1/Extra format 029y3 *****														Standard Deviations											
Time	Secl	MAP	O2	MAT	CLT	Gve	PW	TPlus	Torque/2	DutyCycle1	RPM	batt V	AFR	HP			EG SPEED	TORQUE	HP	AFR	Standard Deviations				
s		kPa	V	degC	degC	%	ms	V	ft-lb	%		V	lbair/lbfuel	bhp			sample	RPM	ft-lb	bhp	ma:mf	ft-lb	hpcov	hpcov	afrcov
6511.416	61	93	1.314	23.9	71.7	100	14.5	1.686	8.43	36.3	3093	11.8	12.628	9.93			s2(500-520)	3091.48	17.24	10.15	12.51	0.1512	0.2519	0.2027	
6511.516	61	96	1.078	23.9	71.7	100	14.9	1.745	8.73	37.3	3092	11.8	12.156	10.28			s2(550-570)	3066.24	17.29	10.12	12.50	0.1479	0.1835	0.2016	
6511.618	61	91	1.275	23.9	71.7	100	14	1.765	8.82	36.2	3176	11.8	12.55	10.67											
6511.718	61	96	1.078	23.9	71.7	100	14.5	1.686	8.43	36.3	3017	11.8	12.156	9.69											
6511.82	61	94	1.392	23.9	71.7	100	14.9	1.745	8.73	38.5	3174	11.5	12.784	10.55											
6511.921	61	93	1.196	23.9	71.7	100	14.5	1.706	8.53	36.3	3083	11.8	12.392	10.01											
6512.024	61	96	1.118	23.9	71.7	100	14.9	1.725	8.63	37.3	3079	11.8	12.236	10.12											
6512.125	61	94	1.392	23.9	71.7	100	14.7	1.745	8.73	38	3153	11.8	12.784	10.48											
6512.225	61	96	1.333	23.9	71.7	100	14.2	1.686	8.43	35.5	3157	11.8	12.666	10.13											
6512.327	61	98	1.333	23.9	71.7	100	14.9	1.765	8.82	37.3	3086	11.8	12.666	10.37											
6512.417	62	94	1.235	23.9	71.7	100	14.7	1.686	8.43	36.8	3089	11.8	12.47	9.92											
6512.517	62	95	1.176	23.9	71.7	100	14.5	1.725	8.63	36.3	3091	11.8	12.352	10.16											
6512.618	62	90	1.294	23.9	71.7	100	15	1.686	8.43	37.5	3088	11.8	12.588	9.91											
6512.718	62	94	1.176	23.9	71.7	100	14.4	1.765	8.82	36	3082	11.6	12.352	10.35											
6512.819	62	95	1.353	23.9	71.7	100	14.9	1.706	8.53	37.3	3087	11.9	12.706	10.03											
6512.92	62	95	1.294	23.9	71.7	100	14.9	1.706	8.53	37.3	3080	11.8	12.588	10.00											
6512.99	62	94	1.392	23.9	71.7	100	14.4	1.765	8.82	36	3007	11.8	12.784	10.10											
6513.09	62	95	1.353	23.9	71.7	100	14.9	1.725	8.63	37.3	3093	11.8	12.706	10.16											
6513.191	62	96	1.157	23.9	71.7	100	15	1.706	8.53	37.5	3015	11.8	12.314	9.79											
6513.293	62	92	1.196	23.9	71.7	100	14.5	1.765	8.82	36.3	3090	11.8	12.392	10.38											
6513.393	63	92	1.255	23.9	71.7	100	14.7	1.706	8.53	36.8	3089	11.8	12.51	10.03											
6513.487	63	92	1.294	23.9	71.7	100	14.4	1.745	8.73	36	3015	11.6	12.588	10.02											
6513.58	63	95	1.098	23.9	71.7	100	14.5	1.725	8.63	37.5	3164	11.8	12.196	10.40											
6513.68	63	95	1.314	23.9	71.7	100	15	1.765	8.82	37.5	3079	11.8	12.628	10.34											
6513.774	63	94	1.039	23.9	71.7	100	14.5	1.725	8.63	36.3	3082	11.6	12.078	10.13											
6513.877	63	97	1.412	23.9	71.7	100	14.7	1.765	8.82	36.8	3013	11.8	12.824	10.12											
6513.977	63	88	1.373	23.9	71.7	100	15	1.706	8.53	37.5	3164	11.8	12.746	10.28											
6514.079	63	96	1.137	23.9	71.7	100	14.4	1.765	8.82	36	3084	11.8	12.274	10.36											
6514.18	63	94	1.275	23.9	71.7	100	14.7	1.706	8.53	36.8	3078	11.8	12.55	10.00											
6514.281	63	96	1.333	23.9	71.7	100	14.9	1.706	8.53	37.3	3083	11.6	12.666	10.01											
6514.366	63	95	1.275	23.9	71.7	100	14.2	1.686	8.43	35.5	3164	11.8	12.55	10.16											
6514.468	64	94	1.176	23.9	71.7	100	14.7	1.765	8.82	36.8	3079	11.8	12.352	10.34											
6514.57	64	95	1.471	23.9	71.7	100	14.9	1.745	8.73	37.3	3006	11.6	12.942	9.99											
6514.67	64	94	1.098	23.9	71.7	100	14.4	1.745	8.73	36	3080	11.8	12.196	10.24											
6514.755	64	93	1.196	23.9	71.7	100	14.9	1.686	8.43	37.3	3078	11.8	12.392	9.88											
6514.857	64	93	1.314	23.9	71.7	100	14.9	1.765	8.82	36	2992	11.8	12.628	10.05											
6514.95	64	95	1.176	23.9	72.2	100	14.2	1.667	8.33	35.5	3149	11.8	12.352	9.99											
6515.06	64	96	1.353	23.9	72.2	100	14.9	1.745	8.73	37.3	3079	11.8	12.706	10.24											
6515.161	64	95	1.235	23.9	72.2	100	14.9	1.765	8.82	37.3	3074	11.8	12.47	10.32											
6515.253	64	94	1.196	23.9	72.2	100	14.2	1.765	8.82	35.5	3076	11.8	12.392	10.33											
6515.339	64	95	1.216	23.9	72.2	100	14.5	1.686	8.43	37.5	3002	11.8	12.432	9.64											
6515.44	65	94	1.392	23.9	72.2	100	15	1.882	9.41	37.5	3083	11.8	12.784	11.05											
6515.541	65	91	1.137	23.9	72.2	100	14.2	1.706	8.53	36.7	3162	11.8	12.274	10.27											
6515.643	65	96	1.176	23.9	72.2	100	14.7	1.725	8.63	36.8	3009	11.8	12.352	9.89											
6515.744	65	94	1.275	23.9	72.2	100	14.7	1.745	8.73	36.8	3088	11.8	12.55	10.27											
6515.836	65	94	1.059	23.9	72.2	100	14.2	1.745	8.73	36.7	3167	11.8	12.118	10.53											
6515.915	65	96	1.098	23.9	72.2	100	14.7	1.725	8.63	38	3156	11.8	12.196	10.37											
6516.015	65	95	1.314	23.9	72.2	100	14.9	1.725	8.63	37.3	3077	11.6	12.628	10.11											
6516.1	65	95	1.294	23.9	72.2	100	14.4	1.765	8.82	34.8	2994	11.8	12.588	10.06											
6516.195	65	96	1.255	23.9	72.2	100	14.5	1.706	8.53	35	3161	11.8	12.51	10.27											
6516.295	65	95	1.255	23.9	72.2	100	15	1.765	8.82	37.5	3003	11.8	12.51	10.09											
6516.385	65	94	1.039	23.9	72.2	100	14.4	1.686	8.43	36	3158	11.6	12.078	10.14											
6516.487	66	97	1.431	23.9	72.2	100	14.7	1.765	8.82	36.8	3072	11.8	12.862	10.32											
6516.587	66	90	1.176	23.9	72.2	100	15	1.706	8.53	37.5	3066	11.6	12.352	9.96											
6516.689	66	93	1.275	23.9	72.2	100	14.4	1.784	8.92	36	3072	11.8	12.55	10.43											
6516.79	66	94	1.392	23.9	72.2	100	14.7	1.706	8.53	35.5	2995	11.8	12.784	9.73											
6516.892	66	96	1.098	23.9	72.2	100	14.9	1.725	8.63	37.3	3069	11.8	12.196	10.09											
6516.993	66	94	1.333	23.9	72.2	100	14.7	1.725	8.63	36.8	3071	11.8	12.666	10.09											
6517.079	66	95	1.235	23.9	72.2	100	14.4	1.765	8.82	36	3069	11.6	12.47	10.31											
6517.179	66	95	1.373	23.9	72.2	100	14.9	1.706	8.53	37.3	3078	11.8	12.746	10.00											
6517.272	66	93	1.255	23.9	72.2	100	14.9	1.765	8.82	37.3	3077	11.6	12.51	10.33											
6517.365	66	95	1.353	23.9	72.2	100	14.4	1.706	8.53	36	3157	11.8	12.706	10.25											
6517.467	67	95	1.137	23.9																					

Table B-5: 3250 RPM Data

MS1/Extra format 029y3 *****														Standard Deviations										
Time	SecL	MAP	O2	MAT	CLT	Gve	PW	TPlus	Torque/2	DutyCycle1	RPM	batt V	AFR	HP			EG SPEED	TORQUE	HP	AFR	tqstd	hpstd	afrstd	
s		kPa	V	degC	degC	%	ms	V	ft-lb	%		V	lbair/lbfuel	bhp			sample	RPM	ft-lb	bhp	ma:mf	ft-lb	bhp	ma:mf
95578.86	129	95	0.627	24.4	93.3	100	19.9	1.392	6.96	53.1	3246	10.6	11.254	8.60			s1	3275.19	14.40	8.98	11.50	0.1458	0.1956	0.1169
95578.98	129	94	0.706	24.4	93.3	100	20.3	1.431	7.16	54.1	3255	10.7	11.412	8.88			s2(50-70)	3270.38	14.27	8.88	11.49	0.1949	0.2383	0.1192
95579.08	129	90	0.765	24.4	93.3	100	19.9	1.392	6.96	53.1	3277	10.7	11.53	8.69										
95579.18	129	95	0.745	24.4	93.3	100	20.5	1.471	7.35	56.4	3309	10.6	11.49	9.26							Coefficients of Variance			
95579.28	129	93	0.804	24.4	93.3	100	20.3	1.49	7.45	54.1	3281	10.7	11.608	9.31							tqcov	hpcov	afrcov	
95579.39	129	90	0.804	24.4	93.3	100	19.2	1.451	7.25	51.2	3267	10.6	11.608	9.02							ft-lb	bhp	ma:mf	
95579.48	129	94	0.765	24.4	93.3	100	19.8	1.431	7.16	52.8	3279	10.7	11.53	8.94							0.0101	0.0218	0.0102	
95579.58	129	94	0.765	24.4	93.3	100	19.6	1.451	7.25	52.3	3271	10.6	11.53	9.03							0.0137	0.0268	0.0104	
95579.66	129	93	0.784	24.4	93.3	100	19.2	1.451	7.25	51.2	3234	10.7	11.568	8.93										
95579.75	129	93	0.765	24.4	93.3	100	19.9	1.412	7.06	53.1	3287	10.7	11.53	8.84							COV expressed as percent			
95579.84	130	95	0.765	24.4	93.3	100	19.6	1.412	7.06	52.3	3324	10.7	11.53	8.94							tq %	hp %	afr %	
95579.92	130	93	0.784	24.4	93.3	100	19.3	1.431	7.16	51.5	3273	10.7	11.568	8.92							1.01	2.18	1.02	
95580.02	130	94	0.745	24.4	93.3	100	20.3	1.471	7.35	54.1	3235	10.7	11.49	9.05							1.37	2.68	1.04	
95580.12	130	94	0.765	24.4	93.3	100	20.6	1.471	7.35	54.9	3284	10.6	11.53	9.19										
95580.2	130	97	0.824	24.4	93.3	100	20.3	1.471	7.35	54.1	3278	10.7	11.648	9.17										
95580.29	130	95	0.627	24.4	93.3	100	20.3	1.431	7.16	54.1	3298	10.7	11.254	8.99										
95580.38	130	93	0.745	24.4	93.3	100	20.3	1.451	7.25	54.1	3285	10.6	11.49	9.07										
95580.47	130	94	0.706	24.4	93.3	100	19.2	1.412	7.06	51.2	3265	10.7	11.412	8.78										
95580.57	130	94	0.784	24.4	93.3	100	19.8	1.451	7.25	52.8	3281	10.6	11.568	9.06										
95580.67	130	93	0.804	24.4	93.3	100	19.6	1.471	7.35	52.3	3288	10.7	11.608	9.20										
95580.77	130	92	0.627	24.4	93.3	100	20.3	1.392	6.96	54.1	3262	10.6	11.254	8.65										
95580.87	131	95	0.765	24.4	93.3	100	20.3	1.431	7.16	54.1	3271	10.8	11.53	8.92										
95580.96	131	95	0.706	24.4	93.3	100	20.5	1.471	7.35	56.4	3313	10.5	11.412	9.27										
95581.06	131	88	0.686	24.4	93.3	100	19.9	1.412	7.06	53.1	3274	10.6	11.372	8.80										
95581.16	131	95	0.784	24.4	93.3	100	20.5	1.451	7.25	54.7	3269	10.6	11.568	9.03										
95581.26	131	94	0.784	24.4	93.3	100	19.1	1.471	7.35	50.9	3272	10.6	11.568	9.16										
95581.35	131	94	0.745	24.4	93.3	100	19.6	1.412	7.06	52.3	3275	10.7	11.49	8.80										
95581.45	131	94	0.804	24.4	93.3	100	19.4	1.471	7.35	51.7	3284	10.6	11.608	9.19										
95581.54	131	94	0.804	24.4	93.3	100	20.3	1.431	7.16	55.8	3332	10.8	11.608	9.08										
95581.62	131	95	0.784	24.4	93.3	100	19.8	1.471	7.35	52.8	3281	10.7	11.568	9.18										
95581.72	131	95	0.745	24.4	93.3	100	20.5	1.451	7.25	54.7	3280	10.8	11.49	9.06										
95581.82	132	94	0.725	24.4	93.3	100	20.3	1.471	7.35	54.1	3287	10.6	11.45	9.20										
95581.92	132	93	0.804	24.4	93.3	100	20.3	1.51	7.55	54.1	3281	10.7	11.608	9.43										
95582.01	132	94	0.765	24.4	93.3	100	19.5	1.471	7.35	53.6	3341	10.6	11.53	9.35										
95582.11	132	93	0.784	24.4	93.3	100	19.1	1.471	7.35	52.5	3253	10.7	11.568	9.10										
95582.2	132	94	0.725	24.4	93.3	100	20.3	1.431	7.16	54.1	3278	10.7	11.45	8.94										
95582.3	132	94	0.706	24.4	93.3	100	19.6	1.412	7.06	52.3	3276	10.7	11.412	8.81										
95582.39	132	97	0.725	24.4	93.3	100	20.3	1.471	7.35	54.1	3264	10.7	11.45	9.14										
95582.49	132	96	0.824	24.4	93.3	100	20.6	1.471	7.35	54.9	3270	10.7	11.648	9.15										
95582.58	132	97	0.725	24.4	93.3	100	20.3	1.451	7.25	54.1	3257	10.8	11.45	8.99										
95582.68	132	96	0.725	24.4	93.3	100	20.6	1.431	7.16	54.9	3240	10.7	11.45	8.83										
95582.77	132	95	0.765	24.4	93.3	100	20.3	1.412	7.06	54.1	3233	10.7	11.53	8.69										
95582.87	133	97	0.725	24.4	93.3	100	20.3	1.451	7.25	54.1	3248	10.6	11.45	8.97										
95582.97	133	91	0.745	24.4	93.3	100	20.6	1.392	6.96	54.9	3259	10.7	11.49	8.64										
95583.07	133	96	0.725	24.4	93.3	100	20.3	1.412	7.06	54.1	3261	10.6	11.45	8.77										
95583.17	133	94	0.784	24.4	95	100	20.6	1.451	7.25	54.9	3269	10.6	11.568	9.03										
95583.28	133	92	0.784	24.4	95	100	19.9	1.431	7.16	53.1	3247	10.7	11.568	8.85										
95583.37	133	94	0.745	24.4	95	100	20.6	1.412	7.06	54.9	3246	10.6	11.49	8.73										
95583.47	133	95	0.784	24.4	95	100	20.3	1.471	7.35	54.1	3264	10.6	11.568	9.14										
95583.57	133	94	0.804	24.4	95	100	19.1	1.49	7.45	50.9	3264	10.5	11.608	9.26										
95583.67	133	91	0.765	24.4	95	100	19.6	1.431	7.16	52.3	3266	10.7	11.53	8.91										
95583.77	133	93	0.667	24.4	95	100	19.2	1.392	6.96	51.2	3263	10.6	11.334	8.65										
95583.88	134	96	0.765	24.4	95	100	19.9	1.431	7.16	53.1	3278	10.7	11.53	8.94										
95583.98	134	96	0.765	24.4	95	100	20.5	1.451	7.25	54.7	3285	10.7	11.53	9.07										
95584.07	134	96	0.765	24.4	95	100	20.3	1.412	7.06	54.1	3295	10.5	11.53	8.86										
95584.15	134	94	0.667	24.4	95	100	20.3	1.431	7.16	54.1	3275	10.7	11.334	8.93										
95584.25	134	94	0.765	24.4	95	100	20.5	1.392	6.96	54.7	3264	10.5	11.53	8.65										
95584.34	134	93	0.804	24.4	95	100	19.9	1.451	7.25	53.1	3259	10.7	11.608	9.00										
95584.44	134	90	0.745	24.4	95	100	19.5	1.392	6.96	53.6	3331	10.5	11.49	8.83										
95584.54	134	95	0.627	24.4	95	100	19.1	1.392	6.96	50.9	3292	10.6	11.254	8.73										
95584.63	134	92	0.863	24.4	95	100	19.8	1.431	7.16	52.8	3286	10.7	11.726	8.96										
95584.73	134	91	0.627	24.4	95	100	20.5	1.392	6.96	54.7	3278	10.7	11.254	8.69										
95584.83	135	95	0.725	24.4	95	100	20.3	1.412	7.06	54.1	3266	10.6	11.45	8.78										
95584.93	135	94	0.706	24.4	95	100	20.6	1.451	7.25	54.9	3259	10.6	11.412	9.00										
95585.03	135	93	0.804																					

Table B-6: 3500 RPM Data

MS1/Extra format 029y3 *****															Standard Deviations								
Time	SecL	MAP	O2	MAT	CLT	Gve	PW	TPlus	Torque/2	DutyCycle1	RPM	batt V	AFR	HP			EG SPEED	TORQUE	HP	AFR	tqstd	hpstd	afstddev
s		kPa	V	degC	degC	%	ms	V	ft-lb	%		V	lbair/lbfuel	bhp		sample	RPM	ft-lb	bhp	ma:mf	ft-lb	bhp	ma:mf
94706.85	105	93	1.549	24.4	55.6	72	14.1	1.941	9.71	40	3490	10.7	13.098	12.90		s1	3486.43	19.34	12.84	13.28	0.1748	0.2519	0.2337
94706.97	106	95	1.784	24.4	55.6	72	14.5	1.941	9.71	41.1	3490	10.8	13.568	12.90		s2(50-70)	3482.33	19.06	12.64	13.22	0.1582	0.2530	0.2031
94707.05	106	87	1.745	24.4	55.6	71	13	1.961	9.8	36.8	3488	10.6	13.49	13.02									
94707.15	106	87	1.627	24.4	55.6	71	13	1.863	9.31	36.8	3440	10.8	13.254	12.20									
94707.24	106	92	1.627	24.4	55.6	72	13.7	1.941	9.71	38.8	3488	10.6	13.254	12.90									
94707.33	106	94	1.549	24.4	55.6	72	14.4	1.922	9.61	40.8	3486	10.8	13.098	12.76									
94707.43	106	93	1.549	24.4	55.6	72	14.1	1.922	9.61	40	3487	10.7	13.098	12.76									
94707.51	106	89	1.608	24.4	55.6	71	13	2.039	10.2	36.8	3487	10.7	13.216	13.54									
94707.61	106	88	1.784	24.4	55.6	71	13	1.922	9.61	36.8	3490	10.7	13.568	12.77									
94707.7	106	90	1.706	24.4	55.6	70	13.5	1.922	9.61	38.3	3489	10.6	13.412	12.90									
94707.79	106	95	1.745	24.4	55.6	72	14.4	1.941	9.71	40.8	3488	10.7	13.49	12.90									
94707.89	106	92	1.725	24.4	56.1	72	14.4	1.961	9.8	40.8	3489	10.8	13.45	13.02									
94707.99	107	92	1.49	24.4	56.1	72	13	1.941	9.71	36.8	3488	10.8	12.98	12.90									
94708.09	107	90	1.647	24.4	56.1	71	13	1.941	9.71	36.8	3493	10.7	13.294	12.92									
94708.17	107	92	1.529	24.4	56.1	72	13.7	1.961	9.8	38.8	3488	10.7	13.058	13.02									
94708.27	107	97	1.784	24.4	56.1	73	14.4	1.941	9.71	40.8	3490	10.6	13.568	12.90									
94708.37	107	95	1.843	24.4	56.1	72	14.4	1.941	9.71	40.8	3487	10.8	13.686	12.89									
94708.45	107	93	1.392	24.4	56.1	69	13	1.902	9.51	36.8	3484	10.7	12.784	12.62									
94708.55	107	93	1.549	24.4	56.1	69	13	1.882	9.41	36.8	3488	10.9	13.098	12.50									
94708.64	107	90	1.569	24.4	56.1	72	13.5	1.902	9.51	38.3	3490	10.7	13.138	12.64									
94708.74	107	91	1.627	24.4	56.1	72	13.7	1.922	9.61	38.8	3495	10.8	13.254	12.79									
94708.84	107	94	1.627	24.4	56.1	73	14.1	1.882	9.41	40	3492	10.7	13.254	12.51									
94708.93	107	94	1.333	24.4	56.1	71	13	1.922	9.61	36.8	3484	10.8	12.666	12.75									
94709.02	108	90	1.569	24.4	56.1	71	13	1.941	9.71	37.9	3532	10.8	13.138	13.06									
94709.12	108	89	1.706	24.4	56.1	71	13	1.902	9.51	36.8	3476	10.8	13.412	12.59									
94709.22	108	88	1.706	24.4	56.1	71	13	1.902	9.51	36.8	3429	10.8	13.412	12.42									
94709.29	108	94	1.608	24.4	56.1	72	14.4	1.882	9.41	40.8	3478	10.6	13.216	12.46									
94709.39	108	94	1.647	24.4	56.1	73	14.4	1.922	9.61	40.8	3480	10.8	13.294	12.74									
94709.48	108	93	1.667	24.4	56.1	70	13	1.902	9.51	36.8	3479	10.7	13.334	12.60									
94709.58	108	94	1.451	24.4	56.1	69	13	1.961	9.8	36.8	3481	10.8	12.902	12.99									
94709.67	108	88	1.686	24.4	56.1	71	13	1.902	9.51	36.8	3477	10.8	13.372	12.59									
94709.77	108	96	1.784	24.4	56.1	70	13.5	1.882	9.41	38.3	3485	10.8	13.568	12.49									
94709.87	108	95	1.765	24.4	56.1	72	13.7	1.882	9.41	38.8	3488	10.6	13.53	12.50									
94709.95	109	92	1.686	24.4	56.1	72	14.4	1.961	9.8	40.8	3489	10.8	13.372	13.02									
94710.05	109	92	1.686	24.4	56.1	72	13	1.922	9.61	36.8	3487	10.6	13.372	12.76									
94710.14	109	95	1.647	24.4	56.1	69	13.7	1.882	9.41	38.8	3487	10.6	13.294	12.50									
94710.24	109	93	1.725	24.4	56.1	69	13.5	1.941	9.71	38.3	3490	10.6	13.45	12.90									
94710.34	109	94	1.549	24.4	56.1	69	14.4	1.961	9.8	40.8	3483	10.7	13.098	13.00									
94710.44	109	96	1.392	24.4	56.1	72	14.4	1.941	9.71	40.8	3488	10.7	12.784	12.90									
94710.53	109	94	1.49	24.4	56.7	72	14.4	1.902	9.51	40.8	3443	10.7	12.98	12.47									
94710.63	109	93	1.588	24.4	56.7	71	13	1.922	9.61	36.8	3441	10.7	13.176	12.59									
94710.73	109	87	1.529	24.4	56.7	71	13	1.902	9.51	36.8	3431	10.7	13.058	12.43									
94710.83	109	96	1.529	24.4	56.7	70	13.7	1.882	9.41	38.8	3484	10.7	13.058	12.48									
94710.92	109	95	1.667	24.4	56.7	72	14	1.922	9.61	39.7	3482	10.7	13.334	12.74									
94711.02	110	97	1.706	24.4	56.7	73	14.4	1.941	9.71	40.8	3484	10.6	13.412	12.88									
94711.12	110	95	1.667	24.4	56.7	72	14.4	1.941	9.71	40.8	3487	10.7	13.334	12.89									
94711.2	110	94	1.765	24.4	56.7	69	13	1.961	9.8	36.8	3493	10.7	13.53	13.04									
94711.3	110	93	1.51	24.4	56.7	69	13.2	1.961	9.8	37.4	3490	10.7	13.02	13.02									
94711.38	110	91	1.588	24.4	56.7	72	13.7	1.941	9.71	38.8	3442	10.6	13.176	12.73									
94711.48	110	94	1.706	24.4	56.7	72	14	1.882	9.41	39.7	3535	10.8	13.412	12.67									
94711.59	110	94	1.627	24.4	56.7	72	14.4	1.882	9.41	40.8	3482	10.7	13.254	12.48									
94711.66	110	91	1.804	24.4	56.7	70	13	1.922	9.61	36.8	3476	10.8	13.608	12.72									
94711.77	110	87	1.627	24.4	56.7	71	13	1.863	9.31	36.8	3475	10.7	13.254	12.32									
94711.86	110	95	1.49	24.4	56.7	69	13.7	1.863	9.31	38.8	3474	10.7	12.98	12.32									
94711.94	110	94	1.667	24.4	56.7	71	14	1.922	9.61	39.7	3477	10.8	13.334	12.72									
94712.05	111	94	1.608	24.4	56.7	72	14.4	1.902	9.51	42	3526	10.8	13.216	12.77									
94712.14	111	92	1.431	24.4	56.7	73	14.4	1.882	9.41	40.8	3480	10.6	12.862	12.47									
94712.24	111	90	1.627	24.4	56.7	72	14.4	1.843	9.22	40.8	3431	10.7	13.254	12.05									
94712.33	111	94	1.431	24.4	56.7	69	13	1.941	9.71	36.8	3484	10.7	12.862	12.88									
94712.44	111	93	1.529	24.4	56.7	69	13.1	1.941	9.71	38.2	3535	10.7	13.058	13.07									
94712.52	111	91	1.627	24.4	56.7	71	13.7	1.882	9.41	38.8	3483	10.7	13.254	12.48									
94712.62	111	94	1.569	24.4	56.7	72	13.7	1.882	9.41	38.8	3429	10.7	13.138	12.29									
94712.7	111	94	1.569	24.4	56.7	71	14.4	1.922	9.61	40.8	3476	10.7	13.138	12.72									
94712.78	111	92	1.686	24.4	56.7	69	13	1.902	9.51	36.8	3480	10.8	13.372	12.60									
94712.89	111	94	1.51	24.4	56.7	69	13.5	1.922	9.61	38.3	3476	10.7	13.02	12.72									

Table B-7: AFR Data

Note that this data includes only variables that were pertinent to the testing being performed. In this case the testing included transients, so no errors were computed.

MAP	O2	TPlus	Torque/2	EG SPEED	AFR	Power	Averaged Data						
kPa	V	V	ft-lbs	RPM	ma:mf	bhp	AFR RANGE	AVG AFR	STDEVAFR	COVAFR	AVGHP	STDEVHP	COVHP
95	2.824	2.02	10.1	2787	15.648	10.72	ma:mf	ma:mf	ma:mf	ma:mf	bhp	bhp	bhp
95	2.686	2.02	10.1	2798	15.372	10.76	10	10.12	0.00	0.0000	6.75	0.15	0.0217
94	3.137	1.961	9.8	2827	16.274	10.55	11	11.88	0.21	0.0178	10.07	0.31	0.0305
91	2.647	2.078	10.39	2809	15.294	11.11	12	12.81	0.35	0.0272	11.81	0.30	0.0257
95	2.882	1.98	9.9	2847	15.764	10.73	13	13.21	0.24	0.0184	12.01	0.33	0.0274
95	2.647	2.098	10.49	2857	15.294	11.41	14	14.50	0.15	0.0104	11.91	0.38	0.0321
93	2.275	2.118	10.59	2926	14.55	11.80	15	15.32	0.32	0.0208	11.38	0.39	0.0344
94	2.647	1.98	9.9	2891	15.294	10.90							
94	2.353	2.137	10.69	2938	14.706	11.96							
95	2.804	2.039	10.2	2887	15.608	11.21							
91	2.824	2.098	10.49	2872	15.648	11.47							
91	2.706	2.059	10.29	2873	15.412	11.26							
95	2.745	2.02	10.1	2885	15.49	11.10							
91	2.725	2.059	10.29	2838	15.45	11.12							
95	2.608	2.059	10.29	2843	15.216	11.14							
96	2.255	2.078	10.39	2850	14.51	11.28							
94	2.431	2.137	10.69	2866	14.862	11.67							
94	2.647	2.294	11.47	2901	15.294	12.67							
95	2.863	2.059	10.29	2879	15.726	11.28							
97	2.608	2.078	10.39	2835	15.216	11.22							
95	2.549	2.059	10.29	2855	15.098	11.19							
95	2.765	2.039	10.2	2884	15.53	11.20							
94	2.627	2.039	10.2	2889	15.254	11.22							
94	2.824	2.078	10.39	2859	15.648	11.31							
94	2.588	2.157	10.78	2863	15.176	11.75							
93	3.059	2.039	10.2	2858	16.118	11.10							
95	2.784	2	10	2792	15.568	10.63							
96	2.647	2.039	10.2	2784	15.294	10.81							
93	2.392	2.176	10.88	2904	14.784	12.03							
93	2.314	2.176	10.88	2938	14.628	12.17							
95	2.216	2.157	10.78	2990	14.432	12.27							
95	2.118	2.157	10.78	2952	14.236	12.12							
92	2.137	2.196	10.98	2951	14.274	12.34							
88	2.353	2.176	10.88	2911	14.706	12.06							
95	2.294	2.098	10.49	2955	14.588	11.80							
93	2.314	2.118	10.59	2921	14.628	11.78							
93	2.196	2.216	11.08	3015	14.392	12.72							
94	2.235	2.157	10.78	3003	14.47	12.33							
89	2.255	2.118	10.59	2926	14.51	11.80							
95	2.235	2.078	10.39	2961	14.47	11.72							
94	2.294	2.235	11.18	2971	14.588	12.65							
95	2.137	2.078	10.39	2968	14.274	11.74							
94	2.255	2.196	10.98	2983	14.51	12.47							
96	1.941	2.157	10.78	2941	13.882	12.07							
95	2.078	2.078	10.39	3029	14.156	11.98							
96	2.118	2.216	11.08	2980	14.236	12.57							
96	2.235	2.059	10.29	2982	14.47	11.68							
95	2.275	2.078	10.39	2924	14.55	11.57							
95	2.255	2.137	10.69	2966	14.51	12.07							
95	2.353	2.078	10.39	2969	14.706	11.75							
94	2.176	2.02	10.1	3012	14.352	11.58							
93	2.176	2.157	10.78	2967	14.352	12.18							
94	2.275	2.039	10.2	3012	14.55	11.70							
97	2.412	2.176	10.88	2926	14.824	12.12							
95	2.216	2.039	10.2	2966	14.432	11.52							
95	2.314	2.059	10.29	3012	14.628	11.80							
91	2.235	2.216	11.08	2962	14.47	12.50							
95	2.294	2.02	10.1	2983	14.588	11.47							
93	2.157	2.176	10.88	2988	14.314	12.38							
96	2.235	2.059	10.29	2909	14.47	11.40							
93	2.294	2.176	10.88	2945	14.588	12.20							
91	2.137	2.137	10.69	3032	14.274	12.34							
94	2	2.059	10.29	2985	14	11.70							
94	1.863	2.157	10.78	2984	13.726	12.25							
94	1.902	2.078	10.39	3034	13.804	12.00							
94	1.922	2.098	10.49	2990	13.844	11.94							
92	2.059	2.196	10.98	2994	14.118	12.52							
94	1.765	2.039	10.2	2990	13.53	11.61							

92	1.745	2.176	10.88	2996	13.49	12.41								
94	1.647	2	10	2996	13.294	11.41								
88	1.843	2.118	10.59	2999	13.686	12.09								
92	1.824	2.157	10.78	2992	13.648	12.28								
94	1.98	2.02	10.1	2990	13.96	11.50								
94	2.157	2.176	10.88	2993	14.314	12.40								
95	1.902	2.059	10.29	2998	13.804	11.75								
94	1.941	2.02	10.1	2994	13.882	11.52								
94	1.804	2.176	10.88	2992	13.608	12.40								
93	1.882	2.176	10.88	2990	13.764	12.39								
94	1.882	2.196	10.98	2955	13.764	12.36								
93	1.863	2.216	11.08	2995	13.726	12.64								
94	1.804	2.02	10.1	2950	13.608	11.35								
93	1.882	2.176	10.88	2993	13.764	12.40								
88	1.824	2.078	10.39	2991	13.648	11.83								
95	1.784	2.098	10.49	3043	13.568	12.16								
94	1.961	2.196	10.98	3000	13.922	12.54								
93	1.843	2.216	11.08	3046	13.686	12.85								
94	1.843	2	10	2990	13.686	11.39								
94	1.745	2.039	10.2	2994	13.49	11.63								
94	1.882	2.176	10.88	2993	13.764	12.40								
95	1.745	2.118	10.59	2989	13.49	12.05								
88	1.686	2.078	10.39	2989	13.372	11.83								
94	1.745	2.02	10.1	2953	13.49	11.36								
93	1.804	2.196	10.98	2988	13.608	12.49								
95	1.706	2.118	10.59	2993	13.412	12.07								
88	1.745	2.137	10.69	3038	13.49	12.37								
95	1.784	2.098	10.49	3041	13.568	12.15								
95	1.961	2.216	11.08	3001	13.922	12.66								
94	1.588	2.02	10.1	2957	13.176	11.37								
93	1.902	2.196	10.98	3001	13.804	12.55								
88	1.784	2.098	10.49	3001	13.568	11.99								
93	1.98	2.196	10.98	2996	13.96	12.53								
89	1.804	2.078	10.39	2992	13.608	11.84								
96	1.98	2.216	11.08	3030	13.96	12.78								
95	1.784	2.02	10.1	2941	13.568	11.31								
94	1.843	2.157	10.78	2985	13.686	12.25								
95	1.667	2.078	10.39	2949	13.334	11.67								
88	1.51	2.098	10.49	3020	13.02	12.06								
94	1.549	2.02	10.1	2941	13.098	11.31								
97	1.706	2.157	10.78	2943	13.412	12.08								
92	1.51	2.059	10.29	3026	13.02	11.86								
97	1.569	2.196	10.98	3027	13.138	12.66								
93	1.412	2.078	10.39	2980	12.824	11.79								
95	1.431	2.118	10.59	2940	12.862	11.86								
96	1.549	2.02	10.1	2934	13.098	11.28								
92	1.706	2.137	10.69	3024	13.412	12.31								
94	1.51	2.078	10.39	2970	13.02	11.75								
92	1.627	2.137	10.69	2928	13.254	11.92								
94	1.471	2.039	10.2	3013	12.942	11.70								
93	1.725	2.196	10.98	2972	13.45	12.43								
94	1.608	2.039	10.2	2936	13.216	11.40								
97	1.686	2.235	11.18	2976	13.372	12.67								
92	1.686	2.078	10.39	2980	13.372	11.79								
93	1.588	2.078	10.39	2979	13.176	11.79								
93	1.627	2.157	10.78	3016	13.254	12.38								
96	1.608	2.098	10.49	2972	13.216	11.87								
91	1.667	2.137	10.69	2930	13.334	11.93								
94	1.627	2.078	10.39	2980	13.254	11.79								
95	1.725	2.137	10.69	2977	13.45	12.12								
92	1.725	2.137	10.69	2975	13.45	12.11								
94	1.765	2.216	11.08	2938	13.53	12.40								
94	1.471	2.02	10.1	2976	12.942	11.45								
94	1.51	2.196	10.98	2934	13.02	12.27								
95	1.353	2.118	10.59	2941	12.706	11.86								
91	1.608	2.098	10.49	3024	13.216	12.08								
94	1.549	2.137	10.69	3016	13.098	12.28								
95	1.51	2.078	10.39	2976	13.02	11.77								
96	1.784	2.216	11.08	2939	13.568	12.40								
94	1.471	2.039	10.2	3005	12.942	11.67								

91	1.706	2.176	10.88	3010	13.412	12.47								
95	1.588	2.02	10.1	2969	13.176	11.42								
94	1.627	2.157	10.78	2966	13.254	12.18								
89	1.647	2.059	10.29	2964	13.294	11.61								
97	1.608	2.176	10.88	3002	13.216	12.44								
95	1.51	2.039	10.2	2928	13.02	11.37								
96	1.667	2.078	10.39	2972	13.334	11.76								
91	1.51	2.118	10.59	2957	13.02	11.92								
94	1.647	2.078	10.39	3005	13.294	11.89								
93	1.706	2.176	10.88	2971	13.412	12.31								
94	1.549	2.02	10.1	3014	13.098	11.59								
94	1.706	2.157	10.78	2926	13.412	12.01								
96	1.569	2.118	10.59	3018	13.138	12.17								
94	1.627	2.176	10.88	2972	13.254	12.31								
95	1.471	2.039	10.2	2970	12.942	11.54								
92	1.784	2.235	11.18	2966	13.568	12.63								
95	1.706	2.039	10.2	2932	13.412	11.39								
91	1.706	2.176	10.88	2973	13.412	12.32								
94	1.392	2.059	10.29	2972	12.784	11.65								
94	1.667	2	10	2935	13.334	11.18								
95	1.745	2.157	10.78	3013	13.49	12.37								
94	1.647	2.02	10.1	3012	13.294	11.58								
97	1.627	2.196	10.98	2972	13.254	12.43								
93	1.353	2.078	10.39	3018	12.706	11.94								
93	1.451	2.157	10.78	3014	12.902	12.37								
96	1.471	2.137	10.69	3016	12.942	12.28								
94	1.569	1.98	9.9	3012	13.138	11.36								
94	1.608	2.137	10.69	2968	13.216	12.08								
92	1.647	2.059	10.29	2928	13.294	11.47								
93	1.667	2.176	10.88	2932	13.334	12.15								
94	1.706	2.157	10.78	2975	13.412	12.21								
95	1.51	2.118	10.59	2970	13.02	11.98								
93	1.49	2.02	10.1	2964	12.98	11.40								
96	1.471	2.118	10.59	2923	12.942	11.79								
95	1.549	2.039	10.2	2926	13.098	11.37								
95	1.725	2.176	10.88	2930	13.45	12.14								
93	1.431	2.176	10.88	2963	12.862	12.28								
95	1.118	2.039	10.2	2984	12.236	11.59								
95	1.353	2.118	10.59	2903	12.706	11.71								
93	1.118	2.059	10.29	2945	12.236	11.54								
88	1.314	2.059	10.29	2988	12.628	11.71								
94	1.392	2.098	10.49	2981	12.784	11.91								
96	1.235	2.118	10.59	2977	12.47	12.01								
89	1.373	2.137	10.69	2902	12.746	11.81								
95	1.294	2.059	10.29	2903	12.588	11.38								
94	1.412	2.137	10.69	2985	12.824	12.15								
95	1.275	2.02	10.1	2981	12.55	11.47								
95	1.314	2.039	10.2	2987	12.628	11.60								
93	1.333	2.157	10.78	2939	12.666	12.06								
94	1.353	2	10	2943	12.706	11.21								
93	1.275	2.098	10.49	2898	12.55	11.58								
94	1.235	2.02	10.1	2935	12.47	11.29								
92	1.431	2.118	10.59	2907	12.862	11.72								
95	1.118	2.059	10.29	2907	12.236	11.39								
92	1.196	2.137	10.69	2982	12.392	12.14								
96	1.255	2.118	10.59	2983	12.51	12.03								
89	1.431	2.039	10.2	2937	12.862	11.41								
93	1.451	2.039	10.2	2932	12.902	11.39								
96	1.294	2.098	10.49	2934	12.588	11.72								
94	1.353	2.039	10.2	2944	12.706	11.44								
94	1.255	2.118	10.59	2942	12.51	11.86								
95	1.275	2	10	2937	12.55	11.18								
94	1.353	2.118	10.59	2940	12.706	11.86								
95	1.059	2.02	10.1	2928	12.118	11.26								
91	1.314	2.059	10.29	2886	12.628	11.31								
93	1.451	2.098	10.49	2885	12.902	11.52								
92	1.353	2.039	10.2	2975	12.706	11.56								
96	1.255	2.118	10.59	2894	12.51	11.67								
89	1.373	2.078	10.39	2977	12.746	11.78								
93	1.412	2.059	10.29	2938	12.824	11.51								

92	1.412	2	10	2945	12.824	11.21											
93	1.451	2.098	10.49	2943	12.902	11.76											
95	1.314	2	10	2902	12.628	11.05											
92	1.412	2.078	10.39	2988	12.824	11.82											
94	1.235	2	10	2902	12.47	11.05											
95	1.431	2.118	10.59	2944	12.862	11.87											
95	1.098	2	10	2976	12.196	11.33											
88	1.275	2.059	10.29	2937	12.55	11.51											
93	1.431	2.118	10.59	2937	12.862	11.84											
92	1.412	2.039	10.2	2943	12.824	11.43											
93	1.431	2.059	10.29	2943	12.862	11.53											
94	1.353	2.02	10.1	2943	12.706	11.32											
94	1.588	2.098	10.49	2937	13.176	11.73											
95	1.353	2.039	10.2	2945	12.706	11.44											
96	1.314	1.98	9.9	2905	12.628	10.95											
92	1.353	2.059	10.29	2941	12.706	11.52											
94	1.216	2	10	2932	12.432	11.17											
88	1.49	1.961	9.8	2939	12.98	10.97											
94	1.235	2	10	2938	12.47	11.19											
96	1.353	1.98	9.9	2897	12.706	10.92											
92	1.471	2.059	10.29	2974	12.942	11.65											
95	1.216	2	10	2974	12.432	11.33											
93	1.51	2	10	2893	13.02	11.02											
91	1.412	2.02	10.1	2926	12.824	11.25											
94	1.275	2.02	10.1	2930	12.55	11.27											
95	1.176	2.02	10.1	2920	12.352	11.23											
95	1.314	2	10	2914	12.628	11.10											
93	1.333	2	10	2917	12.666	11.11											
94	1.373	1.941	9.71	2912	12.746	10.77											
96	1.392	1.941	9.71	2953	12.784	10.92											
91	1.431	1.941	9.71	2954	12.862	10.92											
92	1.471	1.961	9.8	2904	12.942	10.84											
92	1.412	1.824	9.12	2907	12.824	10.10											
91	1.412	1.922	9.61	2901	12.824	10.62											
96	0.941	1.784	8.92	2964	11.882	10.07											
96	0.922	1.765	8.82	2971	11.844	9.98											
91	0.98	1.824	9.12	2967	11.96	10.30											
94	0.922	1.804	9.02	3011	11.844	10.34											
93	0.941	1.824	9.12	3005	11.882	10.44											
95	0.745	1.745	8.73	2970	11.49	9.87											
94	0.922	1.863	9.31	2971	11.844	10.53											
96	0.843	1.765	8.82	2970	11.686	9.98											
95	0.961	1.863	9.31	2975	11.922	10.55											
95	0.824	1.765	8.82	3001	11.648	10.08											
91	0.961	1.804	9.02	2918	11.922	10.02											
92	0.059	1.549	7.75	2361	10.118	6.97											
89	0.059	1.529	7.65	2361	10.118	6.88											
72	0.059	1.549	7.75	2361	10.118	6.97											
92	0.059	1.549	7.75	2355	10.118	6.95											
78	0.059	1.51	7.55	2350	10.118	6.76											
83	0.059	1.529	7.65	2318	10.118	6.75											
92	0.059	1.529	7.65	2351	10.118	6.85											
79	0.059	1.51	7.55	2356	10.118	6.77											
81	0.059	1.529	7.65	2352	10.118	6.85											
92	0.059	1.529	7.65	2353	10.118	6.85											
82	0.059	1.529	7.65	2353	10.118	6.85											
92	0.059	1.529	7.65	2355	10.118	6.86											
72	0.059	1.51	7.55	2348	10.118	6.75											
81	0.059	1.49	7.45	2346	10.118	6.66											
93	0.059	1.49	7.45	2345	10.118	6.65											
72	0.059	1.529	7.65	2343	10.118	6.83											
93	0.059	1.51	7.55	2351	10.118	6.76											
92	0.059	1.49	7.45	2334	10.118	6.62											
87	0.059	1.49	7.45	2335	10.118	6.62											
92	0.059	1.471	7.35	2333	10.118	6.53											
90	0.059	1.451	7.25	2328	10.118	6.43											
78	0.059	1.49	7.45	2334	10.118	6.62											
84	0.059	1.471	7.35	2339	10.118	6.55											

Appendix C : Error Analysis

In order to properly evaluate the data taken by the apparatus described in this thesis, it was necessary to perform an error analysis on the equipment and test data. This analysis is divided into two sections. The first section covers measurement error associated with the load cells and their mounting system, the second covers a more broad analysis.

C.1 Load Measurement Error

The main issue with load measurement was the way in which the generator was mounted in relation to the load cells. The reason that this caused a problem was the possibility for the load cells to carry some of the weight of the generator when a torque was applied, causing a measurement error. Note that the torque itself can be considered a free vector and applied directly to the pivot (Hibbeler). Figure C 1 illustrates this issue; the figure on the left shows the case of no load, where the weight of the generator is balanced on the pivot point. In the figure on the right, a load is applied, causing a deflection in the load cells (represented by the small rectangles at the ends of the structure). This deflection shifts the balance of the weight so that some of it bears on the load cells.

Figure C 1: Generator Pivot Diagram

In order to quantify this effect, analytical and experimental analyses were performed. The analytical side consisted of studying the forces applied to the load cells with no load versus with a load applied. Studying the forces in the right side of Figure C 1 produces the force diagram in Figure C 2 , taken at the center of gravity of the generator.

Figure C 2: Force Diagram

This diagram shows that in the case where the generator is pivoted by angle Φ , the radial component of the weight (Wg) will act on the pivot as force F_r , and the perpendicular component of the weight F_t will act on the load cells. To calculate this force, the angle Φ must be known. Using the fact that the maximum deflection of the load cells as specified by the manufacturer is .020", this angle can be calculated as:

$$\Phi = \tan^{-1} \left(\frac{.02}{12} \right) = .00167^\circ \quad (C1)$$

Now using Figure C 2 and the known weight of the generator (108lbs), F_t can be calculated as:

$$F_t = (Wg) \tan(\Phi) = .179 \text{ lbs} \quad (C2)$$

It should be noted that this would be the error at the maximum load rating of the cell (25 lbs) representing an error of .72 percent.

To verify this experimentally, a 23.5 inch long lever arm was attached to the input shaft of the generator, the rotor was fixed by clamping one cooling fan blade to the body using a c-clamp, and a weight was placed on the lever arm to produce a specific torque. The moment due to the weight of the lever arm needed to be taken into account by first weighing it (5.0lbs) and then calculating the moment. Since the centroid of the arm was 1 foot from the center of the shaft, this moment was 5 ft-lbs. This process is illustrated in Figure C 3. Adding this to the measurement weight produced an equation for the torque:

$$\tau = 5 + 2Wc \quad (C3)$$

Figure C 3: Calibration Diagram

Using calibration weights (W_c) of 4 and 6 pounds, torques of 13 and 17 ft-lbs were applied, resulting in load cell measurements of 13.04 and 17.16 ft-lbs, respectively. These measurements represent errors of .3% and .9%. Taking into account that the resolution of the torque measurement by the engine controller is .097lbs, or .4% error at full load, these errors can be considered negligible.

C.2 Overall Error

Since the fueling for the tests used in this thesis was set manually, the only sources of error were in the output data. This comes down to three variables- air to fuel ratio, torque, and engine speed (RPM). No data from the manufacturer was available on the error associated with the oxygen sensor used to measure air to fuel ratio, but other sources state that its accuracy can be expected to be +/- .1 AFR, or 1% of full range (Kojima). The engine speed measurement is assumed to be based on the counter-timer circuit within the controller, and therefore should have error commensurate with the speed of the clock crystal (32 MHz) divided by some multiplier. Assuming this multiplier is 256 or less yields a resolution of .03 RPM at 3500 RPM, indicating a maximum error of .0008%. The torque measurement has several factors: error from the generator stand as described in the previous section at a maximum theoretical value of .72%, error from the cells at .03%, error from the conditioners at .2%, and error from the A/D at .4%.

Using an error progression on all these errors (starting with an assumed value, and applying the maximum error from each source in series) yields a maximum total error of 1.02% in the case where AFR is related to horsepower.