

Performance and Emission Characteristics of an Aircraft Turbo Diesel Engine using JET-A Fuel

by

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Abstract

Performance and emission data was acquired by testing an aircraft turbo diesel engine with JET-A at the Mal Harned Propulsion Laboratory of the University of Kansas. The performance data was analyzed and compared to the presented data of the manufacturer. The performance test data of the engine was similar to those reported in the handbook of the engine. The emission data was collected in percent of volume, mass, and part per million units. The different types of pollutants that were evaluated were NO_x , CO, CO_2 , and HC. The emission investigation demonstrates that the aircraft turbo diesel emission data (g/kg fuel) was close to other turbine engines reported in the literature. The emission data of the diesel engine was not predicted to equal the turbine engine, but was predicted to be smaller. In addition, the emission testing established that the CO emission from the diesel engine was significantly lower than a spark-ignition reciprocating aircraft engine. Emission regulations were used to verify the turbo diesel engine's emission data. The engine passed all the requirements from the International Civil Aviation Organization and the Federal Aviation Administration.

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Nomenclature

Symbol	Definition
A	Area
C	Carbon Element
cf	Correction Factor
CFC	Chlorofluorocarbons
Cl	Chlorine Element
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
C _# H _#	Hydrocarbon Molecule
D	Diameter
d	Distance
d/dt	Derivative Respect to Time
D _p	Mass of Pollutant
F	Fluorine Element or Force
F _{oo}	Rated Output
H	Hydrogen Element
H ₂ O	Water
HCl	Hydrochloric Acid
HF	Hydrofluoric Acid
J	Advance Ratio
m	Mass
M	Moment
\dot{m}_e	Mass Flow Rate of Exhaust
\dot{m}_f	Mass Fuel Flow Rate
N	Nitrogen Element
N	Revolutions per Second
N ₂	Nitrogen
NH ₃	Ammonia
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
NO _x	Nitrogen Oxides
O	Oxygen Element
O ₂	Oxygen
O ₃	Ozone

Symbol	Definition
P	Power
p	Pressure
PAN	Peroxyacety Nitrate
r	Radius
rO	Rated Output
rPR	Rated Pressure Ratio
S	Sulfur Element
SN	Smoke Number
SO ₂	Sulfur Dioxide
T	Temperature
t	Time
THC	Total Hydrocarbon
V or v	Velocity

Greek Letter	Definition
δ	Pressure Correction
η	Efficiency
θ	Temperature
λ	Equivalence Ratio
π	Pressure Ratio
ρ	Density
τ	Torque
ω	Angular Velocity

Subscripts	Definition
#	Number of Atoms
a	Actual
e	Exit
f	Fuel
inf	Free Stream
o	Point
Pr	Prop
T	Thrust
x	Compound Family

Abbreviations**Definition**

AFR	Air Fuel Ratio
BHP	Brake Horsepower
CED	Compact Engine Display
CFR	Code of Federal Regulations
CReSIS	Center for Remote Sensing of Ice Sheets
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
FID	Flame Ionization Detector
GHG	Green House Gas
ICAO	International Civil Aviation Origination
NDIR	Non-Dispersive Infrared
NDUV	Non-Dispersive Ultraviolet
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
PM	Particulate Matter
SAE	Society of Automotive Engineers
SFC	Specific Fuel Consumption
THP	Thrust Horsepower
TRI	Transportation Research Institute
TSFC	Thrust Specific Fuel Consumption
UAV	Unmanned Aerial Vehicle
US	United States
VOC	Volatile Organic Compound

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1 Introduction

1.1 Objective

The objective of this work is to present the performance and emission data for a Turbo Diesel aircraft engine and to show an evaluation of the turbo diesel with other engine records and manufacturer data. Another objective is for emission regulations to be implemented for general aviation, which must be created to ensure the future of the planet's ecosystem.

1.2 Global Warming

Global warming is a topic that the world has been addressing in the recent years. Its concept includes the heating of the oceans and air temperatures. Many agencies have vigorously debated about the climate change topic, but the data of human activity shows that humanity is damaging the planet. Its commotion has been rapidly increasing the concentration of greenhouse gases in the atmosphere since the 1920's. Greenhouse gases are substances that trap heat in the atmosphere, which cause the warming of the planet.

The greenhouse effect is the capture of heat and aids the regulation of Earth's temperature. It's one of the world's natural processes and essential for life. The greenhouse gases are emitted to the atmosphere by natural processes or by human activities. Carbon Dioxide (CO₂) occurs naturally in the environment, but also is emitted by man. A list of greenhouse gases that are the cause of human activities are:

Carbon Dioxide, Methane, Nitrous Oxide, and Fluorinated Gases. [ref 1 & 2] The increase of Carbon Dioxide over the past years can be seen in Figure 1.

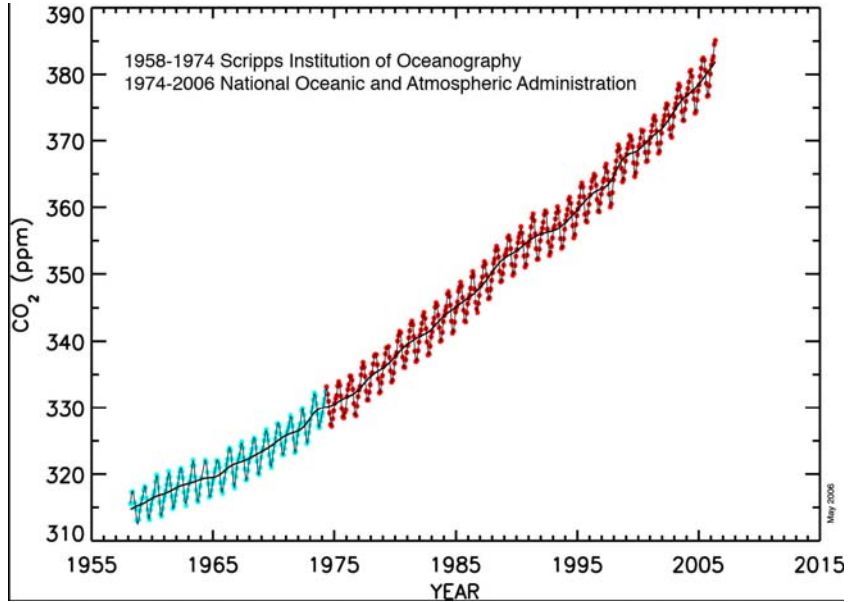


Figure 1: Atmospheric Carbon Dioxide [ref 3]

The boost of greenhouse gases is now causing a frightening future for the planet. In Figure 2, the prediction of the temperature increase for the upcoming years is compared to the 1960's to 1990's temperatures.

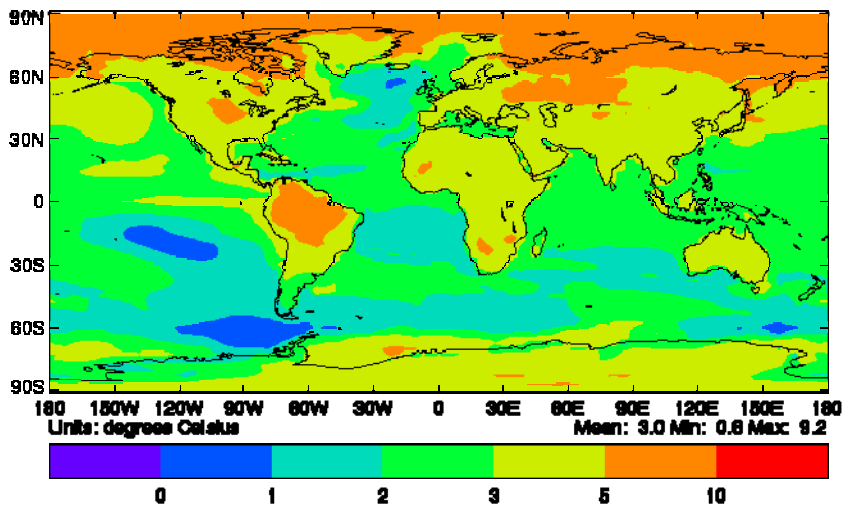


Figure 2: Global Warming Predictions [ref 4]

The world is moving to a cleaner globe, by passing new laws and treaties to benefit the future of man-kind. The most important action the world can take is to recognize their responsibilities as individuals.

1.3 Center for Remote Sensing of Ice Sheets (CReSIS)

The Center for Remote Sensing of Ice Sheets (CReSIS) was established in 2005 by the National Science Foundation (NSF), for the mission of developing new technologies and models to measure and predict the response of sea level change to the mass balance of ice sheets in Greenland and Antarctica. CReSIS will be using an Unmanned Aerial Vehicle (UAV) to map the ice sheets in Greenland and Antarctica. [ref 5] The funding for this paper and testing is the result of CReSIS using the Thielert Centurion 1.7/2.0 for the UAV. The data collected from these tests will aid CReSIS in the performance and emission analysis/understanding of the engine, so the engine will be acceptable for the Antarctica's environment.

1.4 Emission

Emission is the term used to describe something that is released into the environment by different type of sources. [ref 6] There are many types of emissions, the following shows the major emissions in today world:

- Noise Emissions
- Light Emissions
- Exhaust Emissions
- Radio Communication Emissions
- Electromagnetic Radiation Emissions

This report will be focusing on the exhaust emissions of a turbo diesel engine. The conditions of a diesel engine are different from an ignition engine. The fuel is combusted by using compressor pressure versus a spark from a plug. The power is controlled by the fuel supply directly in a diesel engine without a turbo; therefore at low power the engine has enough oxygen to burn all the fuel. As the power increases the fuel that is not burned completely and significant amount of pollutants are produced. This statement is opposite using a turbo diesel engine. [ref 7]

1.4.1 Emission Pollutants

Pollutants are substances that are not naturally found in the air or at greater concentrations. Pollutants are classified into two categories of primary or secondary. Primary pollutants are directly emitted from a human or natural cause. For example, a volcanic eruption is revealed to produce SO_2 , CO_2 , HF, HCL, and Ash, which is shown in Figure 3. [ref 8]

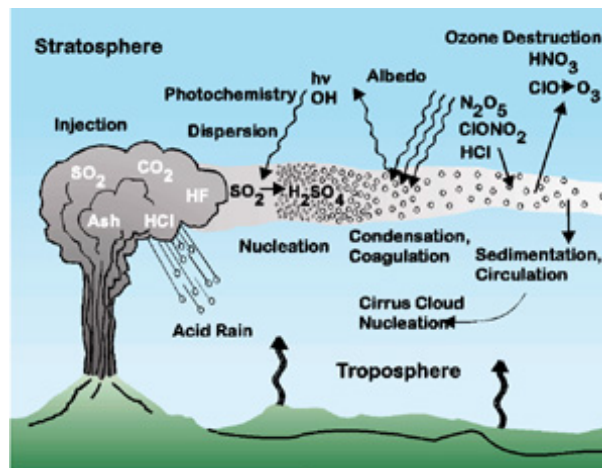


Figure 3: Volcanic Emission Example [ref 8]

A list of primary pollutants can be viewed in Table I.

Table I: Primary Pollutants [ref 9]

Type	Description
Sulfur Oxides (SO _x)	emitted from burning of coal and oil – acid rain formed - with the aid of the catalyst Nitrogen Dioxide (NO ₂)
Nitrogen Oxides (NO _x)	emitted from high temperature fossil fuel combustion - poisonous gas – city haze
Carbon Monoxides (CO)	emitted from natural gas, fossil fuel, and wood - poisonous gas
Carbon Dioxides (CO ₂)	emitted from combustion, major - greenhouse gas
Volatile Organic Compounds (VOC)	non-combusted fuel - Hydrocarbons (THC) and solvent
Particulate Matter (PM)	smoke and dust from the emission
Toxic Metals	lead, copper, and cadmium
Chlorofluorocarbons (CFCs)	emitted from banned products – harmful to the ozone lay
Ammonia (NH ₃)	emitted from agricultural processes - both caustic and hazardous

Secondary pollutants are called non-emitted substances, where the pollutant is not emitted directly in the environment. This means, the products of the primary pollutants which form through photochemical and thermal reactions in the atmosphere are the secondary pollutants. One of the main secondary pollutants is the ground level ozone (O₃). Table II shows the list of secondary pollutants caused by the primary pollutants.

Table II: Secondary Pollutants [ref 9]

Type	Description
Peroxyacetyl Nitrate (PAN)	Formed from NO _x and VOCs
Ground Level Ozone (O ₃)	Formed from NO _x and VOCs

An example, for the primary and secondary pollutants, is shown in Figure 4.

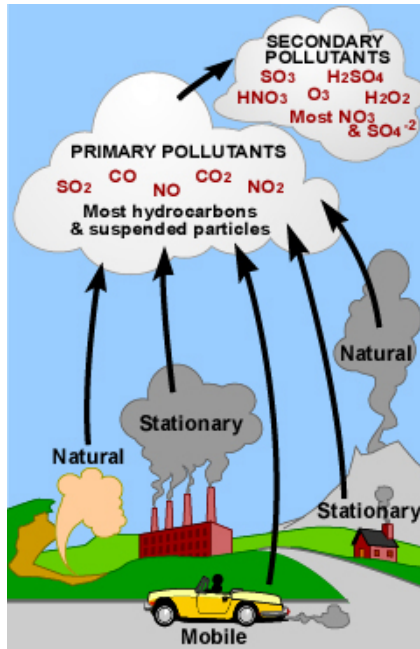


Figure 4: Primary and Secondary Pollutants [ref 9]

The primary pollutants that are studied in this paper are from the combusting of JET A fuel in an aircraft turbo diesel engine. When the combustion happens in the diesel engine the compounds Water, Hydrocarbons, Carbon Monoxide, Carbon Dioxide, Nitric Oxide, and Nitrogen Dioxide are formed. The majority of compounds produced by the engine are shown to be primary pollutants. The secondary pollutants can form in the climate by the primary pollutants of Nitrogen Oxides and Hydrocarbons.

1.4.2 Emission Requirements

In most research and regulatory works, large turbine based propulsion engines seem to be the major source of exhaust emissions in aviation. The problem with this idea is there is relatively no regulation for small airplanes in operation. Talking to

one of the emission personal at the FAA about the regulation of small engine, he said “At this time, there are no emissions requirements for aero piston engines of any type. The emissions for turbine engines are actually defined in the Code of Federal Regulations, (CFR) 14 part 34.” There is only regulation about the smoke spot number, which describes the soot content in the exhaust gas. According to Thielert, the engine manufacturer of the turbo diesel, they only worry about the smoke spot number less than three. If the number is higher than three then the smoke will become visible and fail.

The focus of this paper is the engine emissions from a new general aviation engine. Majority of these aircraft have either pistons or small gas turbine engines. Future emission testing at the University of Kansas will involve a small turboprop turbine engine. The fuels consumed by these small engines are avgas, unleaded gasoline, diesel, and jet fuel. They mostly run on the same fuel as cars and truck, which have standards for emission. The main organizations that influence the emission standards for aircraft in the United States are:

- International Civil Aviation Organization (ICAO)
- Federal Aviation Administration (FAA)
- Environmental Protection Agency (EPA)

1.4.2.1 International Civil Aviation Organization (ICAO)

The International Civil Aviation Organization (ICAO) is an agency of the United Nations, which the job of the ICAO is to ensure safe and orderly growth of the Aviation community. The ICAO headquarters is in Montreal, Canada. The ICAO

council adopts standards and practices concerning aviation operations and environment emission codes for the international civil aviation. [ref 10]

The ICAO regulates the aircraft engine emissions only at a local area (around airports), but continuous growth and increasing public awareness mean this is not enough. The regulations for local emissions may change to global emission in the near future as the effect of emissions at altitude on climate change becomes more significant. The emission regulations are split up into two categories: smoke emission and gaseous emission. The provisions of the standards for smoke apply to engines whose date of manufacture is on or after 1 January 1983. The gaseous emissions standards apply only to engines whose rated output is greater than 26.7 kN thrust. This mean all small engine are not regulated on gaseous emission. The smoke and gaseous emission regulations can be seen in Appendix A. [ref 10]

The ICAO has new findings related to aviation emissions, which are: [ref 10]

- Due to developing scientific knowledge and more recent data estimates of the climate effects of contrails have been lowered and aircraft in 2005 are now estimated to contribute about 3.0 % of the total anthropogenic radiative forcing by all human activities (radiative forcing is defined as the change in net irradiance at the tropopause.)
- Total CO₂ aviation emissions are approximately 2 % of the Global Greenhouse Emissions;

- The amount of CO₂ emissions from aviation is expected to grow around 3-4 percent per year, which excludes the effects of possible changes in cirrus clouds;
- Medium-term mitigation for CO₂ emissions from the aviation sector can potentially come from improved fuel efficiency. However, such improvements are expected to only partially offset the growth of CO₂ aviation emissions.

1.4.2.2 Federal Aviation Administration (FAA)

In 1958, the United States of America created The Federal Aviation Act of 1958, which in turn created the group with the name of Federal Aviation Agency. In 1967, the Federal Aviation Agency changes its name to the Federal Aviation Administration (FAA). The FAA is an agency that is apart of the United States Department of Transportation with authority to regulate and oversee the aspects of civil aviation in the United States. [ref 11] The FAA is the single most influential governmentally-run aviation agency in the world. The Federal Aviation Administration's major roles include: [ref 11]

- Regulating U.S. commercial space transportation
- Encouraging and developing civil aeronautics, including new aviation technology
- Regulating civil aviation to promote safety

- Developing and operating a system of air traffic control and navigation for both civil and military aircraft
- Researching and developing the National Airspace System and civil aeronautics
- Developing and carrying out programs to control aircraft noise and other environmental effects of civil aviation

The regulations for emission are the same as the ICAO requirements for aviation aircrafts. These regulations can be found in the FAA Code of Federal Regulations, (CFR) 14 part 34, Appendix B. [ref 10] The same problems also arise with small aircraft and globalization emission. The FAA only regulates the local (airport) noise and emission from aircraft. There are still no regulations for global emissions requirement, which means the aircrafts are still producing emissions at high altitudes without limits. The small aircraft regulations are the same as the ICAO; only the smoke number seems to be the important part of the engine.

1.4.2.3 Environmental Protection Agency (EPA)

The Environmental Protection Agency (EPA) was formed on December 2, 1970, which was established by President Richard Nixon. The mission of the EPA is to protect human health and safeguard the natural environment: air, water, and land from human activities. Most of the EPA standards in emission is focused on automobiles, but a recent petition from environmentalists seeking regulations curbing greenhouse gas (GHG) emissions from aircraft engines, made the EPA look at the emission of aircraft engines. The EPA confirms that aircrafts contribute about 10

percent of GHG emissions in the U.S. transportation sector and 3 percent of all GHG emissions in the U.S. [ref 12]

In the past, EPA has followed the approach of the International Civil Aviation Organization, since international consistency is beneficial and aircraft engines are international commodities. EPA will now look at potential technological controls for aircraft engines and operational measures to reduce emissions. EPA will work with the FAA in planning new emission standards and technology. [ref 12]

1.4.3 Emission Technology

1.4.3.1 Catalytic Converter

Gasoline vehicles produce a lot of emission, but with aircraft engines there are no devices to limit the pollutants. In 1975, a remarkable device called a catalytic converter was invented. The job of the catalytic converter was, and still is, to convert harmful pollutants into less harmful emissions before they leave the exhaust system of a car. Catalytic converters reduce the primary pollutants by using catalysts in a ceramic converter. [ref 13] An example of a catalytic converter is shown in Figure 5.

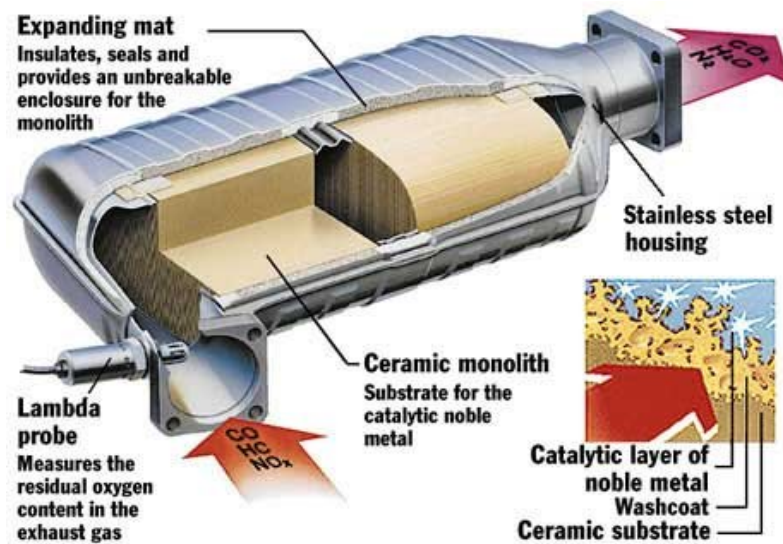


Figure 5: Catalytic Converter [ref 14]

A catalyst is a substance that causes or accelerates a chemical reaction without itself being affected. Catalysts participate in the reactions, but are neither a reactant nor a product of the reaction they catalyze. [ref 13]

There are two catalysts in the catalytic converter:

- Reduction Catalyst
- Oxidation Catalyst

These catalysts are constructed on a ceramic structure where the coating of metal is the catalyst. The metal catalysts are platinum, rhodium and palladium. The purpose for the ceramic structure is to give the exhaust the maximum surface area for the catalyst to react to the emission gases.

Reduction catalysts are used for reducing the Nitrogen Oxides (NO_x) emission with the aid of catalyst platinum and rhodium. The catalyst job is to separate the

nitrogen atoms away from Nitrogen Oxides (NO_x). This action causes the reactants to form Oxygen and Nitrogen molecules. This is shown in Equations 1 and 2. [ref 13]



Oxidation catalyst is the second part of the converting process. It lowers the unburned Hydrocarbons (THC) and Carbon Monoxide (CO) by using a platinum and palladium catalyst, which oxidize the molecules. This process assists the reaction of CO and THC with the lingering oxygen in the exhaust system. The reaction for carbon monoxide and the remaining hydrocarbons are burned off as shown in Equations 3. [ref 13]



Diesel, gasoline, and turbine aircraft engines don't have these types of converters, because performance of the engine would decrease significantly. There is enormous importance to look at aircraft engines closely, because they still produce similar emissions as other fossil burning power plants. Secondly, the emission that is emitted from the aircraft is at the flight altitude, which is significant to the effects on the environment. Since the numbers of cars are above aircrafts worldwide, the majority of emission research focused on vehicles that we drive daily. There is an average of two cars per person in the United States of America. Hence, there is more emission from cars than aircrafts. Aviation also contributes to emissions both locally

and globally and concerns about their effects on the environment are raising interest in aircraft emissions.

1.4.3.2 Ultra Low Emissions Combustor

In 2006, an ultra low emission combustor was invented at Georgia Institute of Technology. These combustors have become a main concern for emission researchers as federal and state restrictions are making rigid requirements on pollution. Organizations are reducing the allowable levels of NO_x and CO for engines, power plants, and industrial processes. [ref 15]

Researchers at Georgia Tech have created a combustor that has low emission of nitrogen oxides and carbon monoxide. It has a simpler design than existing combustors and its manufacturing is much easier and more affordable for jet engines and power plants. [ref 15]

The combustor works by burning fuel in a low temperature reaction over a large portion of the combustor. The high temperature pockets are eliminated for better control of the flow of the reactants and combustion products. The device produces lower levels of NO_x and CO. In addition, the combustor avoids acoustic instabilities that exist in low emission combustors. In the old low emission combustors, fuel is premixed with air by a swirling air flow before injection into the combustor. There are problems doing the premixed swirling such as expensive designs and instabilities in the system. The new combustion is designed to eliminate the complexity of premixing the fuel and air. The fuel and air are separately introduced into the combustor and the shape forces the air and fuel to mix with one

another and with the combustion products before ignition. This can be seen in Figure 6.

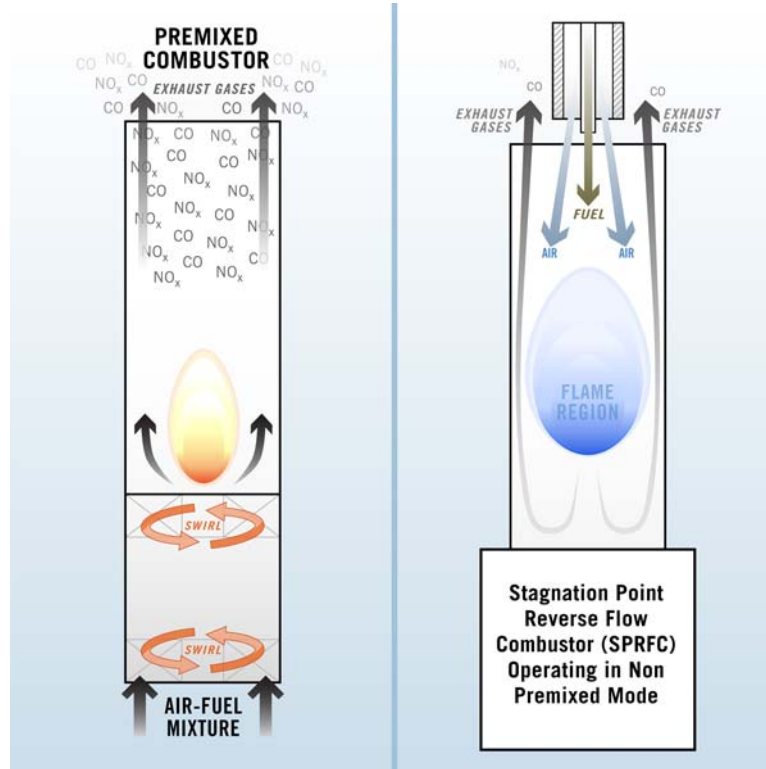


Figure 6: Premixed Combustor and Ultra Low Emissions Combustor [ref 15]

Other technologies are being placed on aircraft engines now (turbochargers, superchargers, fuel injectors, and electronic control system), but intensified efforts to improve technology and operational procedures are recommended for all aircraft types.

1.5 Apparatus and Equipment

1.5.1 Mal Harned Propulsion Laboratory

The tests that are conducted for this report are conducted in the Mal Harned Propulsion Laboratory of the University of Kansas. The facility is located in a hangar at the Lawrence Municipal Airport. The hangar is 3,840 square feet, with the test facility located inside the hangar. The silver hangar is shown in Figure 7.



Figure 7: University of Kansas - Silver Hangar

1.5.1.1 Test Cell

The test cell was redesigned to handle many types of engines from turbojet, turbofan, turboprop, reciprocating engines, and some small test rockets. The cell is constructed of concrete, which is 12 feet wide, 24 feet long, and 10.5 feet high and can be opened to the environment. The test cell can be seen in Figure 8.



Figure 8: Test Cell

1.5.1.2 Test Stand

The test stand in the test cell was redesigned in the summer of 2007 by Andy Pritchard and Sean Underwood. The stand was redesigned to support the Thielert Centurion 1.7/2.0 turbo diesel and the Innodyn 165TE turboprop testing. The test stand provides a simple way to switch engines. The stand uses steel plates to be compatible with the Innodyn, but from these plates more engines can be tested in the Mal Harned Propulsion Laboratory. Figure 9 shows the redesigned test stand at the University of Kansas propulsion testing facility.

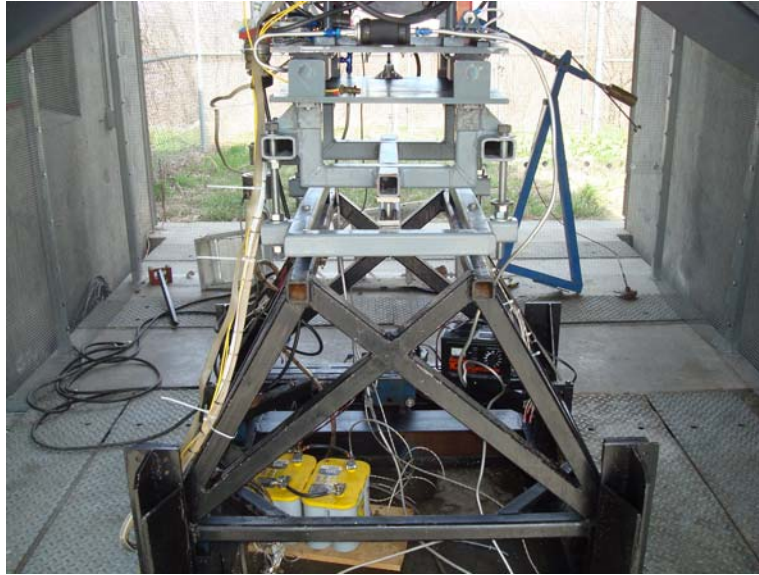


Figure 9: Test Stand

1.5.1.3 Load Cell

Connected to the test stand are two load cells that are designed to measure the torque and thrust of an engine. The load cell converts mechanical motion into volts that are calibrated to give the desirable measurements. The thrust load cell is positioned behind the engine to measure linear movement of the engine on a sliding plate. One end is connected to the moveable stand and the other end is fastened to the rigid test stand. The thrust load cell is shown in Figure 10.



Figure 10: Thrust Load Cell

The torque load cell is placed on the side of the test stand and engine plate. The torque load cell measures the moment of the engine on the stand. This load cell is shown in Figure 11.



Figure 11: Torque Load Cell

1.5.1.4 Control Panel

The control panel for the testing area is designed according to the type of engine and manufacturer. In this case, the control panel was designed for the Thielert Centurion 1.7/2.0. The control panel is made up of a throttle, compact engine display (CED), starter switches/key, and FADEC control panel. The system is shown in Figure 12.



Figure 12: Thielert Centurion's Control Panel

The throttle is operated by percent power otherwise by RPM control throttles. The throttle goes from 0 % power to 100 % power. The CED (electronic display) unit shows the engine safety parameters: Load, Oil Temperature, Oil Pressure, Water Temperature, and Gearbox Temperature. The CED can be seen in Figure 13.



Figure 13: CED

The Full Authority Digital Engine Control (FADEC) control panel is used to test the FADEC system and gives warnings for the systems. The FADEC control panel is shown in Figure 14.



Figure 14: FADEC Control Panel

1.5.2 Thielert - Centurion

Thielert is a German company that started to develop diesel piston engines for the aviation market. One of the most known designs is the Centurion product line. The Centurion is a turbo diesel engine that has the advantage of using Jet A or Diesel

fuel for aviation uses. Two engine models are currently produced for the aviation market: Centurion 2.0 and Centurion 4.0. [ref 16]

In this report the Centurion 1.7 is used for all the testing done. The Centurion 1.7 is the first product by Thielert, which should have the same performance as the Centurion 2.0. The Centurion 1.7 is shown in Figure 15.



Figure 15: Thielert Centurion 1.7 [ref 16]

The dimensions and weights are shown in the following table: Table III.

Table III: Dimensions and Weights [ref 17]

Number Cylinders	4
Bore	80.00 mm
Stroke	84.00 mm
Cylinder Spacing	90.00 mm
Displacement Total	1689 cm ³
Displacement (per cylinder)	422 cm ³
Compression Ratio	18:1 or 19:1
Firing Order	1-3-4-2
Weight (dry)	134 kg

Thielert include the performance and operational data and they are given in Table IV.

Table IV: Performance and Operational Data [ref 17]

Max Takeoff Power	99 kw at 2300 rpm
Max Continuous Power	99 kw at 2300 rpm
Recommended Cruise Power	71 kw at 2010 rpm
Best Economy	71 kw at 2010 rpm
Idling Speed	890 rpm
Normal Oil Pressure	2.3 – 6 bar
Optimum Oil Temperature	90 to 100°C
Optimum Coolant Temperature	85 to 100°C
Optimum Gearbox Temperature	70 to 100°C

In Table V, it shows the comparison of engines that are in the same Centurion 1.7 market category.

Table V: Market Engines

Engine	Centurion 1.7	Lycoming IO-360-M1A	Lycoming 0-320-D
Fuel	Jet A, Jet A1, Diesel	Avgas	Avgas
Fuel Delivery	Injectors, Turbocharged	Injectors	Carburetor
Drive Chain	Reduction Gear	Direct	Direct
Propeller Type	Constant Speed (Variable Pitch)	Constant Speed (Variable Speed)	Fixed Pitch
Engine Controls	Full Authority Digital Engine Control (FADEC)	Propeller Speed Manifold Pressure Fuel Mixture	Throttle Fuel Mixture Carburetor Heat
Max RPM Propeller	2300	2700	2700
Max RPM Engine	3900	2700	2700
Power (sea level)	135 HP	180 HP	160 HP
Fuel Consumption	4.9 US gal/hr	10 US gal/hr	~

1.5.2.1 Full Authority Digital Engine Control (FADEC)

Full Authority Digital Engine Control (FADEC) controls all aspects of aircraft engine performance. FADEC have been produced for piston engines and jet engines, their primary difference is the different ways of controlling the engines. The FADEC of the Thielert Centurion have two Electronic Control Units (ECU), which are:

- ECU A
 - Primary Electronic Control Unit
- ECU B
 - Secondary Electronic Control Unit

The FADEC system has multiple systems for controlling the engine. The FADEC system also has a service tool that is designed to provide access to real time data. The tool has an onboard data logger system that records many operation parameters of the engine, which are shown as follows:

- Engine Revolution (RPM)
- Propeller Revolution (RPM)
- Rail Pressure
- Boost Pressure
- Load
- Manifold Pressure
- Battery Voltage
- Water Temperature
- Air Temperature
- Gearbox Temperature
- Oil Temperature
- Oil Pressure
- Barometric Pressure
- Fuel Flow
- Warnings

1.5.2.2 Propeller

The Centurion 1.7 uses a propeller from MT- Propeller. MT-Propeller Entwicklung GmbH was founded in 1981 by Gerd Muehlbauer and is well known in the world of general aviation as a leading manufacturer of natural composite propellers. The model number for the propeller is MTV-6A_187-129. Data for this propeller can be seen in Appendix C and the propeller is shown in Figure 16.



Figure 16: Centurion's Propeller (MTV-6A)

1.5.2.3 Fuels

There are many types of fuel that the Centurion 1.7 can use for optimum operation. In Table VI, the fuels that are recommended from Thielert are shown.

Table VI: Centurion Operation Fuels [ref 17]

Fuel	Jet A-1 (ASTM D 1655)
	Jet A (ASTM D 1655)
	Jet Fuel No. 3 (GB6537-94)
	JP-8 (MIL-DTL-83133)
	JP-8+100 (MIL-DTL-83133E)
Alternative Fuel	Diesel (EN 590)
Fuel Additive Jet A	Prist Hi-Flash Anti-Icing Fuel Additive (MIL-DTL-84470B; ASTM D 4171)
Fuel Additive Diesel	Liqui Moly "Diesel Fliess Fit" No: 5130

This report will cover the testing of JET A in the Centurion, which was accepted to be used in Antarctica by CReSIS. This was chosen because of the abundant supply in

the South Pole compared to the diesel base fuels. Diesel would cost more money for the program to transport for its operational needs.

JET A is the standard jet fuel in the United States as of the 1950's, and the fuel can only be bought in the US. Furthermore, JET A is aviation kerosene; it is very similar to the common kerosene used in home lamps and heaters. [ref 18] Kerosene is a clear liquid that is a mixture of different kinds of hydrocarbons molecules, which is similar to gasoline and diesel fuel in that it is a mixture of hydrocarbons of different sizes. A hydrocarbon molecule is an organic compound that is made up of hydrogen and carbon atoms. The sizes of the molecules are measured in terms of the number of carbon and hydrogen atoms in the each molecule. Kerosene contains a mixture of Hydrocarbon liquids ranging from C₁₂H₂₆ to C₁₅H₃₂. An example of Kerosene compound (C₁₂H₂₆) is shown in Figure 17. [ref 19]

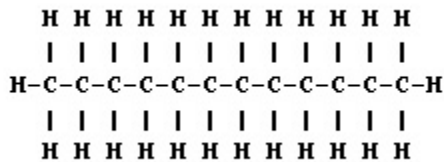
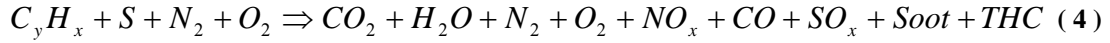


Figure 17: Kerosene Compound (C₁₂H₂₆)

When the combustion of JET A (kerosene base) occurs, the reaction will produce mainly, Carbon Dioxide (CO₂) gas and Water (H₂O) vapor. The kerosene fuel is oilier than gasoline; therefore the fuel must be atomized by an injector. The atomization is not completely efficient and the fuel is not complete combusted. This process produces Carbon Monoxide (CO) and Carbon particles. The emission of this combustion content Water (H₂O), Hydrocarbons (THC), Carbon Monoxide (CO),

Carbon Dioxide (CO₂), Nitric Oxide (NO), Nitrogen Dioxide (NO₂), Sulfur Oxides (SO_x) and Soot. The chemical reaction can be seen in Equation 4.



The fuel is similar to JET A-1, but has a higher freezing point. The following table shows the data for JET A, JET A-1, and Diesel: Table VII.

Table VII: Fuel Types [ref 19]

	JET A	JET A-1	Diesel
Flash Point	38 °C	38 °C	62 °C
Auto Ignition Temperature	210 °C	210 °C	210 °C
Freezing Point	-40 °C	-47 °C	~
Density (15 °C)	.775 to .84 kg/L	0.8075 kg/L	o.720 kg/L

1.5.3 Sensors - Semtech

The Semtech is designed and built by Sensors, Inc. They were founded in 1969 and have over thirty years of experience in emissions analysis. The company supplied over 80% of BAR97 inspection grade 5-gas analyzers for state emission programs. They are one of the world’s leading suppliers of in-use emissions test systems. [ref 20]

The SEMTECH-DS analyzer equipment is used for testing emissions of the Thielert Centurion. SEMTECH-DS is intended for on-vehicle emission monitoring of diesel and gasoline powered vehicles. The SEMTECH-DS is shown in Figure 18.



Figure 18: SEMTECH-DS

The focus of this paper is on the stationary applications of the SEMTECH-DS with an aircraft engine. In tests of the Centurion, the fuel type used was JET-A, the operator of the SEMTECH-DS in the testing, confirm that this fuel works with the device.

The SEMTECH-DS has a list of measurement subsystem:

- Heated Flame Ionization Detector (FID)
 - Total Hydrocarbon (THC) measurement
- Non-Dispersive Ultraviolet (NDUV)
 - Nitric Oxide (NO)
 - Nitrogen Dioxide (NO₂)
- Non-Dispersive Infrared (NDIR)
 - Carbon Monoxide (CO)
 - Carbon Dioxide (CO₂)
- Electrochemical Sensor
 - Oxygen (O₂)

These subsystem methods provide direct comparison to test cell measurements for THC, CO, CO₂, NO and NO₂ in compliance with CFR-40, 1065 Subpart J. Sensors Inc. authenticate that all the subsystems of the SEMTECH have been designed to

match the performance of the laboratory grade instrumentation. [ref 21] The complete specifications for the SEMTECH-DS are shown in Appendix D.

1.5.3.1 Heated Flame Ionization Detector

Measuring total hydrocarbons (THC) at a high accuracy, from a range of 0 to 40,000 ppmC, is done by using a heated flame ionization detector in the SEMTECH-DS. A sample of exhaust gas is routed through the system by a stainless steel tube to the heated flame ionization detection chamber for a precise measurement. The hydrocarbons sampling system is heated 191 °C, to prevent condensation of the heavy hydrocarbon particles in the exhaust sample. The hydrocarbons measuring system is electronically controlled by the SEMTECH-DS to ensure the best possible data. [ref 21]

The tester has the ability to select a range of 100, 1,000, 10,000, and 40,000 ppmC. The Flame Ionization Detector also has higher and lower ranges that can be enabled as a special sampling alternative. The ranges for the Heated Flame Ionization Detector are individually calibrated to zero each time the command is given to reduce the process time. [ref 21]

The Total Hydrocarbon Heated Flame Ionization Detector fuel consists of a 40/60 mixture of hydrogen and helium. [ref 21]

1.5.3.2 Non-Dispersive Ultraviolet

The measurement of Nitric Oxide (NO) and Nitrogen Dioxide (NO₂), from the exhaust gases, are done by using a Non-Dispersive Ultraviolet (NDUV) analyzer.

The sample of the exhaust must be dried in order to remove the heavy hydrocarbons, which will cause contamination to the optic sensors. This is done by using an ambient air temperature coalescing filter and a thermoelectric chiller. There will be a little amount of Nitrogen Dioxide that is lost in the drying process, but this loss is in the acceptable range. [ref 21]

The Non-Dispersive Ultraviolet (NDUV) analyzer can report constant measurements for Oxide (NO) and Nitrogen Dioxide (NO₂) at a rate of 4 Hz to the SEMTECH-DS. The system is shown to be at the same efficiency as laboratory chemiluminescent analyzer. [ref 21]

1.5.3.3 Non-Dispersive Infrared

Non-Dispersive Infrared (NDIR) analyzer is used for the measuring of Carbon Monoxide (CO), Carbon Dioxide (CO₂), and Hydrocarbon (HC) exhaust elements. The exhaust is dried out through a coalescing filter and a thermoelectric chiller to ensure water vapor is removed. The water vapor must be removed to not cause interference in the infrared channels. The system is enclosed in a temperature controlled environment to stabilize and maximize the best results. [ref 21]

The Non-Dispersive Infrared analyzer shows concentration measurements on a continuous 0.833 Hz or 1.2 second period data rate to the SEMTECH-DS. The range for Carbon Monoxide is 0-8%, but the range for typical exhaust is around 1000 ppm or 0.1%. Therefore, the Non-Dispersive Infrared analyzer has accuracy of 50 ppm for Carbon Monoxide. Overall, the Non-Dispersive Infrared analyzer is favorable to the equipment found in an emission testing laboratory. [ref 21]

1.5.3.4 Electrochemical Sensor

The Electrochemical Sensor monitors the oxygen level of the sample exhaust by using an oxygen sensor cartridge. The sensor produces a signal that is proportional to the partial pressure of oxygen in the exhaust gas and then the AMBII module processes the signal and reports the results to the SEMTECH-DS. [ref 21]

1.5.3.5 Exhaust Flow Meter

The SEMTECH-DS have an option of using the SEMTECH EFM (electronic flow meter) to measure the engine exhaust flow accurately. Unfortunately, the engine's exhaust temperature went passed the systems acceptable temperature range (500°F). [ref 21]

2 Analysis

The analysis of this report can be broken up into two main sections:

1. Engine Performance Analysis
2. Engine Emission Analysis

2.1 Engine Performance Analysis

The performance focus of the engine is torque, power, thrust, specific fuel consumption, and RPM's.

Torque (τ) is a vector that measures an applied force on an object for the effect of rotating the object. The concept of torque is also called moment or couple. For example, a force is applied to a lever and the pivot point is a distance away from the force. The product of the distance of the arm with the force is the torque of the system. Equation 5 shows the concept of torque.

$$\tau = d \times \vec{F} \quad (5)$$

Torque is a basic part of engine performance, because some internal parts are rotating around the crank shaft by combustion in the piston chamber. Plus, the power output of an engine is expressed by the torque. This is shown in Equation 6.

$$P = \tau \times \omega \quad (6)$$

Using the imperial unit for power (hp), equation 6 can simplify into a horsepower equation. Equations 7-9 show the derivation of equation 6 to the horsepower equation, which is shown in Equation 9. [ref 22]

$$P = \frac{\vec{F} \times d}{t} \quad (7)$$

$$P = \frac{\left(\frac{\tau}{r}\right) \times (r \times \omega \times t)}{t} \quad (8)$$

$$P = \tau \times \omega = \frac{\tau \times RPM}{5252} \quad (9)$$

The power in Equation 9 is known as brake power and the actual power or power available equation is shown in Equation 10. [ref 23]

$$P_A = \eta_{pr} P \quad (10)$$

where η_{pr} is the propeller efficiency

The brake power is the engine power without any losses to items such as the gearbox and the shaft. Therefore, the efficiency is needed to calculate the power available.

The propeller efficiency is the same as the propulsive efficiency, as shown in Equation 11. [ref 23]

$$\eta_p = \frac{P_A}{P} \quad (11)$$

The propeller efficiency is also a function of the advance ratio, J. The advance ratio equation is shown in Equation 12. [ref 23]

$$J = \frac{V_\infty}{ND} \quad (12)$$

where V_∞ is the free-stream velocity

N is the number of propeller revolutions per second

D is the propeller diameter

In Appendix C, the graph for the propeller efficiency versus advance ratio is shown.

The next important performance parameter is the thrust of the aircraft engine. Thrust is a reaction force described by Newton's Three Laws of Motion:

- I. A physical body will remain at rest, or continue to move at a constant velocity, unless an outside net force acts upon it.
- II. Rate of change of momentum is proportional to the resultant force producing it and takes place in the direction of that force.
- III. To every action there is an equal and opposite reaction.

Thrust is a mechanical force, so the propulsion system must be in physical contact with a working fluid to produce thrust. Thrust is generated most often through the reaction of accelerating a volume of gas. Since thrust is a force, it is a vector quantity having both a magnitude and a direction. The engine does work on the gas and accelerates it the gas to the rear of the engine; the thrust is generated in the opposite direction from the accelerated gas. The magnitude of the thrust depends on the amount of gas that is accelerated and on the difference in velocity of the gas through the engine. The thrust equation can be generated from Newton's second law of motion, the time rate of change of momentum is equal to the force, in this case thrust. The derivation is shown from Equation 13 through 16 with the aid of Figure 19. [ref 23]

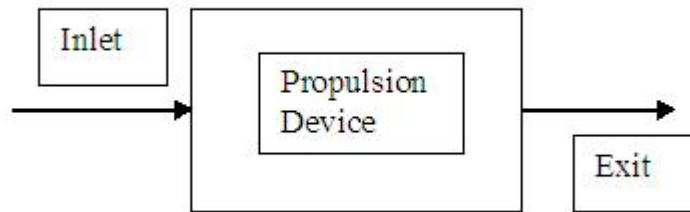


Figure 19: Thrust Example

Stating with Newton's second law of motion,

$$F = \frac{d}{dt}(mv) \quad (13)$$

Looking at Figure 19, there are two positions that are important; the inlet and exit. If a particle is traveling through the propulsion device, the inlet will have t_1 and the exit will have t_2 . Therefore,

$$F = ((mv)_2 - (mv)_1) / (t_2 - t_1) \quad (14)$$

$$F = ((\dot{m}v)_2 - (\dot{m}v)_1) \quad (15)$$

$$\text{where } \dot{m} = \rho * v * A$$

There is additional force acting on the thrust equation, which is the pressure force on the propulsion device. The pressure force takes into account the exit pressure against the inlet free stream pressure.

$$F = ((\dot{m}v)_2 - (\dot{m}v)_1) + (p_2 - p_1)A_e \quad (16)$$

The thrust equation has two possible ways to produce high thrust. One way is to make the engine flow rate as high as possible. Also, if the exit velocity is greater than the free stream velocity, a high engine flow will produce high thrust. This is the design theory behind propeller aircraft and high-bypass turbofan engines. [ref 23]

The last performance analyzes the specific fuel consumption, which is a technical term to describe how efficient the engine is in combusting fuel and converting the chemical energy into power. The equation for specific fuel consumption is given in Equation 17. [ref 23]

$$\text{SFC} = \frac{\dot{m}_f}{P} \quad (17)$$

2.2 Engine Emission Analysis

The level of emission of nitrogen oxides (nitric oxide and nitrogen dioxide) are usually grouped together as NOx. Nitrogen oxides, carbon oxides, unburned hydrocarbons, and particulates are important to an engine operation characteristic.

The gaseous emissions in the engine exhaust gases are usually measured in parts per million or percent by volume. Parts per million corresponds to the mole fraction of the molecule multiplied by one million, and the percent by volume is the mole fraction of the molecule multiplied by one hundred. There are two other common measurements for gaseous emissions: Specific Emissions (SE) and Emission Index (EI). [ref 24]

Specific emissions is the mass flow rate of the pollutant per unit of power output.

Equation 18 shows the formula for the specific emissions for a pollutant. [ref 24]

$$SE_{\text{pollutant}} = \frac{\dot{m}_{\text{pollutant}}}{P} \quad (18)$$

The emission index is commonly used as the alternative emission method. The emission rate is normalized by the fuel flow rate, as shown in Equation 19. [ref 24]

$$EI_{\text{pollutant}} = \frac{\dot{m}_{\text{pollutant}}}{\dot{m}_f} \quad (19)$$

Oxides of Nitrogen

Nitric oxide (NO) and nitrogen dioxide (NO₂) are created mostly from nitrogen in the air. The make up of Air is shown in Table VIII by percent volume. [ref 24]

Table VIII: Atmosphere Composition

Nitrogen	78.0842%
Oxygen	20.9463%
Argon	0.93422%
Carbon dioxide	0.03811%
Water vapor	about 1%
Other	0.002%

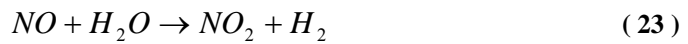
Nitrogen can be found in fuel blends, which may contain small amounts of NH₃, NC, and HCN. Fuel contributes almost nothing to the production of Nitrogen Oxides.

Nitric oxide formation is due to the combustion at near stoichiometric fuel-air mixtures. The governing reactions for formatting NO are shown in Equations 20-22.

[ref 24]



In turn, nitric oxide can react to form nitrogen dioxide by various means. Equations 23 and 24 show how NO changes into NO₂. [ref 24]



The atmospheric nitrogen exists as a stable diatomic molecule at low temperatures. If there is enough energy in the system the stable diatomic molecule will separate.

These high temperatures occur in the combustion chamber of an engine and cause the diatomic nitrogen breaks down to monatomic nitrogen (N). Then the monatomic reacts with oxygen atoms in the system to form nitrogen oxides. Equations 25 - 27 show the production of atmospheric nitrogen forming into nitrogen oxides.



Nitrogen oxides depend on high temperature, pressure, air-fuel ratio, and combustion time within the cylinder. Nitrogen oxides will form in the system when all the criteria are satisfied. [ref 24]

Oxides of Carbon

The main purpose for carbon oxides is to change carbon monoxide into a less dangerous chemical, carbon dioxide. When an engine operates at a fuel-rich equivalence ratio, it causes the system to lack enough oxygen to convert all carbon to carbon dioxides. Some fuel does not get burned and some carbon ends up as carbon monoxide at this equivalence too. Some chemical reaction equations for carbon monoxides are given in Equation 28 -29. [ref 24]



In addition to beginning an undesirable emission, but carbon monoxide is causing the system to lose some of its chemical energy. CO is also a fuel that can be combusted to supply additional thermal energy and it will be change into CO₂. This reaction can be seen in Equation 30. [ref 24]



Carbon monoxide only becomes the primary carbon oxide if the fuel to air ratio is high.

Total Hydrocarbon

Hydrocarbon emission variation depends on the fuel type, fuel to air ratio, operating parameters, and engine combustion chamber geometry. Once in the atmosphere, the hydrocarbon acts as irritants and odorants at which some are

carcinogenic. They form photochemical smog over which abundant supply of HC is in the air. The main cause of hydrocarbon pollution is shown as follow: [ref 24]

- Nonstoichiometric Air-Fuel Ratio
 - HC emission levels are a strong function of Air to Ratio
- Incomplete Combustion
 - Incomplete air to fuel mixture
 - Flame quenching
- Deposits on Combustion Chamber Walls
 - Deposits are absorbing gas particles

Validation

The validation of the emission is done by using the ICAO and FAA guidelines set out in Appendices A and B. In addition, the data from the turbo diesel is compared to other types of engines in present operation. The regulations in the ICAO and FAA handbook are for turbofan and turbojet engines. As stated before, there are no regulations for internal combustion aircraft engines. The paper will look at the lowest standard for the turbofan and turbojet engines, which means the lowest thrust category. The category that was chosen was the engine pressure ratio of 30 or less and the engine thrust is more than 26.7 kN but not more than 89.0 kN. Again, the thrust of the Thielert Centurion is 2.224 kN which doesn't come close to the 26.7 kN. This analysis is to see how close the emissions come to this category. The regulations are given as follows: [ref 10 & 11]

- Hydrocarbons (HC): $\frac{D_p}{F_{oo}} = 19.6$
- Carbon Monoxide (CO): $\frac{D_p}{F_{oo}} = 118$

- Carbon Dioxide (CO₂): No Regulation
- Nitrogen Oxides (NO_x): $\frac{D_p}{F_{oo}} = 37.572 + 1.6\pi_{oo} - 0.2087F_{oo}$

Where D_p is the mass of pollutants, F_{oo} is the rated output, and π_{oo} is the rated pressure ratio. The equation that will determine the specific emission number is given in Equation 31.

$$SE = EI * SFC * Time \quad (31)$$

The time for the each operation mode is shown in Table IX. [ref 10 & 11]

Table IX: ICAO Time Mode Standard

	Time	Load
	(min)	(%)
Takeoff	0.7	100
Climb	2.2	85
Approach	4.0	30
Taxi/Idle	26.0	0-10

The second analysis method is to compare the gaseous emission data with other types of engines in the aviation field. The list of engines and their fuels is shown as follow:

- Allison T56-A-15 [ref 25]
 - Jet Propellant-8 (JP-8)
- Pratt & Whitney PT6-42 [ref 26]
 - JET-A
- Thielert Centurion 1.7 (from Dr. Arentzen)
 - JET-A
- Textron Lycoming 0-320-E2D (from Dr. Arentzen)
 - Avgas
- Williams Research WR 24-6 [ref 28]
 - JET-A
- Garrett GTC85 Series APU [ref 28]
 - JET-A

3 Results and Discussions

3.1 Engine Performance

There is an email to ensure that all data presented in the performance investigation session was approved by the manufacturer in order with the contract.

3.1.1 Test Stand Calibration

The test stand has two load cells that must be calibrated to ensure the best data for the torque and thrust measurements. Load cells are placed in the test stand in the correct positions to monitor how much the test stand deflects under a certain load or moment. These load cells give a voltage that corresponds to a certain deflection from the loading condition. A voltmeter is used to display the voltage magnitude. The relationship between the increase in voltage to the increase in thrust or torque should be linear.

3.1.1.1 Torque Calibration

The torque calibration is started by checking the load cell and voltmeter making sure that they are zeroed out. After the equipment is zeroed out, a torque leverage bar is placed on the stand and is made rigid to the stand with C-clamps. The torque calibration setup can be seen in Figure 20.



Figure 20: Torque Calibration Setup

The bar has a moment arm of 1.75 to 4.75 feet. A weight of 100 pounds and 5 pound hook are positioned on the starting point of 1.75 feet, from here the weight is moved out to 4.75 feet by 0.25 feet. The voltage is recorded at each point to ensure a linear relationship. At 4.75 feet the proceeding steps is redone, by moving inward to 1.75 feet and again outward to 4.75 for three times. The volts of this calibration can be seen in Table X.

Table X: Torque Calibration – Locations/Volts

Location	OUT	IN	OUT	IN	OUT	IN	AVERAGE
(ft)	(volt)	(volt)	(volt)	(volt)	(volt)	(volt)	(volt)
1.75	0.998	0.991	0.991	0.989	0.989	0.989	0.991
2.00	1.141	1.132	1.134	1.133	1.134	1.133	1.135
2.25	1.284	1.278	1.279	1.278	1.279	1.281	1.280
2.50	1.427	1.42	1.422	1.426	1.421	1.423	1.423
2.75	1.57	1.565	1.566	1.567	1.566	1.567	1.567
3.00	1.713	1.707	1.708	1.709	1.708	1.708	1.709
3.25	1.857	1.851	1.852	1.855	1.852	1.851	1.853
3.50	2	1.996	1.997	1.998	1.997	1.993	1.997
3.75	2.143	2.14	2.139	2.141	2.137	2.136	2.139
4.00	2.288	2.285	2.283	2.281	2.281	2.283	2.284
4.25	2.43	2.424	2.425	2.423	2.424	2.423	2.425
4.50	2.574	2.573	2.568	2.569	2.561	2.567	2.569
4.75	2.712	2.712	2.708	2.708	2.705	2.705	2.708

A graphical representation of Table X can be view by using the average volts versus location of the weight. This is shown in Figure 21.

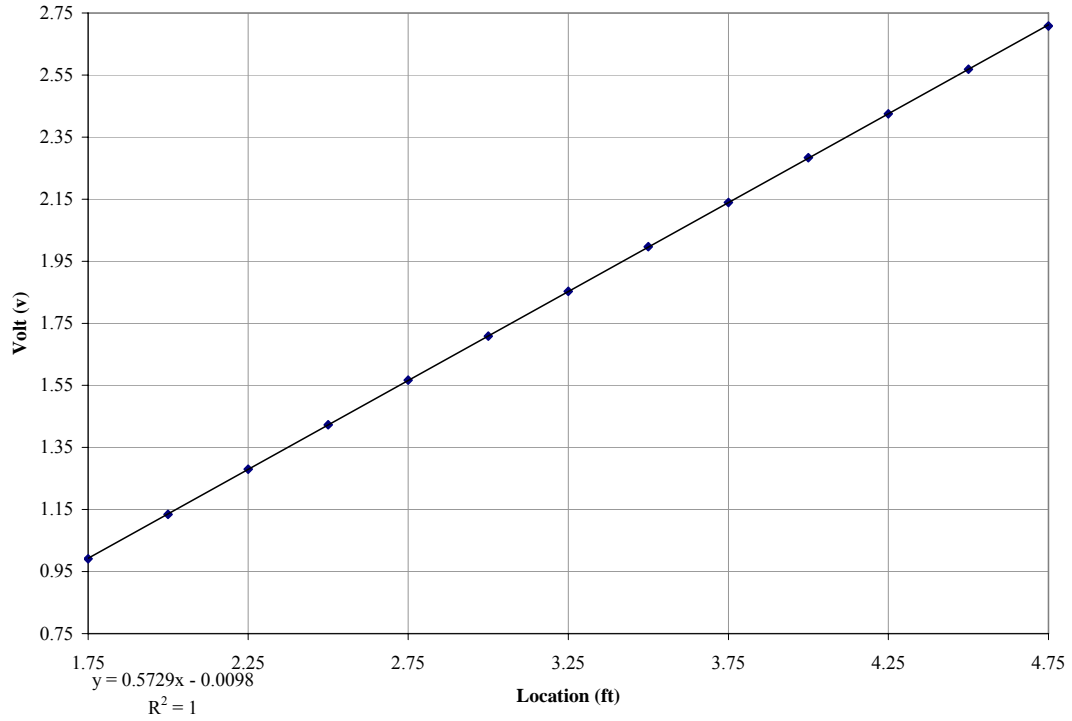


Figure 21: Torque Calibration – Volts vs Location

The linear relationship of the location to the voltage for the 105 pound object is given in Equation 32.

$$Volts = 0.5729(Location) - 0.0098 \quad (32)$$

Using the moment that the 105 pound weight causes, the calibration of the torque versus voltage is computed by a simple static equilibrium. The equation is the sum of the moment, which is shown in Equation 33.

$$\sum M_o = 0 \quad (33)$$

The calibration data for the torque is shown in Table XI.

Table XI: Torque Calibration - Moments/Volts

Location	Avg Volt	Moment
(ft)	(volt)	(lb-ft)
1.75	0.991167	183.75
2.00	1.1345	210
2.25	1.279833	236.25
2.50	1.423167	262.5
2.75	1.566833	288.75
3.00	1.708833	315
3.25	1.853	341.25
3.50	1.996833	367.5
3.75	2.139333	393.75
4.00	2.2835	420
4.25	2.424833	446.25
4.50	2.568667	472.5
4.75	2.708333	498.75

Table XI can be viewed as a graph that can show the relationship between torque to voltage, and this can be viewed in Figure 22.

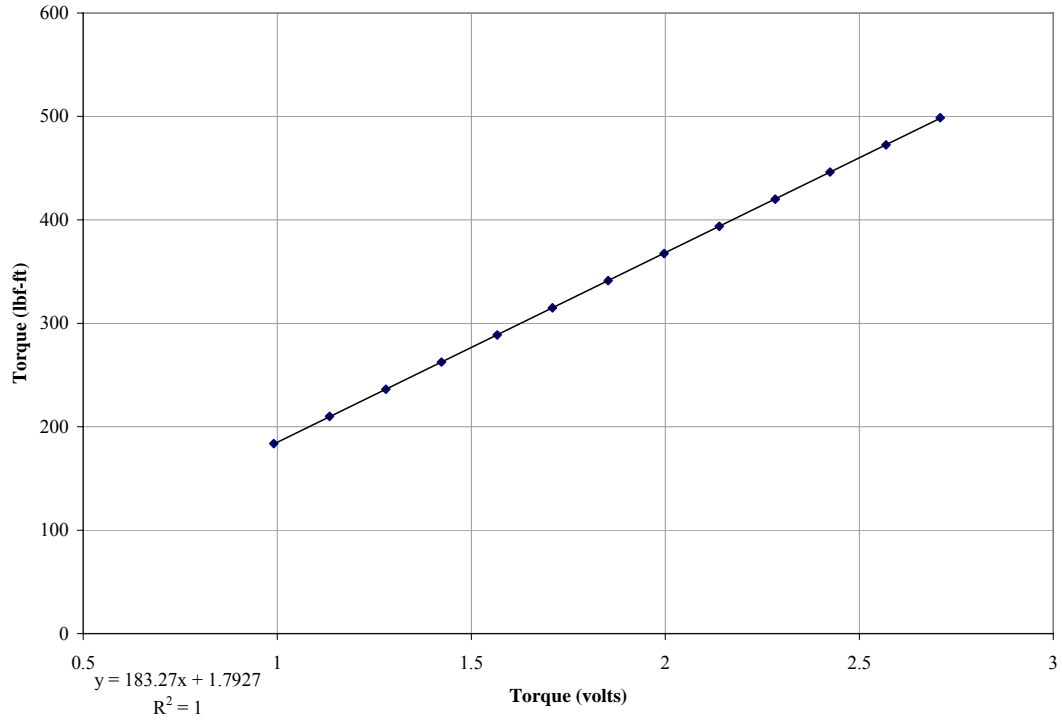


Figure 22: Torque Calibration – Torque/Moment vs Torque Volts

The equation to get the torque from the voltmeter is given in Equation 34.

$$\tau = 183.27(\text{Volts}) + 1.7927 \quad (34)$$

Equation 34 is important in determining the torque of the engine from the voltmeter.

3.1.1.2 Thrust Calibration

The thrust calibration started out like the torque calibration, by zeroing out the load cell and voltmeter. The leverage bar is replaced with a linear lever system. This can be seen in Figure 23.



Figure 23: Thrust Calibration Setup

The leverage bar has a moment arm of 1.25 to 3.25 feet. There is a pivot point and a turnbuckle on the leverage arm to create a linear action on the test stand. The turnbuckle is there to level the arm out and not make any moment on the system. Leveling the system is done with a level, and repeated every time the weight of 44 pounds is moved to a new location. The calibration started at 1.25 feet and increased by 0.25 feet until the outer most position is reached of 3.25 feet. The volt is recorded every position and then the weight is moved inward to 1.25 feet by 0.25 feet. The process is done three times to ensure the calibration is accurate. The voltage of the thrust calibration can be seen in Table XII.

Table XII: Thrust Calibration: Locations/Volts

Location	OUT	IN	OUT	IN	OUT	IN	AVERAGE
(ft)	(volt)	(volt)	(volt)	(volt)	(volt)	(volt)	(volt)
1.25	1.251	1.221	1.221	1.226	1.226	1.238	1.231
1.50	1.528	1.48	1.489	1.503	1.5	1.502	1.500
1.75	1.773	1.777	1.779	1.761	1.799	1.751	1.773
2.00	2.097	2.032	2.057	2.024	2.063	2.024	2.050
2.25	2.348	2.331	2.366	2.289	2.359	2.29	2.331
2.50	2.61	2.571	2.566	2.537	2.597	2.561	2.574
2.75	2.85	2.833	2.845	2.812	2.851	2.825	2.836
3.00	3.159	3.13	3.115	3.081	3.102	3.085	3.112
3.25	3.446	3.446	3.403	3.403	3.393	3.393	3.414

In Figure 24, thrust calibration for the voltmeter and the position of the 44 pound weight is shown.

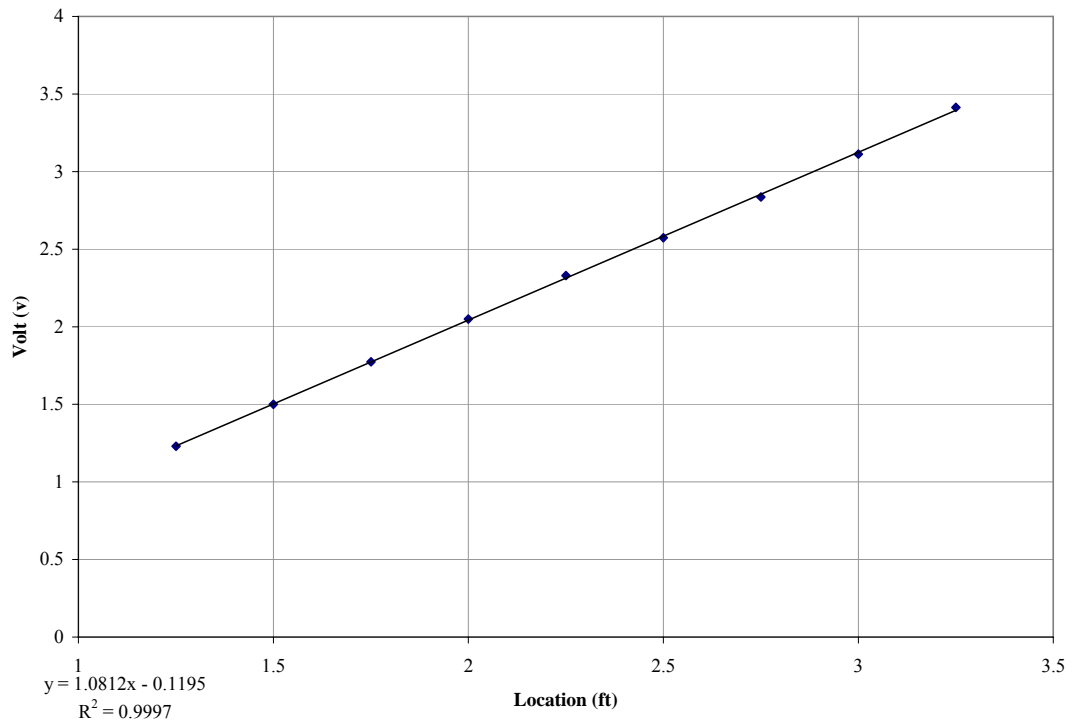


Figure 24: Thrust Calibration – Volts vs Location

The location of the 44 pound object to the measurement of the voltage is represented by Equation 35.

$$\text{Volts} = 1.0812(\text{Location}) - 0.1195 \quad (35)$$

The calibration of the thrust is done by using the sum of the moments on the thrust leveler arm. The equation for the sum of moment is shown in Equation 5. The data collected for the thrust calibration is shown in Table XIII.

Table XIII: Thrust Calibration Force/Volts

Location	Volt	Force
(ft)	(v)	(lbs)
1.25	1.231	220
1.50	1.500	264
1.75	1.773	308
2.00	2.050	352
2.25	2.331	396
2.50	2.574	440
2.75	2.836	484
3.00	3.112	528
3.25	3.414	572

The graph of the Table XIII can be seen in Figure 25.

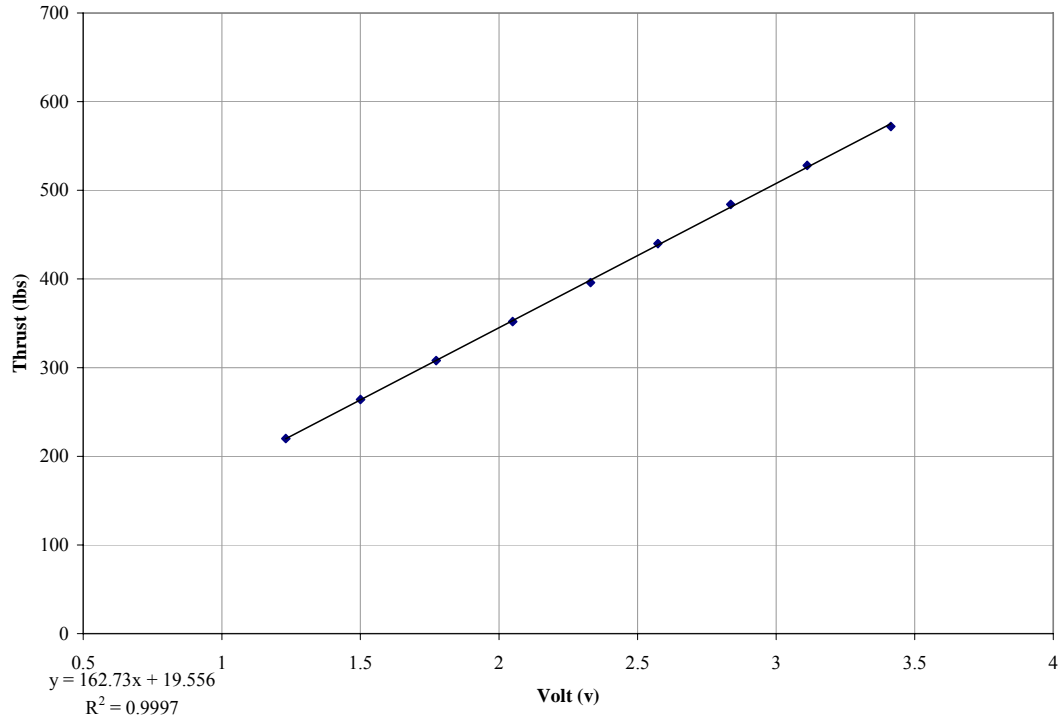


Figure 25: Thrust Calibration – Thrust/Force vs Thrust Volts

The following equivalence enables the thrust calculation from the voltage measurements, given in Equation 36.

$$F_T = 162.73(\text{Volts}) + 19.556 \quad (36)$$

3.1.2 Engine Performance Investigation

There are three engine performance tests to ensure repeatable and accurate numbers from the test data. These investigations main goal is to confirm the horsepower, torque, trust, fuel flow, propeller and engine rpm's with the manufacturer's data. The procedure for the three performance tests are the same. The procedure is shown as follows:

1. Engine Inspection
2. Engine Warm Up – 5 minutes
3. Begin Testing
 - a. Record Data at Load: 0 %
 - i. Recording Duration: 2 minutes
 - b. Record Data at Load: 10 %
 - i. Recording Duration: 2 minutes
 - c. Record Data at Load: 20 %
 - i. Recording Duration: 2 minutes
 - d. Record Data at Load: 30 %
 - i. Recording Duration: 2 minutes
 - e. Record Data at Load: 40 %
 - i. Recording Duration: 2 minutes
 - f. Record Data at Load: 50%
 - i. Recording Duration: 2 minutes
 - g. Record Data at Load: 60 %
 - i. Recording Duration: 2 minutes
 - h. Record Data at Load: 70 %
 - i. Recording Duration: 2 minutes
 - i. Record Data at Load: 80 %
 - i. Recording Duration: 2 minutes
 - j. Record Data at Load: 90 %
 - i. Recording Duration: 2 minutes
 - k. Record Data at Load: 100 %
 - i. Recording Duration: 2 minutes
4. Stop Recording
5. Engine Cool Down – 5 minutes
6. Engine Shutdown
7. Engine Inspection

In each test, the local barometric pressure and temperature were determined and recorded at the Lawrence Municipal Airport. The data was recorded by the engine FADEC system, from which the raw and analyzed data can be viewed in the Appendixes.

- Appendix E - Performance Investigation I
- Appendix F - Performance Investigation II
- Appendix G - Performance Investigation III

The analyzed data was simplified by averaging the raw data for each load range. For example, at load 10 % the fuel flow, engine, and propeller RPM was averaged occurring at the load position of 10 percent. This can be seen in Table XIV.

Table XIV: Average Data – Example for 10 % Load

	CED	FADEC	Engine	Prop	Fuel Flow A	Fuel Flow B
	(% Load)	(% Load)	(RPM)	(RPM)	(l/hr)	(l/hr)
Run One	10	12.40	1792.36	1059.70	2.79	3.01
Run Two	10	14.84	1844.68	1092.10	3.16	3.30
Run Three	10	13.87	1822.85	1079.21	3.06	3.20

In Table XIV, there is a mismatch in values for the CED’s load and FADEC’s load. The manufacturer informed the program of this problem, Thielert said to use the CED load percent over the FADEC for the testing of the engine. Figure 26 shows a graphical outlook of the problem with the CED and FADEC’s percent load mismatch.

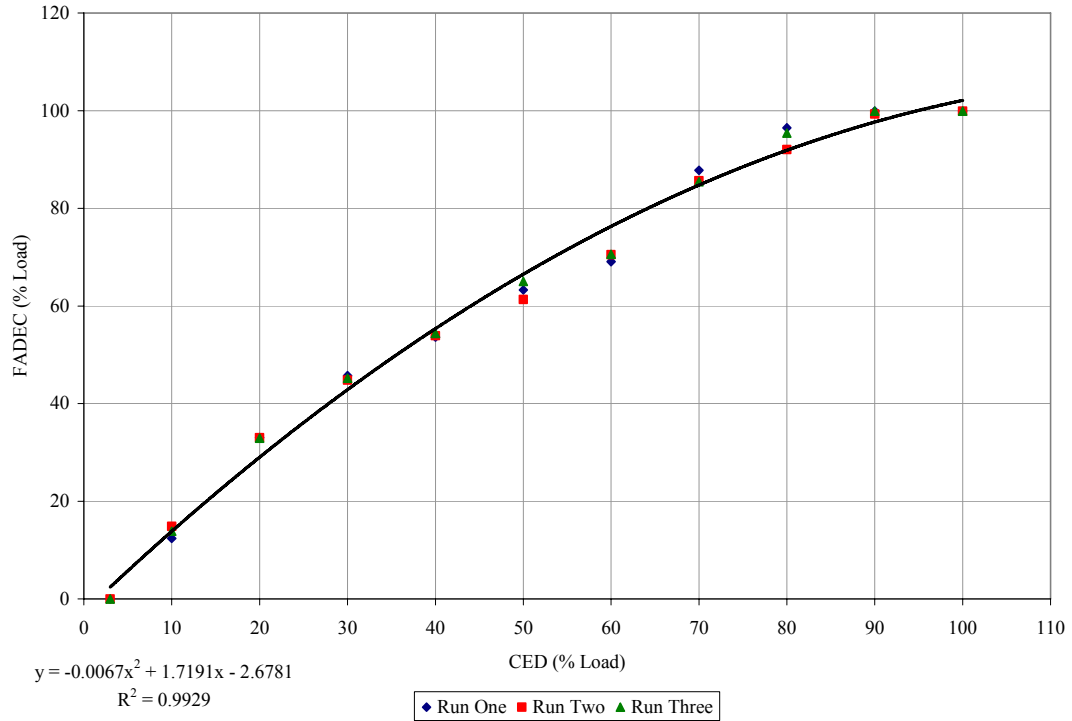


Figure 26: Load Comparison (FADEC vs CED)

At each percent of load the RPM of the engine and propeller was recorded to aid in calculating the horsepower of the engine. The RPM for the three test run can be seen in Figure 27 and 28.

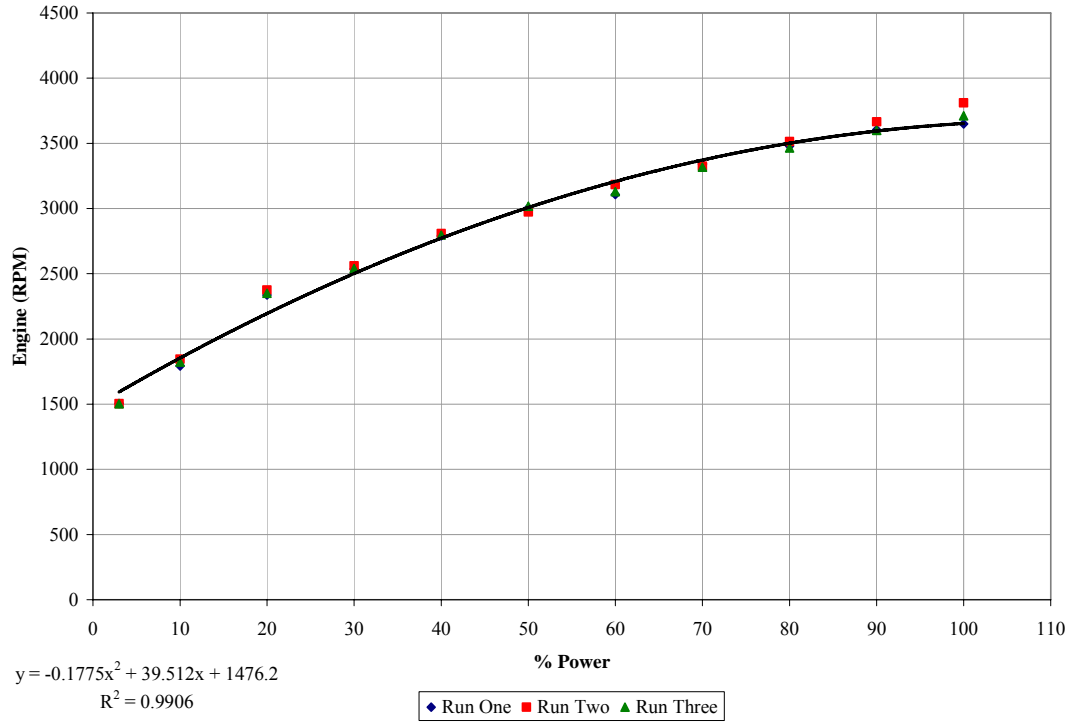


Figure 27: Engine's RPM Data

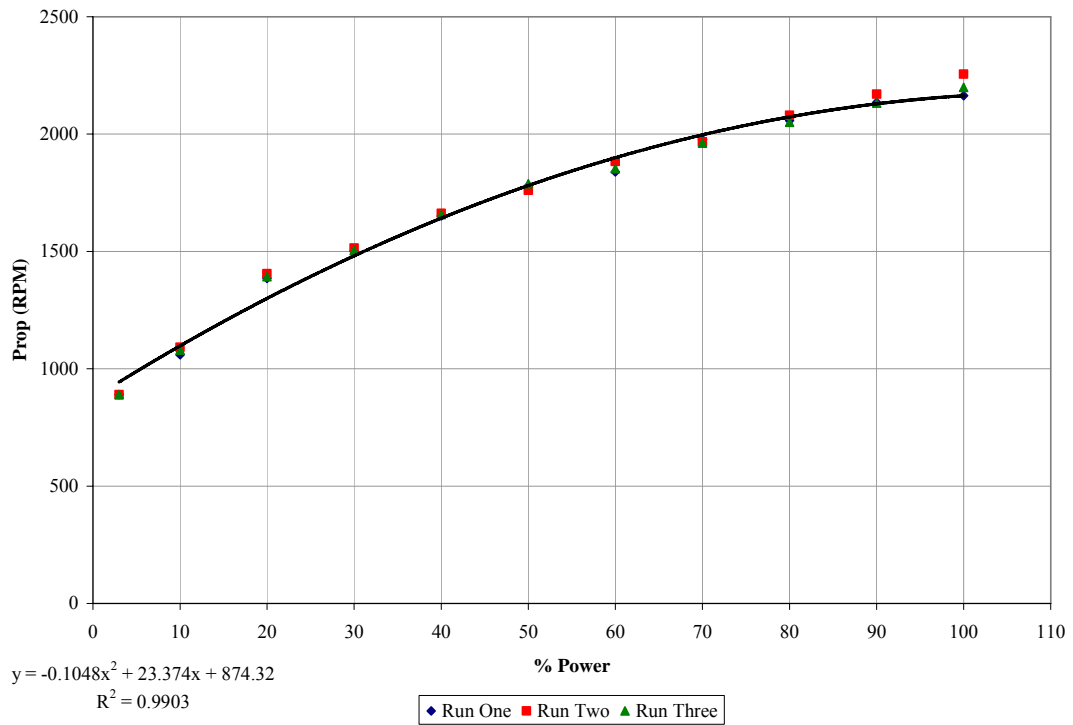


Figure 28: Propeller's RPM Data

The torque of the engine was recorded by hand using the voltmeter and torque load cell. At each load percent the voltage was recorded from the voltmeter. The torque of the engine was calculated by using the torque calibration data. Equation 34 converted the voltage that was collected to the desired torque units, (lbf-ft). The collected and converted data can be seen in Figure 29 for each run.

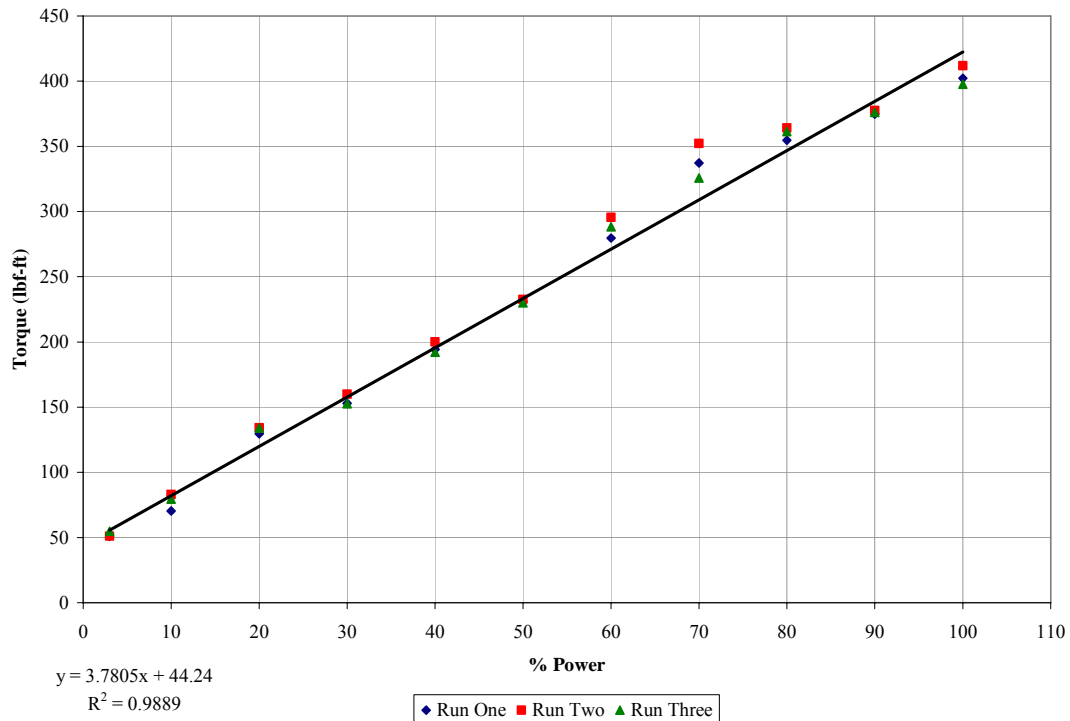


Figure 29: Torque Data

The torque and RPM of the propeller was needed to calculate the Brake Horsepower of the engine. Brake Horsepower (BHP) is a measure of an engine's horsepower without the loss in power caused by the gearbox, generator, differential, water pump and other auxiliaries. Brake refers to where the power is measured at the engine's output shaft. The actual horsepower delivered to the movement of the

aircraft has smaller amounts. The calculation for the brake horsepower of the Centurion was done by using Equation 37.

$$BHP = \frac{(\tau)x(rpm)}{5252} \quad (37)$$

The data for the brake horsepower is shown in Figure 30.

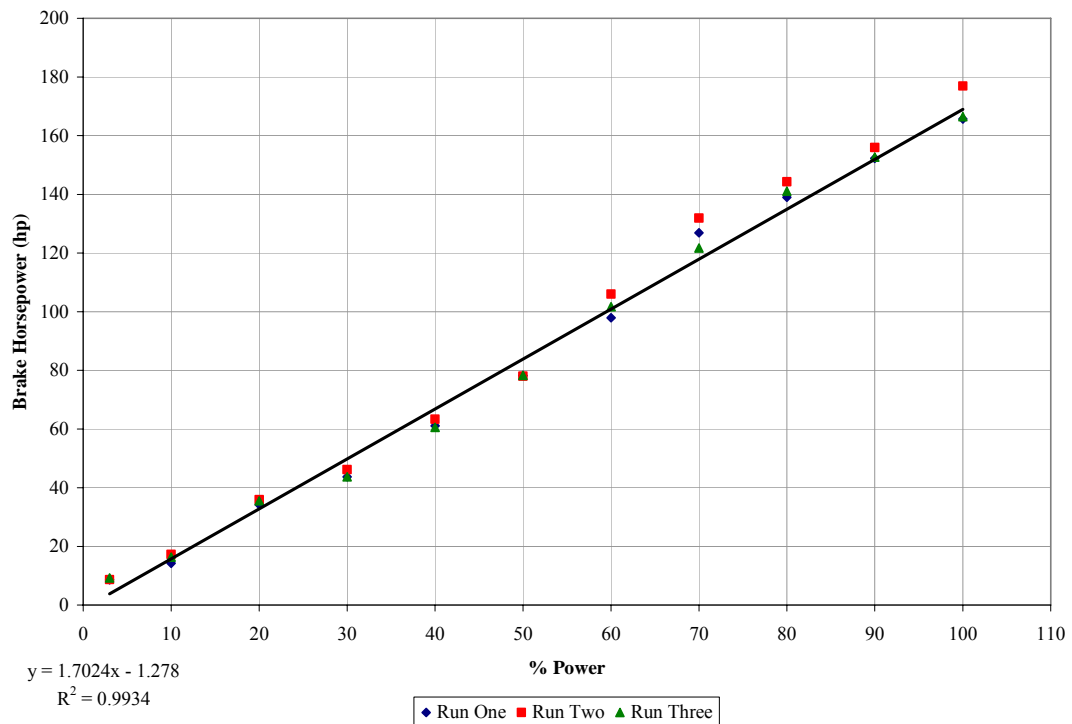


Figure 30: Brake Horsepower

The actual horsepower is also known as the Thrust Horsepower (THP). The thrust horsepower is calculated by the brake horsepower and propeller efficiency (η). Propeller efficiency refers to the percentage of Brake Horsepower (BHP) which gets converted into useful Thrust Horsepower (THP) by the propeller. The propeller is never 100% efficient. Therefore the propeller efficiency is always a number less than

one. The propeller efficient for the MT- Propeller can be found in Appendix C. An average number of 0.75 is taken for the propeller efficiency. The equation for propeller efficiency is shown in Equation 38.

$$\eta = \frac{THP}{BHP} \quad (38)$$

Using Equation 10 in section 2.1, the thrust horsepower can be calculated with Equation 39.

$$THP = BHP \times \eta \quad (39)$$

The data for the thrust horsepower can be seen in Figure 31.

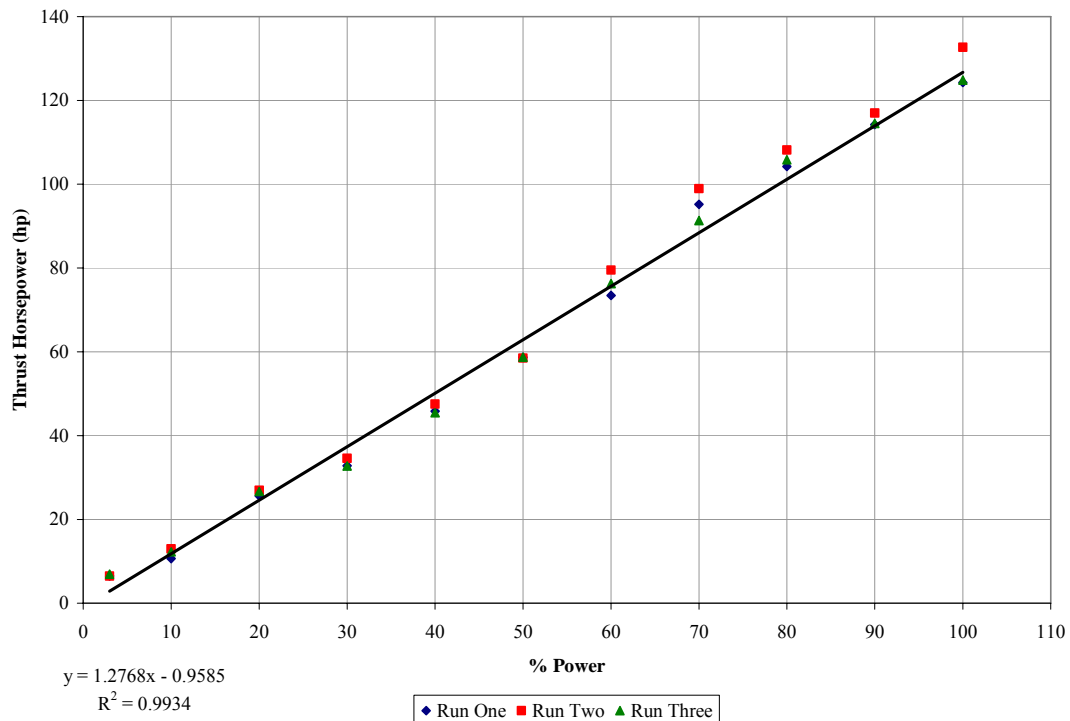


Figure 31: Thrust Horsepower

The thrust of the engine was also recorded by hand with the use of a voltmeter and thrust load cell. The voltage was collected at each load percent, and then converted to the corrected thrust units, (lbf). The converting formula is shown in Equation 36. The thrust data is shown in Figure 32 for each run.

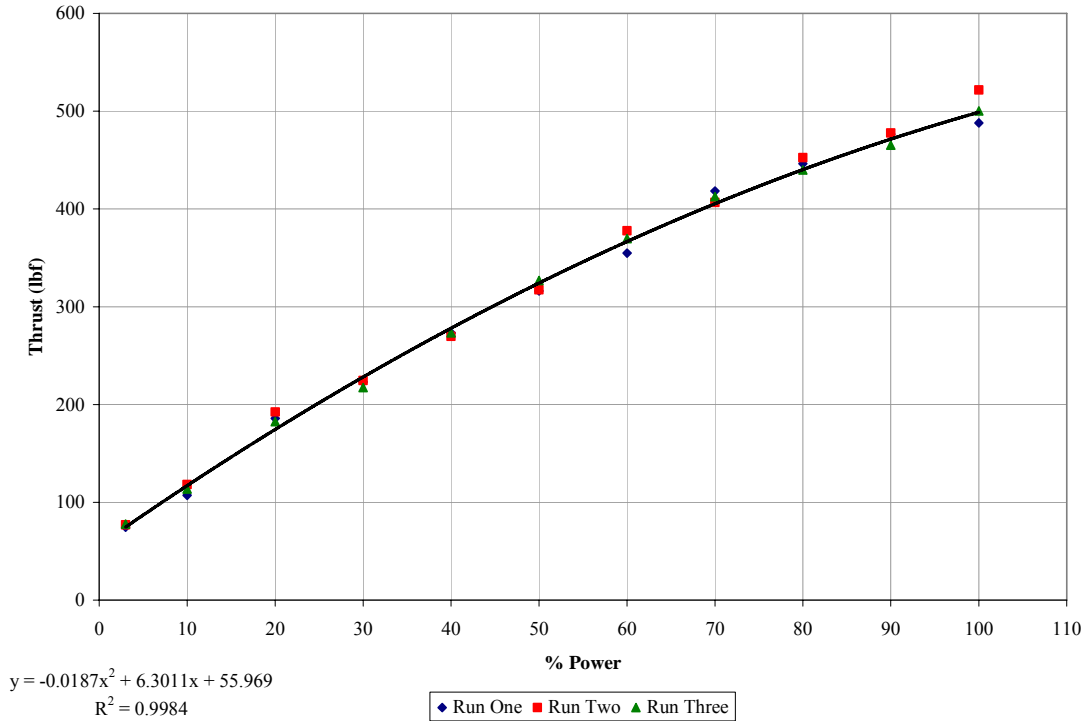


Figure 32: Thrust Data

The last data points that the FADEC system recorded was the fuel flow. The fuel flow of the engine is important in many aspects of performance and emissions. The fuel flow data is shown in Figure 33.

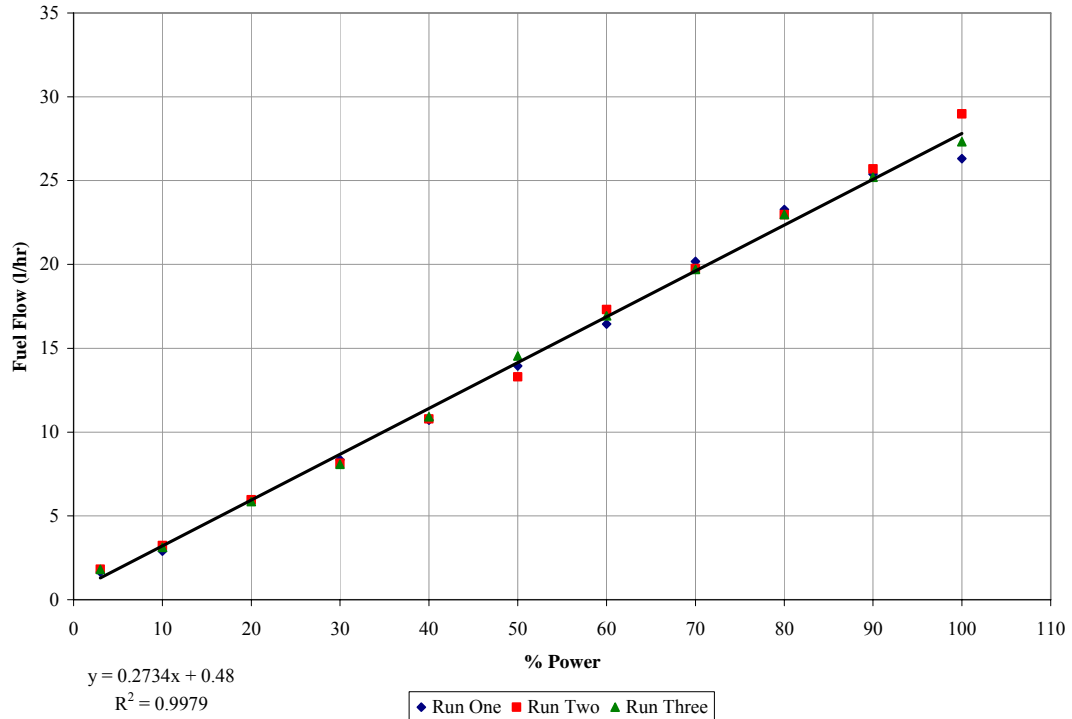


Figure 33: Fuel Flow Data

The fuel flow can determine the Specific Fuel Consumption by using the horsepower and thrust generated by the engine. Specific Fuel Consumption is a measure of the fuel consumed by an engine. There are two types of specific fuel consumption:

- Thrust Specific Fuel Consumption (TSFC)
- Power Specific Fuel Consumption (SFC)

The Power Specific Fuel and Consumption (SFC) can be calculated by using the THP and the fuel flow. The SFC formula is shown in Equation 40.

$$SFC = \frac{\dot{m}_f}{P} \quad (40)$$

The data for the SFC is shown in the Table XV - XVII and Figure 34.

Table XV: SFC Data - Run One

Load	Fuel Flow	THP	SFC
(%)	(lbm/hr)	(hp)	(lbm/hr/hp)
3	2.95	6.47	0.4554
10	5.16	10.64	0.4848
20	10.50	25.62	0.4097
30	14.87	32.80	0.4535
40	19.07	45.80	0.4164
50	24.82	58.66	0.4231
60	29.27	73.43	0.3986
70	35.92	95.18	0.3774
80	41.45	104.22	0.3977
90	45.21	114.22	0.3958
100	46.86	124.27	0.3771

Table XVI: SFC Data - Run Two

Load	Fuel Flow	THP	SFC
(%)	(lbm/hr)	(hp)	(lbm/hr/hp)
3	3.23	6.49	0.4981
10	5.75	12.94	0.4447
20	10.61	26.92	0.3940
30	14.49	34.59	0.4188
40	19.20	47.51	0.4042
50	23.67	58.50	0.4045
60	30.83	79.50	0.3878
70	35.17	98.94	0.3555
80	40.89	108.18	0.3780
90	45.75	116.98	0.3911
100	51.62	132.67	0.3890

Table XVII: SFC Data - Run Three

Load	Fuel Flow	THP	SFC
(%)	(lbm/hr)	(hp)	(lbm/hr/hp)
3	3.21	6.95	0.4622
10	5.57	12.25	0.4546
20	10.43	26.64	0.3916
30	14.39	32.76	0.4392
40	19.43	45.44	0.4276
50	25.89	58.72	0.4409
60	30.16	76.27	0.3955
70	35.09	91.30	0.3843
80	40.92	105.82	0.3867
90	44.86	114.52	0.3918
100	48.63	124.87	0.3895

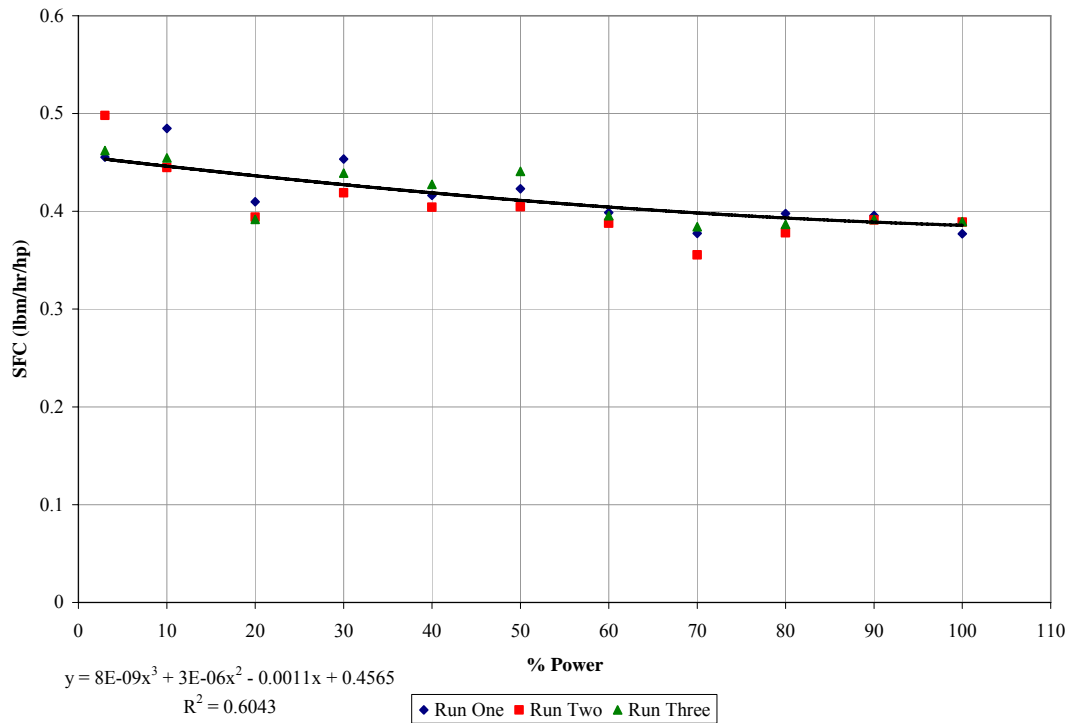


Figure 34: SFC Data

Furthermore, the SFC data shows a bucket shape contour; this is a normal trend as shown in Figure 35. Figure 36 shows experimental data in similar axis labels.

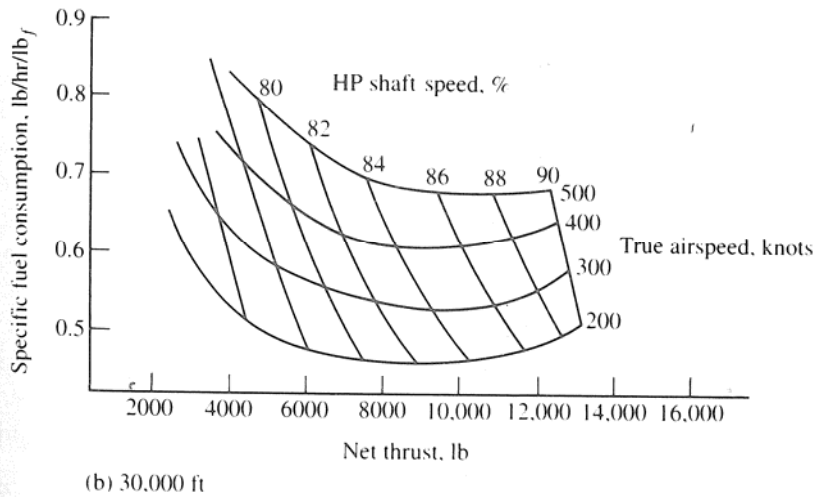
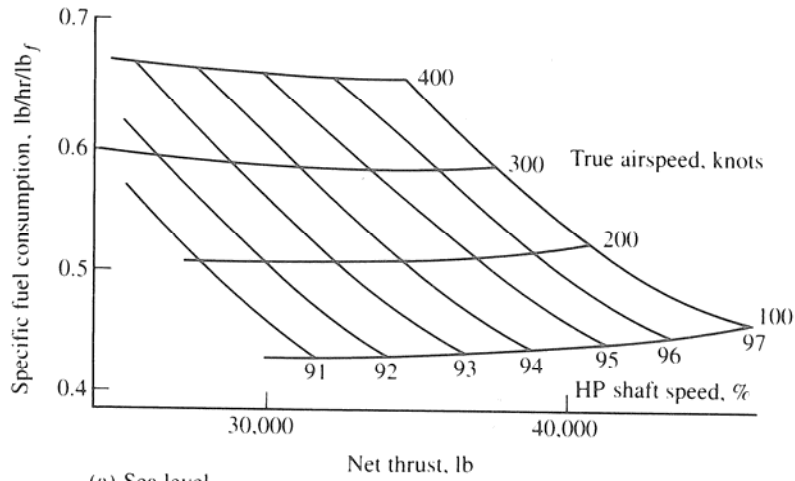


Figure 35: Specific Fuel Consumption – Curve [ref 28]

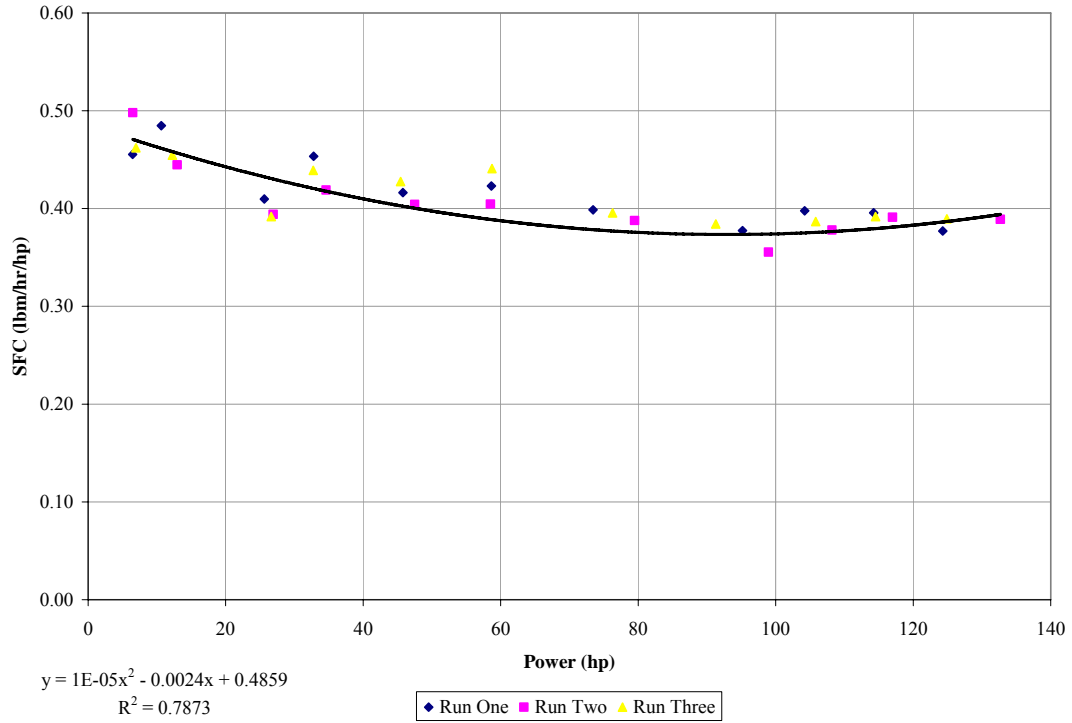


Figure 36: SFC vs Horsepower

The Thrust Specific Fuel Consumption (TSFC) is determined by using the thrust and the fuel flow. The equation for TSFC is shown in Equation 41.

$$TSFC = \frac{\dot{m}_f}{F_T} \quad (41)$$

The data for the TSFC is shown in Table XVIII - XX and Figure 37.

Table XVIII: TSFC Data - Run One

Load	Fuel Flow	Thrust	TSFC
(%)	(lbm/hr)	(lbf)	(lbm/hr/lbf)
3	2.95	74.56	0.0395
10	5.16	107.10	0.0482
20	10.50	185.87	0.0565
30	14.87	222.97	0.0667
40	19.07	273.41	0.0697
50	24.82	316.21	0.0785
60	29.27	354.78	0.0825
70	35.92	418.24	0.0859
80	41.45	446.23	0.0929
90	45.21	476.34	0.0949
100	46.86	487.89	0.0960

Table XIX: TSFC Data - Run Two

Load	Fuel Flow	Thrust	TSFC
(%)	(lbm/hr)	(lbf)	(lbm/hr/lbf)
3	3.23	77.00	0.0420
10	5.75	118.17	0.0487
20	10.61	192.38	0.0551
30	14.49	224.60	0.0645
40	19.20	269.83	0.0712
50	23.67	317.35	0.0746
60	30.83	377.72	0.0816
70	35.17	406.53	0.0865
80	40.89	452.42	0.0904
90	45.75	477.64	0.0958
100	51.62	521.58	0.0990

Table XX: TSFC Data - Run Three

Load (%)	Fuel Flow (lbm/hr)	Thrust (lbf)	TSFC (lbm/hr/lbf)
3	3.21	77.81	0.0413
10	5.57	113.61	0.0490
20	10.43	182.45	0.0572
30	14.39	217.44	0.0662
40	19.43	273.41	0.0711
50	25.89	326.95	0.0792
60	30.16	369.75	0.0816
70	35.09	412.55	0.0850
80	40.92	439.89	0.0930
90	44.86	465.27	0.0964
100	48.63	500.26	0.0972

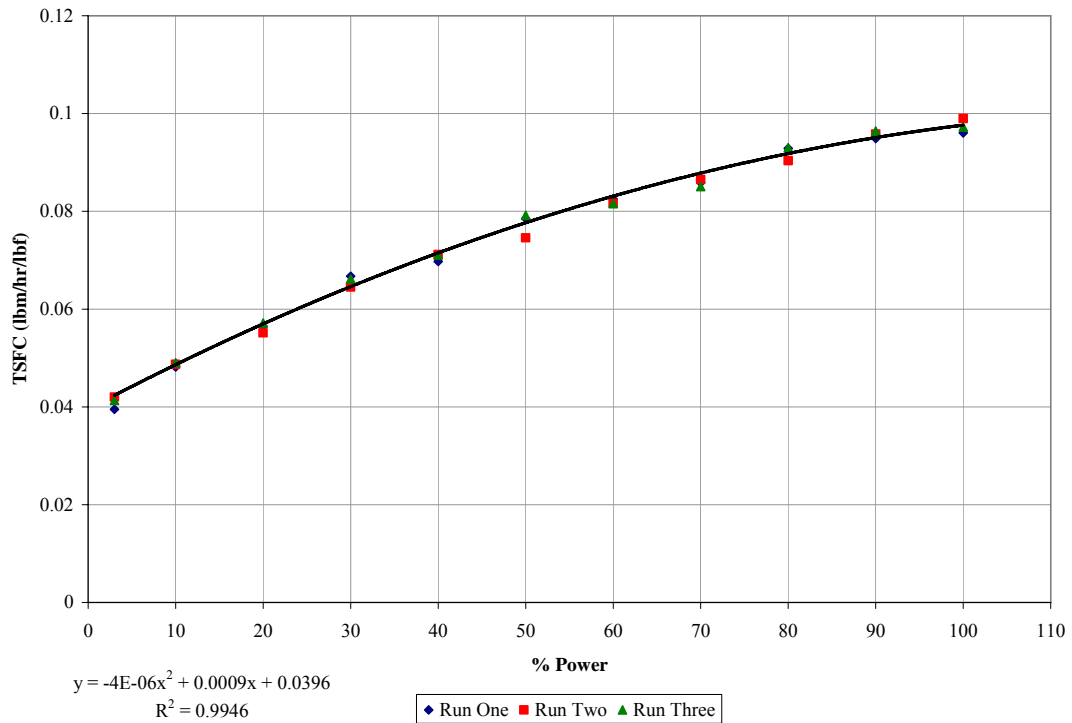


Figure 37: TSFC Data

3.1.3 Performance Data Comparison/Validation

The performance testing done at the University of Kansas Propulsion Laboratory confirms the performance data from Thielert. Table XXI shows the comparison of the test data to the manufacturer.

Table XXI: Performance Comparison

	University of Kansas	Thielert	% difference
Torque (lbf-ft)	403.95	411	1.73
Horsepower (hp)	127.27	135	1.96
Thrust (lbf)	503.24	550	2.96
Engine (rpm)	3724.37	3900	1.54
Prop (rpm)	2205.95	2300	1.39
Gear Ratio	1.688	1.69	0.03
SFC (lbm/hr/hp)	0.3852	0.36	2.25

The performance testing at Mal Harned Propulsion Laboratory was to confirm the performance data of the Thielert Centurion 1.7. In the overview the test found that the University of Kansas numbers are very similar to the manufacturer data. The percent difference could be because of the height above sea level of test laboratories and the environmental conditions.

Correction Factor

The experimental data must be corrected for a standard day and altitude for differences in the manufacturer and tested numbers. The correction factor for air density is for an altitude over 1500 ft; Lawrence, Kansas is at an elevation of 840 ft. There is no correction factor needed for altitude. The standard day correction factor is needed, because testing was done in winter conditions. The Society of Automotive Engineers (SAE) has created a standard method for correcting horsepower and torque

readings so that they will seem as if the readings had all been taken at the same standard test cell where the air pressure, humidity and air temperature are held constant. The equation for the dyno correction factor which is given in SAE J1349 JUN90 is shown in Equations 42 - 45.

$$cf = 1.18 * \left(\frac{\sqrt{\theta}}{\delta} \right) - 0.18 \quad (42)$$

$$\delta = \frac{P_a}{P_{a\ std}} \quad (43)$$

$$\theta = \frac{T_a}{T_{a\ std}} \quad (44)$$

$$cf = 1.18 * \left(\frac{990}{P_d} * \sqrt{\frac{T_c + 273.15}{298}} \right) - 0.18 \quad (45)$$

Where *cf* is the correction factor, P_d is the dry pressure (mbar), and T_c is the temperature. Table XXII shows the pressures, temperatures, and correction factor recording of the test day. Table XXIII is the corrected performance comparison for the Torque, Horsepower, and Thrust.

Table XXII: Correction Factor Data

Temperature	1	°C
Pressure	30.03	inHg
Dew Point	-2	°C
Vapor Pressure	0.16	inHg
Dry Pressure	29.87	inHg
cf	0.9277	

Table XXIII: Corrected Performance Comparison

	University of Kansas	Thielert	% difference
Torque (lbf-ft)	435.42	411	1.92
Horsepower (hp)	137.19	135	0.54
Thrust (lbf)	542.45	550	0.46
Engine (rpm)	4014.50	3900	0.96
Prop (rpm)	2377.80	2300	1.11
Gear Ratio	1.82	1.69	2.47
SFC (lbm/hr/hp)	0.42	0.36	4.75

The numbers from the correction factor shows that the data recorded was closer than before for the Horsepower Thrust, and Prop. The other parameters are higher than previously, but still in the acceptable margin. Overall, the performance investigation was precise and successful.

3.2 Engine Emission

There is an email to ensure that all data presented in the emission investigation session was approved by the manufacturer in order with the contract.

3.2.1 Engine Emission Investigation

The emission investigation was performed by six emission test. Six tests were chosen to make sure that all emission was precise and duplicated. The emission investigation obligation is to look at the gaseous emission of the Thielert's Centurion 1.7 engine. The emission data was accumulated by the SEMTECH-DS and the pollutants are CO, CO₂, NO, NO₂, O₂, THC, and H₂O. The procedure for the six emission investigations are shown as follows:

1. Engine Inspection
2. Engine Warm Up – 5 minutes

3. Begin Testing
 - a. Record Data at Load: 0 % (idle)
 - i. Recording Duration: 5 minutes
 - b. Record Data at Load: 20 % (high idle)
 - i. Recording Duration: 5 minutes
 - c. Record Data at Load: 50 % (cruise)
 - i. Recording Duration: 5 minutes
 - d. Record Data at Load: 100 % (max)
 - i. Recording Duration: 5 minutes
4. Stop Recording
5. Engine Cool Down
6. Engine Shutdown – 5 minutes
7. Engine Inspection

The emission testing was done by using the probe system of the SEMTECH-DS. An extension was added to the exhaust pipe to keep the probe from over heating. The probe was placed inside the extended exhaust pipe of the Centurion; this can be seen in Figure 38.



Figure 38: Probe Setup

The probe's head was located about 12 inches from the exit plane of the exhaust pipe, ensuring accurate measurements of the exhaust gases. The probe was connected

to the SEMTECH-DS by grayish sample hose; this can also be seen in Figure 38.

The setup flow diagram is shown in Figure 39.

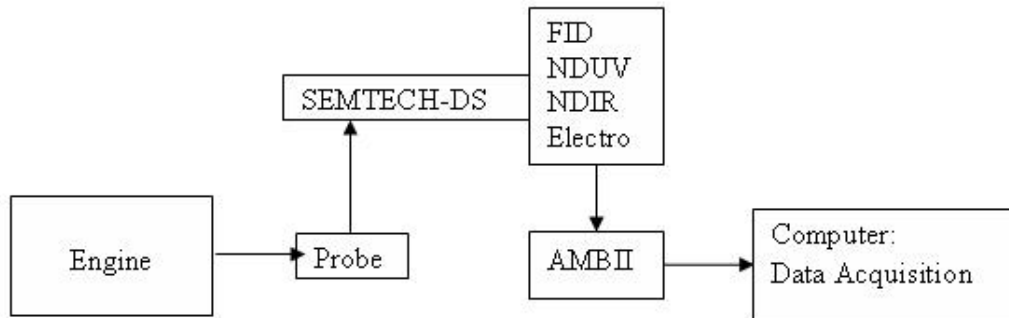


Figure 39: SEMTECH Flow Diagram

The local barometric pressure and temperature were determined and recorded by the Lawrence Municipal Airport for each run. The engine and emissions data was recorded by the FADEC and SEMTECH-DS system, which the raw and analyzed data can be viewed in the Appendixes.

- Appendix H - Emission Investigation I
- Appendix I - Emission Investigation II
- Appendix J - Emission Investigation III
- Appendix K - Emission Investigation IV
- Appendix L - Emission Investigation V
- Appendix M - Emission Investigation VI

The analyzed data was simplified by averaging the raw data for each situation, just as the performance investigations. The engine data include the RPM's, fuel flow, air to fuel ratio, and exhaust temperature. Each engine data is compared to the CED load,

to make the correlation with the emission data. The engine and prop RPM can be found in Figure 40 and 41.

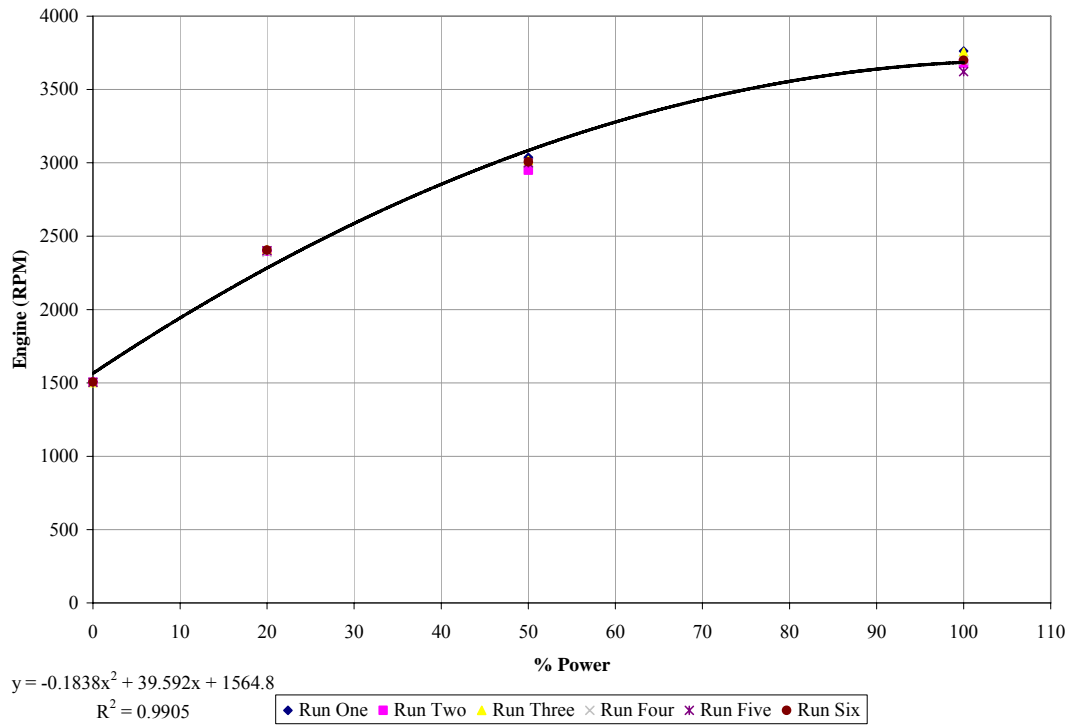


Figure 40: Engine's RPM - Emission Testing

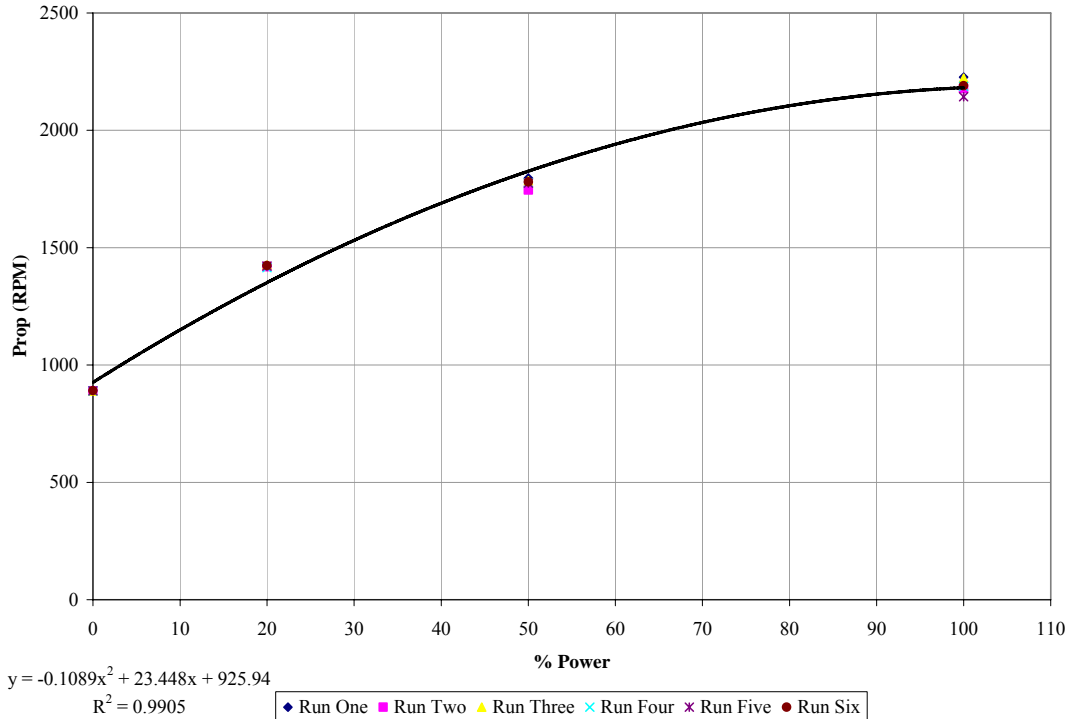


Figure 41: Prop's RPM - Emission Testing

The air-fuel ratios and fuel flow of the engine is given in Figure 42 to 44. The air-fuel ratio (AFR) is the mole ratio of air to fuel present during combustion. AFR is an important measure for anti-pollution and performance tuning. When all the fuel is combined with all the free oxygen, typically within a vehicle's combustion chamber, the mixture is chemically balanced and this AFR is called the stoichiometric mixture. The stoichiometric AFR was found to be around 14.5 for JET-A. Lambda (λ) or air to fuel equivalence ratio is an alternative way to represent the air-fuel ratio. Lambda shows if the combustion is lean or rich, the engine was lean throughout the investigations. Lean is where lambda is greater than one and when lambda is less than one the combustion is rich. If lambda is equal to one, the chemical reaction is stoichiometric. The equation for lambda is shown in Equation 13.

$$\lambda = \frac{AFR}{AFR_{stoichiometric}} \quad (13)$$

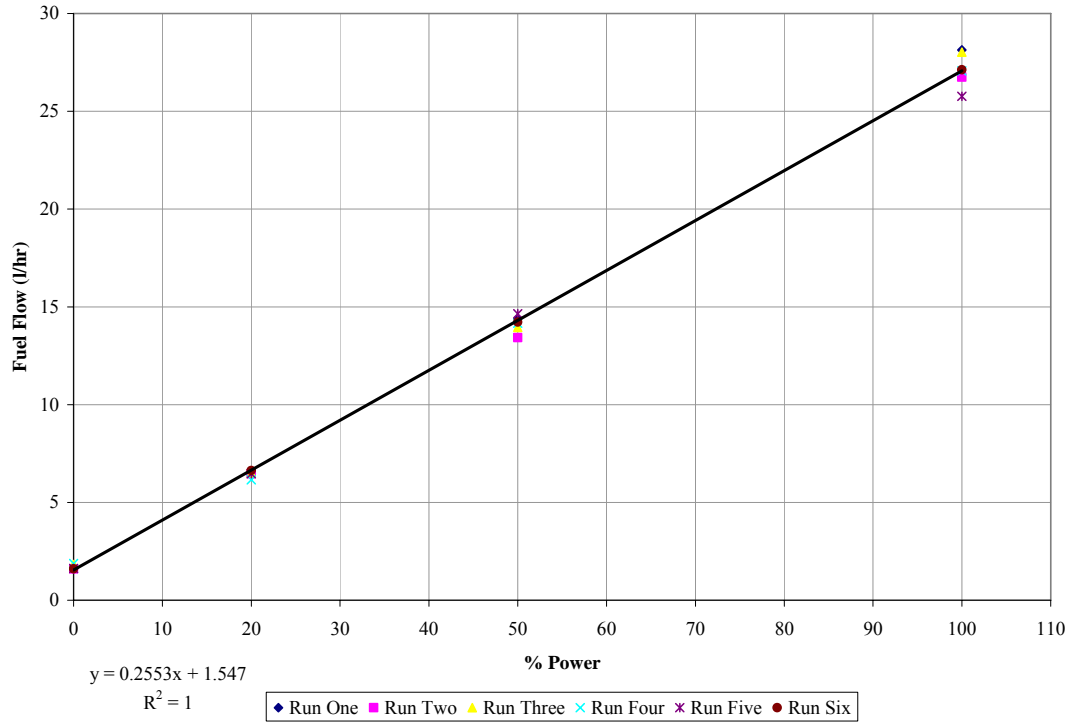


Figure 42: Fuel Flow - Emission Testing

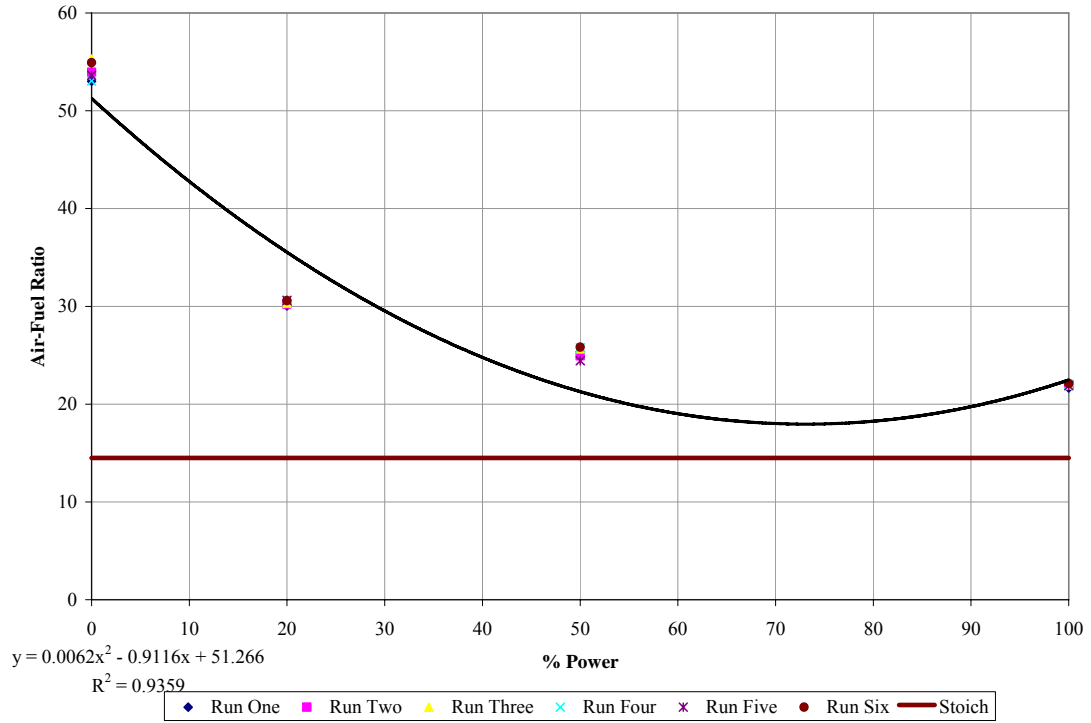


Figure 43: Air-Fuel Ratio

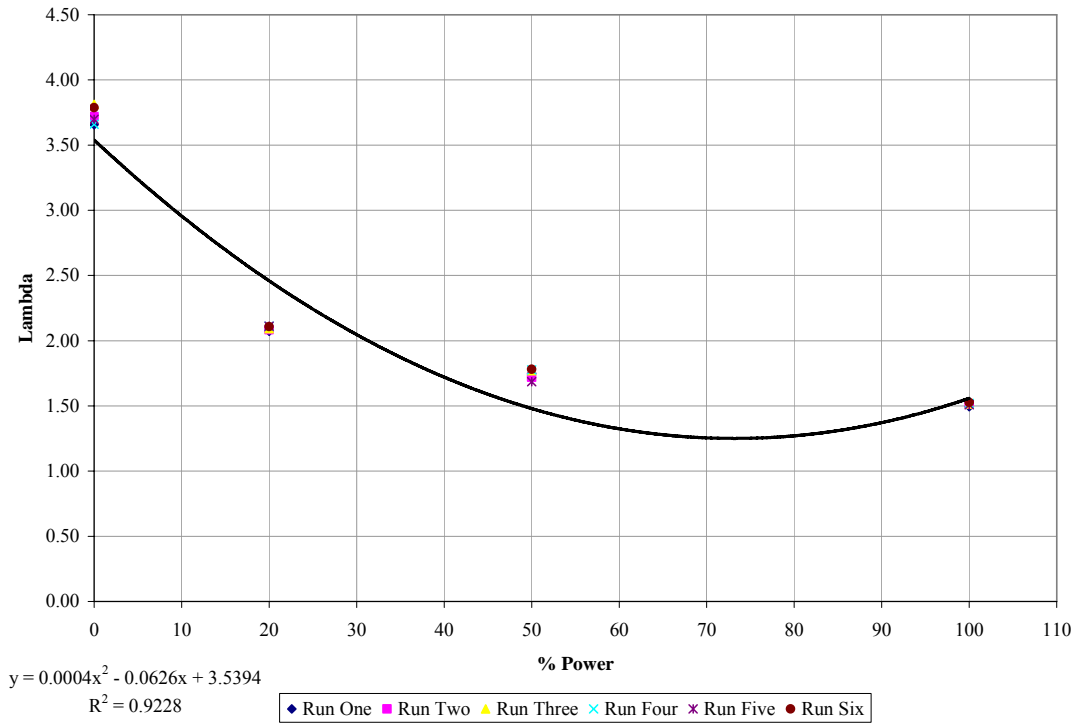


Figure 44: Air-Fuel Ratio - Lambda

During the testing with the flow meter device for the SEMTECH, the silicon pipe (that collected the exhaust for the flow meter) melted from the extreme heat of the exhaust. The probe test was the main source of all the data, but exhaust temperature was calculated from an auxiliary temperature probe. The temperature of the exhaust can be viewed in Figure 45.

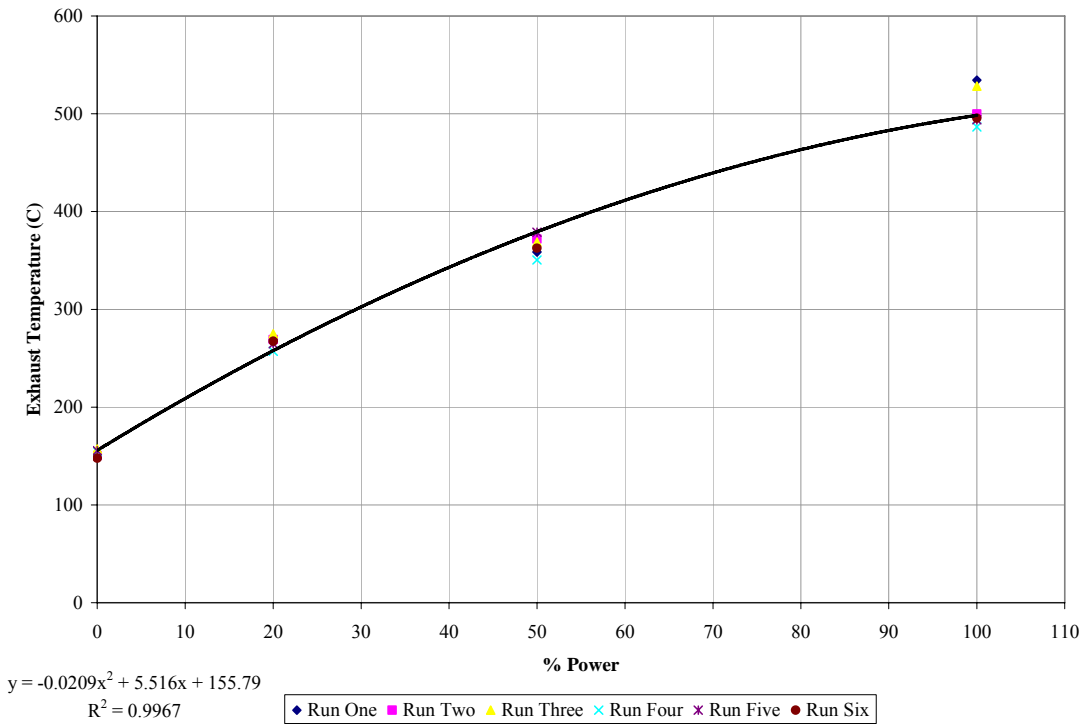


Figure 45: Exhaust Temperature

The emission data was collected in percent (%), parts-per million, and mass (g/kg-fuel). The carbon oxides and oxygen are presented in percent and mass units, while the other pollutants are given in parts-per million and mass units. Figure 46 to 49 shows the carbon oxides data for the six investigations.

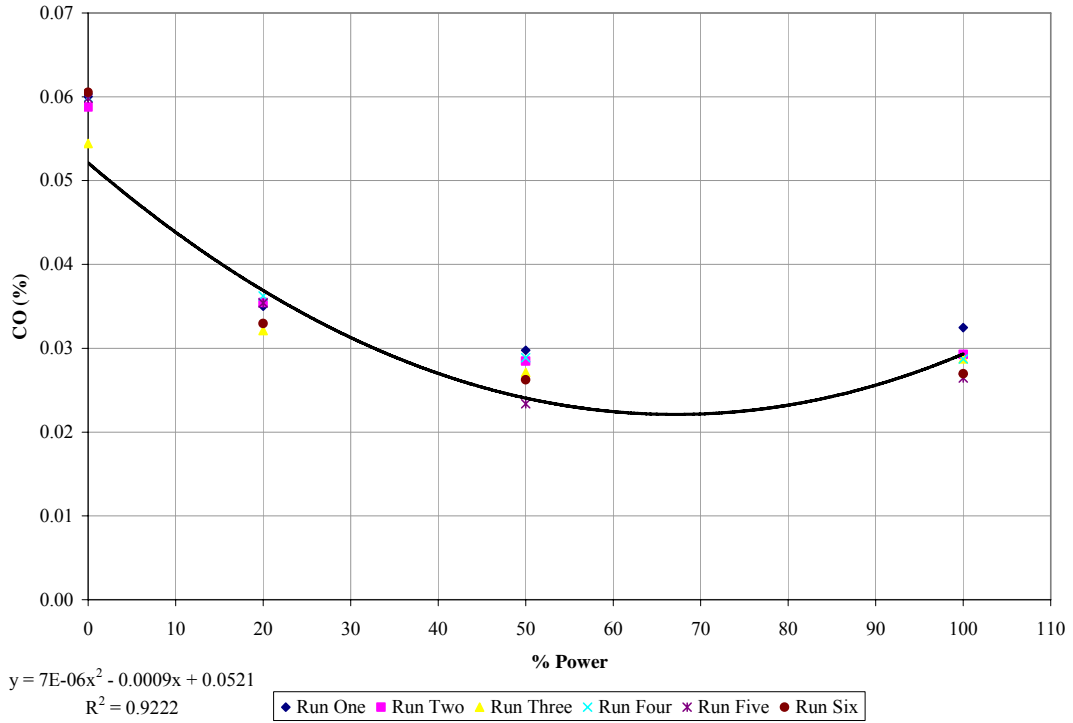


Figure 46: Carbon Monoxide - Percent

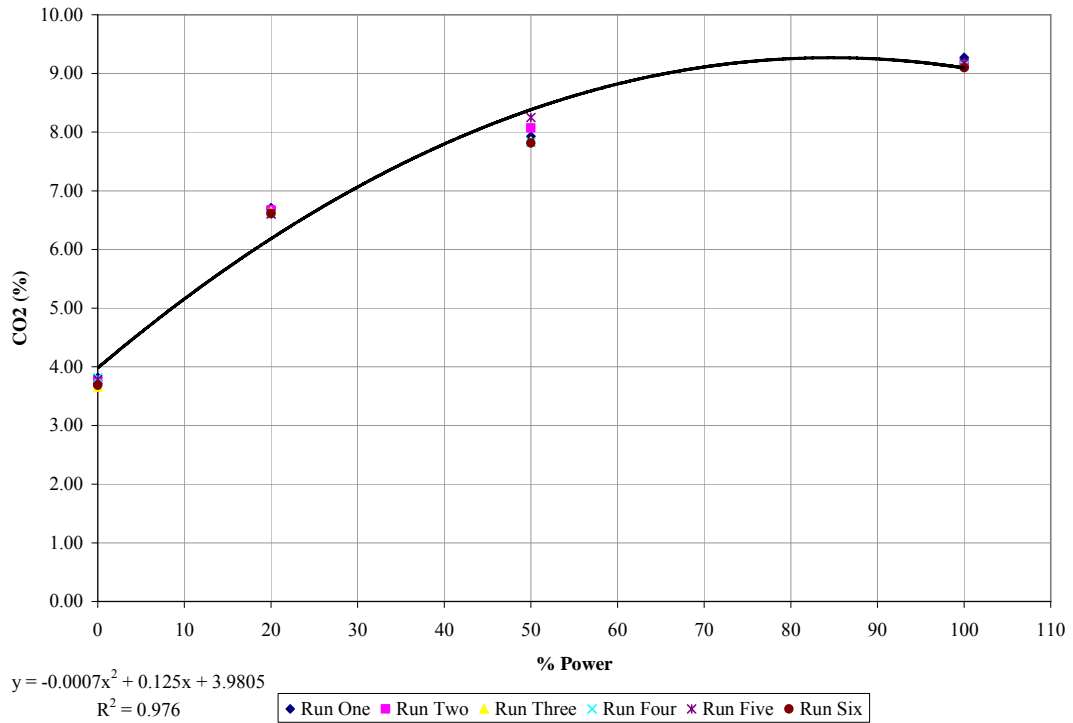


Figure 47: Carbon Dioxide – Percent

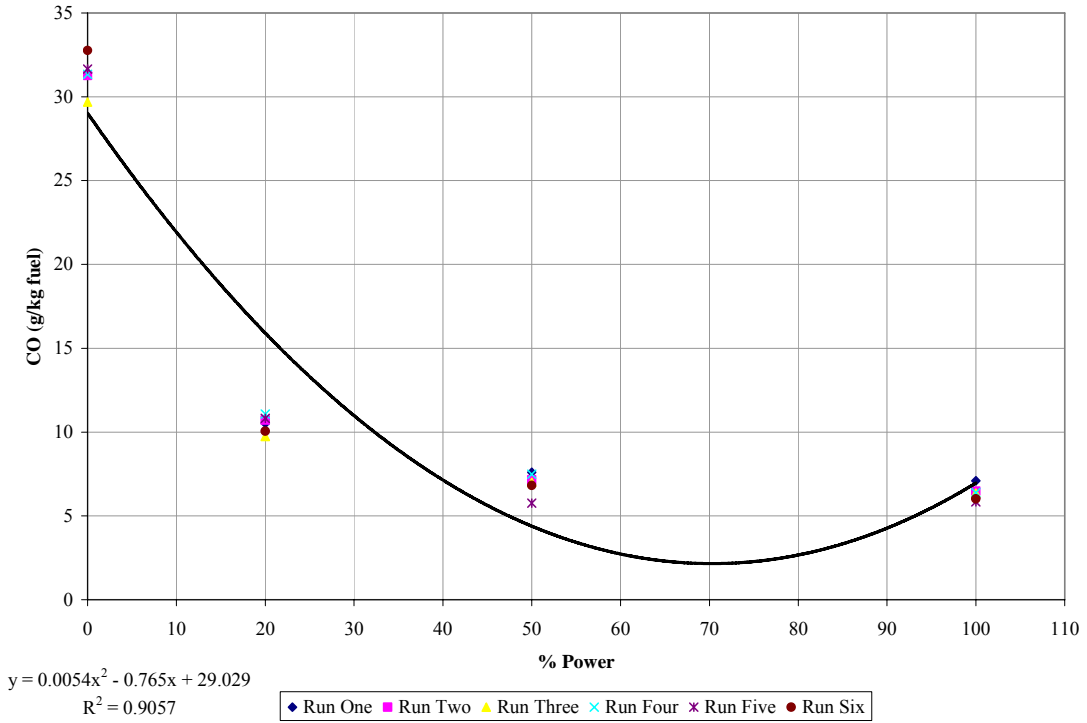


Figure 48: Carbon Monoxide - Mass

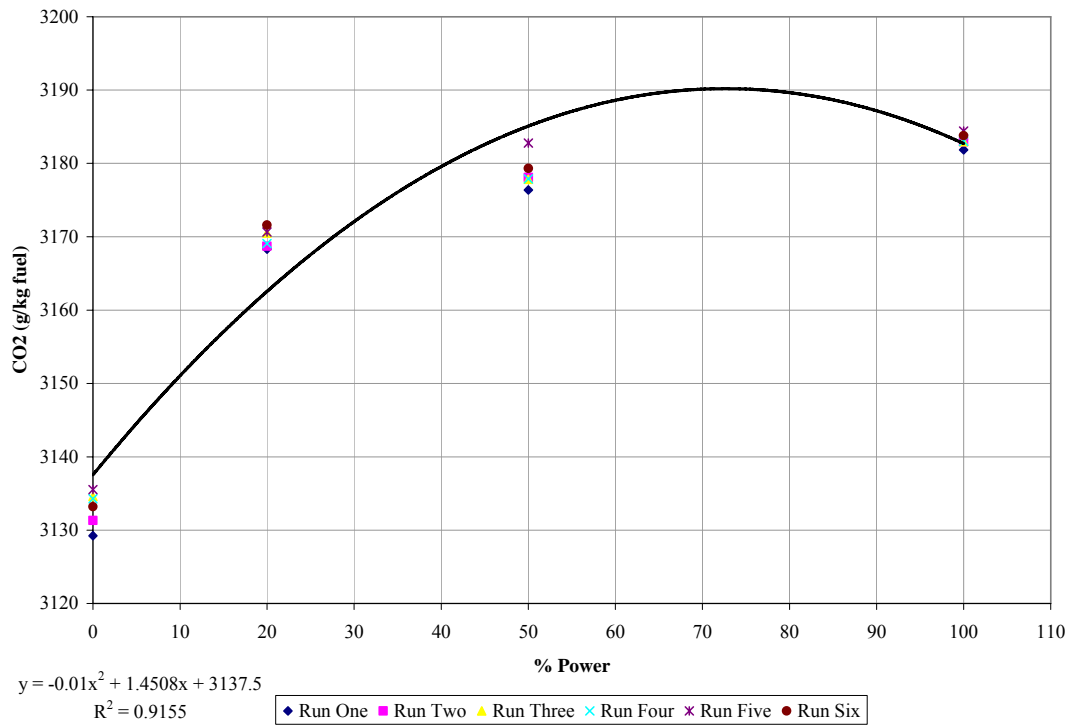


Figure 49: Carbon Dioxide - Mass

The carbon oxides figures show that as the load increase, the CO decreasing while the CO₂ is increasing. This happens to the triple and double bond of the carbon oxides. Carbon Monoxide has a triple bond and Carbon Dioxide has a double bond. A double bond is stronger than a single bond, and similarly a triple bond is stronger than a double bond, which means there must be more energy to break and form the triple bond. The kinetic energy of the atoms is amplified as the fuel increase at 100 percent, but the air to fuel ratio is still above the limit to make CO₂ primarily. If there is a limited supply of air (only half as much oxygen is added to the carbon) and temperature above 800 °C, carbon monoxide is formed mainly. Therefore, carbon dioxide is stealing all the oxygen atoms in the system as the load is augmented. This can be seen in the oxygen figures and nitrogen oxide figures. Figures 50 to 51 show the oxygen percent and mass as the load is increase.

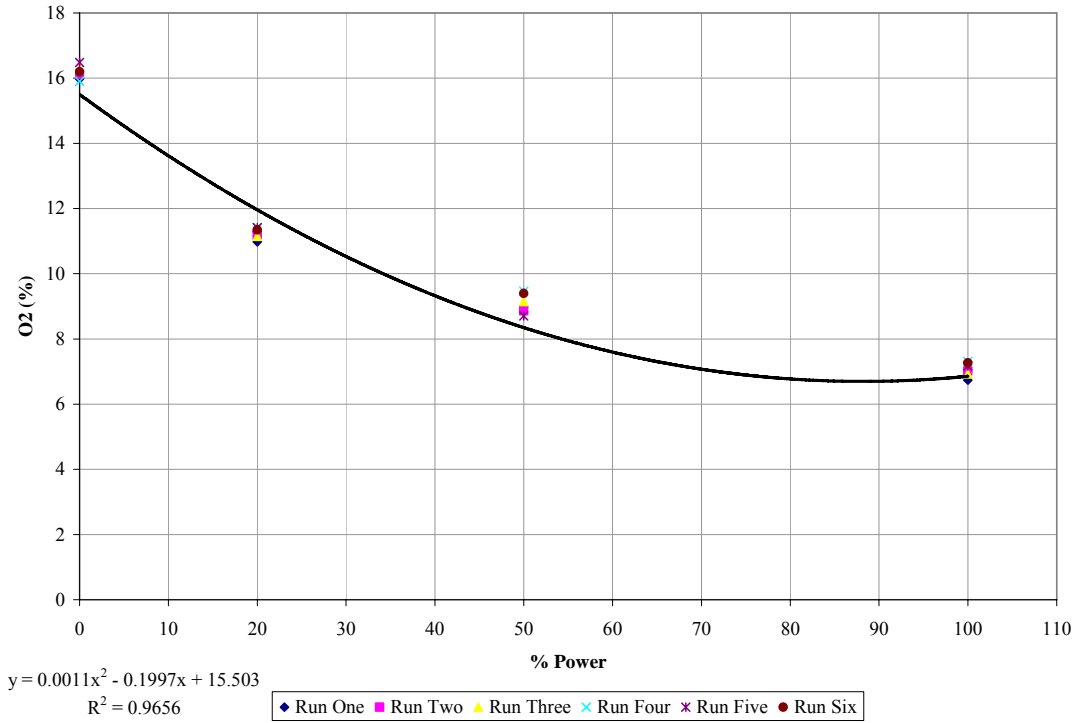


Figure 50: Oxygen - Percent

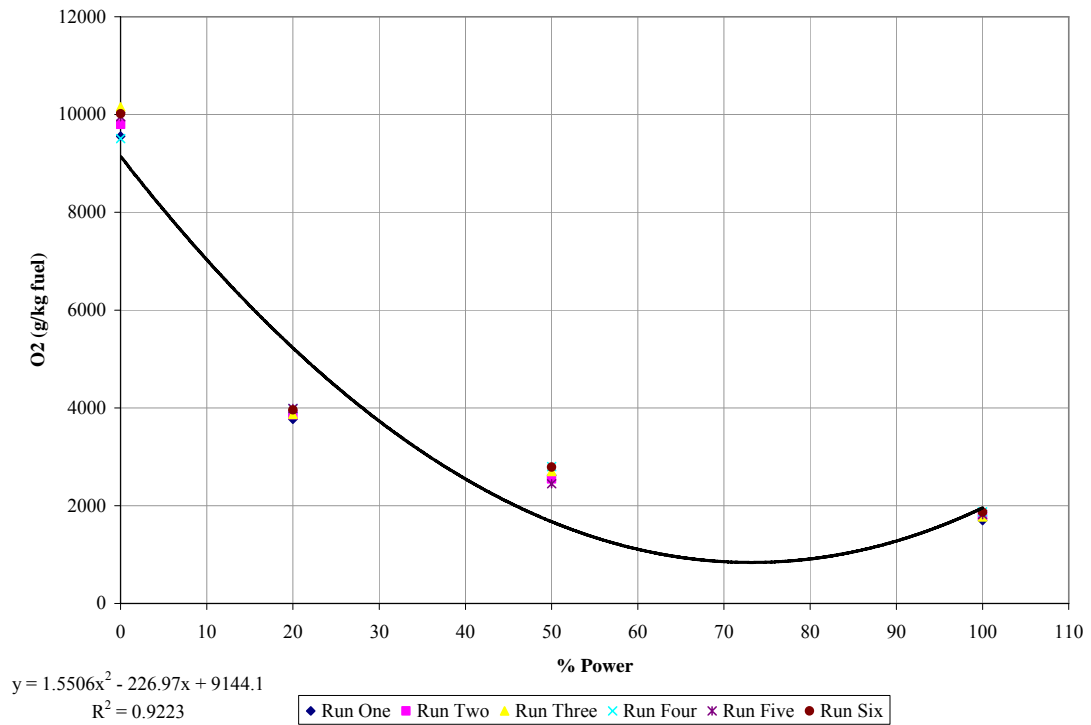


Figure 51: Oxygen - Mass

Nitrogen oxide is not part of the atmosphere normal compounds, from a thermodynamic perspective the conversion from Nitrogen and Oxygen is a very slow process at ambient temperature. The heat in order to form nitrogen oxides is endothermic and the synthesis of the molecular nitrogen and oxygen requires elevated temperatures more or less of 1000 °C. Figures 52 to 57 show the emission of the nitrogen oxide compounds.

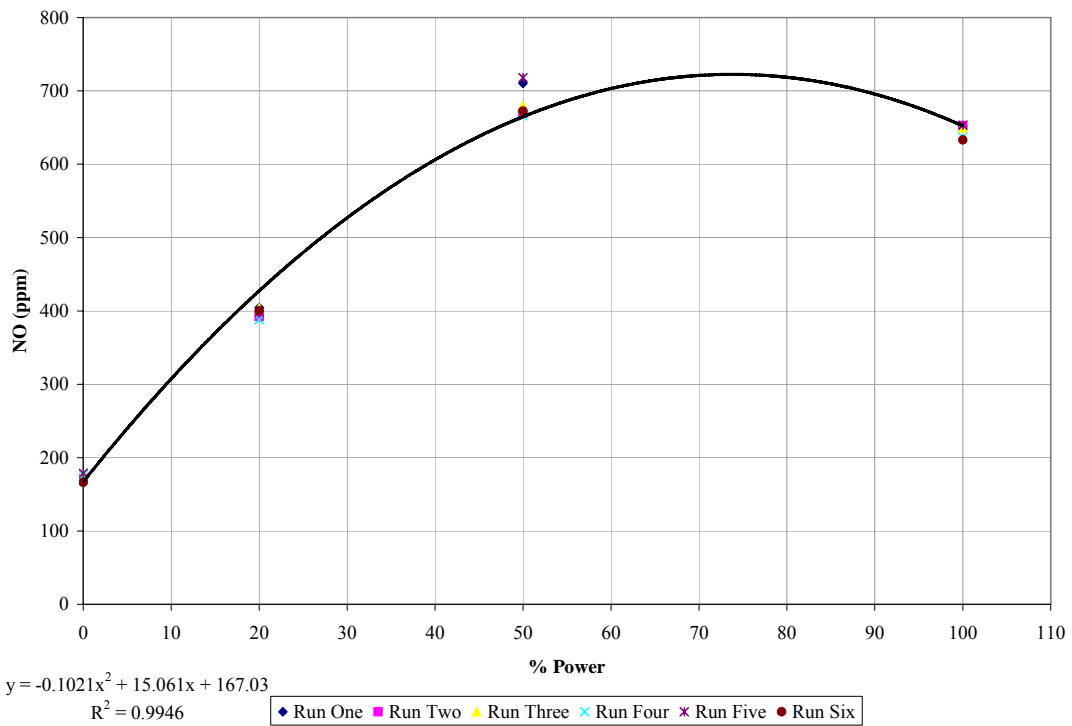


Figure 52: Nitric Oxide – ppm

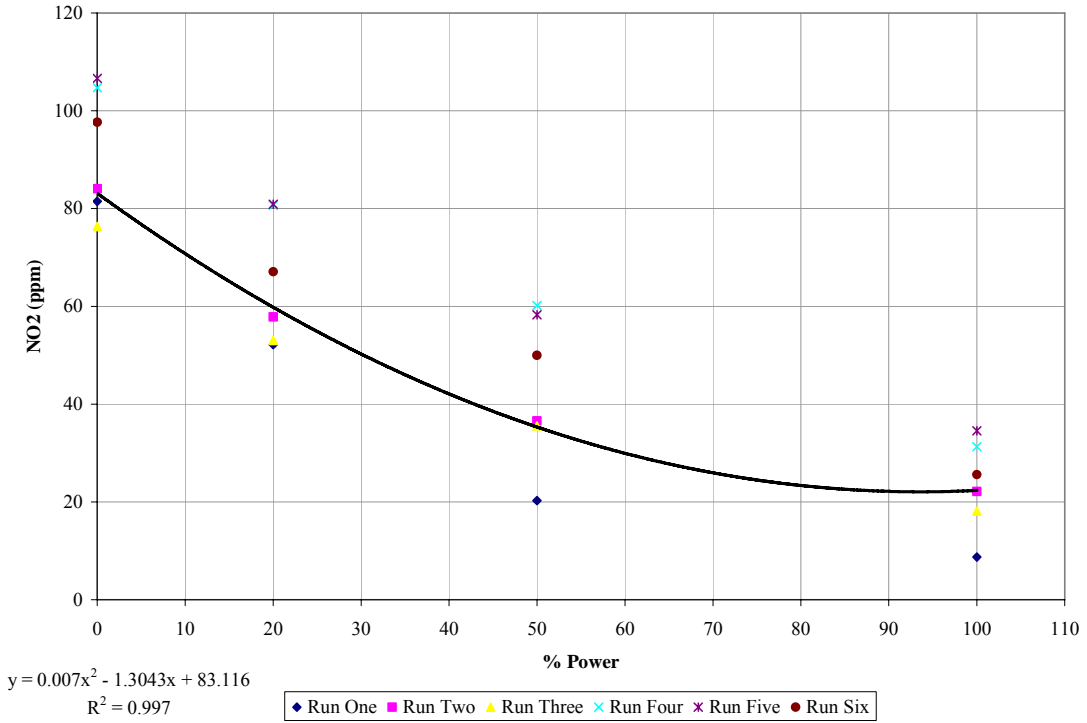


Figure 53: Nitrogen Dioxide - ppm

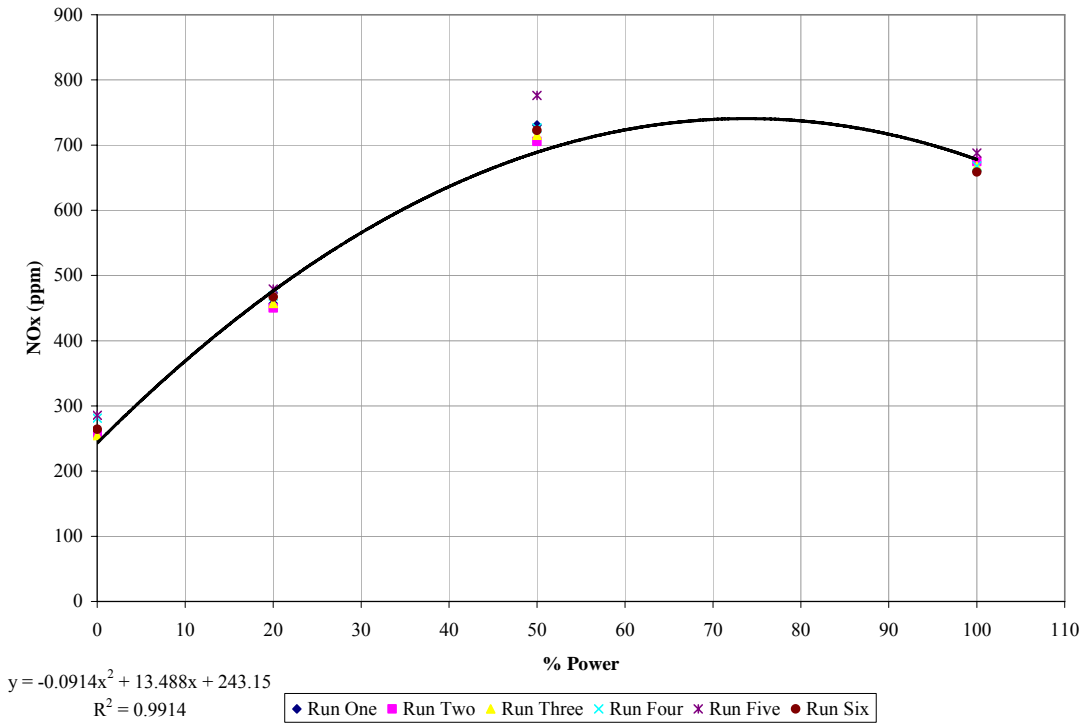


Figure 54: Nitrogen Oxides - ppm

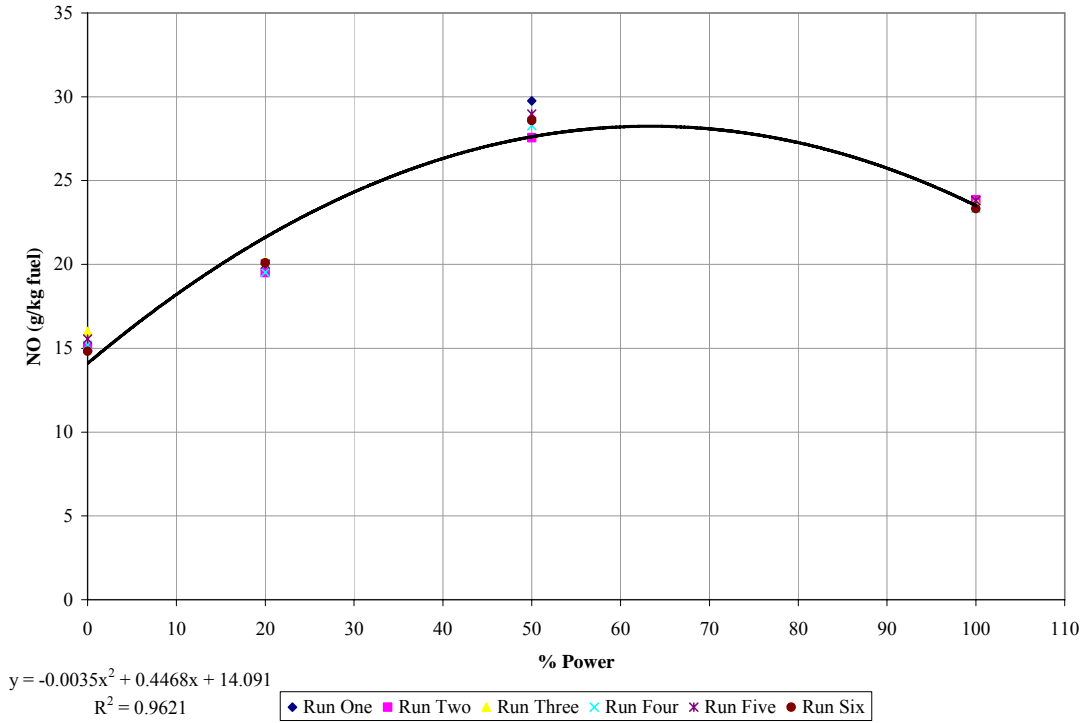


Figure 55: Nitric Oxide - Mass

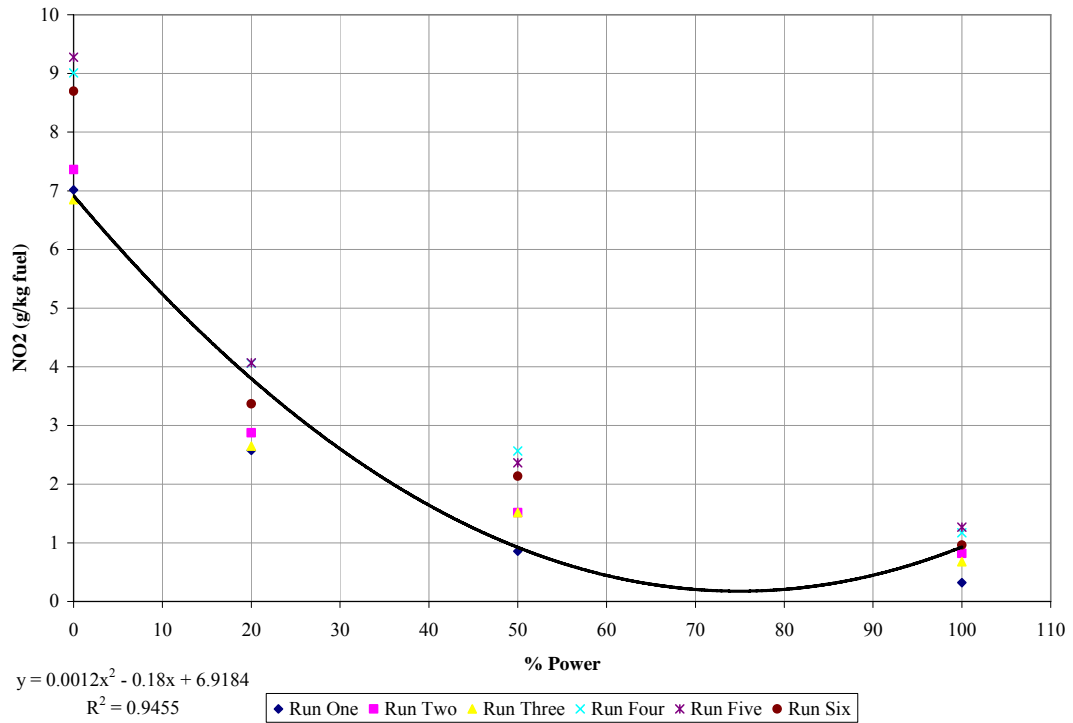


Figure 56: Nitrogen Dioxide - Mass

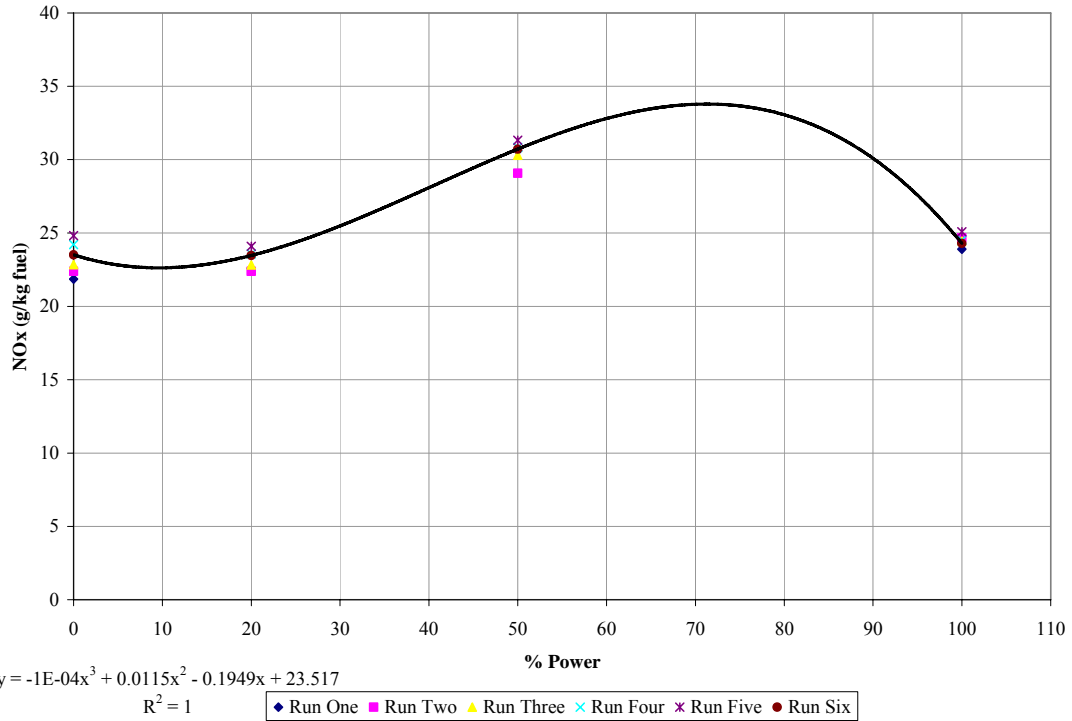


Figure 57: Nitrogen Oxides - Mass

As the temperature in the combustion chamber increases, because of fuel increase, there a rise in Nitrogen Oxides. After the load reaches around 50 percent, the Nitrogen Oxides start to decrease. This is due to the abundant of carbon in the system reacting with the oxygen. The primary product, carbon dioxide, is taking all the oxygen atoms. This also can be due to how fast the reaction is taking place in the combustion chamber and the quantity of nitrogen compounds ingested into the engine.

The last pollutant recorded, is an organic compound consisting entirely of hydrogen and carbon, hydrocarbon or unburned fuel. The figures for all hydrocarbons are shown in Figures 58 and 59.

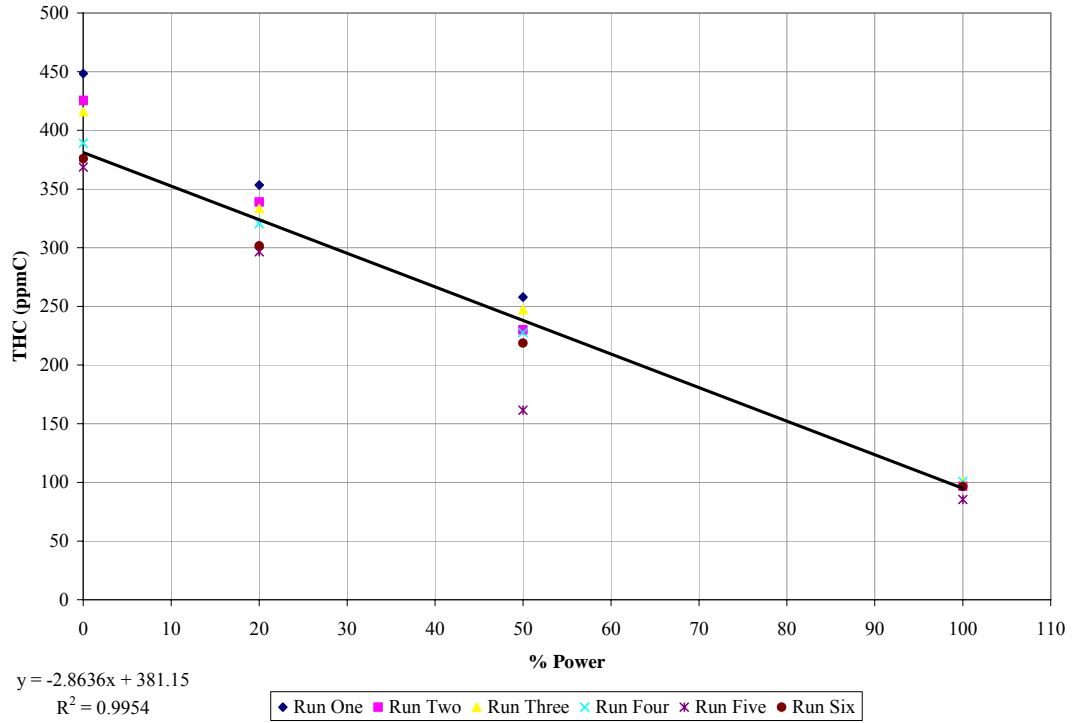


Figure 58: Hydrocarbon - ppmC

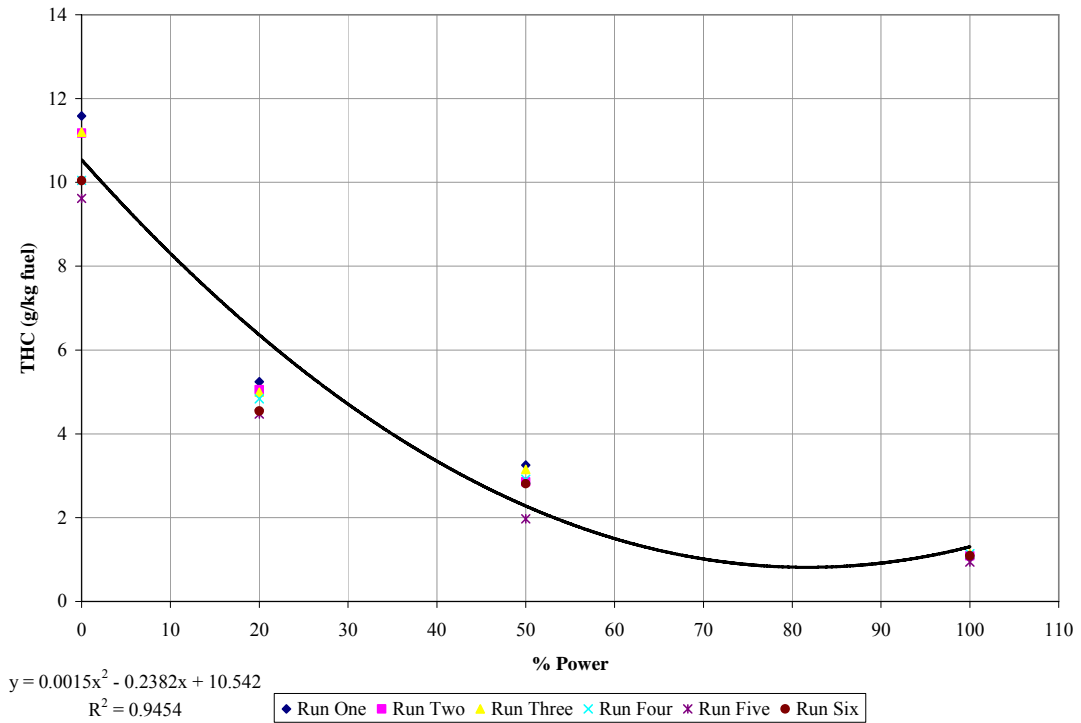


Figure 59: Hydrocarbon – Mass

The hydrocarbon's numbers is shown to drop after the diesel power is increased. This is because the engine is operating by the fuel and air supply directly. Normally, at low power, diesel engine has enough oxygen to burn all the fuel and as the power increases the fuel is not burned completely. This aircraft diesel engine has a turbocharger, in order to feed the system with an acquit amount of cool, compressed air. At high load, the turbocharger is compressed and consuming more air than at a lower load. Therefore, the turbocharger is a great help in diesel engines with the intention of reducing the hydrocarbon pollutant at high load.

Furthermore, the pollutant's experimental data figures show the same trend as the emissions from an SI engine as a function of the equivalence ratio, λ . This can be seen in Figure 60 and 61.

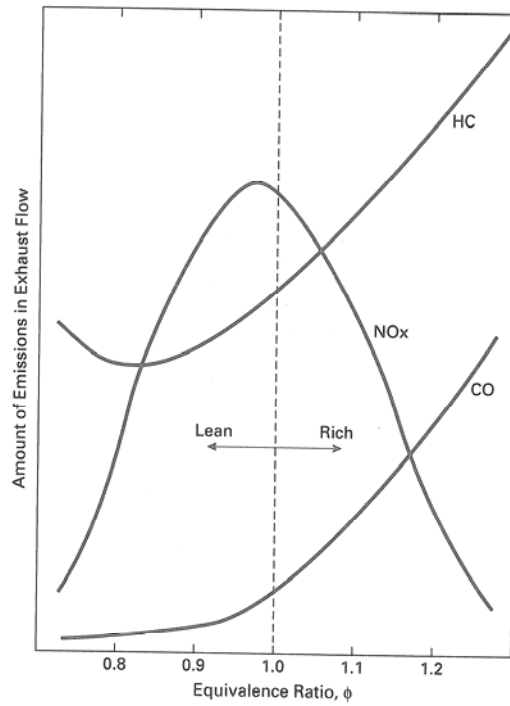


Figure 60: Emission Contours [ref 24]

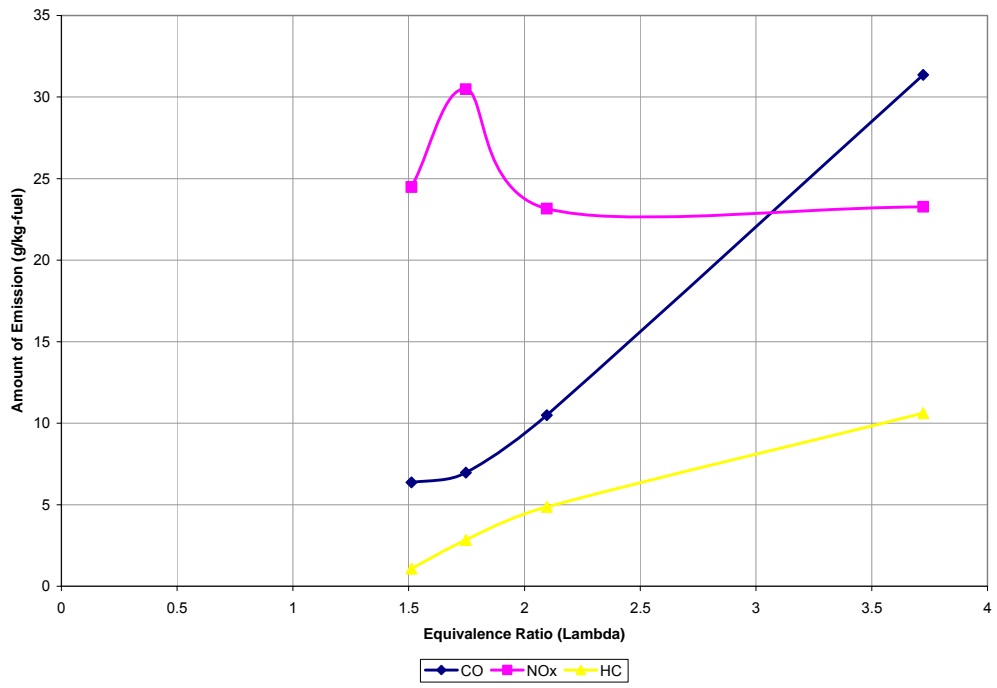


Figure 61: Experimental Emission Data - Contours

3.2.2 Emission Data Comparison/Validation

The emission data, of the Centurion 1.7, is tested against the ICAO and FAA standard to see how the turbo diesel compares to the turbine engines. In Tables XXIV - XXVI, the specific emission equation (Equation 31) was used for each main pollutant to get a Specific Emission (SE) number at different test modes.

Table XXIV: CO Emission Number

	EI_{co}	Time	SFC	SE_{co}
	(g/kg)	(hr)	(kg/hr/kW)	~
Idle	31.36	0.433333	0.3021	4.105701
High Idle	10.49	0.066667	0.2477	0.173194
Max	6.36	0.011667	0.2381	0.017674

Table XXV: NO_x Emission Number

	EI_{NO_x}	Time	SFC	SE_{NO_x}
	(g/kg)	(hr)	(kg/hr/kW)	
Idle	23.27	0.433333	0.3021	3.046722
High Idle	23.16	0.066667	0.2477	0.382388
Max	24.49	0.011667	0.2381	0.068016

Table XXVI: HC Emission Number

	EI_{HC}	Time	SFC	SE_{HC}
	(g/kg)	(hr)	(kg/hr/kW)	
Idle	10.61	0.433333	0.3021	1.389056
High Idle	4.86	0.066667	0.2477	0.080208
Max	1.08	0.011667	0.2381	0.002999

The carbon monoxide limit is 118 for the category, which the Thielert Centurion 1.7 is being compared too. In all the test modes the limit is never reached. The hydrocarbon limit for the ICAO and FAA is 19, which the data shows that emission did not go over the maximum value. The nitrogen oxides standard emission must be calculated from Equation 46, Equation 47 shows the SE number.

$$\frac{D_p}{F_{oo}} = 37.572 + 1.6\pi_{oo} - 0.2087F_{oo} \quad (46)$$

$$\frac{D_p}{F_{oo}} = 37.572 + 1.6 * (19) - 0.2087 * 100 = 47.102 \quad (47)$$

The max limit for emission for NOx is 47.102; again the turbo diesel's emission is less than the limit. Therefore, Thielert Centurion 1.7 aircraft engine passed the regulation of the ICAO and FAA.

The second method, of checking the emission data of the engine, is to compare the emission data with other types of engines using jet fuel. The data for these comparisons are given in Tables XXVII-XXXII.

Table XXVII: Thielert Centurion 1.7 - Emission at Time Mode

	CO	NOx	HC	Fuel Flow
	g/kg fuel	g/kg fuel	g/kg fuel	kg/hr
Idle	31.36	23.27	10.61	1.37
High Idle	10.49	23.16	4.86	5.21
Cruise	6.97	30.48	2.83	11.42
Max	6.36	24.49	1.08	21.92

Table XXVIII: Allison T56-A-15 - Emission at Time Mode

	CO	NOx	HC	Fuel Flow
	g/kg fuel	g/kg fuel	g/kg fuel	kg/hr
Idle	32.9	3.3	~	~
High Idle	5.5	6.3	~	~
Cruise	2	8.5	~	~
Max	2	9.6	~	~

Table XXIX: Pratt & Whitney PT6-42 - Emission at Time Mode

	CO	NOx	HC	Fuel Flow
	g/kg fuel	g/kg fuel	g/kg fuel	kg/hr
Idle	28.9	3.3	6.3	64.8
High Idle	6.9	4.9	0	122.4
Cruise	~	~	~	~
Max	1.9	7.3	0	230.4

Table XXX: Williams Research WR 24-6 - Emission at Time Mode

	CO	NOx	HC	Fuel Flow
	g/kg fuel	g/kg fuel	g/kg fuel	kg/hr
Idle	50	3	~	~
High Idle	15	3.3	~	~
Cruise	10	3.8	~	~
Max	8	4.2	~	~

Table XXXI: Garrett GTC85 Series APU - Emission at Time Mode

	CO	NOx	HC	Fuel Flow
	g/kg fuel	g/kg fuel	g/kg fuel	kg/hr
Idle	52	4	~	~
High Idle	20	3.8	~	~
Cruise	18	3.5	~	~
Max	14	3.6	~	~

Table XXXII: Thielert Centurion 1.7 - Emission at Time Mode

	CO	NOx	HC	Fuel Flow
	g/kg fuel	g/kg fuel	g/kg fuel	kg/hr
Idle	26.48	25.76	15.37	~
High Idle	11.67	23.16	7.53	~
Cruise	6.23	31.16	2.58	~
Max	7.95	24.6	1.19	~

The carbon monoxides, nitrogen oxides, and hydrocarbon data for the different types of engines show a similar number at each time mode. The key is that the turbine engine has a higher fuel flow than the diesel engine; therefore more emission is produced in an hour. The graphic emission comparisons are shown in Figure 62 – 64 for each engine at different time modes for a kilogram of fuel.

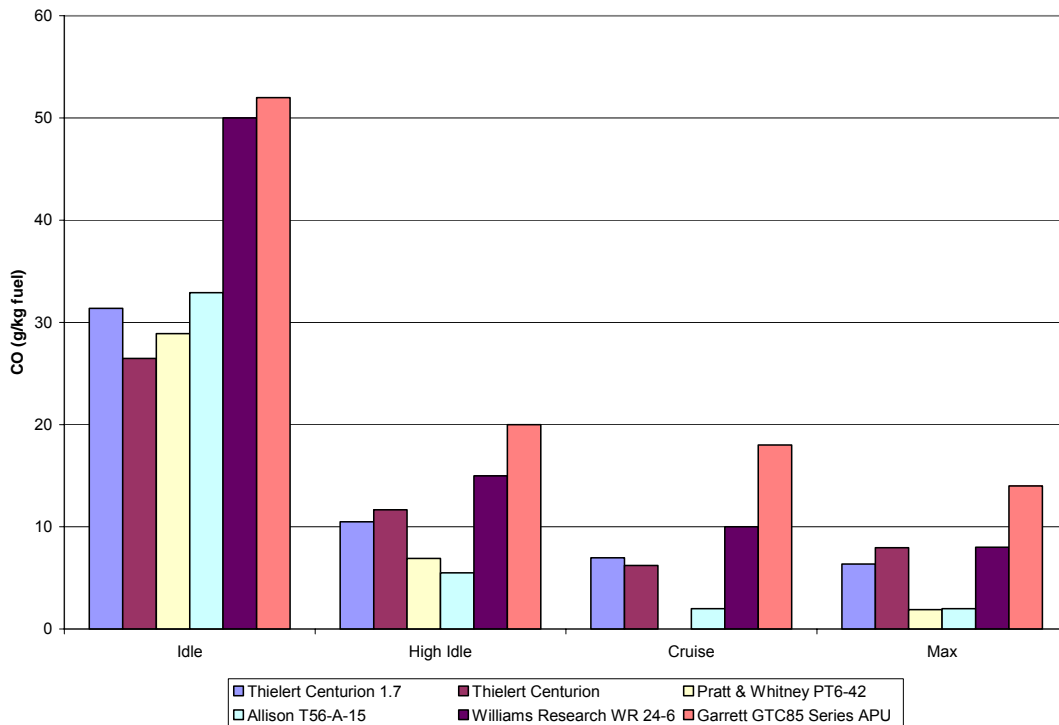


Figure 62: Carbon Monoxide Emission - Operation Mode

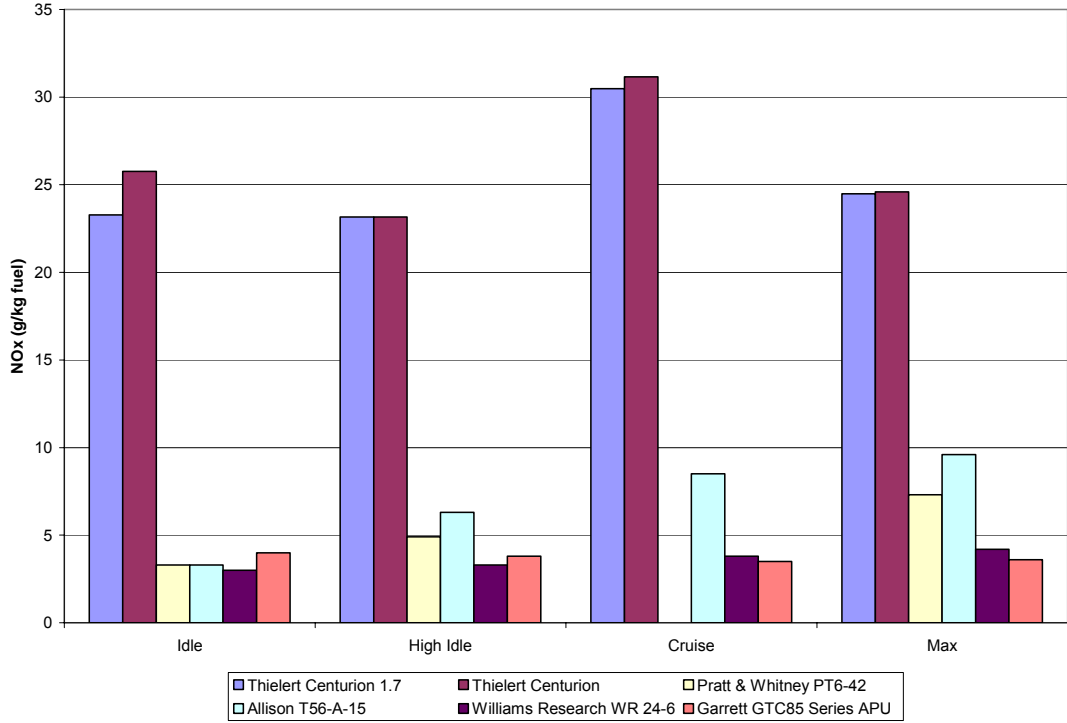


Figure 63: Nitrogen Oxides Emission - Operation Mode

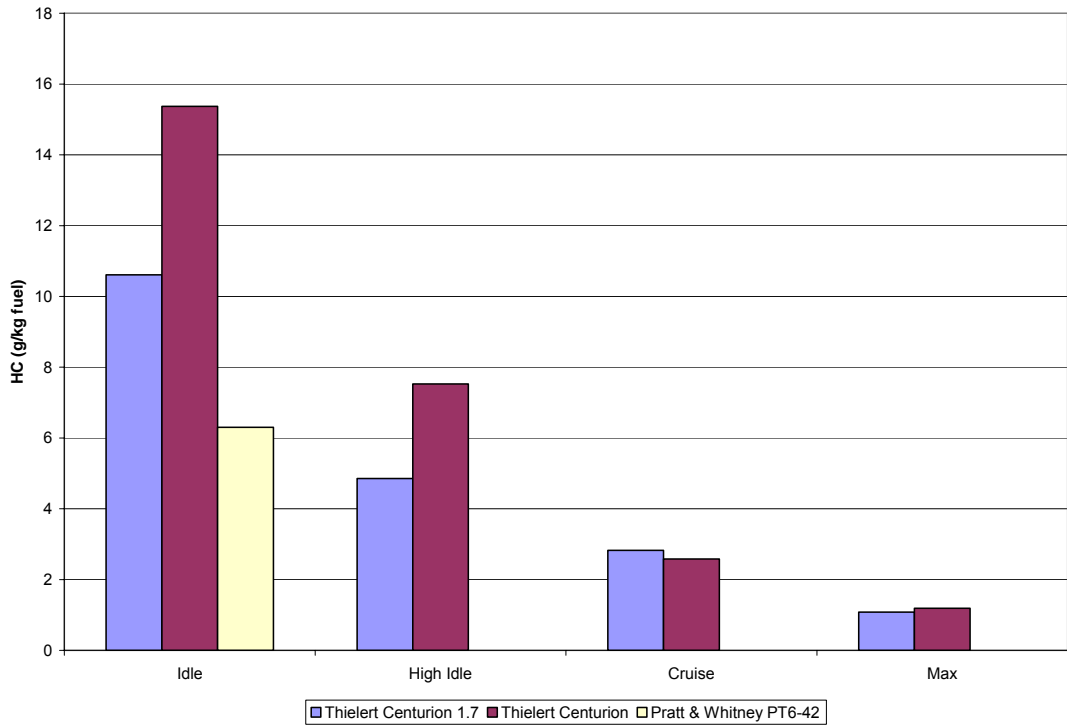


Figure 64: Hydrocarbon Emission - Operation Mode

In addition, to the turbine engine, another reciprocating engine data is compare with the diesel. The Textron Lycoming 0-320-D data is base on the avgas combustion, which is a different type of hydrocarbon versus JET-A. Table XXXIII shows the emission data of the Lycoming at the operation time mode.

Table XXXIII: Textron Lycoming 0-320-E2D - Emission at Time Mode

	CO	NOx	HC	Fuel Flow
	g/kg fuel	g/kg fuel	g/kg fuel	kg/hr
Idle	984.3	0.15	66.47	~
High Idle	~	~	~	~
Cruise	625.4	13.21	10.61	~
Max	~	~	~	~

Figure 65 shows how different these fuels are in emission at the standard maneuver modes.

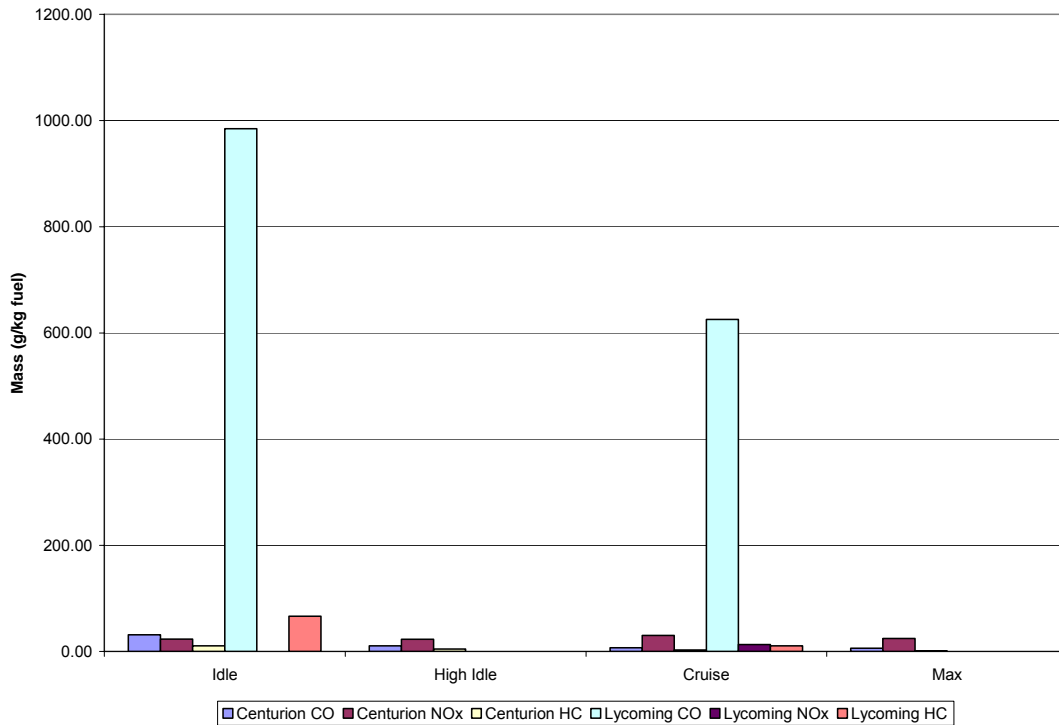


Figure 65: Centurion vs Lycoming - Emission at Time Mode

The most astonishing number is the carbon monoxide emission data in the comparison of the Lycoming and Centurion. The carbon monoxide output of the Lycoming is over 30 times the amount of the Centurion emission. The difference in numbers can be due to the following:

1. Avgas vs JET-A
 - a. Gasoline: C_7H_{16} to $C_{11}H_{24}$
 - b. Kerosene: $C_{12}H_{26}$ to $C_{15}H_{32}$
2. Spark Ignition vs Compressor Ignition
3. Rich vs Lean Mixture

In addition, the specific fuel consumption for the Centurion is 20% better than the Lycoming. The Centurion engine and JET-A seems to be the better combination than the Lycoming and Avgas.

4 Conclusions

The testing of the Thielert Centurion 1.7 was split up into two investigations:

1. Performance Investigation
2. Emission Investigation

The performance investigation included three test runs during which data was collected at each percent load for the full range of the engine (starting at 0 % to 100 % with a 10 % interval). The recordings of the performance investigation were accurate: each data point closely matched the data from the manufacturer. The largest percent difference was 2.25 percent (SFC).

The emission investigation was performed by six test runs and was collected by the SEMTECH-DS system. Each run was tested at the engines standard operating conditions: Idle, High Idle, Cruise, and Max.

The nitrogen oxides data shows that the turbo diesel produces more NO_x pollutants than the turbine based engine. The nitrogen oxides data from the Centurion is around 4 times greater compared to the turbine engines, but the fuel flow of the turbine is over 10 times larger than the diesel engine. Therefore, over time the turbine engines will produce more emission of nitrogen oxides.

The carbon monoxides emission had the most interesting data points over the other pollutants. There was around twice as much CO pollutants coming from the diesel engine than the turbine engine, but the SFC was not taken into account. In addition, the comparison with the Lycoming shows an interesting result: the CO emission from the Lycoming was 60 times greater than the CO from the Centurion.

In addition, Lycoming has a 20% higher SFC than the Centurion; therefore Centurion looks like it will have an incredible future in General Aviation.

The last emission comparison was the hydrocarbon production of the turbo diesel and other aircraft engines. The relationship showed that the hydrocarbon emission by the Centurion is around 3 times greater than the Pratt & Whitney PT6-42, but around 6 times less than the Textron Lycoming 0-320-E2D.

Regulation comparisons show that the Centurion is way under the requirements set by the FAA and ICAO. How could this happen with the recordings declared in this paper? The answer involves the Specific Fuel Consumption. The turbines fuel consumption is elevated compared to reciprocating engines; however the ICAO's policies include the time of the operation mode and SFC into the emission equation to evaluate the engine. Overall, the standard requirements for commercial aircraft work well, but there is a need for gaseous emission's regulations for General Aviation.

5 Recommendations

Although the investigations of the Thielert Centurion 1.7 demonstrated satisfactory information comparing with other engine and environmental regulations, there are some more investigations needed to complete the research. The recommendations for future work are listed as follows:

1) Fuel Source

- a. An excellent contrast can be done by using diesel fuel in the Centurion. The JET-A emission and the diesel emission data collected from the Centurion can show which fuel is better for the engine and environment.
- b. Bio-Fuel and Avgas can then be tested in a piston-driven aircraft engine to support and increase the validation of the emission data that is collected.
- c. These different types of fuel will be better in their own category, but the best fuel will be the one that will increase the performance and decrease emission for the engine.

2) Different Engine Types

- a. Other reciprocating engines, in the same class as the Centurion, needs to be tested to check the performance and emission data
- b. A small turboprop engines can be tested to compare the emission and performance to the Centurion data. The Innodyn is a good choice for turboprop engine testing.

3) Seasons Testing

- a. Most all the testing for the Centurion was done in the winter. Testing must be done in the summer to get the other extreme environment effects. Temperature, pressure, moisture, etc play a major role in the performance of an engine. Testing for all seasons will give good data for the effect of the environment on the Centurion.

4) Emissions Model

- a. A computer model can be created to test the theoretical part of the emissions against the experimental. The model could be the focus of all validations of the emission data for the Centurion and future engine testing.

The final recommendation is to change the emission regulation for all aircraft. The changes for emission regulations are given:

1) General Aviation Engine

- a. The Centurion shows that reciprocating engines can produce the same amount of emissions for a kilogram of JET-A fuel as turbine engines.
- b. Even if the turbine produces more emissions over time, because of their SFC and TSFC, there should be regulations for small aircraft engines.
- c. There is a rise in small aircraft numbers and there should be guidelines before these aircraft become an environmental problem.
- d. Engines under the commercial thrust limit need to be looked at:

- i. Reciprocating aircraft engines should have a set of emission standards.
- ii. Small turboprop aircraft engines should have a set of emission standards.
- iii. Small turbojet aircraft engines should have a set of emission standards.

2) Global Emission

- a. All emission requirements are based on the local emission (airport emission) and no requirements are created for global emission (altitude flight).
 - i. Aircraft emissions are unusual in that a significant proportion is emitted at cruise altitude.
 - ii. Emissions at cruise are given off not at one location but across the path of the aircraft. (Large distances are effected by the aircraft emissions)

New emission regulations for general aviation must be made to ensure the future of the planet, and to ease the dilemma of enforcing the standards in the future with the increase of general aviation aircraft. Regulations at cruise should be in place to prevent global emissions by aircrafts. In addition, new emission technology must also be pursued, to ensure the planet's health.

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Appendix A: ICAO Emission Regulations

Annex 16 – Environmental Protection – Volume 2 – Aircraft Engine Emissions

Smoke

Applicability

The regulatory levels are applicable to engines whose date of manufacture is on or after 1 January 1983.

Regulatory smoke number

The characteristic level of the smoke number at any thrust setting, measured in accordance with Annex 16, Volume II, must not exceed $83.6 (F_{oo})^{-0.274}$ or a value of 50, whichever is lower.

Gaseous emissions

Applicability

The regulatory levels apply to engines whose rated output is greater than 26.7 kN and whose date of manufacture is on or after 1 January 1986 and as further specified for oxides of nitrogen.

Regulatory levels

The characteristic levels of the gaseous emissions measured over the LTO cycle in accordance with Annex 16, Volume II, must not exceed the following regulatory levels:

- Hydrocarbons (HC): $\frac{D_p}{F_{oo}} = 19.6$
- Carbon monoxide (CO): $\frac{D_p}{F_{oo}} = 118$

- Oxides of nitrogen (NOx):
 - for engines of a type or model of which the date of manufacture of the first individual production model was on or before 31 December 1995 and for which the date of manufacture of the individual engine was on or before 31 December 1999:

$$\frac{D_p}{F_{oo}} = 40 + 2\pi_{oo}$$

- for engines of a type or model of which the date of manufacture of the first individual production model was after 31 December 1995 or for which the date of manufacture of the individual engine was after 31 December 1999:

$$\frac{D_p}{F_{oo}} = 32 + 1.6\pi_{oo}$$

- or engines of a type or model of which the date of manufacture of the first individual production model was after 31 December 2003:

- for engines with a pressure ratio of 30 or less:
 - for engines with a maximum rated thrust of more than 89.0 kN:

$$\frac{D_p}{F_{oo}} = 19 + 1.6\pi_{oo}$$

- for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$$\frac{D_p}{F_{oo}} = 37.572 + 1.6\pi_{oo} - 0.2087F_{oo}$$

- for engines with a pressure ratio of more than 30 but less than 62.5:

- for engines with a maximum rated thrust of more than 89.0 kN:

$$\frac{D_p}{F_{oo}} = 7 + 2\pi_{oo}$$

- for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$$\frac{D_p}{F_{oo}} = 42.71 + 1.4286\pi_{oo} - 0.4013F_{oo} + 0.0064\pi_{oo}F_{oo}$$

- for engines with a pressure ratio of 62.5 or more:

$$\frac{D_p}{F_{oo}} = 32 + 1.6\pi_{oo}$$

Appendix B: FAA Emission Regulations

**Part 34 FUEL VENTING AND EXHAUST EMISSION REQUIREMENTS
FOR TURBINE ENGINE POWERED AIRPLANES**

Subpart C--Exhaust Emissions (New Aircraft Gas Turbine Engines)

Sec. 34.21

Standards for Exhaust Emissions:

- a) Exhaust emissions of smoke from each new aircraft gas turbine engine of class T8 manufactured on or after February 1, 1974, shall not exceed a smoke number (SN) of 30.
- b) Exhaust emissions of smoke from each new aircraft gas turbine engine of class TF and of rated output of 129 kilonewtons (29,000 pounds) thrust or greater, manufactured on or after January 1, 1976, shall not exceed:

$$SN = 83.6 (rO)^{-0.274} (rO \text{ is in kilonewtons}).$$

- c) Exhaust emission of smoke from each new aircraft gas turbine engine of class T3 manufactured on or after January 1, 1978, shall not exceed a smoke number (SN) of 25.
- d) (d) Gaseous exhaust emissions from each new aircraft gas turbine engine shall not exceed:

- 1) For Classes TF, T3, T8 engines greater than 26.7 kilonewtons (6000 pounds) rated output:

- i. Engines manufactured on or after January 1, 1984:

Hydrocarbons: 19.6 grams/kilonewton rO.

- ii. Engines manufactured on or after July 7, 1997.

Carbon Monoxide: 118 grams/kilonewton rO.

- iii. Engines of a type or model of which the date of manufacture of the first individual production model was on or before December 31, 1995, and for which the date of manufacture of the individual engine was on or before December 31, 1999:

Oxides of Nitrogen: $(40+2(rPR))$ grams/kilonewtons rO.

- iv. Engines of a type or model of which the date of manufacture of the first individual production model was after December 31, 1995, or for which the date of manufacture of the individual engine was after December 31, 1999:

Oxides of Nitrogen: $(32+1.6(rPR))$ grams/kilonewtons rO.

- v. The emission standards prescribed in paragraphs (d)(1)(iii) and (iv) of this section apply as prescribed beginning July 7, 1997.

- 2) For Class TSS Engines manufactured on or after January 1, 1984:

Hydrocarbons = $140(0.92)^{rPR}$ grams/kilonewton rO.

- e) Smoke exhaust emissions from each gas turbine engine of the classes specified below shall not exceed:

- 1) Class TF of rated output less than 26.7 kilonewtons (6000 pounds) manufactured on or after August 9, 1985

$SN = 83.6(rO)^{-0.274}$ (rO is in kilonewtons)

not to exceed a maximum of $SN = 50$.

- 2) Classes T3, T8, TSS, and TF of rated output equal to or greater than 26.7 kilonewtons (6000 pounds) manufactured on or after January 1, 1984.

$$SN = 83.6(rO)^{-0.274} \text{ (rO is in kilonewtons)}$$

not to exceed a maximum of SN = 50.

- 3) For Class TP of rated output equal to or greater than 1,000 kilowatts manufactured on or after January 1, 1984:

$$SN = 187(rO)^{-0.168} \text{ (rO is in kilowatts)}$$

- f) The standards set forth in paragraphs (a), (b), (c), (d), and (e) of this section refer to a composite gaseous emission sample representing the operating cycles set forth in the applicable sections of Subpart G of this part, and exhaust smoke emissions emitted during operations of the engine as specified in the applicable sections of Subpart H of this part, measured and calculated in accordance with the procedures set forth in those subparts.

**Part 34 FUEL VENTING AND EXHAUST EMISSION REQUIREMENTS FOR
TURBINE ENGINE POWERED AIRPLANES**

Subpart D--Exhaust Emissions (In-Use Aircraft Gas Turbine Engines)

Sec. 34.31

Standards for exhaust emissions.

- a) Exhaust emissions of smoke from each in-use aircraft gas turbine engine of Class T8, beginning February 1, 1974, shall not exceed a smoke number (SN) of 30.

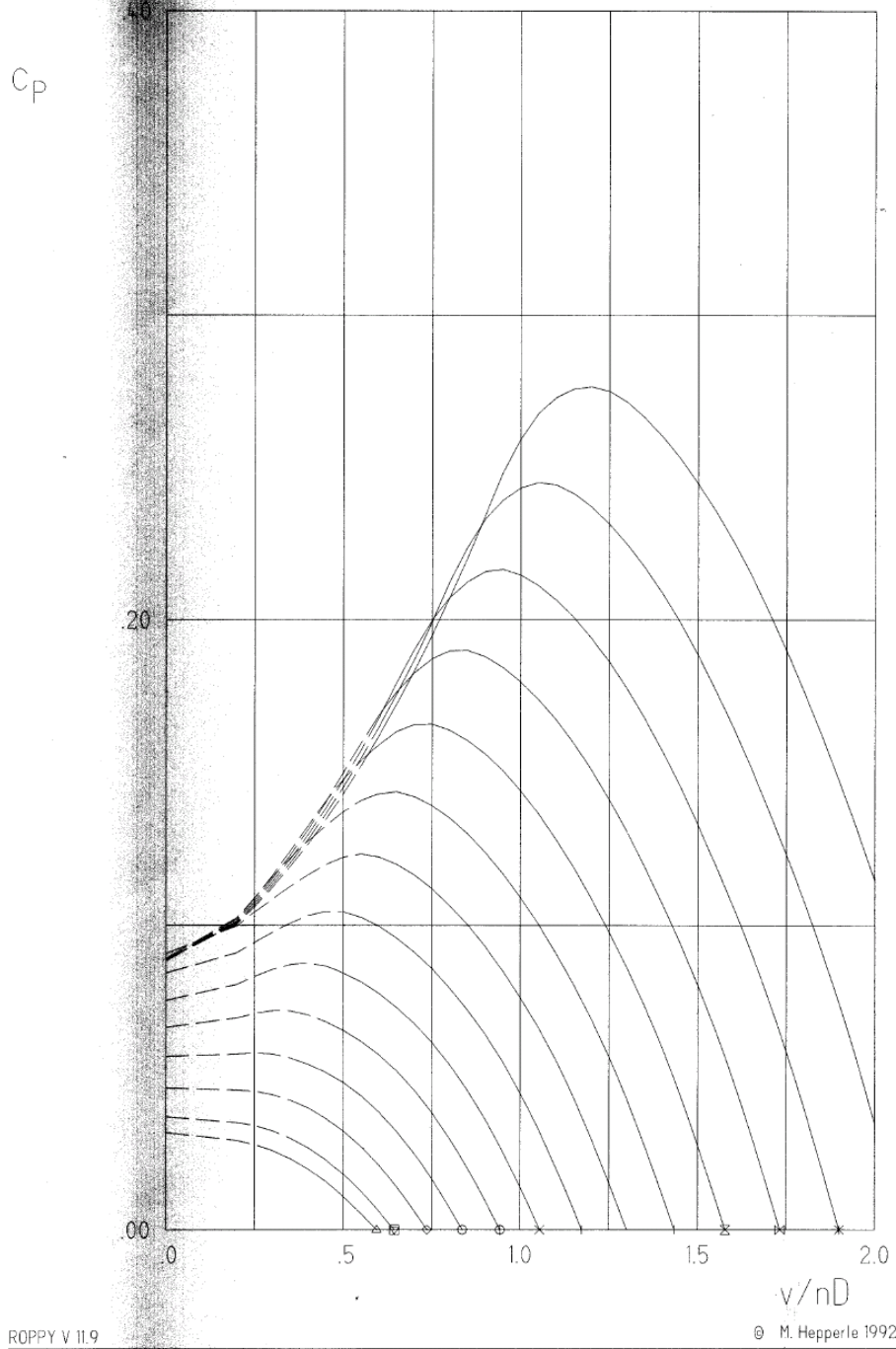
- b) Exhaust emissions of smoke from each in-use aircraft gas turbine engine of Class TF and of rated output of 129 kilonewtons (29,000 pounds) thrust or greater, beginning January 1 1976, shall not exceed

$$SN = 83.6(rO)^{-0.274} \text{ (rO is in kilonewtons).}$$

- c) The standards set forth in paragraphs (a) and (b) of this section refer to exhaust smoke emissions emitted during operations of the engine as specified in the applicable section of Subpart H of this part, and measured and calculated in accordance with the procedure set forth in this subpart.

Appendix C: Propeller Specifications

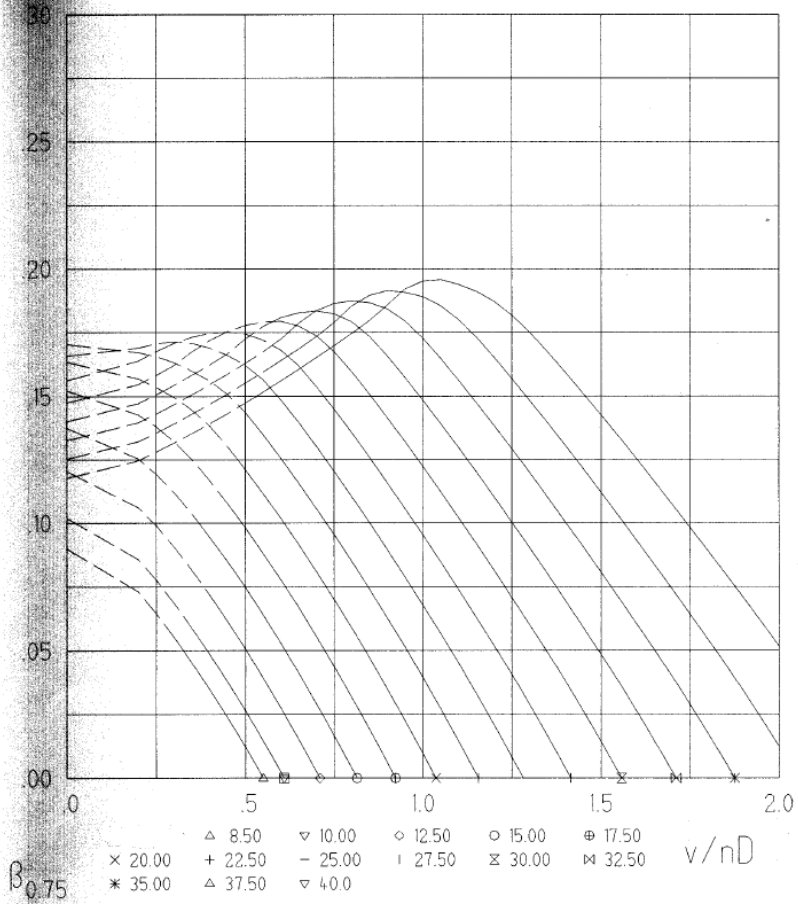
>HELIX SYSTEM< *CP*		MTV-6-A/187-129		R0295M20		11.03.02					
Flughöhe	0 m	*Adv.R. J vo	0.20 -	entsp. V vo		51.6 km/h					
entspr.	0 ft		bi 2.20 -			bi 567.7 km/h					
		(= 20 Intervalle)									
P-Drehzahl	2300 1/min	*Cp*E-2	vo 2.0 -	>> P_eff vo		29.5 %					
Dchm.Prop.	1.87 m		bi 22.0 -			bi 324.4 %					
		(= 20 Intervalle)									
Copyright: MT-Propeller Entwicklung GmbH & Co. KG, Postfach 0720, D-94307 Straubing											
Wirkungsgrad etaP in Abhängigkeit von J und Cp											
	Cp*E-2 =										
J =	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00
0.200	0.487	0.474	0.447	0.419	0.389	0.357	0.322	0.257	0.224	0.198	0.177
0.300	0.605	0.617	0.595	0.570	0.547	0.518	0.485	0.448	0.359	0.317	0.283
0.400	0.673	0.710	0.696	0.676	0.656	0.636	0.613	0.585	0.552	0.450	0.400
0.500	0.715	0.767	0.763	0.749	0.733	0.717	0.700	0.680	0.657	0.634	0.604
0.600	0.742	0.803	0.806	0.798	0.787	0.774	0.761	0.746	0.728	0.709	0.689
0.700	0.759	0.824	0.834	0.831	0.823	0.814	0.804	0.793	0.780	0.764	0.747
0.800	0.768	0.836	0.850	0.851	0.847	0.841	0.834	0.826	0.816	0.804	0.790
0.900	0.769	0.841	0.859	0.864	0.863	0.860	0.855	0.849	0.842	0.833	0.822
1.000	0.759	0.838	0.862	0.871	0.873	0.872	0.869	0.865	0.860	0.854	0.846
1.100	0.744	0.830	0.860	0.873	0.878	0.880	0.879	0.877	0.873	0.868	0.862
1.200	0.721	0.818	0.854	0.872	0.880	0.884	0.885	0.884	0.882	0.878	0.874
1.300	0.148	0.802	0.846	0.868	0.879	0.885	0.888	0.888	0.888	0.886	0.882
1.400	1.304	0.784	0.836	0.861	0.876	0.884	0.888	0.891	0.891	0.890	0.888
1.500	1.213	0.765	0.823	0.854	0.871	0.881	0.887	0.891	0.893	0.893	0.891
1.600	1.370	0.746	0.808	0.842	0.863	0.876	0.884	0.889	0.892	0.893	0.893
1.700	#####	0.365	0.791	0.831	0.854	0.870	0.880	0.887	0.890	0.892	0.893
1.800	#####	0.134	0.771	0.816	0.844	0.862	0.874	0.882	0.887	0.890	0.892
1.900	#####	#####	0.747	0.800	0.831	0.853	0.867	0.876	0.883	0.887	0.889
2.000	#####	#####	0.723	0.782	0.818	0.841	0.858	0.870	0.878	0.883	0.886
2.100	#####	#####	0.163	0.760	0.802	0.829	0.848	0.862	0.871	0.877	0.882
2.200	#####	#####	0.075	0.734	0.782	0.813	0.836	0.851	0.863	0.870	0.876
	Cp*E-2 =										
J =	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00	21.00	22.00
0.200	0.177	0.159	0.145	0.132	0.121	0.111	0.102	0.095	0.088	0.082	0.076
0.300	0.283	0.254	0.230	0.210	0.192	0.177	0.163	0.151	0.140	0.131	0.122
0.400	0.400	0.359	0.324	0.295	0.269	0.247	0.228	0.211	0.195	0.181	0.169
0.500	0.604	0.477	0.430	0.390	0.356	0.326	0.300	0.276	0.256	0.237	0.221
0.600	0.689	0.667	0.637	0.498	0.453	0.415	0.381	0.351	0.324	0.300	0.279
0.700	0.747	0.730	0.712	0.691	0.574	0.521	0.476	0.436	0.401	0.371	0.344
0.800	0.790	0.776	0.761	0.745	0.728	0.703	0.604	0.539	0.497	0.458	0.423
0.900	0.822	0.810	0.797	0.784	0.770	0.756	0.738	0.701	0.628	0.561	0.515
1.000	0.846	0.836	0.825	0.814	0.802	0.790	0.777	0.762	0.741	0.700	0.644
1.100	0.862	0.855	0.846	0.836	0.826	0.816	0.805	0.793	0.781	0.765	0.740
1.200	0.874	0.868	0.861	0.853	0.845	0.835	0.826	0.816	0.806	0.795	0.782
1.300	0.882	0.877	0.872	0.865	0.858	0.850	0.842	0.834	0.825	0.816	0.806
1.400	0.888	0.884	0.879	0.874	0.868	0.862	0.855	0.847	0.840	0.832	0.823
1.500	0.891	0.888	0.885	0.881	0.875	0.870	0.864	0.858	0.851	0.844	0.836
1.600	0.893	0.891	0.888	0.885	0.881	0.876	0.871	0.865	0.859	0.853	0.847
1.700	0.893	0.892	0.890	0.887	0.884	0.880	0.876	0.871	0.866	0.860	0.854
1.800	0.892	0.892	0.890	0.888	0.886	0.883	0.879	0.875	0.870	0.865	0.860
1.900	0.889	0.890	0.890	0.888	0.886	0.884	0.881	0.877	0.873	0.869	0.864
2.000	0.886	0.887	0.887	0.887	0.886	0.884	0.881	0.878	0.875	0.871	0.867
2.100	0.882	0.884	0.885	0.885	0.884	0.883	0.881	0.878	0.875	0.872	0.868
2.200	0.876	0.879	0.881	0.881	0.881	0.881	0.879	0.877	0.875	0.872	0.869
Cp = P / (rho*n^3*D^5)			J = v / (n*D)				Ct = Cp*etaP/J				



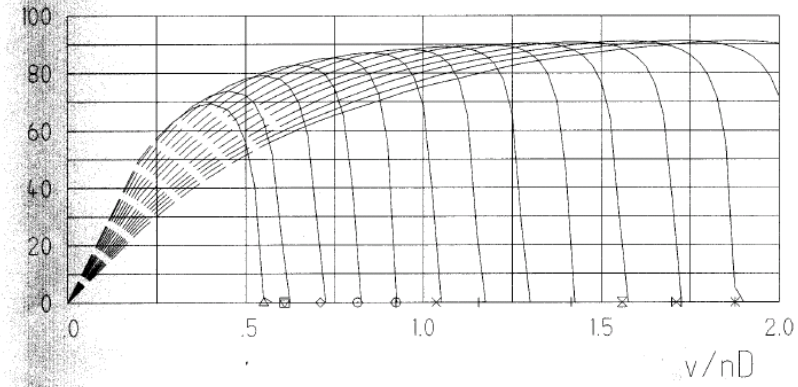
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Appendix D: SEMTECH Specifications

Revision 1.10

SEMTECH-DS User Manual

14 Specifications

NOTE: Specifications are subject to change without notice. While due caution has been exercised in the production of this document, possible errors and omissions can occur.

14.1 System Specifications

Power requirements (approximate)	12 Vdc nominal (10.5 – 14.5 Vdc) 70 A during warm-up (840 W), 30 A at steady state (360 W)																								
Storage temperature	Dry –40 to 60 °C ambient																								
Operating temperature	0 to 45 °C ambient																								
Dimensions	<table border="0"> <tr> <td>Chassis Only:</td> <td>Height</td> <td>14.0 in</td> <td>(355 mm)</td> </tr> <tr> <td></td> <td>Width</td> <td>17.0 in</td> <td>(432 mm)</td> </tr> <tr> <td></td> <td>Depth</td> <td>21.6 in</td> <td>(549 mm)</td> </tr> <tr> <td>With Protrusions:</td> <td>Height</td> <td>15.9 in</td> <td>(404 mm)</td> </tr> <tr> <td></td> <td>Width</td> <td>20.3 in</td> <td>(516 mm)</td> </tr> <tr> <td></td> <td>Depth</td> <td>24.5 in</td> <td>(622 mm)</td> </tr> </table>	Chassis Only:	Height	14.0 in	(355 mm)		Width	17.0 in	(432 mm)		Depth	21.6 in	(549 mm)	With Protrusions:	Height	15.9 in	(404 mm)		Width	20.3 in	(516 mm)		Depth	24.5 in	(622 mm)
Chassis Only:	Height	14.0 in	(355 mm)																						
	Width	17.0 in	(432 mm)																						
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With Protrusions:	Height	15.9 in	(404 mm)																						
	Width	20.3 in	(516 mm)																						
	Depth	24.5 in	(622 mm)																						
Weight	78 lbs (35.4 kg)																								
Warm-up time	60 minutes (at 20 °C ambient temperature) minimum before use. Specifications quoted below apply after a 120 minute warm-up time.																								
Data acquisition	User selectable reported data rate User selectable raw data acquisition rate (varies by device)																								
Time resolution	1 millisecond resolution on all recorded data timestamps																								
Data storage capacity	Over 48 hours at 1 Hz data acquisition rate																								
Data transmission	802.3 (10BaseT) and 802.3u (100BaseTX) wired, and 802.11b or 802.11g (DSSS) wireless Ethernet																								
Electromagnetic interference and susceptibility	<p>CE Standards: IEC 61326: 2002-2</p> <ul style="list-style-type: none"> • EN 55022:1995, Radiated Emissions, Class A • EN 61000-4-2:1995 IEC 61326: 2002\ ESD Immunity; +/- 4kV contact, +/-8 kV air discharge • EN 61000-4-3:1996 and ENV 50204 IEC 61326: 2002\ Radiated Electromagnetic Immunity; 10 V/m • EN 610000-4-6:1996 IEC 61326: 2002\ Conducted Electromagnetic Immunity; 3 Voc • EN 61000-4-4:1995 IEC 61326: 2002\ Electrical Fast Transient/Burst Immunity; +/-2 kV, +/-1 kV • EN 61000-4-5: 1995 IEC 61326: 2002\ Surge; +/-2 kV, +/-1 kV • EN 61000-4-8:1993 IEC 61326: 2002\ Power Frequency Magnetic Field Immunity; 30 A/m • EN 61000-4-11: 1994 IEC 61326: 2002\ Voltage Dips and Interruptions 																								

14.2 Total Hydrocarbon Heated FID Specifications

Range of measurement	0 – 100, 0 – 1,000, 0 – 10,000, and 0 – 40,000 ppmC ⁸ User Selectable			
	0 – 100 ppmC Range	0 – 1,000 ppmC Range	0 – 10,000 ppmC Range	0 – 40,000 ppmC Range ⁸
Accuracy	±2.0 % of reading or ±5 ppmC whichever is greater	±2.0 % of reading or ±5 ppmC whichever is greater	±2.0 % of reading or ±25 ppmC whichever is greater	±2.0 % of reading or ±100 ppmC whichever is greater
Resolution	0.1 ppmC	1.0 ppmC	1.0 ppmC	10.0 ppmC
Linearity	Intercept ≤ 0.5 % of range. 0.990 ≤ Slope ≤ 1.01 SEE ≤ 1.0 % of range $r^2 \geq 0.998$			
Repeatability	±1.0 % of reading or ±2 ppmC whichever is greater	±1.0 % of reading or ±2 ppmC whichever is greater	±1.0 % of reading or ±10 ppmC whichever is greater	±1.0 % of reading or ±40 ppmC whichever is greater
Noise	±2 ppmC	±2 ppmC	±10 ppmC	±40 ppmC
Span drift (over 8 hours)	±1.0 % of reading or 3 ppmC whichever is greater	±1.0 % of reading or 3 ppmC whichever is greater	±1.0 % of reading or 15 ppmC whichever is greater	±1.0 % of reading or 60 ppmC whichever is greater
Zero drift (over 2 hours)	±5 ppmC	±5 ppmC	±10 ppmC	±20 ppmC
Response time	T90 ≤ 2 seconds	T90 ≤ 2 seconds	T90 ≤ 2 seconds	T90 ≤ 2 seconds
Flow rate	2 lpm	2 lpm	2 lpm	2 lpm
Data rate	Up to 4 Hz, configurable	Up to 4 Hz, configurable	Up to 4 Hz, configurable	Up to 4 Hz, configurable
Operating temperature	191 °C	191 °C	191 °C	191 °C

14.3 NDIR CO, CO₂ and HC Specifications

Gas	CO	CO ₂	HC
Range of measurement	0 – 8 %	0 – 20 %	0 – 2,000 ppm hexane 0 – 4,000 ppm propane
Accuracy	±3 % of reading or 50 ppm, whichever is greater	±3 % of reading or ±0.1%, whichever is greater	±3 % of reading or 4.0 ppmC ₆ , whichever is greater
Resolution	10 ppm	0.01%	1 ppmC ₆

⁸ The 0 – 40,000 ppmC range is not available on the Single-Mode SEMTECH-DS.

Gas	CO	CO ₂	HC
Linearity	Intercept \leq 0.5 % of range. 0.990 \leq Slope \leq 1.01 SEE \leq 1.0 % of range $r^2 \geq$ 0.998		
Repeatability	± 2 % of reading or 20 ppm, whichever is greater	± 2 % of reading or ± 0.05 %, whichever is greater	± 2 % of reading or 2.0 ppmC6, whichever is greater
Noise	± 20 ppm	± 0.02 %	± 1 ppmC6
Span drift (over 8 hours)	± 2 % of reading or 20 ppm, whichever is greater	± 2 % of reading or 0.1 %, whichever is greater	± 2 % of reading or 2.0 ppmC6, whichever is greater
Zero drift (over 2 hours)	± 0.005 % (50 ppm)	± 0.1 %	± 4 ppmC6
Response time	T90 \leq 3 seconds	T90 \leq 3 seconds	T90 \leq 3 seconds
Data rate	0.833 Hz	0.833 Hz	0.833 Hz
Flow rate	2 lpm	2 lpm	2 lpm

14.4 NDUV NO and NO₂ Specifications

Gas	NO	NO ₂
Range of measurement	0 to 2,500 ppm	0 to 500 ppm
Accuracy	± 3 % of reading or 15 ppm, whichever is greater	± 3 % of reading or 10 ppm, whichever is greater
Resolution	1 ppm	1 ppm
Linearity	Intercept \leq 0.5 % of range. 0.990 \leq Slope \leq 1.01 SEE \leq 1.0 % of range $r^2 \geq$ 0.998	Intercept \leq 1.0 % of range. 0.985 \leq Slope \leq 1.015 SEE \leq 1.0 % of range $r^2 \geq$ 0.998
Repeatability	± 2 % of reading or 5 ppm, whichever is greater	± 2 % of reading or 5 ppm, whichever is greater
Noise	± 2 ppm	± 2 ppm
Span drift (over 8 hours)	± 2 % of reading or 20 ppm, whichever is greater	± 10 ppm
Zero drift (over 2 hours)	± 10 ppm	± 10 ppm
Response time	T90 \leq 2 seconds	T90 \leq 2 seconds
Data Rate	Up to 4 Hz, configurable	Up to 4 Hz, configurable
Flow rate	3 lpm	3 lpm

14.5 Oxygen Sensor Specifications

Range of measurement	0 to 25 %
Accuracy	±1 % oxygen
Resolution	0.1 %
Linearity	±0.5 % of reading or ±0.5 % whichever is greater
Repeatability	±0.25 % of reading or ±0.3 % oxygen whichever is greater
Noise	±0.1 % oxygen
Span drift	±1.0 % of reading or ±0.5 % Oxygen whichever is greater
Response time	T90 < 6 seconds
Flow rate	0.5 to 3 lpm

14.6 Weather Probe and Ambient Pressure Specifications

Sensor	Temperature	Relative Humidity	Ambient Pressure
Range of measurement	-39 °C to 60 °C	0.8% to 100% RH	15 to 115 kPa
Accuracy	±0.2 °C	±2% RH at 0 to 90% RH ±3% RH at 90 to 100% RH	±1.5% 0 to 85 °C
Response time		T90 ≤ 10 seconds at 20 °C	T90 ≤ 4 seconds

14.7 External Analog Inputs

There are three external analog inputs available via the ANALOG I/O front panel connector. These inputs are bipolar and are read through a 12-bit analog to digital converter; therefore the full range is 2^{12} or 4096 counts. The theoretical resolution is calculated by dividing the full scale range by 4096.

Channel	Description	Voltage Range (Vdc)	Resolution (mVdc)
EAI-1	External analog input 1	-10.000 – 10.000	4.88
EAI-2	External analog input 2	-5.000 – 5.000	2.44
EAI-3	External analog input 3	-10.000 – 10.000	4.88

14.8 Optional Vehicle Interface Module Specifications

Module Type	Supported Protocols
Heavy-Duty	SAE-J1708 / SAE-1587 and SAE-J1939 / SAE-1587 (CAN)
Light-Duty	SAE-J1850 PWM, SAE-J1850 VPW, ISO-9141-2, ISO-14230 (KWP-2000), ISO-15765 (CAN), and ISO-11898 (CAN)

14.9 Optional SEMTECH-NMHC Specifications

NOTE: The specifications in this section apply to the actual measurement of methane by the SEMTECH-NMHC instrument. The Non-methane hydrocarbon (NMHC) value is derived from the separate methane and total hydrocarbon measurements, as described in Section 11.11.

Range of measurement	0 – 100, 0 – 1,000, and 0 – 10,000 ppm Methane User Selectable		
	0 – 100 ppm Range	0 – 1,000 ppm Range	0 – 10,000 ppm Range
Accuracy	±5.0 % of reading or ±5 ppm whichever is greater	±5.0 % of reading or ±10 ppm whichever is greater	±5.0 % of reading or ±25 ppm whichever is greater
Resolution	0.1 ppm	1.0 ppm	1.0 ppm
Linearity	±5.0 % of reading or ±5 ppm whichever is greater	±5.0 % of reading or ±10 ppm whichever is greater	±5.0 % of reading or ±25 ppm whichever is greater
Noise	±5 ppm	±5 ppm	±10 ppm
Span drift (over 8 hours)	±1.0 % of reading or 3 ppmC whichever is greater	±1.0 % of reading or 3 ppmC whichever is greater	±1.0 % of reading or 15 ppmC whichever is greater
Zero drift (over 2 hours)	±5 ppm	±5 ppm	±10 ppm
Response time	T90 ≤ 5 seconds	T90 ≤ 5 seconds	T90 ≤ 5 seconds
Flow rate	2 lpm	2 lpm	2 lpm
Data rate	Up to 4 Hz, configurable	Up to 4 Hz, configurable	Up to 4 Hz, configurable
Operating temperature	130 °C	130 °C	130 °C

14.10 Recommended Gas Bottles

Gas	Audit	Span Calibration
CO ₂	4 – 6%	12 – 14%
CO	200 – 400 ppm	1,200 – 1,400 ppm
NO	200 – 400 ppm	1,500 – 2,000 ppm
HC	250 – 350 ppm propane	2,500 – 3,500 ppm propane
THC	30 – 50 ppm propane (90 – 150 ppmC THC) – when using the 1,000 ppmC FID range	200 – 300 ppm propane (600 – 900 ppmC THC) – when using the 1,000 ppmC FID range
NO ₂	50 – 80 ppm	200 – 300 ppm
CH ₄	80 – 120 ppm	450 – 550 ppm

In general, the span gas concentration should be between 50% and 100% of the analyzer range, and the audit gas concentration should be between 25% and 50% of the span gas concentration.

For example, when using the 10,000 ppmC FID range, an appropriate span gas is 2,000 ppm propane (equivalent to 6,000 ppmC THC). Using this span gas concentration, 500 ppm propane (1,500 ppmC THC) is an appropriate audit gas concentration.

IMPORTANT: All span calibration and audit gas bottles, except NO₂, should be blended with balance N₂. The NO₂ span calibration and audit bottles should be balance air.

14.11 Recommended FID Fuel

Gas	Concentration	Hydrocarbon Contamination
H ₂ – He blend	0.400 ± 0.004 mol/mol hydrogen, balance helium	less than 0.05 µmol/mol THC

This FID fuel purity level complies with Title 40 of the Code of Federal Regulations Part 1065, Subpart H (1065.750).

14.12 Default Audit Limits

The following table lists the default limits used in the gas audit screen. These values can be changed by the user as described in Section 8.6.5.1.

Gas	Absolute Tolerance Limit	Relative Tolerance Limit
CO	0.005%	3.0 % of bottle value
CO ₂	0.2 %	3.0 % of bottle value
O ₂	0.5 %	3.0 % of bottle value
NO	15.0 ppm	3.0 % of bottle value
NO ₂	12.0 ppm	3.0 % of bottle value
HC	4.0 ppmC6	3.0 % of bottle value
THC (100 ppmC)	6.0 ppmC	2.0 % of bottle value
THC (1,000 ppmC)	6.0 ppmC	2.0 % of bottle value
THC (10,000 ppmC)	27.0 ppmC	2.0 % of bottle value
CH ₄ (100 ppmC)	5.0 ppmC	5.0 % of bottle value
CH ₄ (1,000 ppmC)	10.0 ppmC	5.0 % of bottle value
CH ₄ (10,000 ppmC)	25.0 ppmC	5.0 % of bottle value

Appendix E: Engine Performance Data - Investigation I
 (February 18, 2008)

Table XXXIV: Atmospheric Condition (Performance Test One)

Local Temperature	1 °C or 33.8 °F
Local Barometric Pressure	30.02 inHg

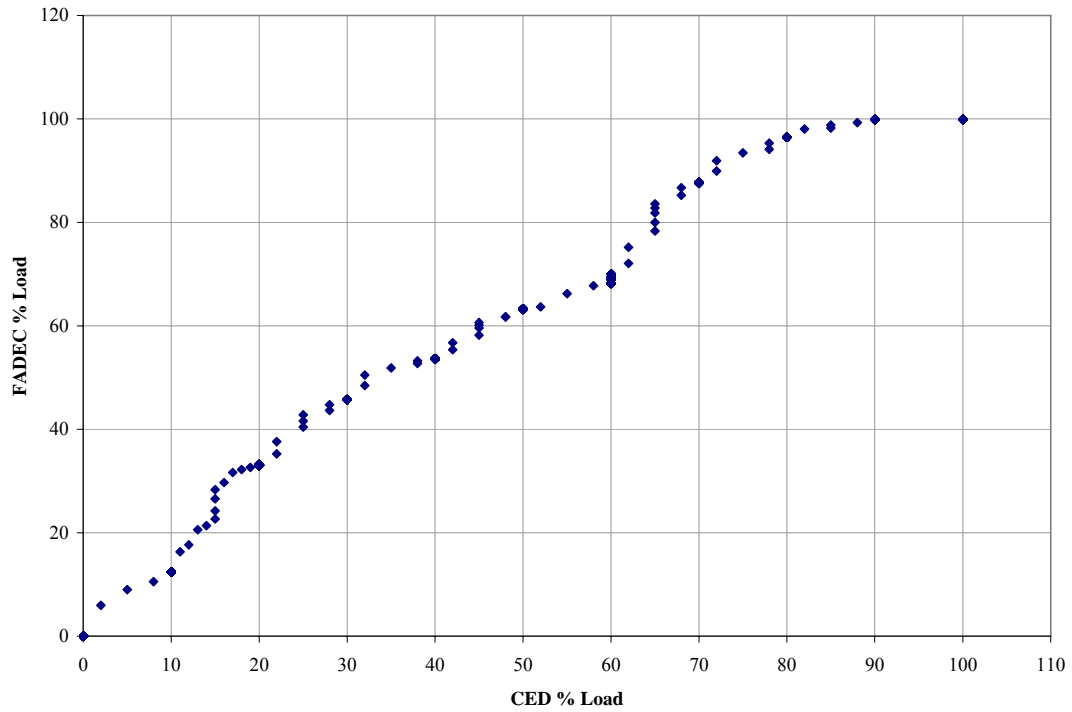


Figure 66: Load Comparison (Performance Test One: RawData)

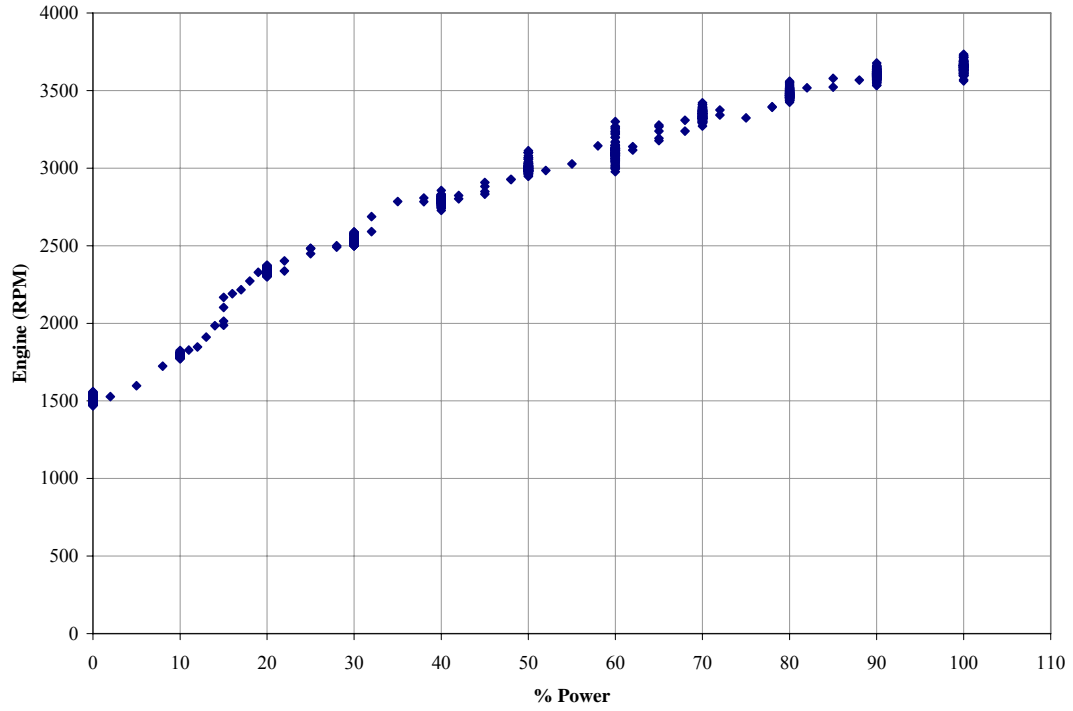


Figure 67: Engine RPM Data (Performance Test One: Raw Data)

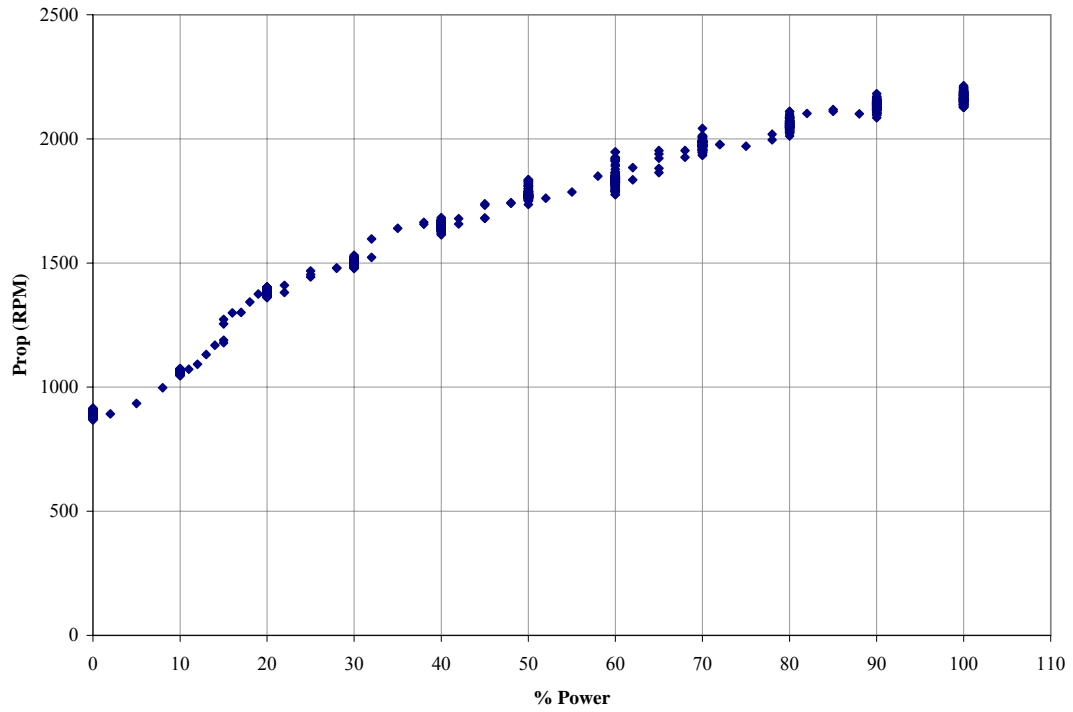


Figure 68: Prop RPM Data (Performance Test One: Raw Data)

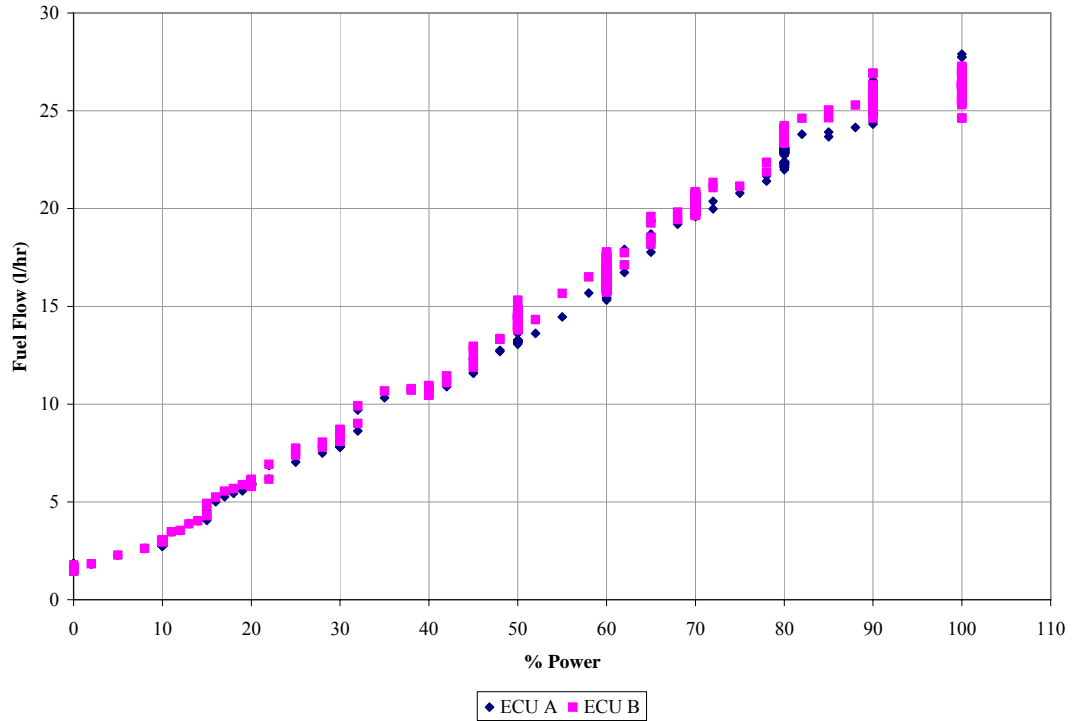


Figure 69: Fuel Flow (Performance Test One: Raw Data)

Table XXXV: FADEC Data (Performance Test One)

CED <i>(% Load)</i>	FADEC <i>(% Load)</i>	Engine <i>(RPM)</i>	Propeller <i>(RPM)</i>	Fuel Flow A <i>(l/hr)</i>	Fuel Flow B <i>(l/hr)</i>
3	0.0000	1505.3625	890.0125	1.6954	1.6142
10	12.4023	1792.3645	1059.7009	2.7884	3.0071
20	33.0556	2337.6020	1384.8571	5.8912	5.8973
30	45.7031	2536.5093	1501.4259	8.1926	8.5142
40	53.6105	2791.1346	1651.2308	10.7113	10.7086
50	63.2794	3005.0769	1779.3462	13.5890	14.2904
60	69.0645	3107.8349	1838.8532	16.1935	16.6816
70	87.7736	3341.7736	1976.7547	20.0366	20.3092
80	96.4844	3479.1495	2058.2617	22.7878	23.7667
90	99.9014	3604.7130	2134.4352	25.1892	25.5869
100	99.9023	3649.6696	2163.5804	26.3824	26.2506

Table XXXVI: Performance Data (Performance Test One)

Load (%)	Propeller (RPM)	Torque (volt)	Torque (lb-ft)	Thrust (volt)	Thrust (lbf)	Brake HP (Hp)	n (~)	Thrust Hp (Hp)
3	890.0125	0.2680	50.9091	0.338	74.55874	8.6269	0.75	6.4702
10	1059.7009	0.3740	70.3357	0.538	107.10474	14.1914	0.75	10.6435
20	1384.8571	0.6970	129.5319	1.022	185.86606	34.1545	0.75	25.6159
30	1501.4259	0.8250	152.9905	1.25	222.9685	43.7355	0.75	32.8016
40	1651.2308	1.0500	194.2262	1.56	273.4148	61.0635	0.75	45.7976
50	1779.3462	1.2500	230.8802	1.823	316.21279	78.2191	0.75	58.6644
60	1838.8532	1.5160	279.6300	2.06	354.7798	97.9032	0.75	73.4274
70	1976.7547	1.8300	337.1768	2.45	418.2445	126.9043	0.75	95.1782
80	2058.2617	1.9250	354.5875	2.622	446.23406	138.9600	0.75	104.2200
90	2134.4352	2.0350	374.7472	2.807	476.33911	152.2956	0.75	114.2217
100	2163.5804	2.1850	402.2377	2.878	487.89294	165.6997	0.75	124.2748

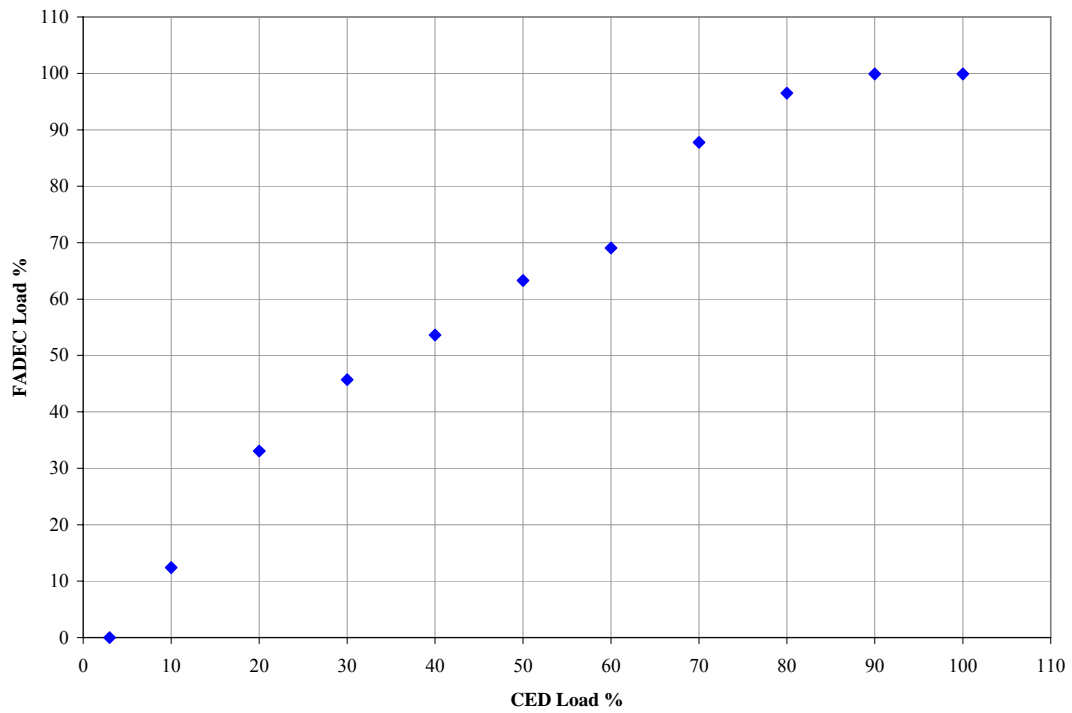


Figure 70: Load Comparison (Performance Test One: Analyzed Data)

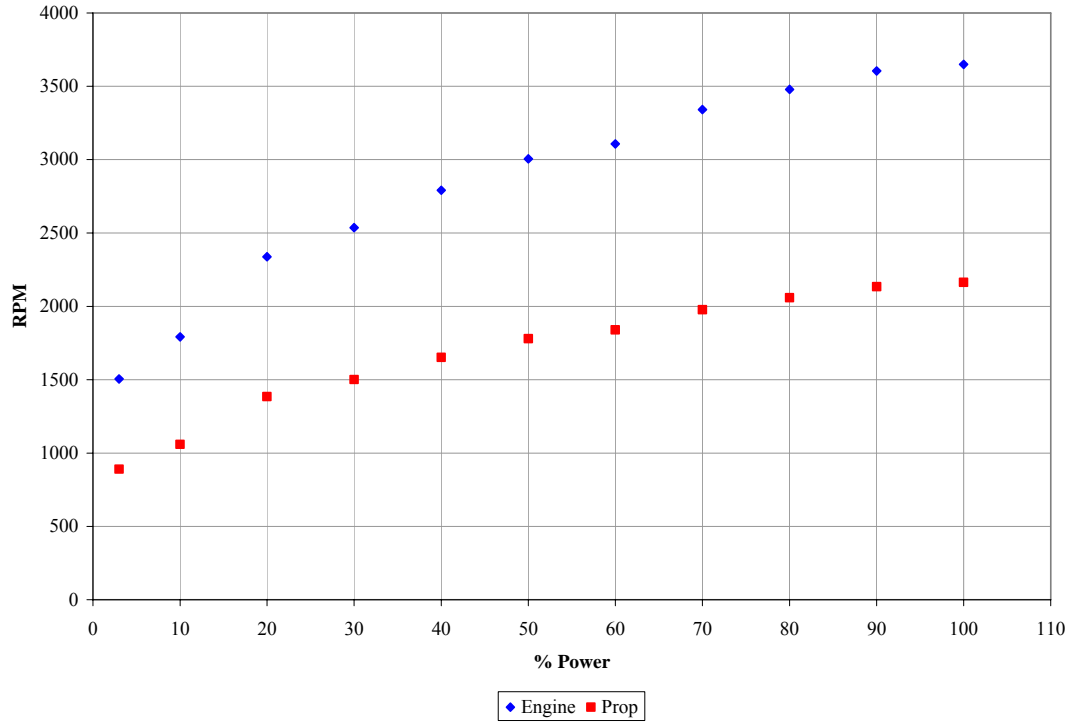


Figure 71: RPM Data (Performance Test One: Analyzed Data)

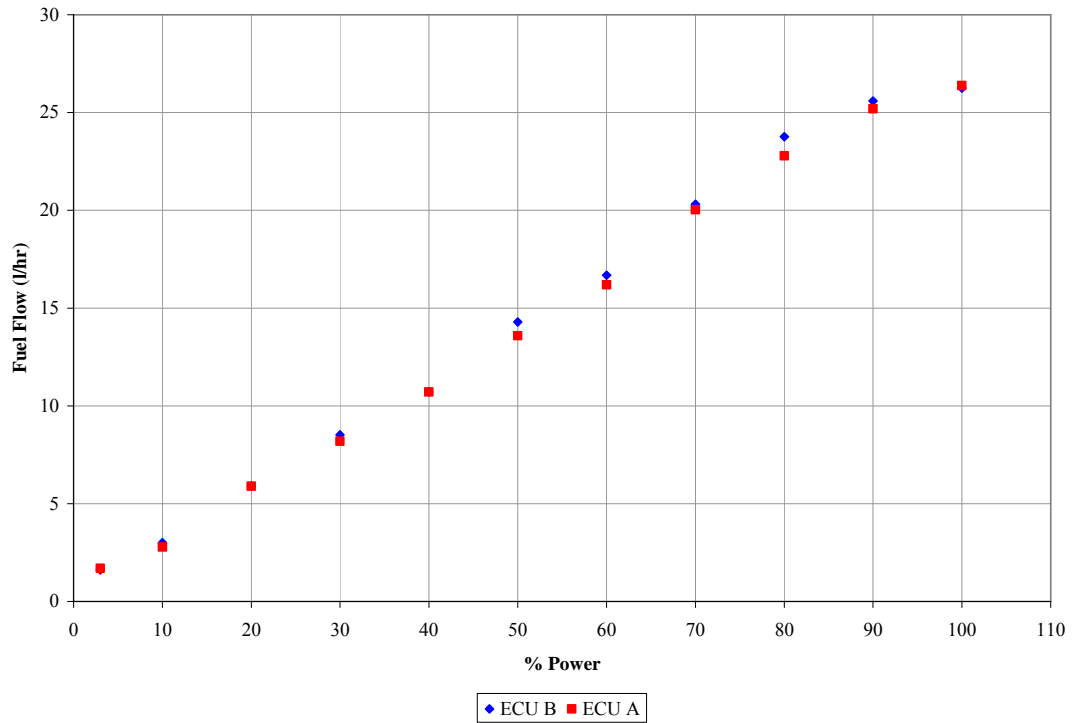


Figure 72: Fuel Flow (Performance Test One: Analyzed Data)

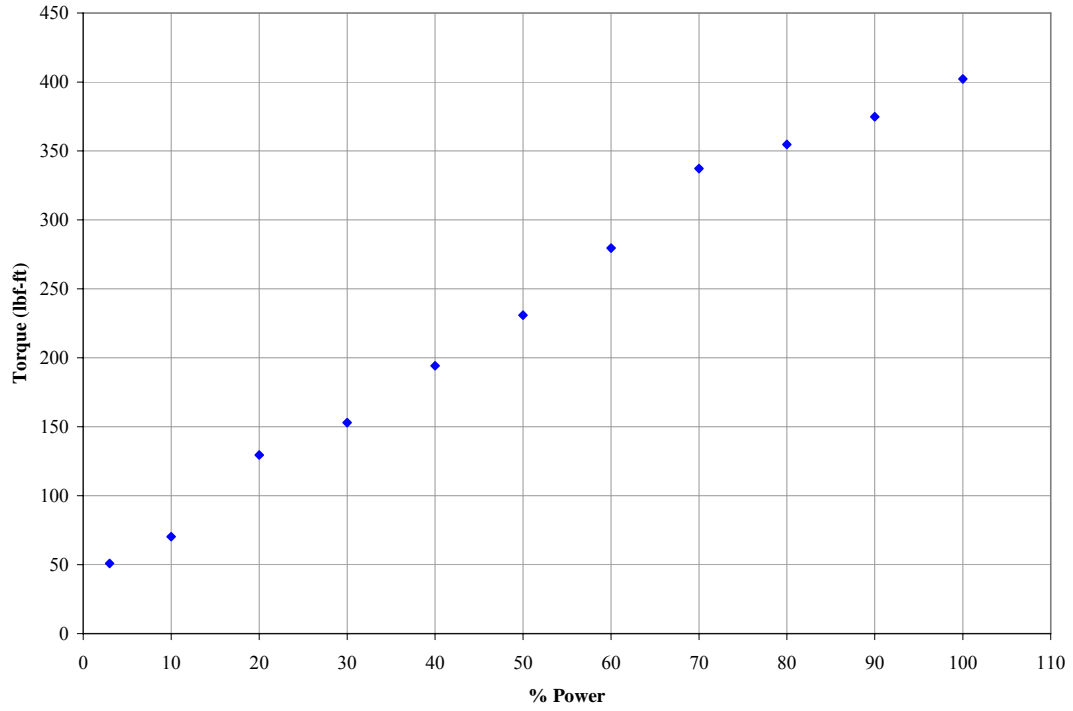


Figure 73: Torque Data (Performance Test One: Analyzed Data)

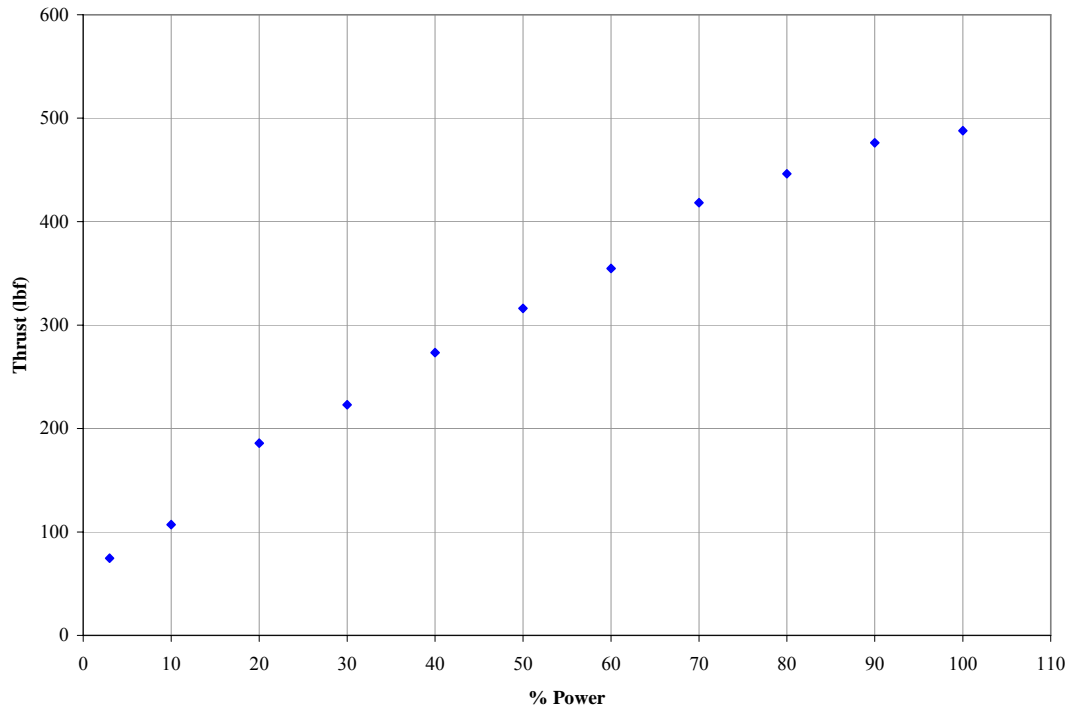


Figure 74: Thrust Data (Performance Test One: Analyzed Data)

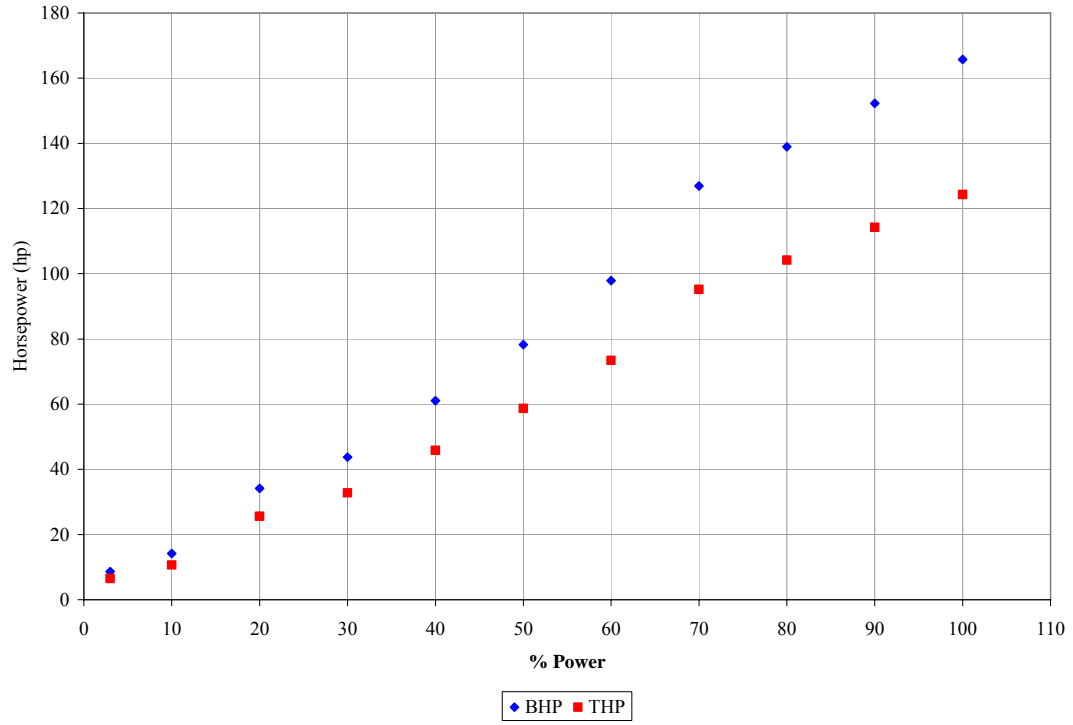


Figure 75: Horsepower (Performance Test One: Analyzed Data)

Appendix F: Engine Performance Data - Investigation II
 (February 18, 2008)

Table XXXVII: Atmospheric Condition (Performance Test Two)

Local Temperature	1 °C or 33.8 °F
Local Barometric Pressure	30.03 inHg

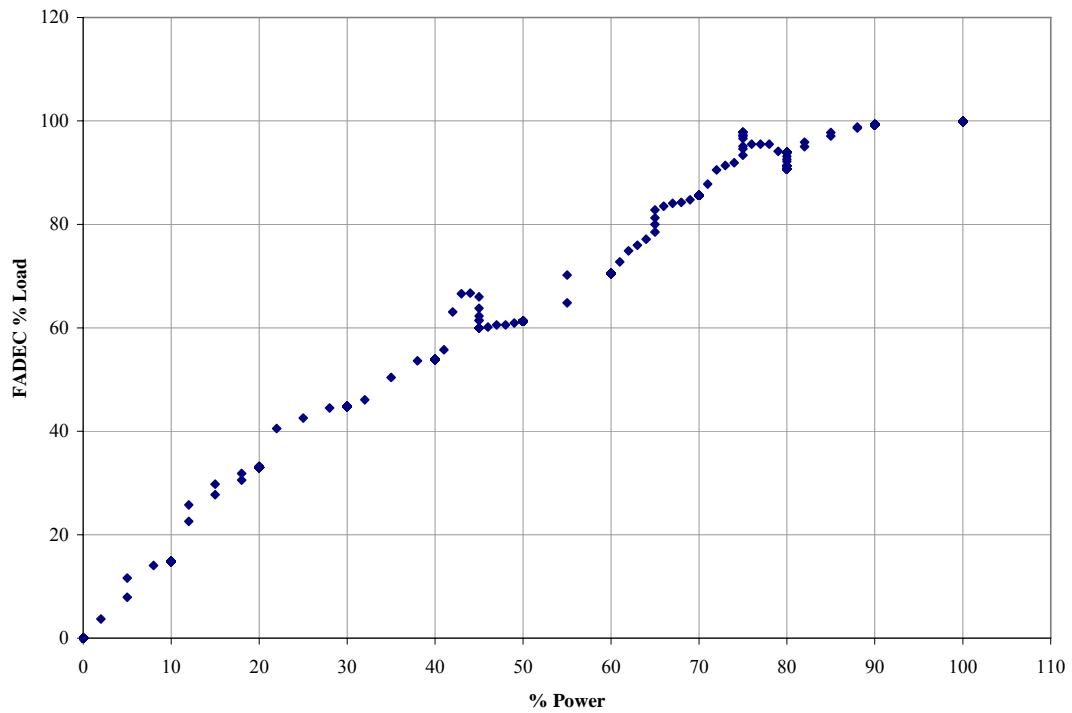


Figure 76: Load Comparison (Performance Test Two: RawData)

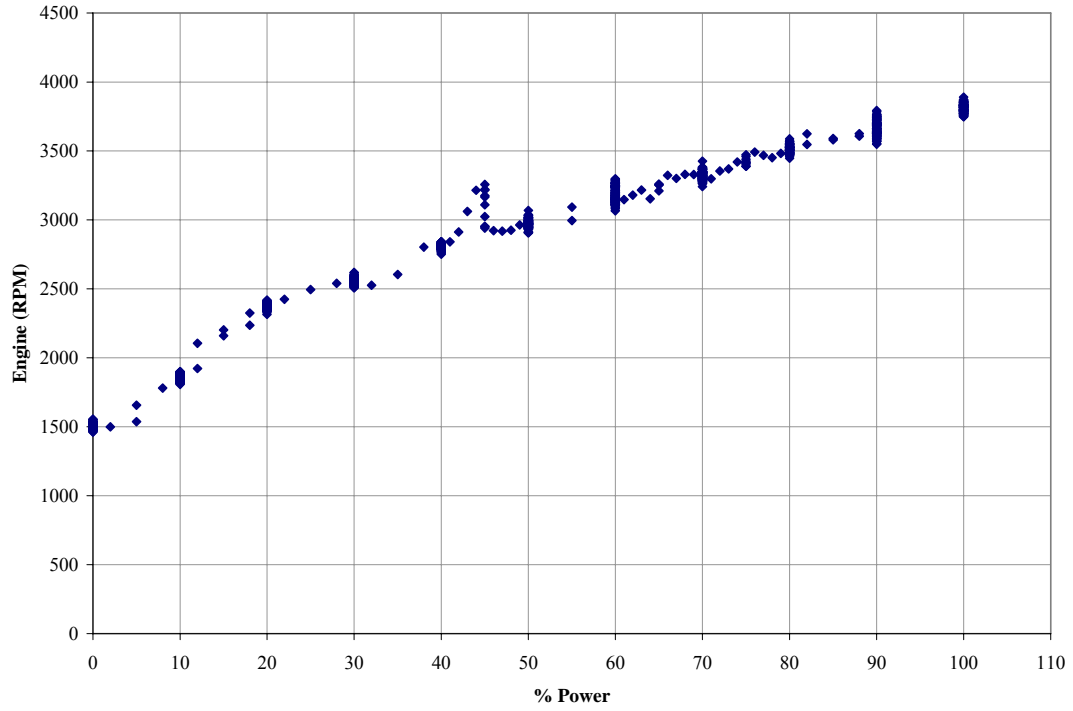


Figure 77: Engine RPM Data (Performance Test Two: Raw Data)

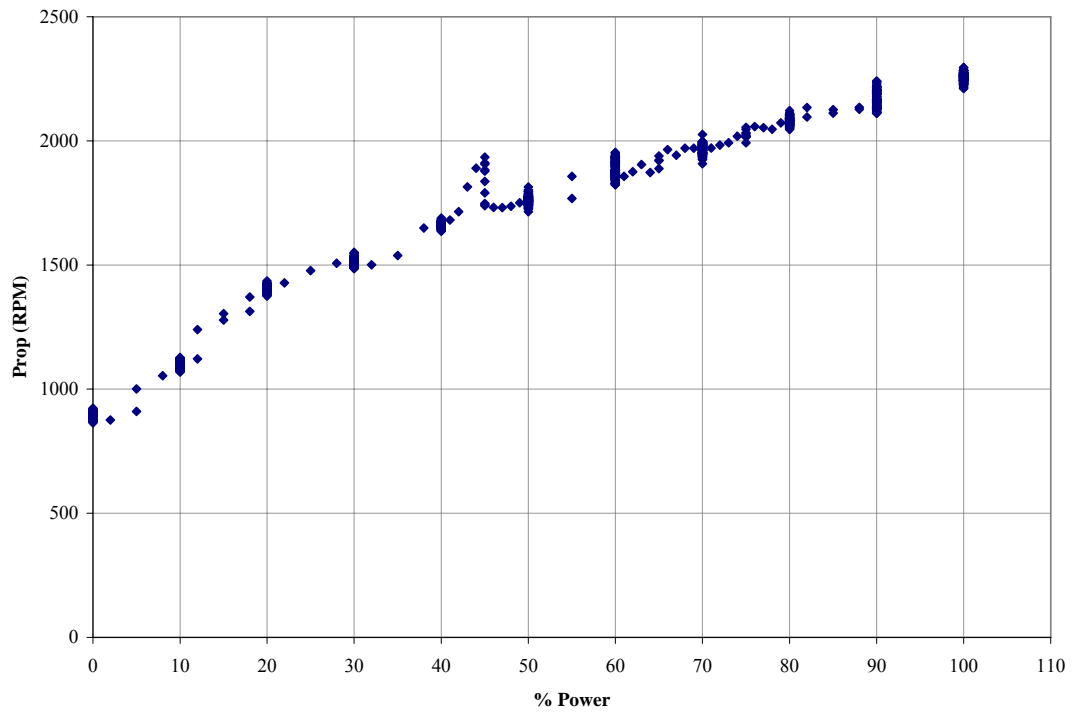


Figure 78: Prop RPM Data (Performance Test Two: Raw Data)

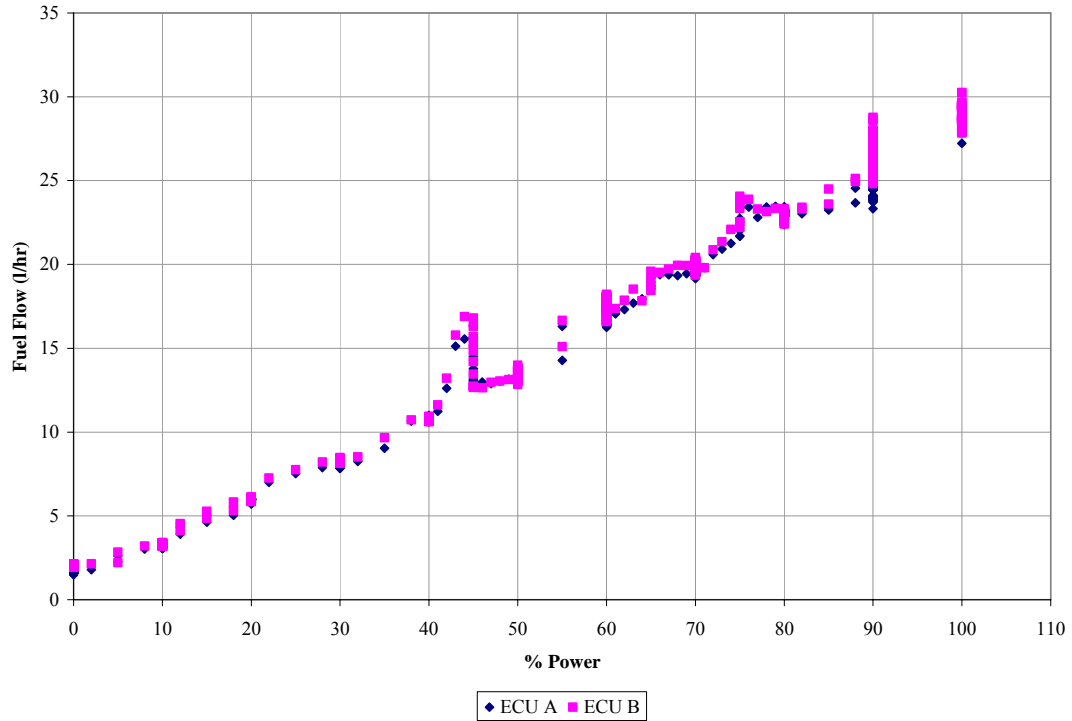


Figure 79: Fuel Flow (Performance Test Two: Raw Data)

Table XXXVIII: FADEC Data (Performance Test Two)

CED <i>(% Load)</i>	FADEC <i>(% Load)</i>	Engine <i>(RPM)</i>	Prop <i>(RPM)</i>	Fuel Flow A <i>(l/hr)</i>	Fuel Flow B <i>(l/hr)</i>
3	0.0000	1503.9123	889.8421	1.6185	2.0137
10	14.8438	1844.6762	1092.1048	3.1636	3.2999
20	33.0152	2375.3679	1405.7358	5.9310	5.9842
30	44.8242	2560.2973	1514.4955	7.9878	8.2867
40	53.9063	2808.9434	1662.7358	10.7863	10.7829
50	61.3281	2974.1979	1760.4792	13.2879	13.2948
60	70.5078	3183.9813	1883.4206	17.0933	17.5359
70	85.6445	3324.1100	1967.1900	19.5653	19.9379
80	92.0462	3513.6702	2080.4681	23.0278	22.9023
90	99.2894	3666.1143	2170.1238	25.0738	26.3145
100	99.9023	3811.7043	2255.2870	28.9749	28.9991

Table XXXIX: Performance Data (Performance Test Two)

Load	Prop	Torque	Torque	Thrust	Thrust	BHP	n	THP
<i>(%)</i>	<i>(RPM)</i>	<i>(volt)</i>	<i>(lbf-ft)</i>	<i>(volt)</i>	<i>(lbf)</i>	<i>(Hp)</i>	<i>(~)</i>	<i>(Hp)</i>
3	889.8421	0.2690	51.0923	0.353	76.99969	8.6563	0.75	6.4923
10	1092.1048	0.4430	82.9813	0.606	118.17038	17.2548	0.75	12.9411
20	1405.7358	0.7220	134.1136	1.062	192.37526	35.8957	0.75	26.9218
30	1514.4955	0.8630	159.9547	1.26	224.5958	46.1244	0.75	34.5933
40	1662.7358	1.0820	200.0908	1.538	269.83474	63.3456	0.75	47.5092
50	1760.4792	1.2600	232.7129	1.83	317.3519	78.0041	0.75	58.5031
60	1883.4206	1.6030	295.5745	2.201	377.72473	105.9937	0.75	79.4953
70	1967.1900	1.9120	352.2049	2.378	406.52794	131.9191	0.75	98.9393
80	2080.4681	1.9770	364.1175	2.66	452.4178	144.2343	0.75	108.1757
90	2170.1238	2.0500	377.4962	2.815	477.64095	155.9779	0.75	116.9834
100	2255.2870	2.2380	411.9510	3.085	521.57805	176.8941	0.75	132.6705

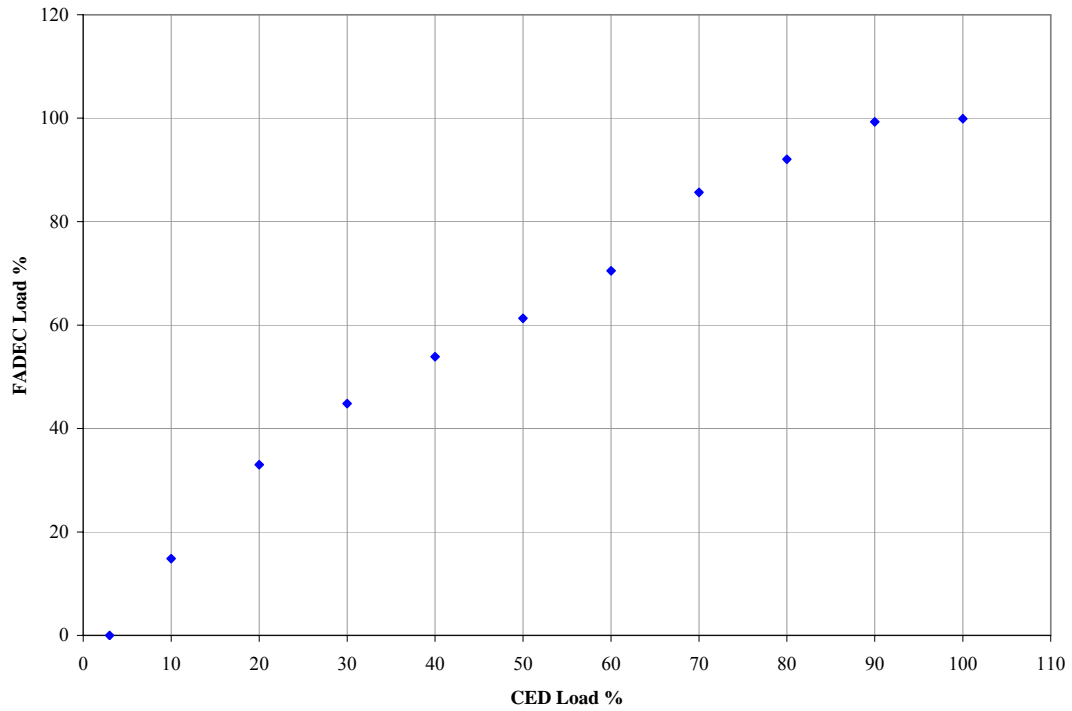


Figure 80: Load Comparison (Performance Test Two: Analyzed Data)

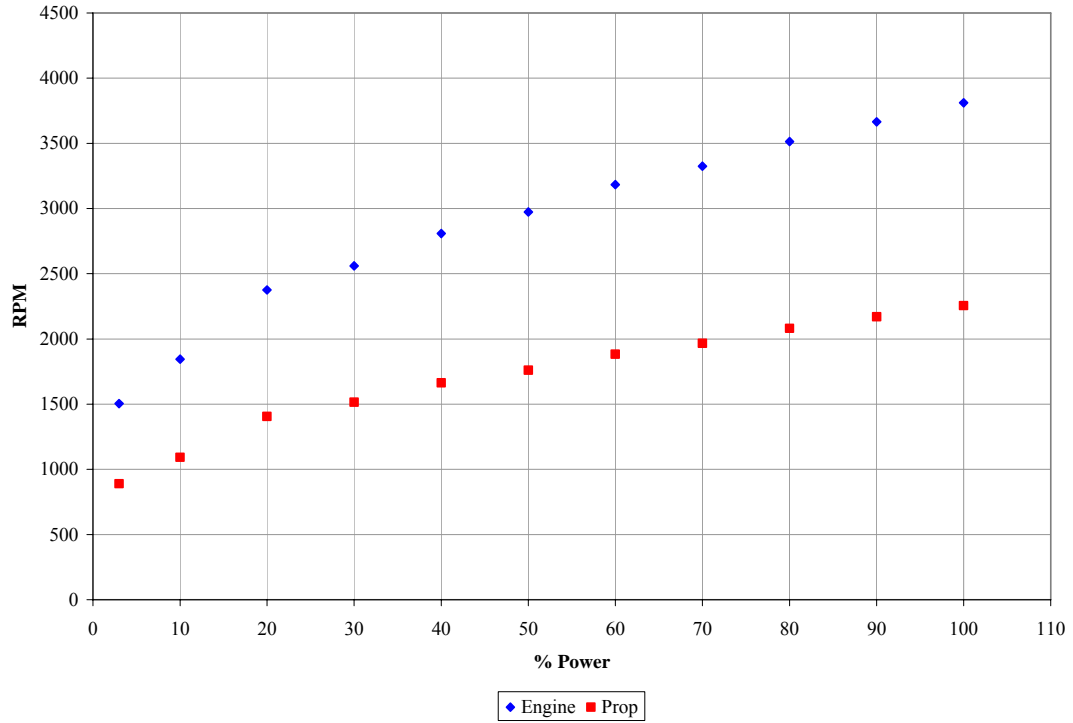


Figure 81: RPM Data (Performance Test Two: Analyzed Data)

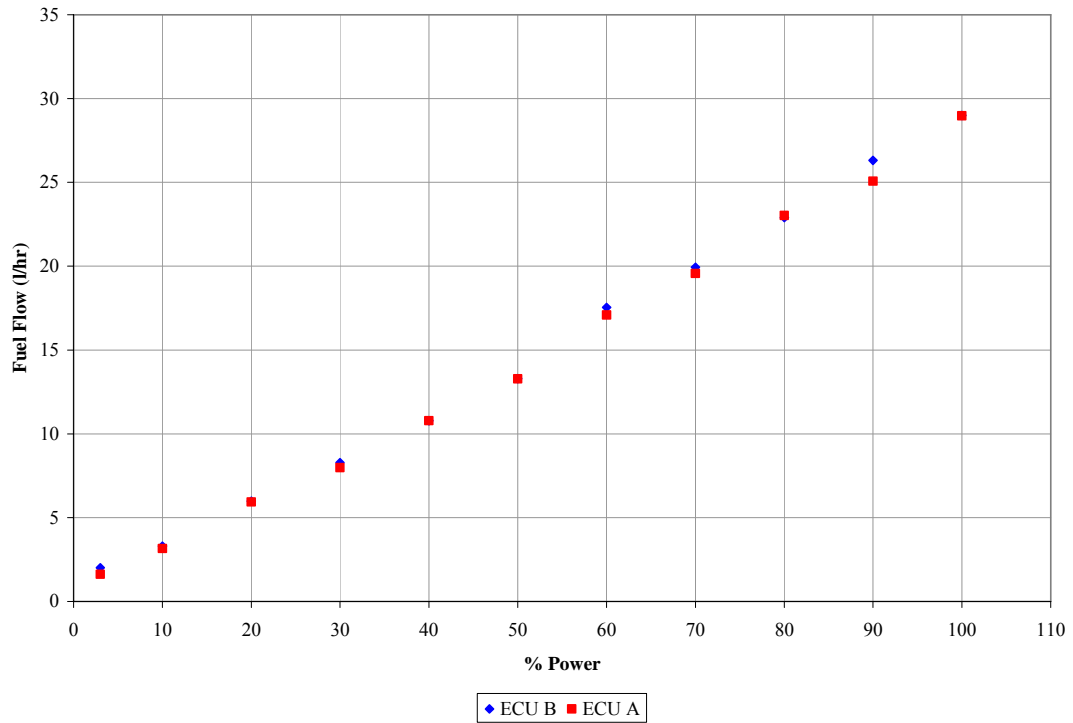


Figure 82: Fuel Flow (Performance Test Two: Analyzed Data)

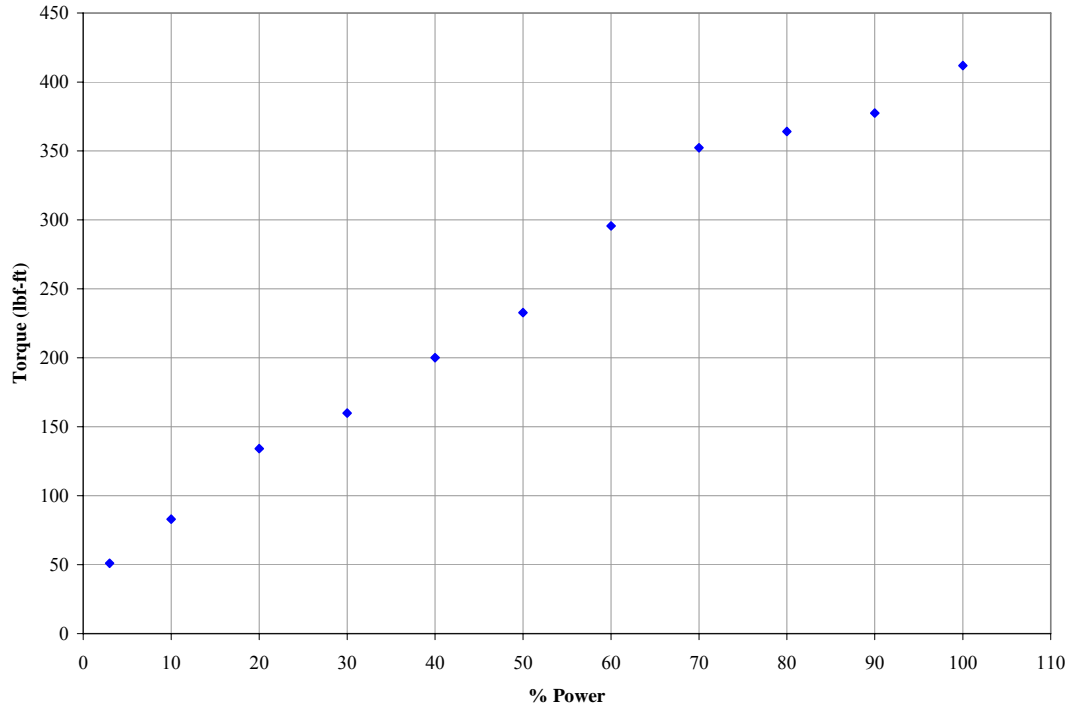


Figure 83: Torque Data (Performance Test Two: Analyzed Data)

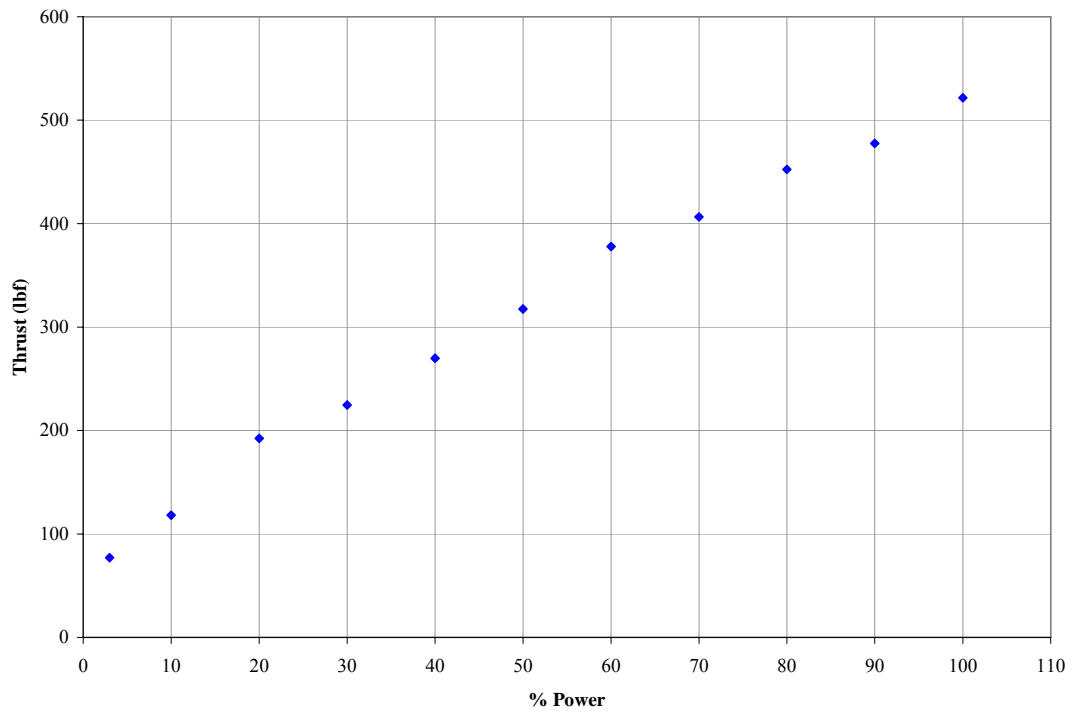


Figure 84: Thrust Data (Performance Test Two: Analyzed Data)

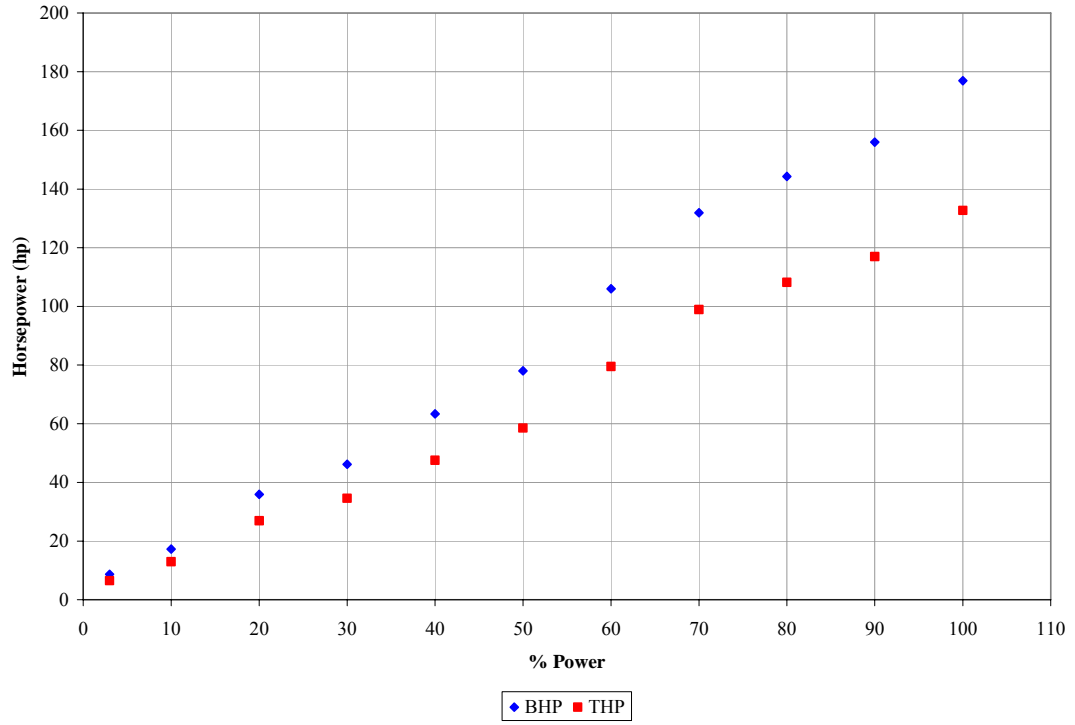


Figure 85: Horsepower (Performance Test Two: Analyzed Data)

Appendix G: Engine Performance Data - Investigation III
 (February 18, 2008)

Table XL: Atmospheric Condition (Performance Test Three)

Local Temperature	1 °C or 33.8 °F
Local Barometric Pressure	30.03 inHg

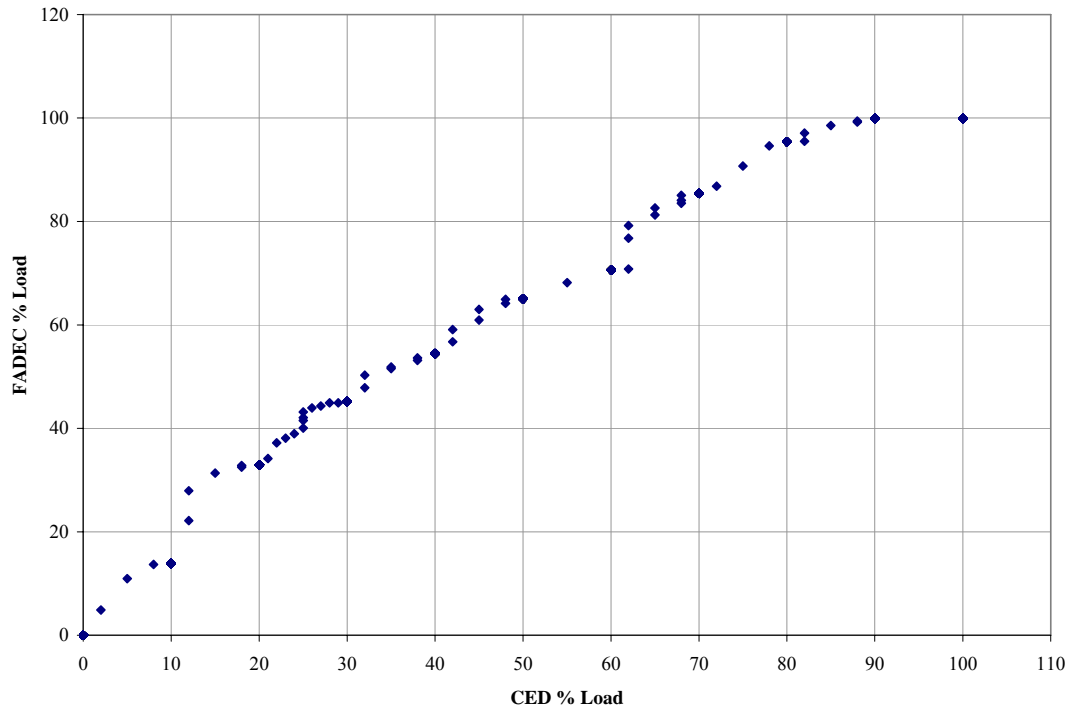


Figure 86: Load Comparison (Performance Test Three: RawData)

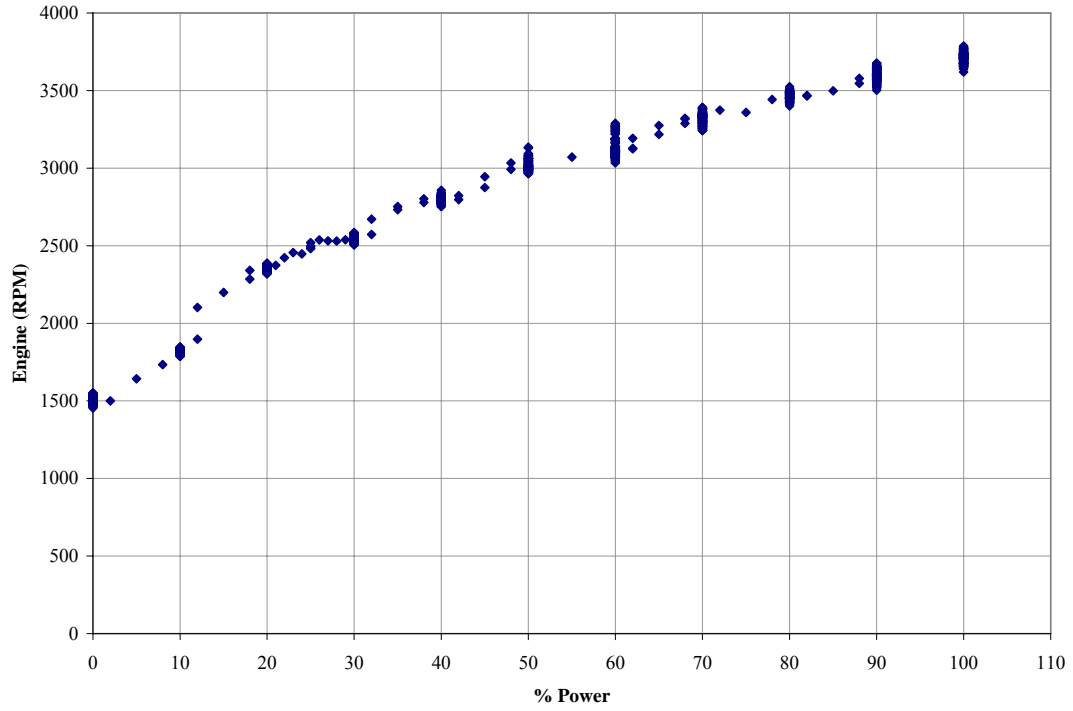


Figure 87: Engine RPM Data (Performance Test Three: Raw Data)

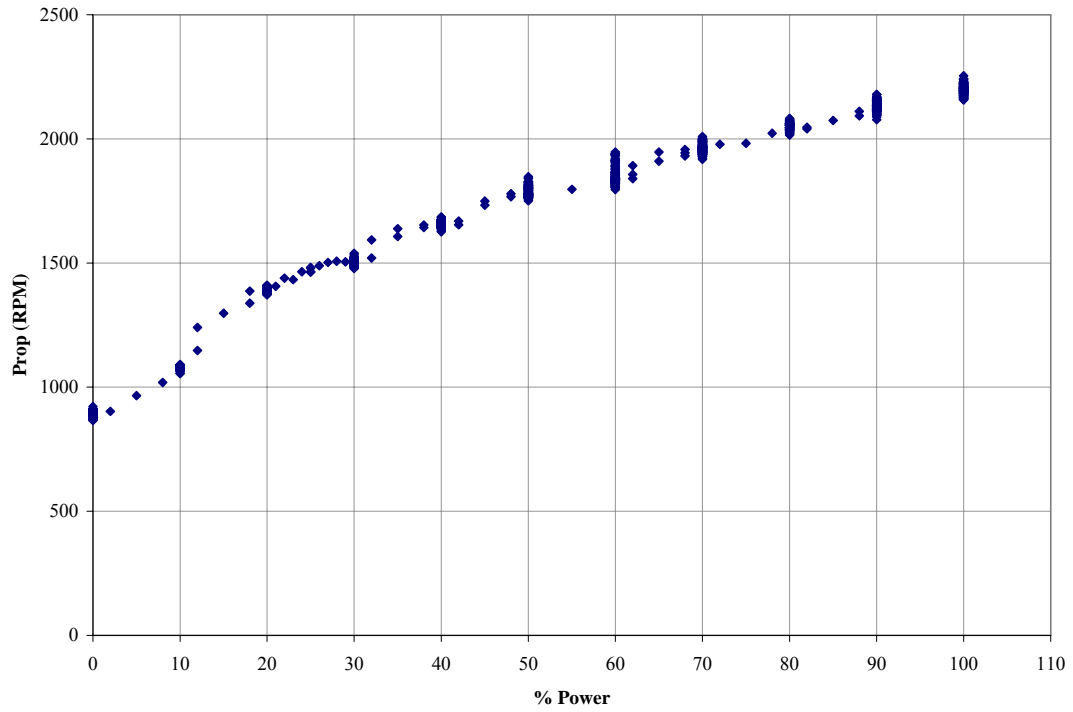


Figure 88: Prop RPM Data (Performance Test Three: Raw Data)

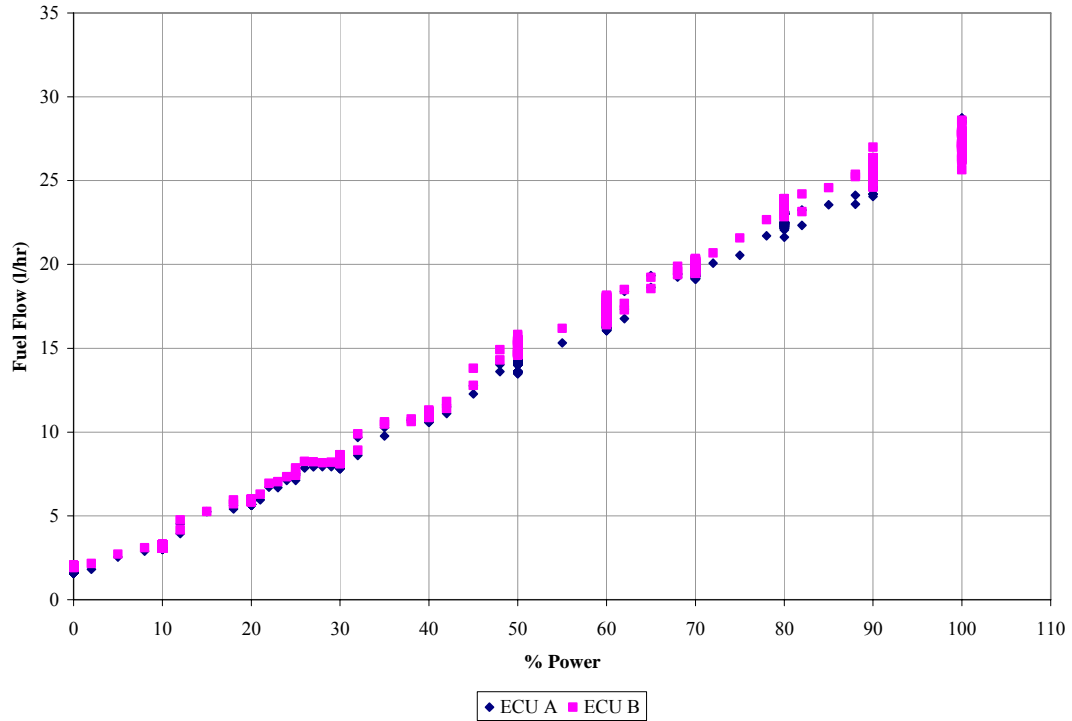


Figure 89: Fuel Flow (Performance Test Three: Raw Data)

Table XLI: FADEC Data (Performance Test Three)

CED <i>(% Load)</i>	FADEC <i>(% Load)</i>	Engine <i>(RPM)</i>	Prop <i>(RPM)</i>	Fuel Flow A <i>(l/hr)</i>	Fuel Flow B <i>(l/hr)</i>
3	0.0000	1502.7563	889.0813	1.6296	1.9796
10	13.8672	1822.8491	1079.2075	3.0589	3.1969
20	32.9102	2349.9352	1392.7870	5.7979	5.9199
30	45.2148	2539.3846	1502.9519	7.9228	8.2361
40	54.3964	2797.3235	1657.0196	10.7475	11.0742
50	65.0391	3018.4667	1788.2286	14.0572	15.0241
60	70.6055	3130.3486	1852.8807	16.6997	17.1761
70	85.4492	3317.1455	1962.2909	19.5065	19.9013
80	95.4102	3464.4808	2050.7308	22.5844	23.3769
90	99.9023	3599.6132	2132.6226	24.8034	25.5875
100	99.9023	3711.7227	2198.9748	27.3250	27.3009

Table XLII: Performance Data (Performance Test Three)

Load (%)	Prop (RPM)	Torque (volt)	Torque (lbf-ft)	Thrust (volt)	Thrust (lbf)	BHP (Hp)	n (~)	THP (Hp)
3	889.0813	0.2890	54.7577	0.358	77.81334	9.2694	0.75	6.9521
10	1079.2075	0.4240	79.4992	0.578	113.61394	16.3355	0.75	12.2517
20	1392.7870	0.7210	133.9304	1.001	182.44873	35.5165	0.75	26.6373
30	1502.9519	0.8230	152.6239	1.216	217.43568	43.6751	0.75	32.7563
40	1657.0196	1.0380	192.0270	1.56	273.4148	60.5837	0.75	45.4378
50	1788.2286	1.2450	229.9639	1.889	326.95297	78.2976	0.75	58.7232
60	1852.8807	1.5630	288.2437	2.152	369.75096	101.6888	0.75	76.2666
70	1962.2909	1.7680	325.8141	2.415	412.54895	121.7304	0.75	91.2978
80	2050.7308	1.9620	361.3684	2.583	439.88759	141.0993	0.75	105.8245
90	2132.6226	2.0420	376.0300	2.739	465.27347	152.6871	0.75	114.5154
100	2198.9748	2.1600	397.6559	2.954	500.26042	166.4921	0.75	124.8691

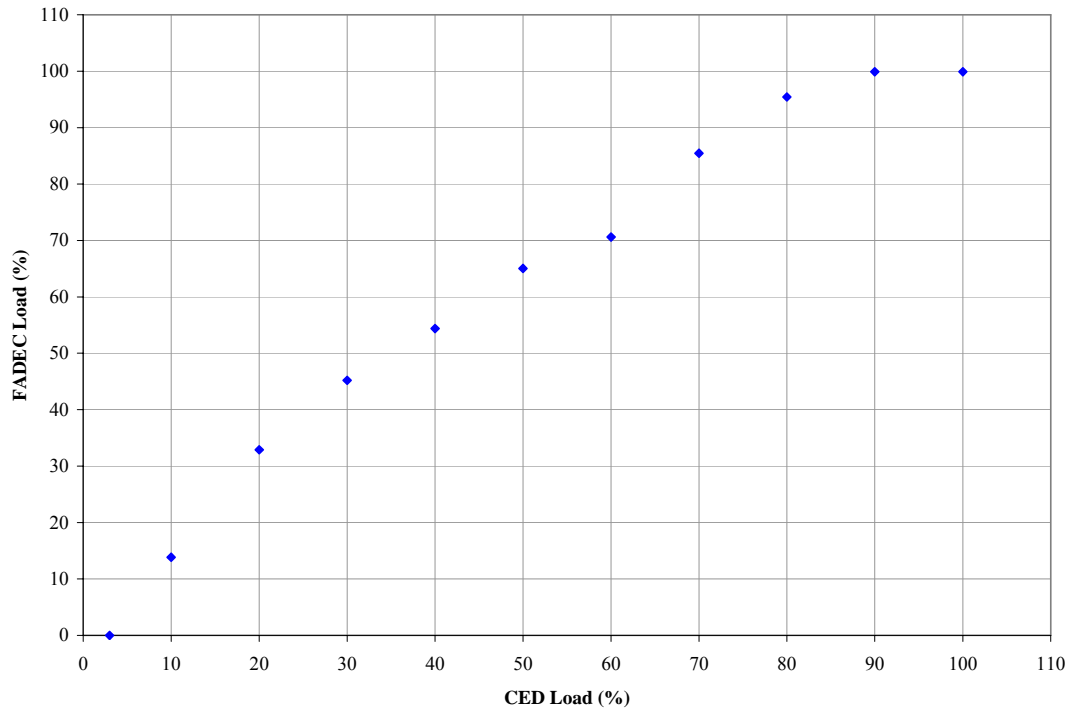


Figure 90: Load Comparison (Performance Test Three: Analyzed Data)

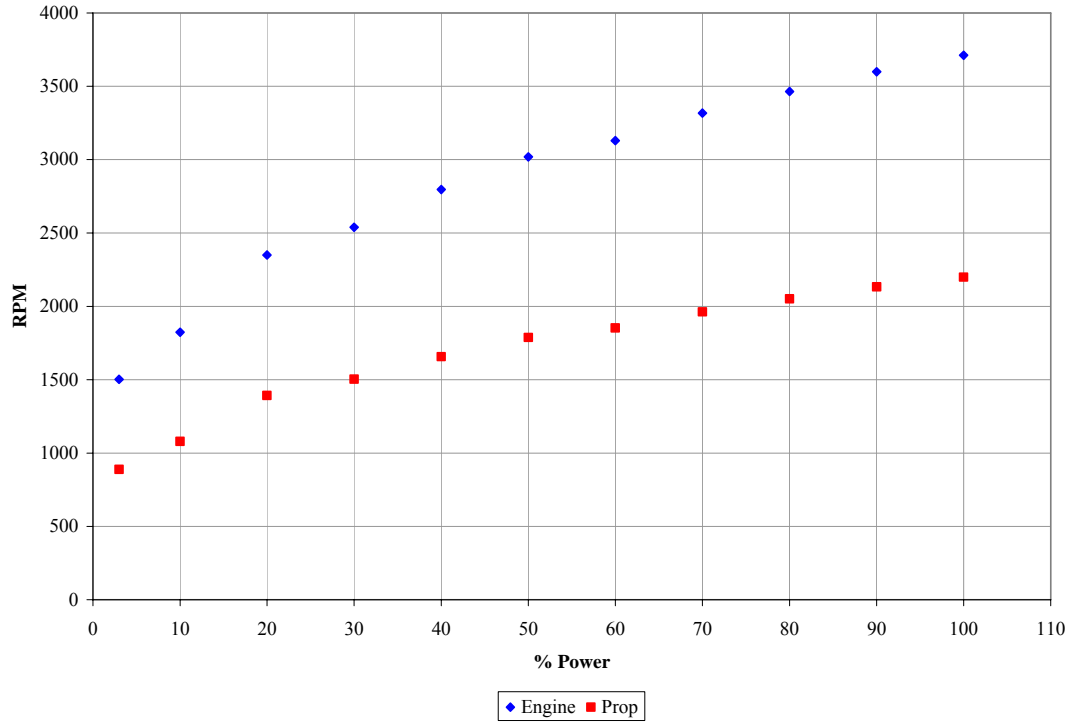


Figure 91: RPM (Performance Test Three: Analyzed Data)

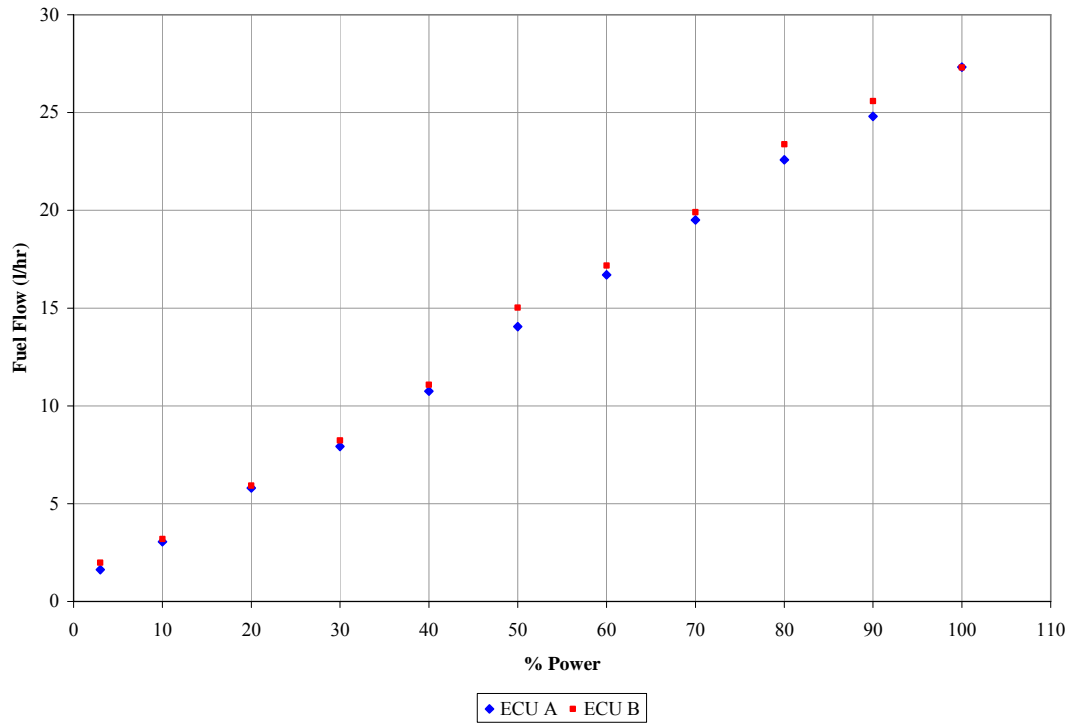


Figure 92: Fuel Flow (Performance Test Three: Analyzed Data)

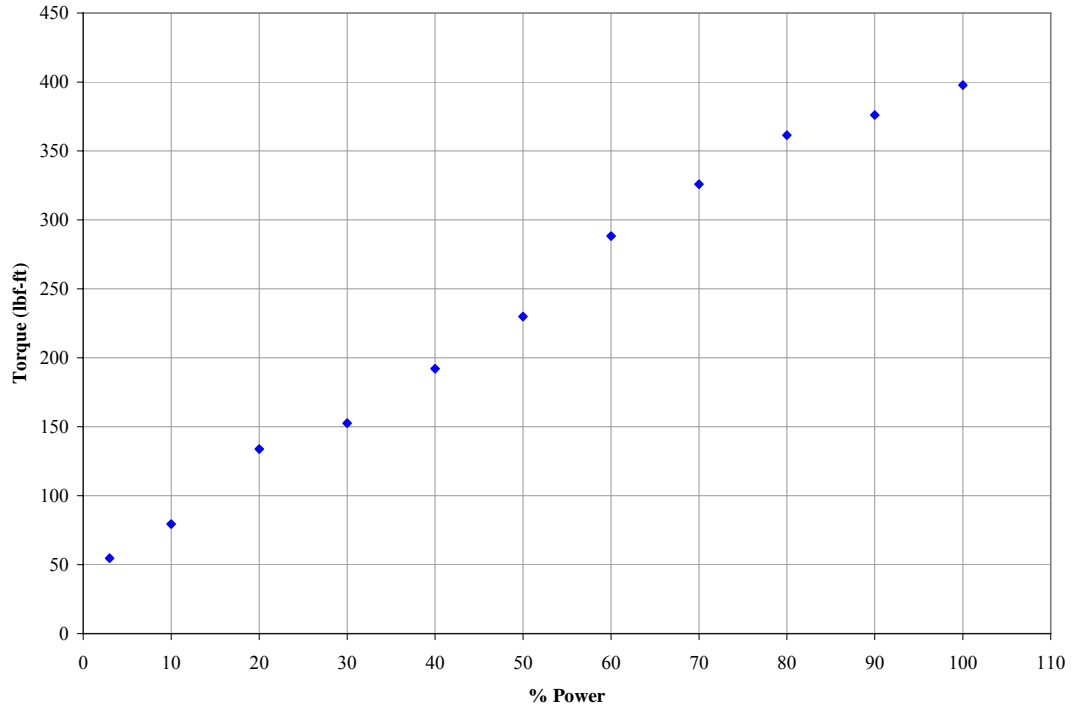


Figure 93: Torque Data (Performance Test Three: Analyzed Data)

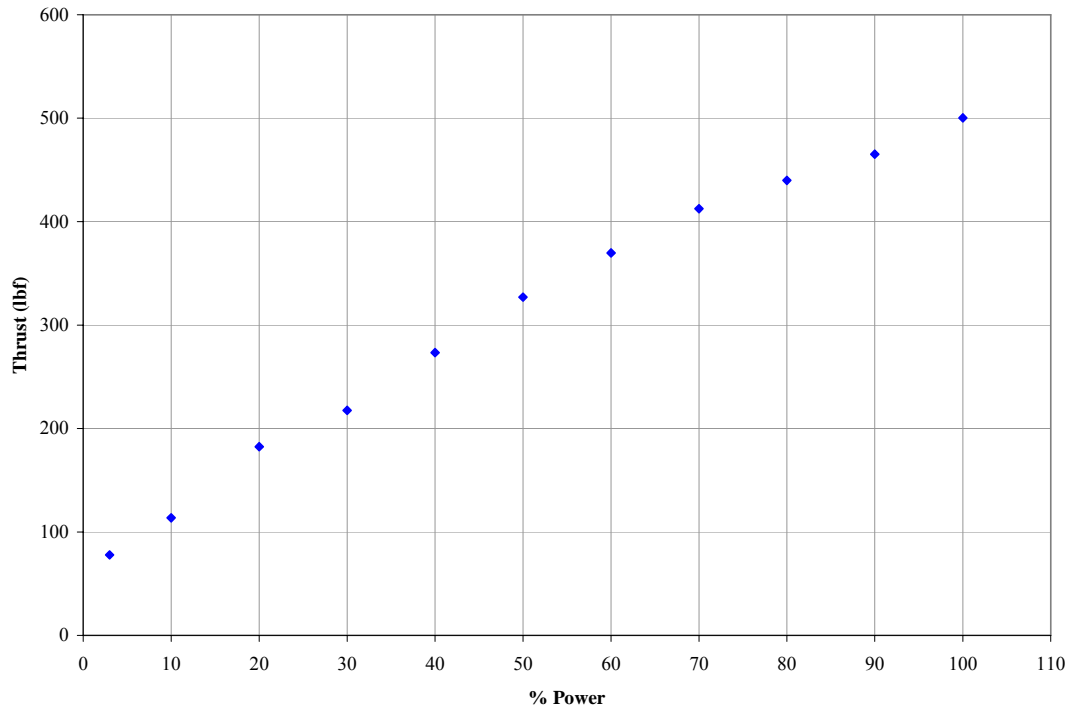


Figure 94: Thrust Data (Performance Test Three: Analyzed Data)

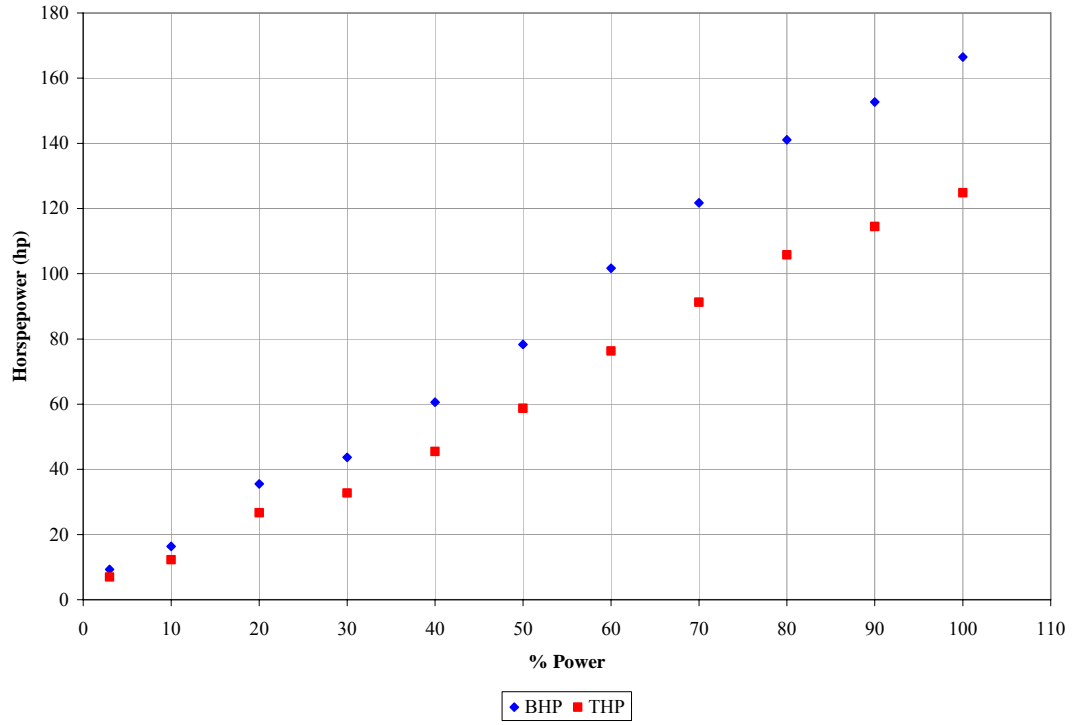


Figure 95: Horsepower (Performance Test Three: Analyzed Data)

Appendix H: Engine Emission Data - Investigation I
 (February 13, 2008)

Table XLIII: Atmospheric Condition (Emission Run One)

Local Temperature	2 °C or 35.6 °F
Local Barometric Pressure	30.01 inHg

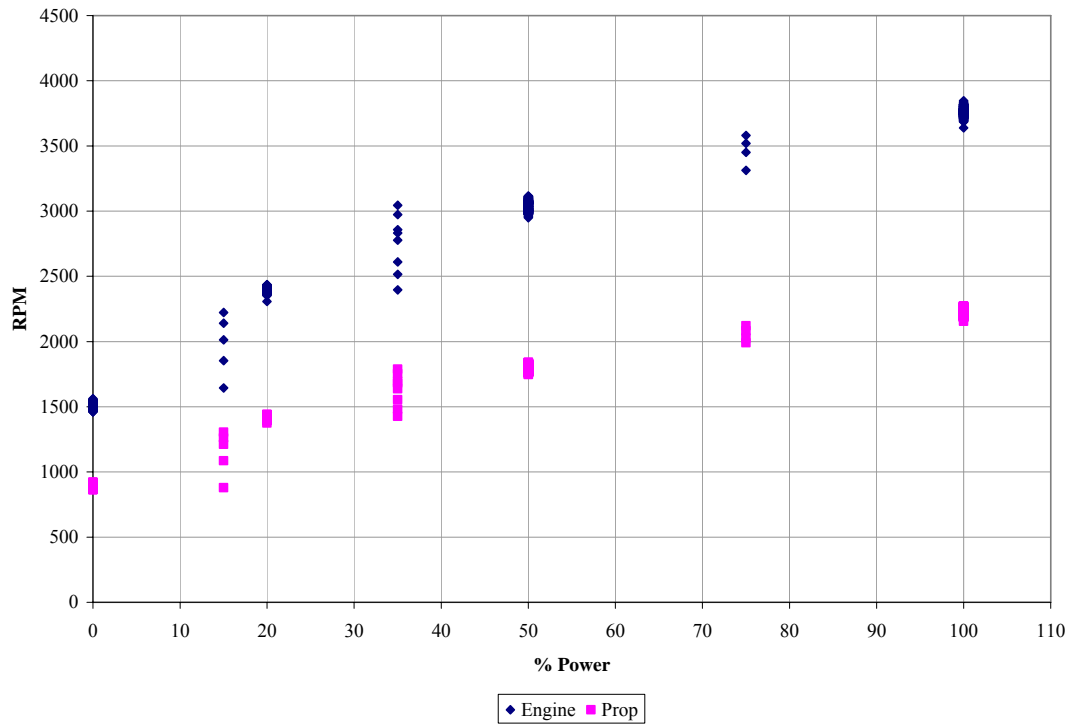


Figure 96: Engine/Prop RPM Data (Emission Run One: Raw Data)

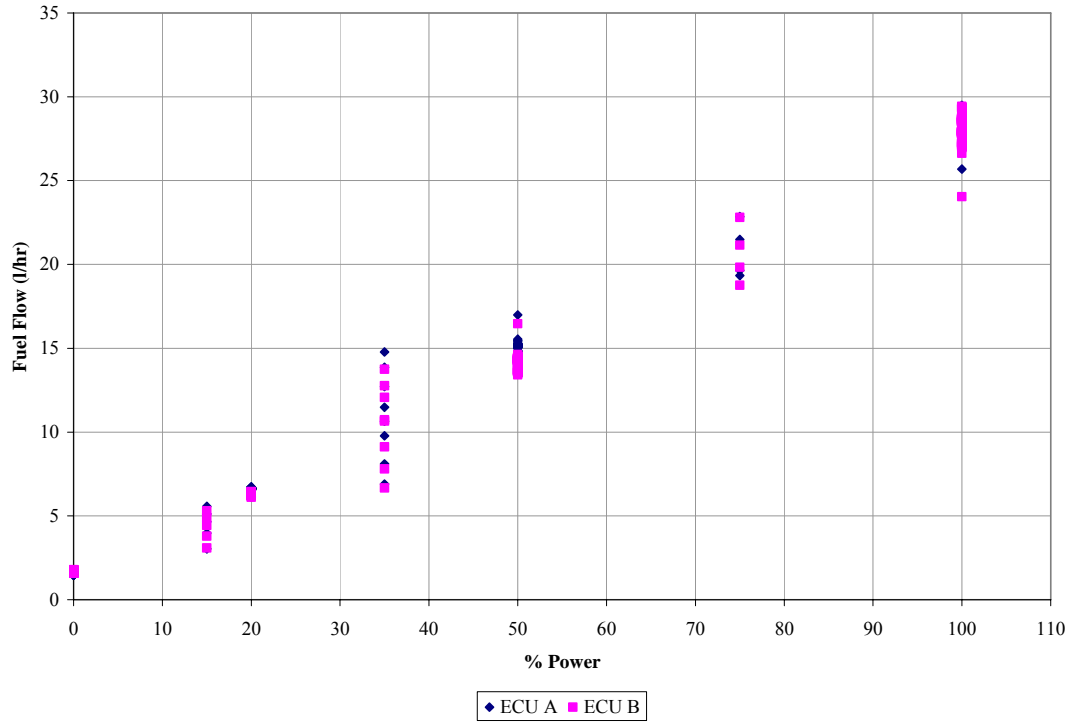


Figure 97: Fuel Flow (Emission Run One: Raw Data)

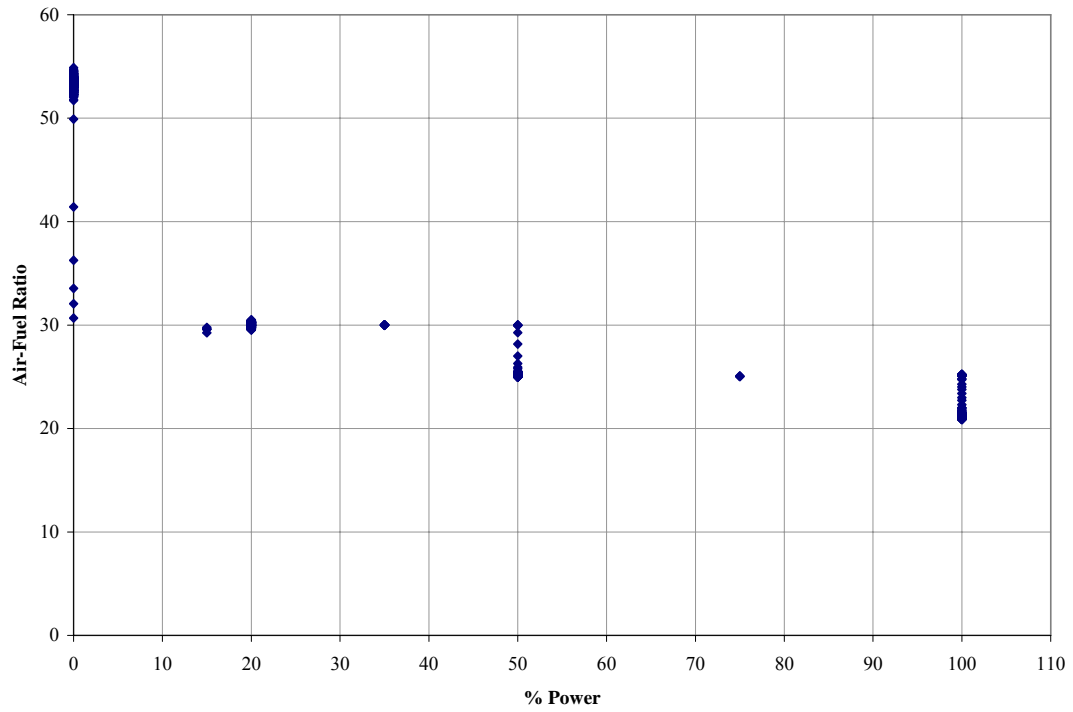


Figure 98: Air-Fuel Ratio (Emission Run One: Raw Data)

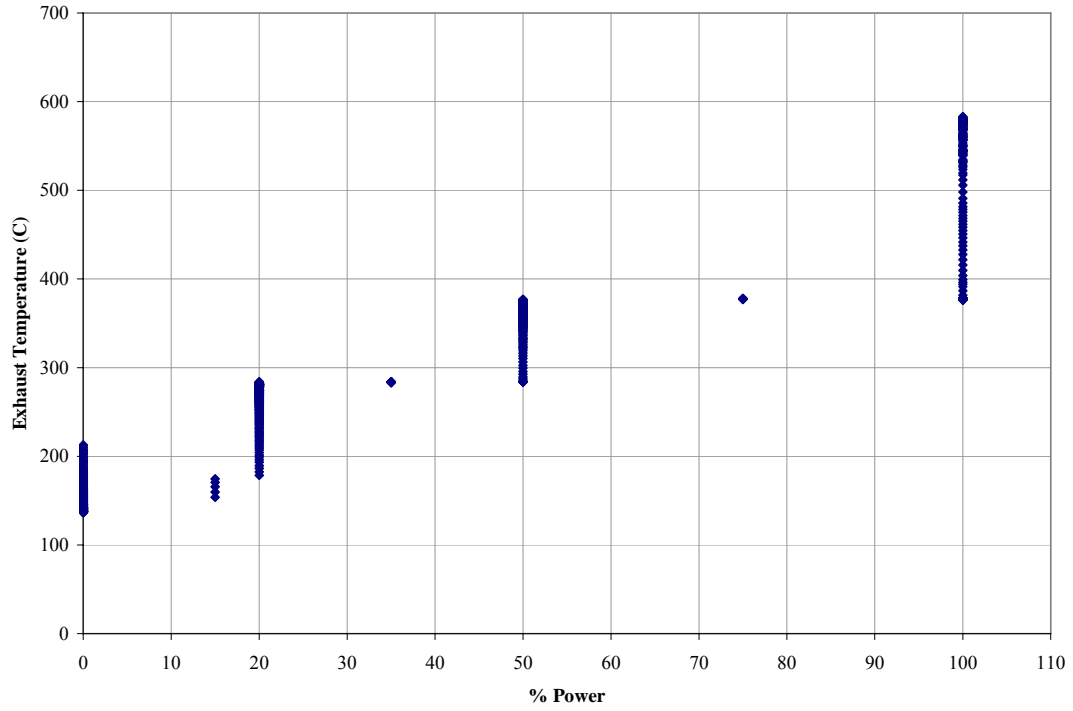


Figure 99: Exhaust Temperature (Emission Run One: Raw Data)

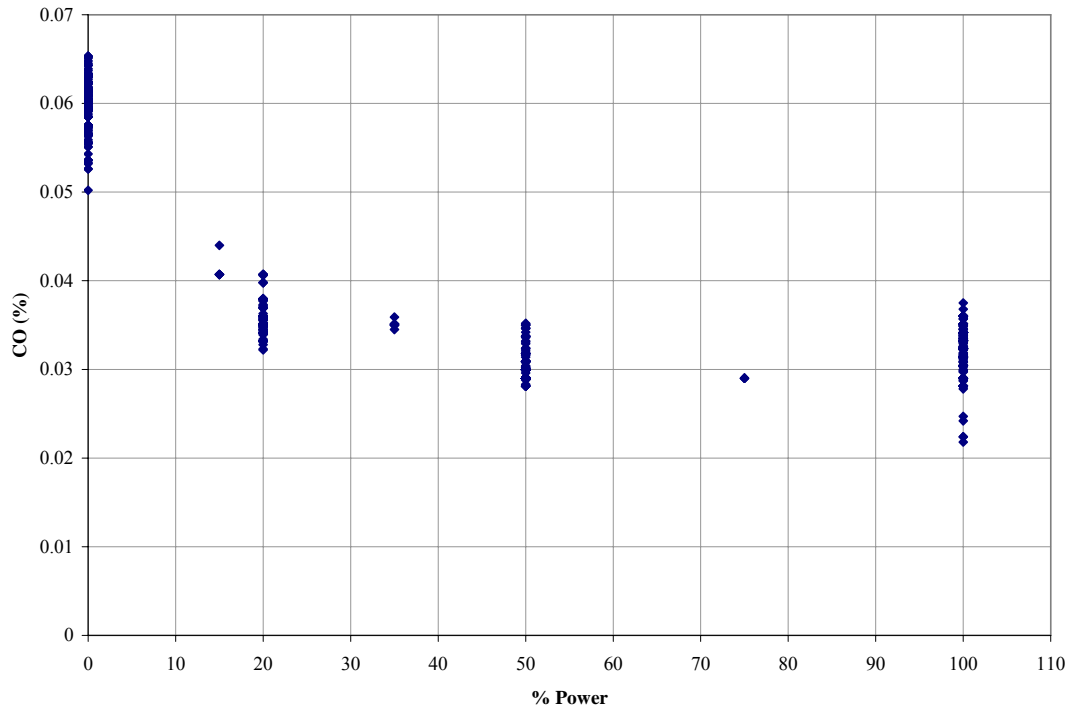


Figure 100: Carbon Monoxide (Emission Run One: % Raw Data)

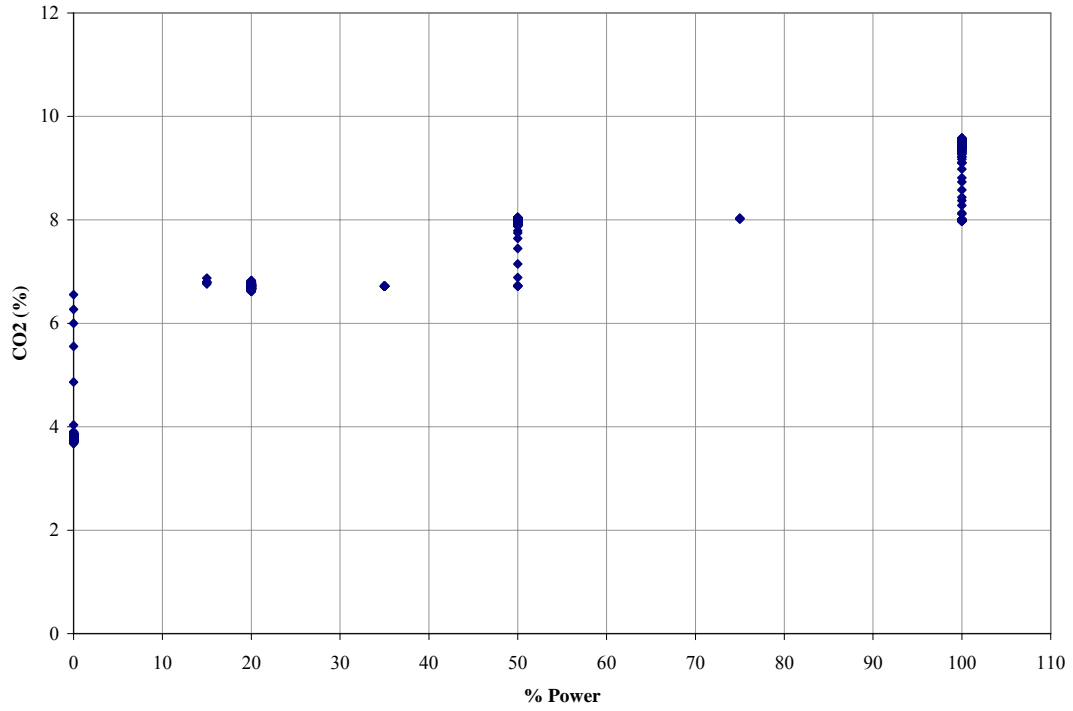


Figure 101: Carbon Dioxide (Emission Run One: % Raw Data)

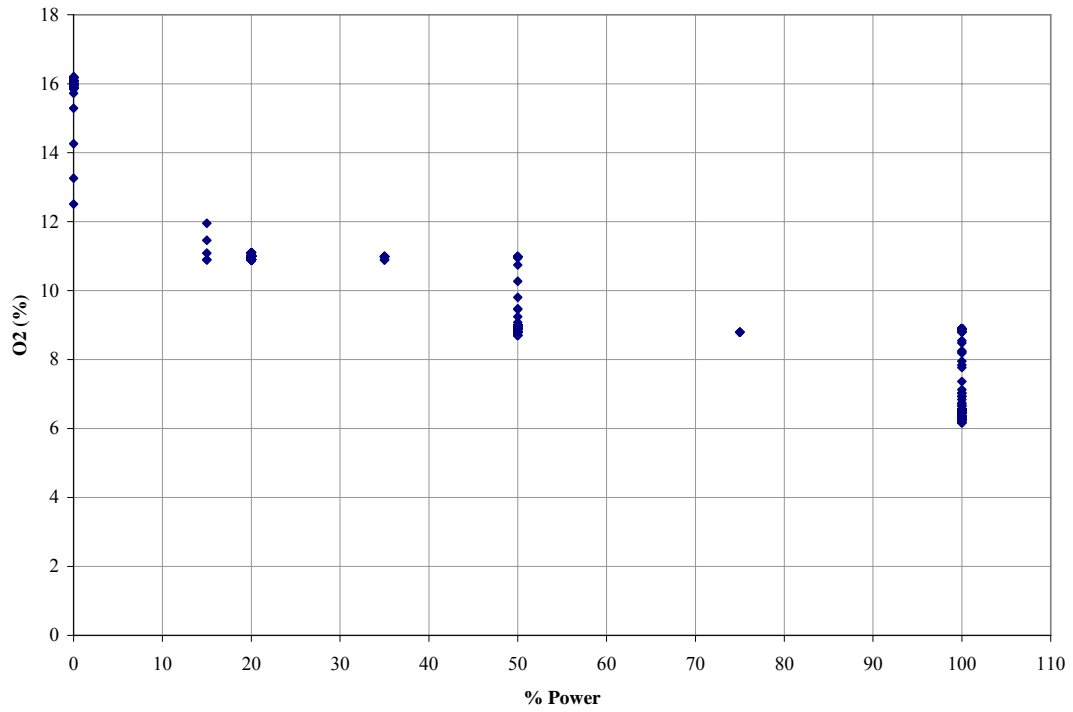


Figure 102: Oxygen (Emission Run One: % Raw Data)

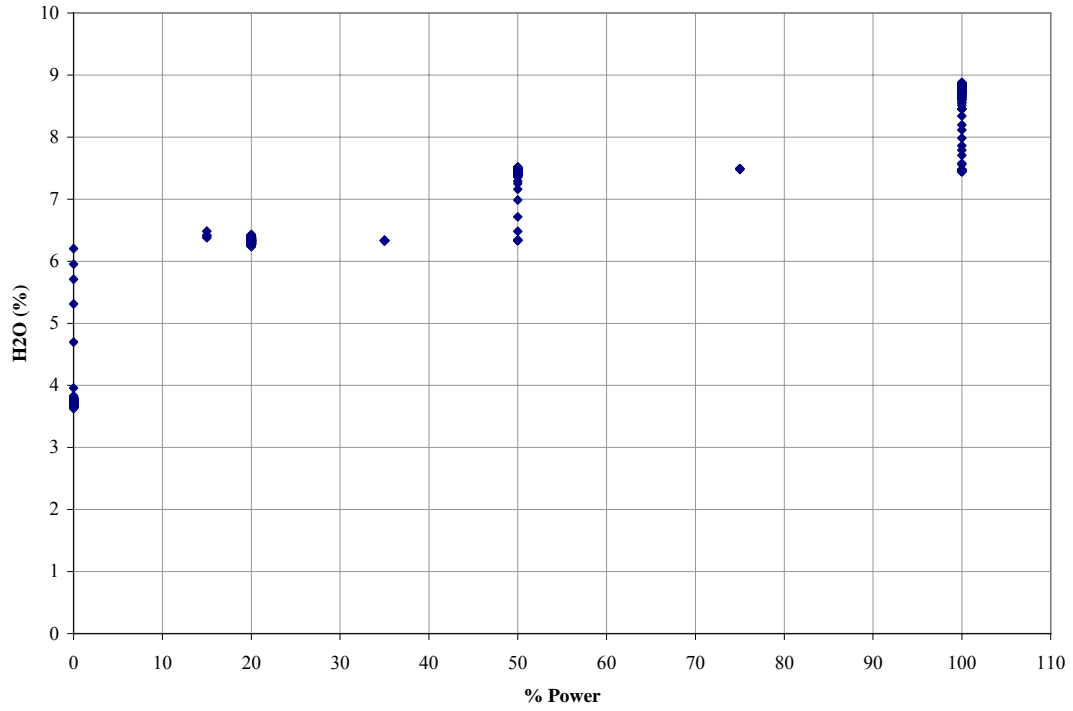


Figure 103: Water Vapor (Emission Run One: % Raw Data)

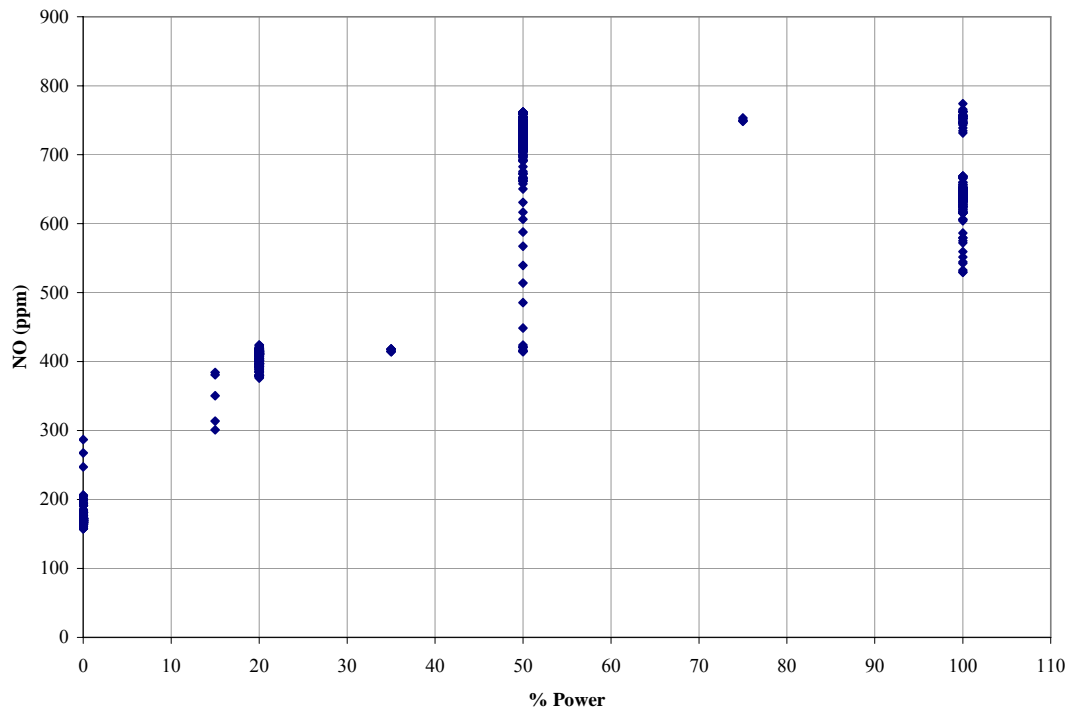


Figure 104: Nitric Oxide (Emission Run One: ppm Raw Data)

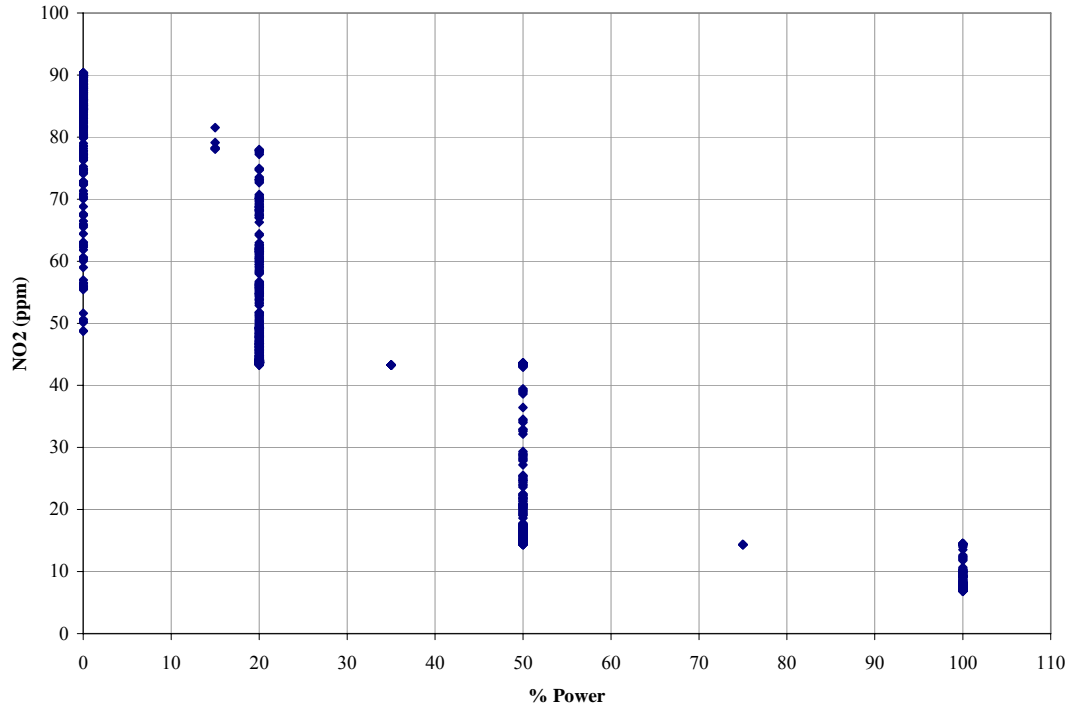


Figure 105: Nitrogen Dioxide (Emission Run One: ppm Raw Data)

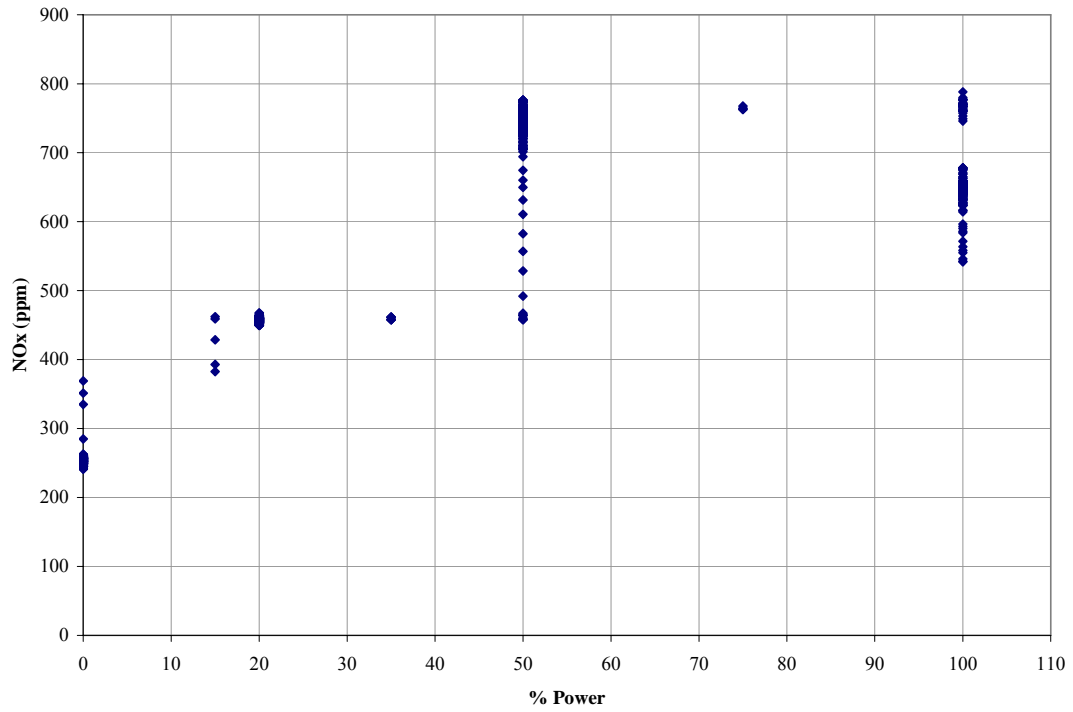


Figure 106: Nitrogen Oxides (Emission Run One: ppm Raw Data)

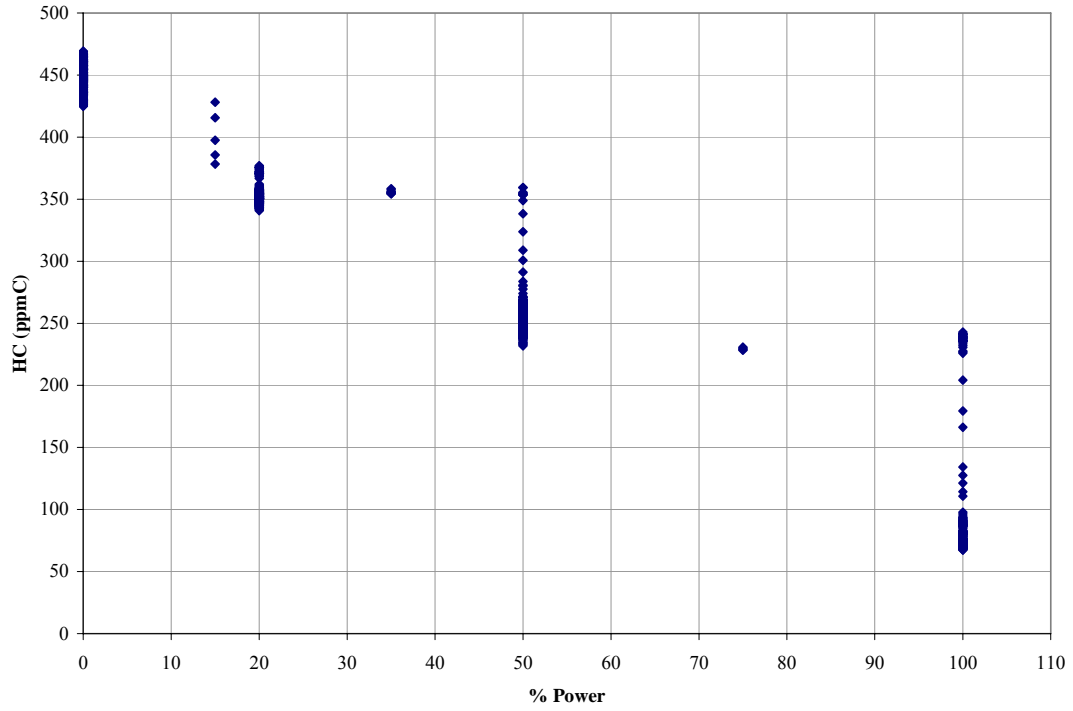


Figure 107: Hydrocarbon (Emission Run One: ppmC Raw Data)

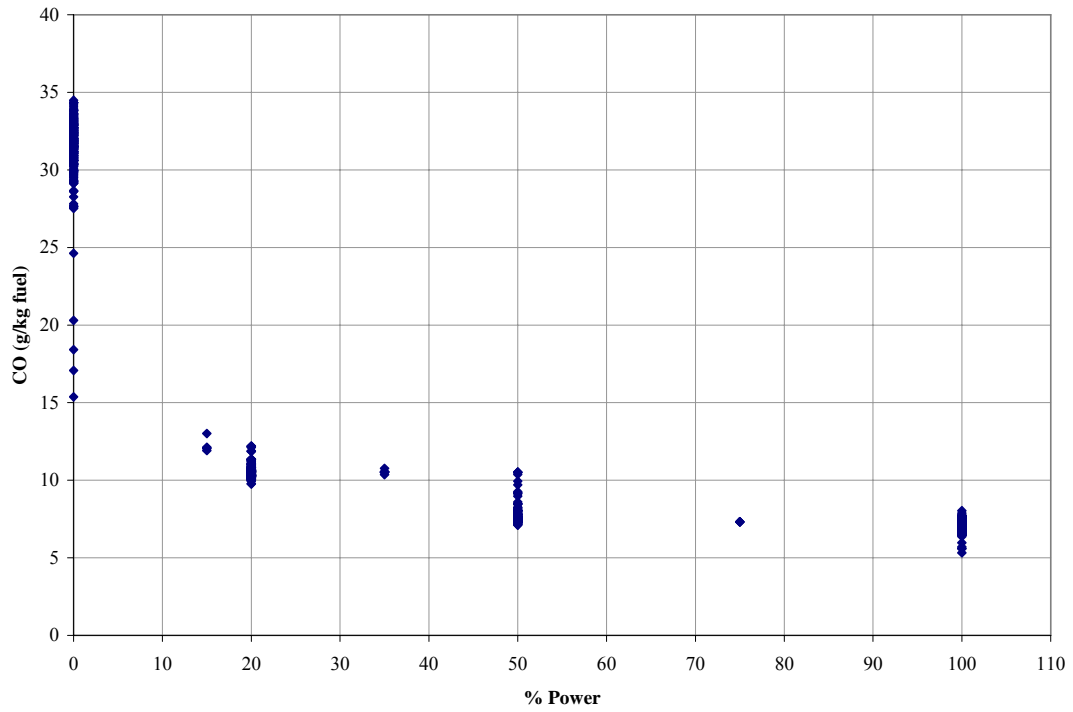


Figure 108: Carbon Monoxide (Emission Run One: Mass Raw Data)

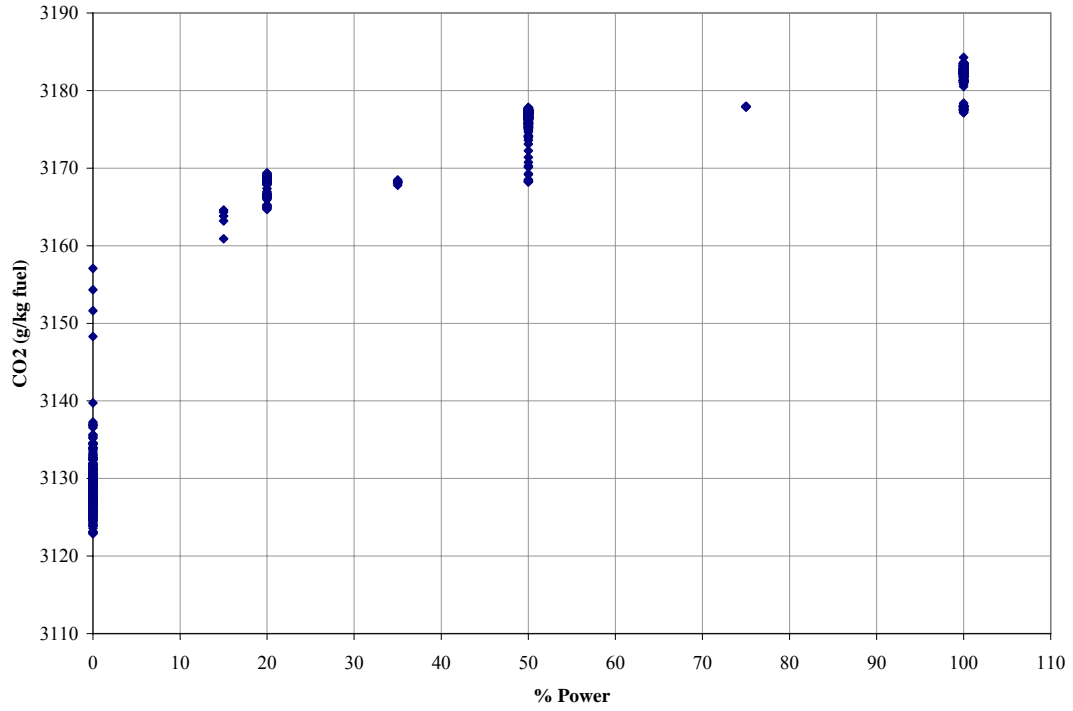


Figure 109: Carbon Dioxide (Emission Run One: Mass Raw Data)

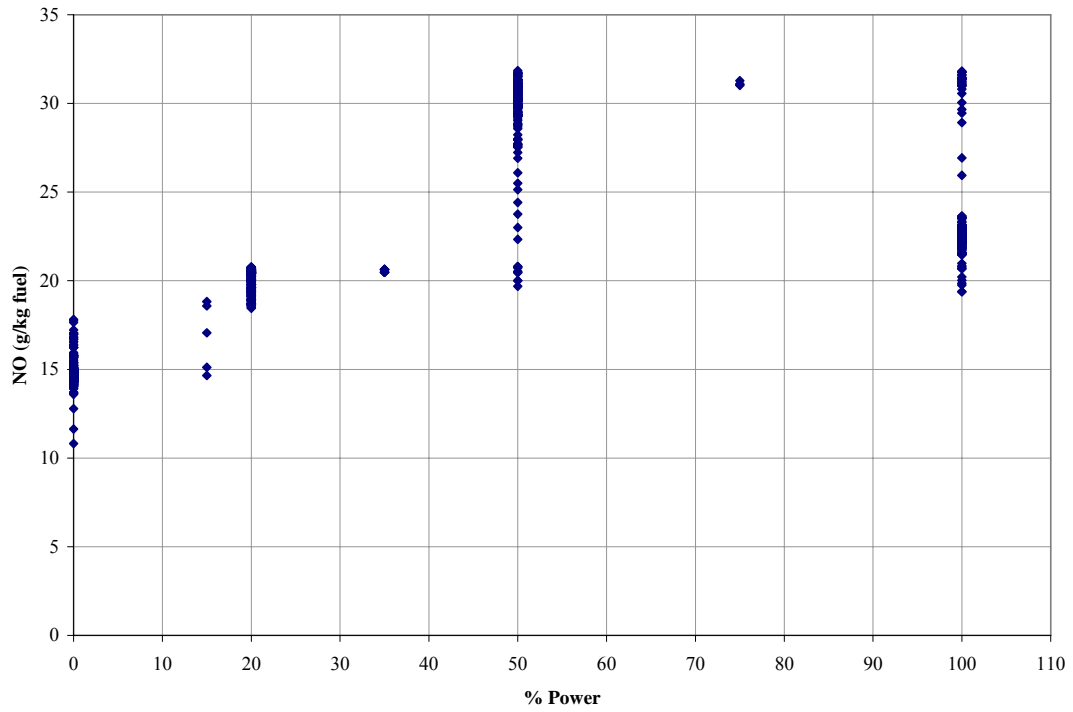


Figure 110: Nitric Oxide (Emission Run One: Mass Raw Data)

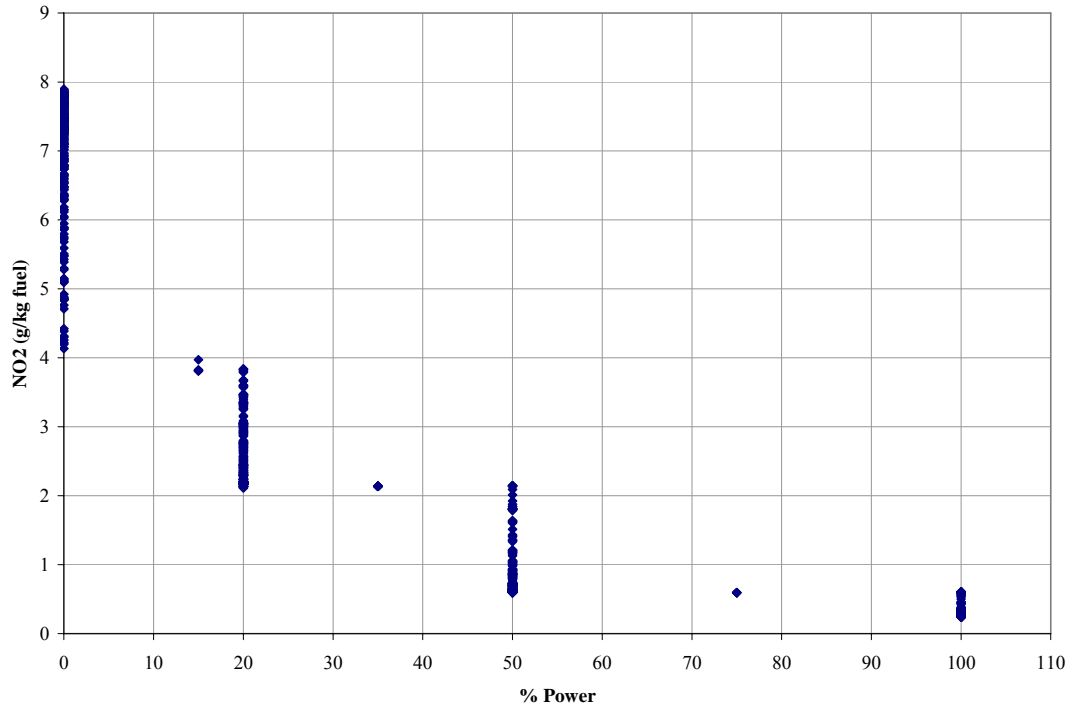


Figure 111: Nitrogen Dioxide (Emission Run One: Mass Raw Data)

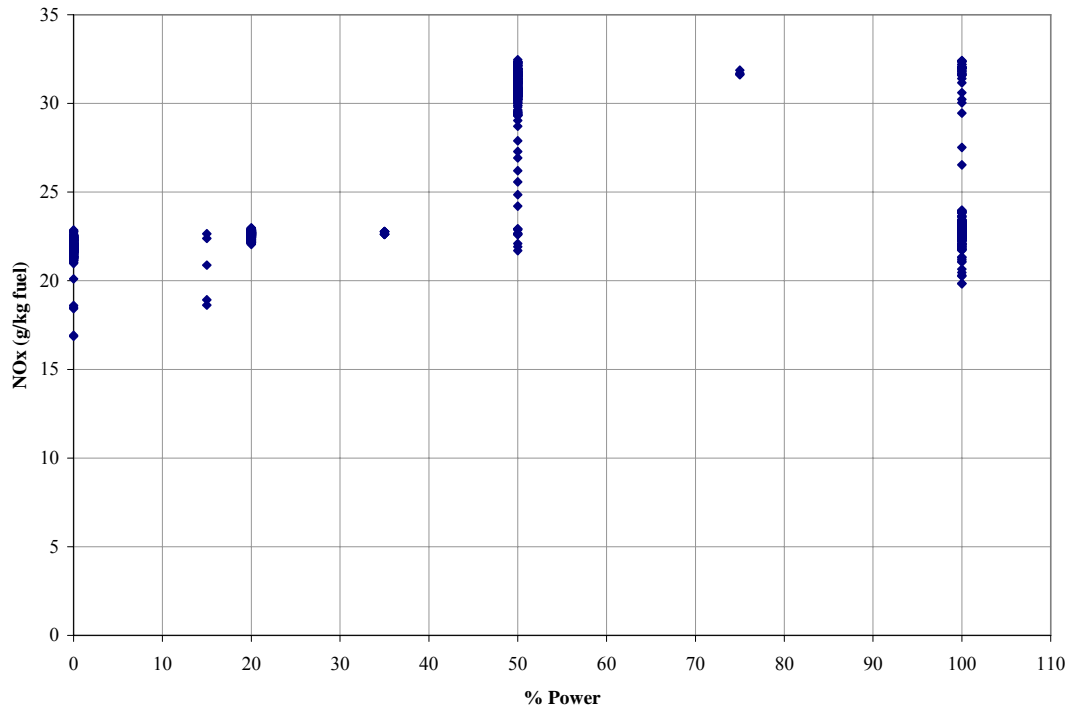


Figure 112: Nitrogen Oxides (Emission Run One: Mass Raw Data)

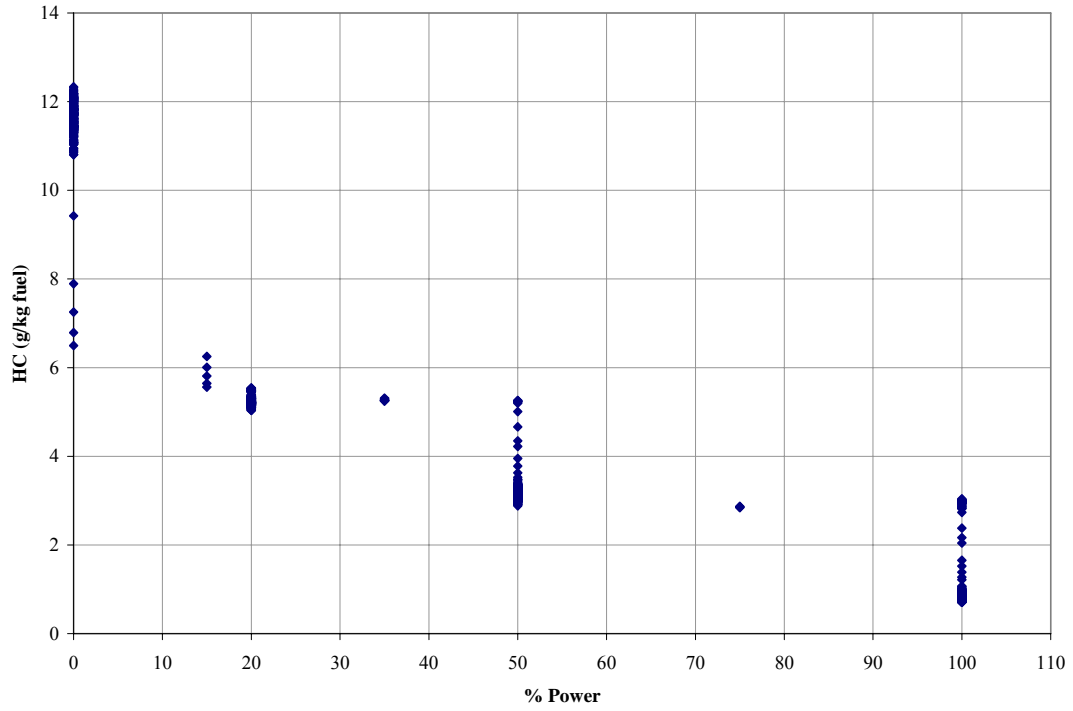


Figure 113: Hydrocarbon (Emission Run One: Mass Raw Data)

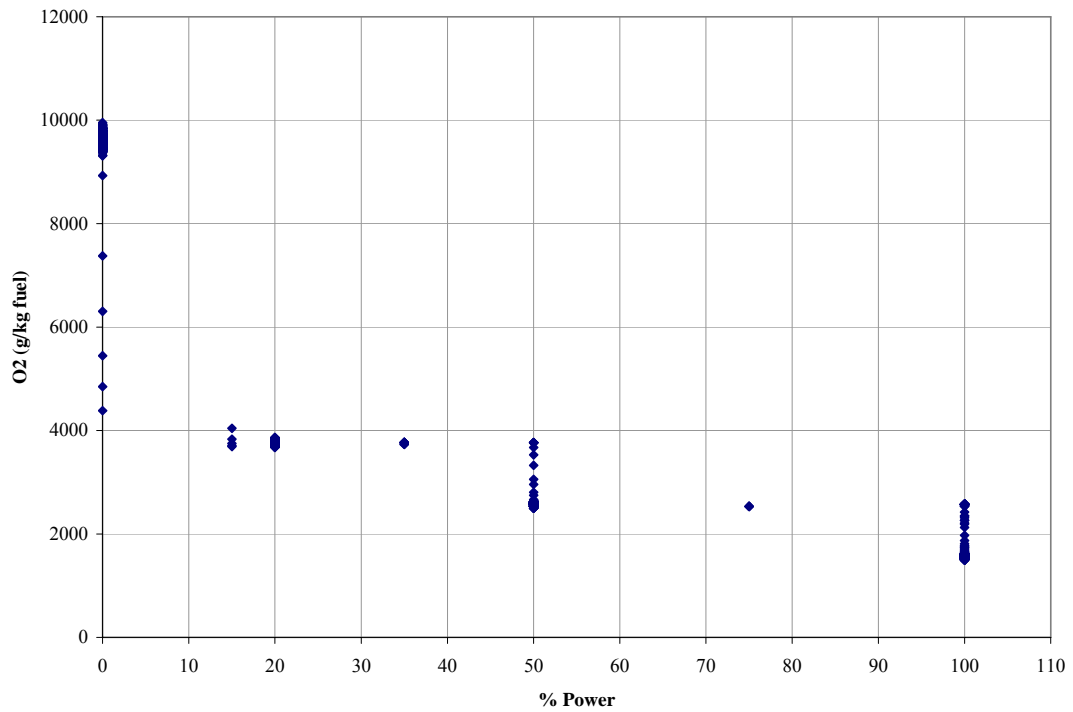


Figure 114: Oxygen (Emission Run One: Mass Raw Data)

Table XLIV: Engine Parameters (Emission Run One)

CED Load	Engine	Prop	Fuel Flow	Exhaust Temperature	AFRs	AFR	Lambda
<i>%</i>	<i>RPM</i>	<i>RPM</i>	<i>l/hr</i>	<i>deg C</i>	<i>~</i>	<i>~</i>	<i>~</i>
0	1507.36	891.57	1.63	151.85	14.50	53.02	3.66
20	2399.60	1419.68	6.48	266.52	14.50	30.05	2.07
50	3037.06	1796.92	14.40	358.66	14.50	25.38	1.75
100	3761.67	2226.26	28.14	534.34	14.50	21.65	1.49

Table XLV: Emission Data (Emission Run One: % and PPM)

CED Load	CO2	CO	O2	H2O	NO	NO2	NOx	HC
<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>ppm</i>	<i>ppm</i>	<i>ppm</i>	<i>ppmC</i>
0	3.82	0.06	15.98	3.75	172.74	81.48	254.22	448.38
20	6.71	0.04	10.98	6.32	404.74	52.15	456.89	353.42
50	7.93	0.03	8.98	7.41	710.31	20.28	730.58	257.84
100	9.27	0.03	6.74	8.60	651.80	8.72	660.52	96.92

Table XLVI: Emission Data (Emission Run One: Mass)

CED Load	CO2	CO	NO	NO2	NOx	HC	O2
<i>%</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>
0	3129.23	31.44	14.84	7.01	21.85	11.58	9557.62
20	3168.32	10.52	20.01	2.58	22.59	5.24	3768.48
50	3176.39	7.60	29.76	0.86	30.61	3.25	2620.59
100	3181.85	7.09	23.57	0.32	23.89	1.08	1698.55

Appendix I: Engine Emission Data - Investigation II

(February 13, 2008)

Table XLVII: Atmospheric Condition (Emission Run Two)

Local Temperature	4 °C or 39.2 °F
Local Barometric Pressure	29.90 inHg

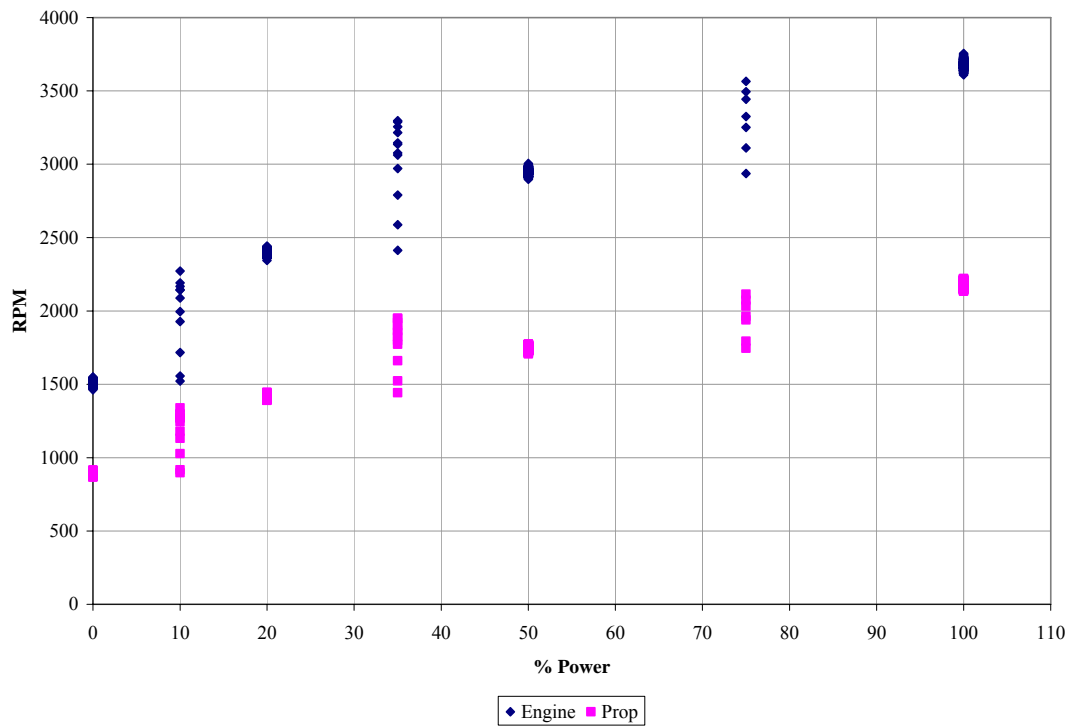


Figure 115: Engine/Prop RPM Data (Emission Run Two: Raw Data)

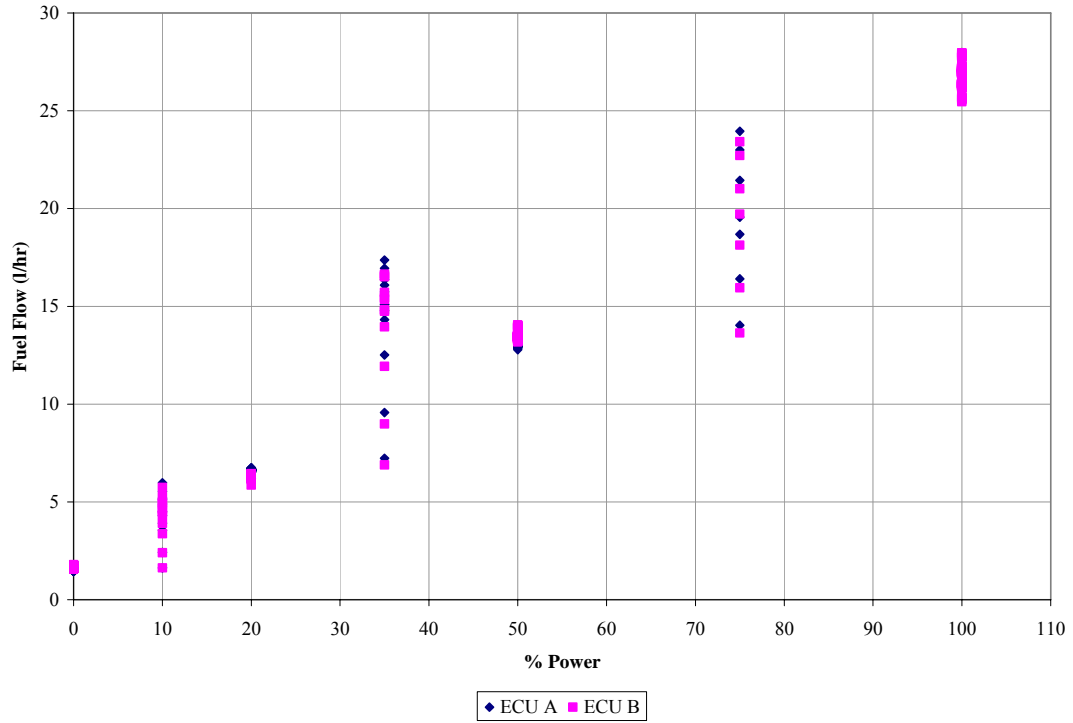


Figure 116: Fuel Flow (Emission Run Two: Raw Data)

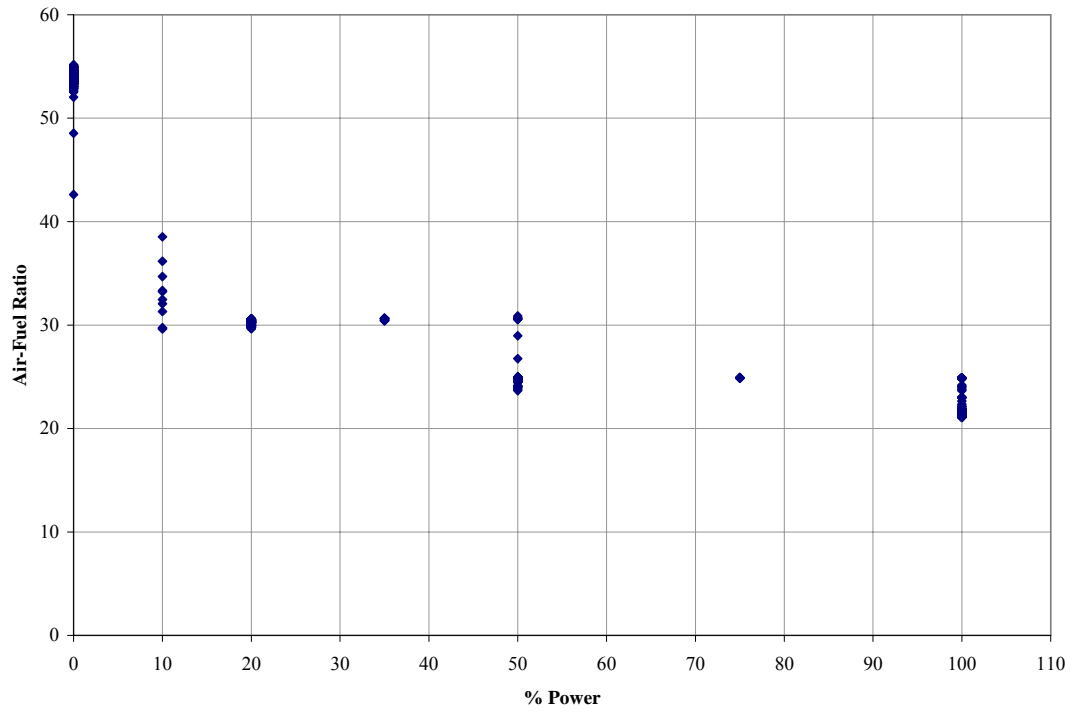


Figure 117: Air-Fuel Ratio (Emission Run Two: Raw Data)

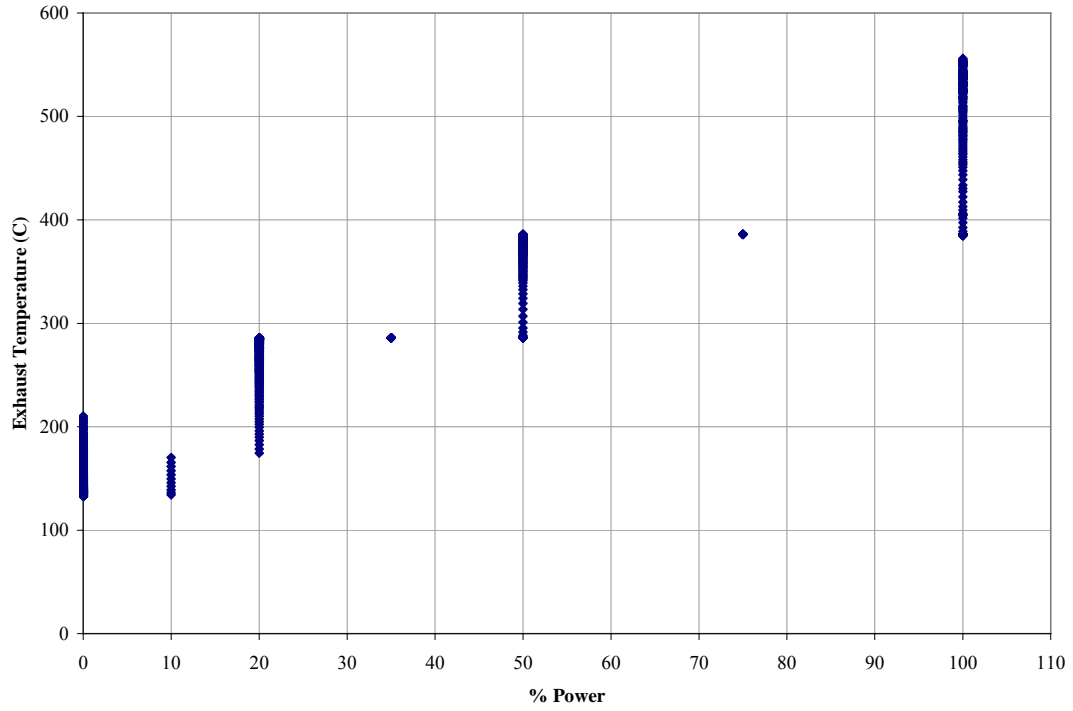


Figure 118: Exhaust Temperature (Emission Run Two: Raw Data)

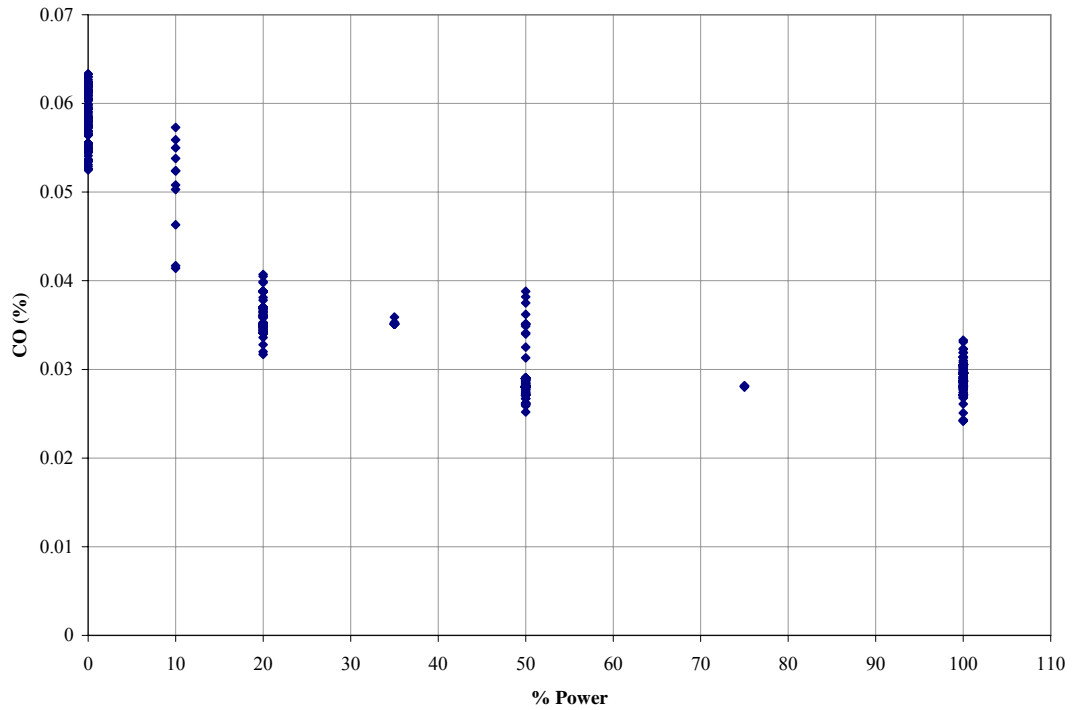


Figure 119: Carbon Monoxide (Emission Run Two: % Raw Data)

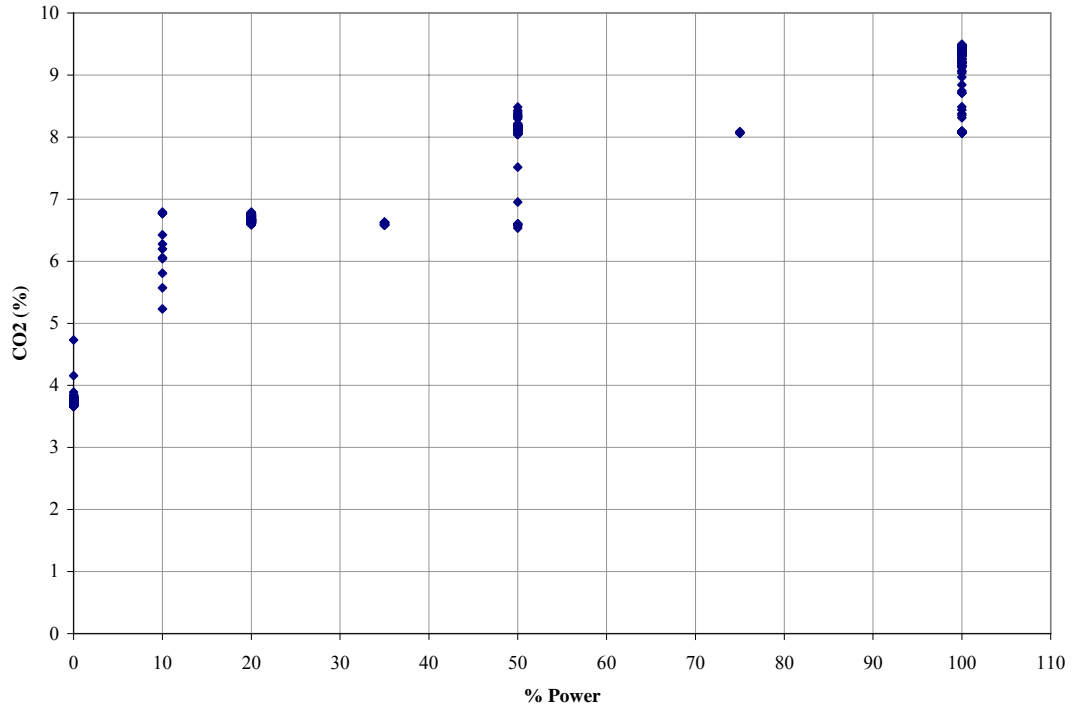


Figure 120: Carbon Dioxide (Emission Run Two: % Raw Data)

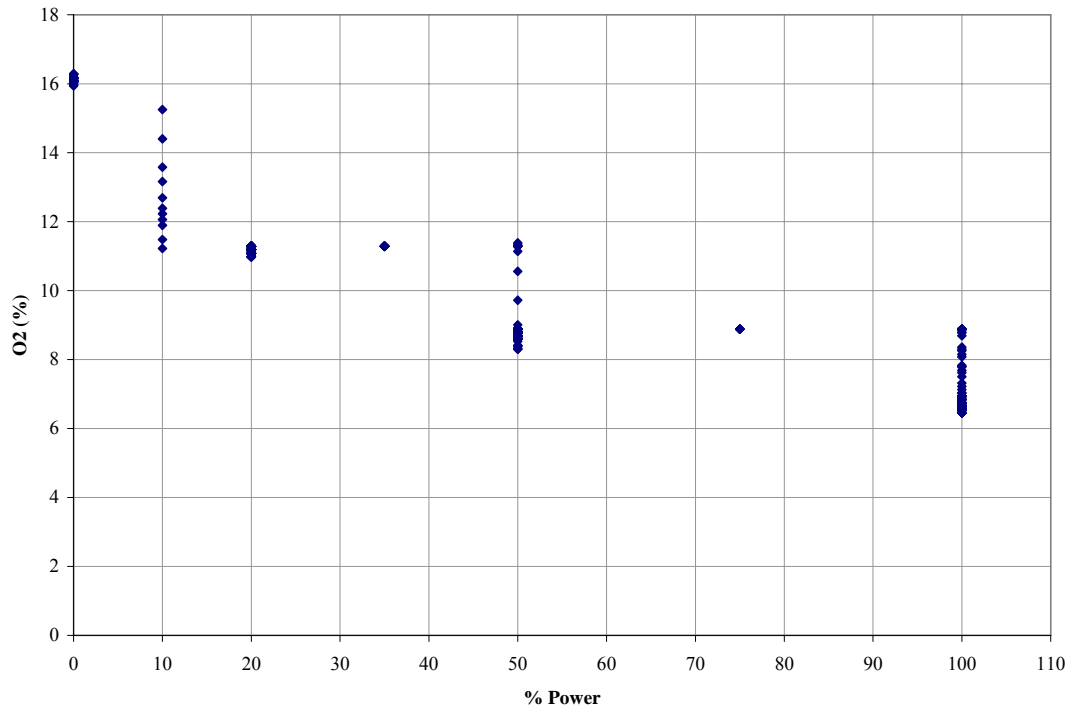


Figure 121: Oxygen (Emission Run Two: % Raw Data)

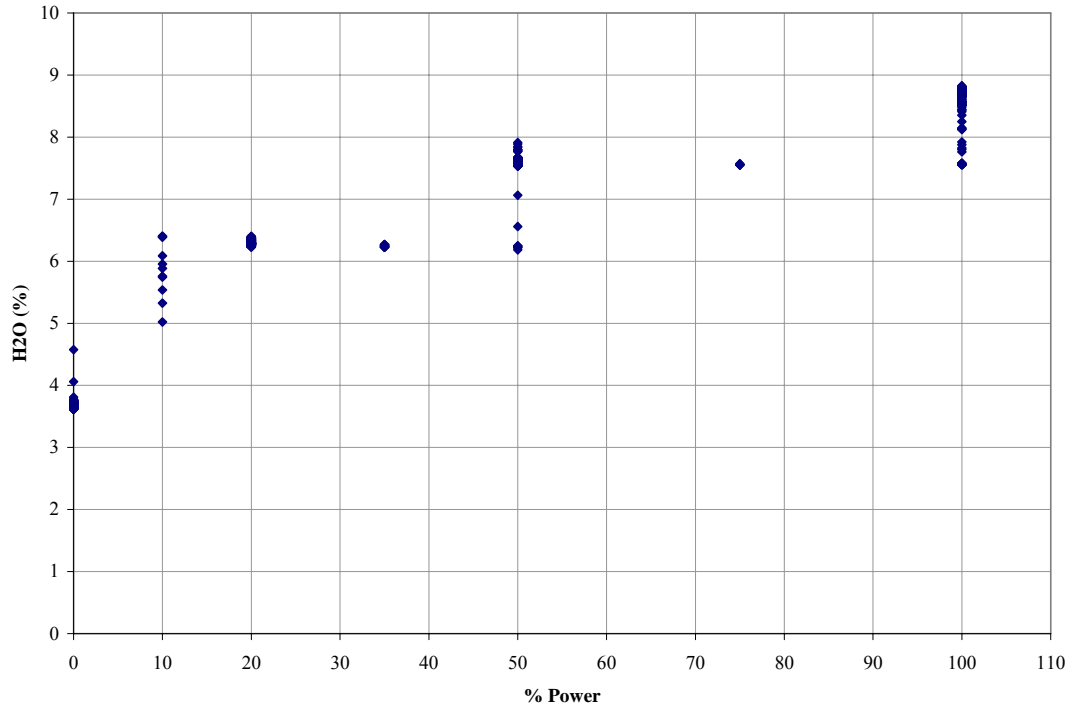


Figure 122: Water Vapor (Emission Run Two: % Raw Data)

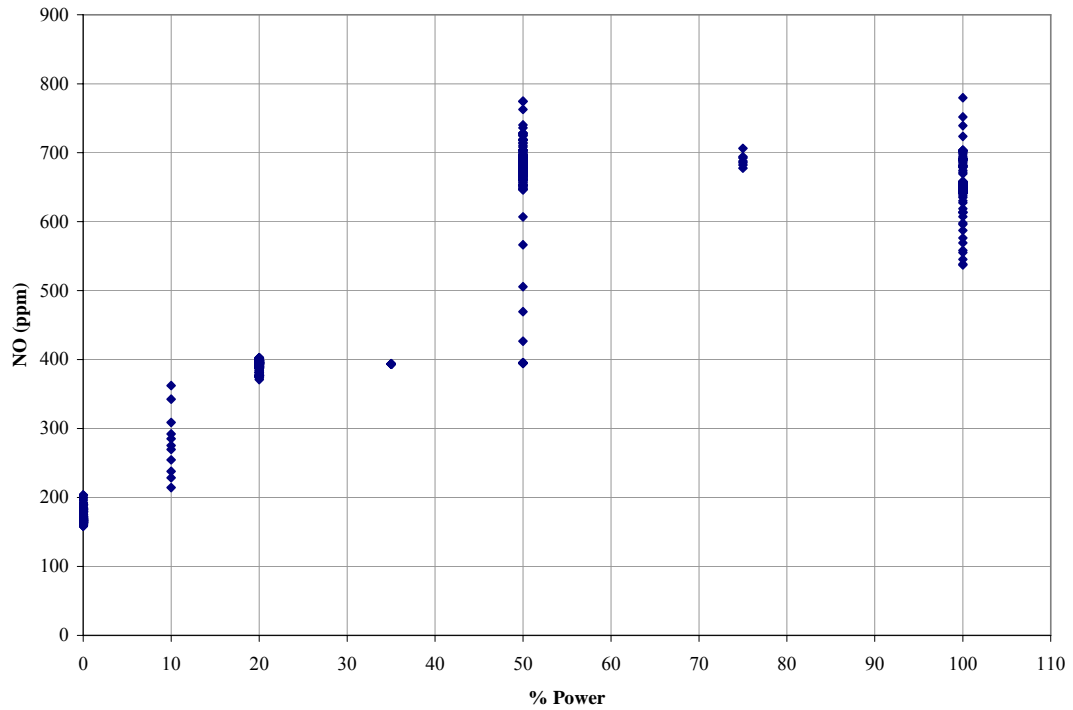


Figure 123: Nitric Oxide (Emission Run Two: ppm Raw Data)

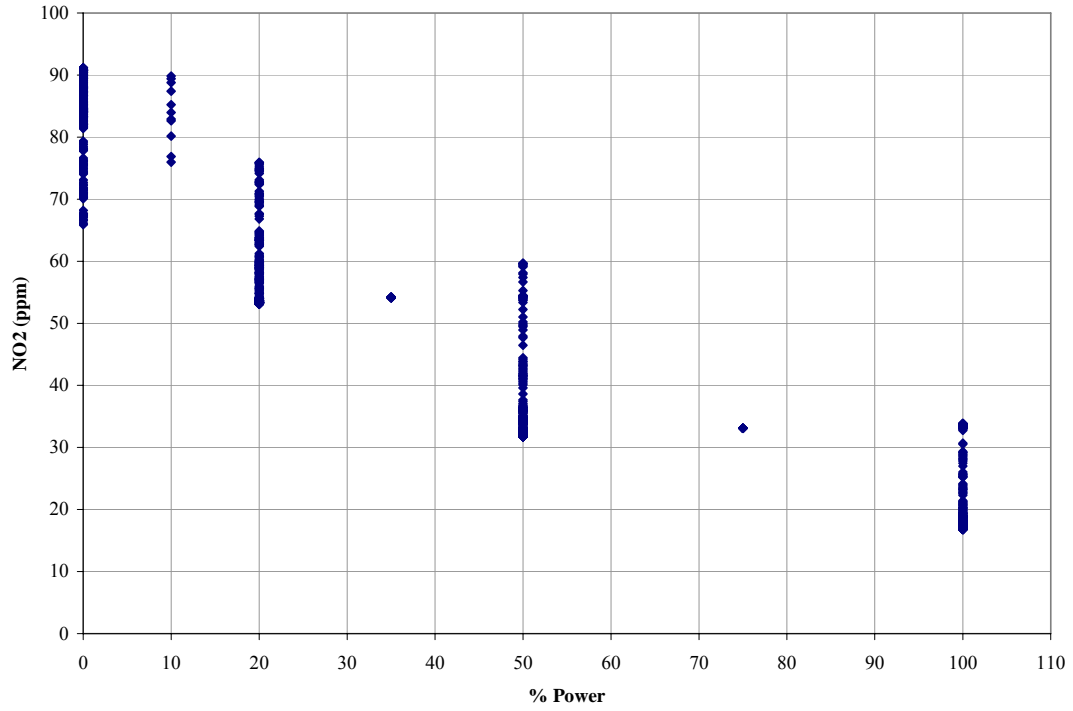


Figure 124: Nitrogen Dioxide (Emission Run Two: ppm Raw Data)

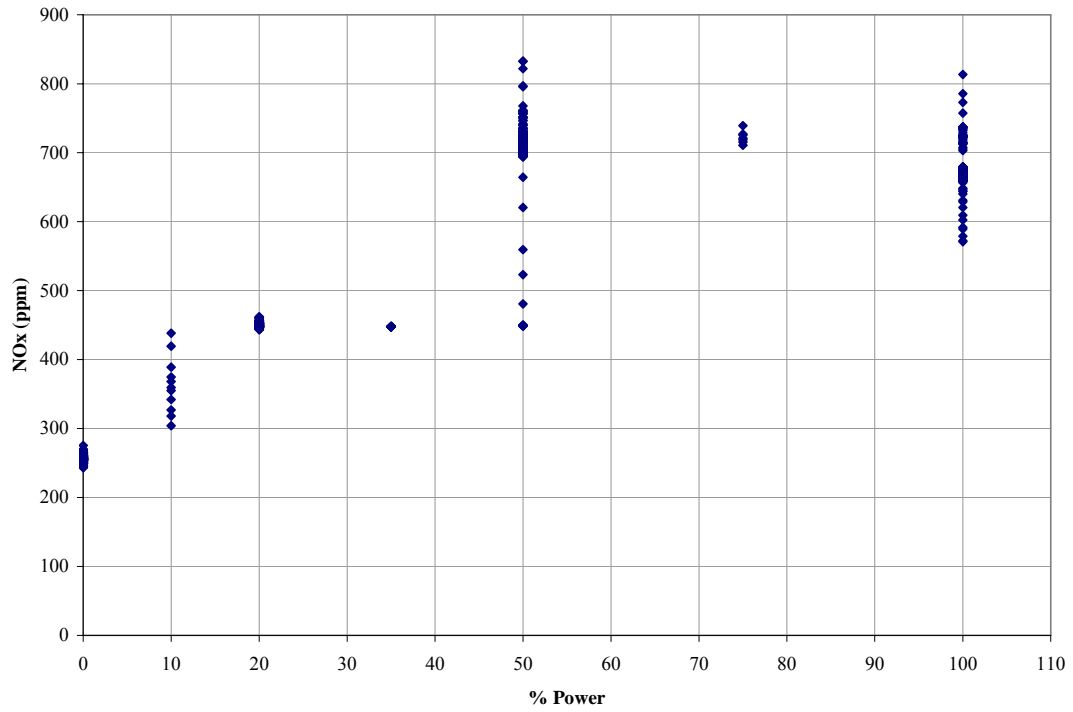


Figure 125: Nitrogen Oxides (Emission Run Two: ppm Raw Data)

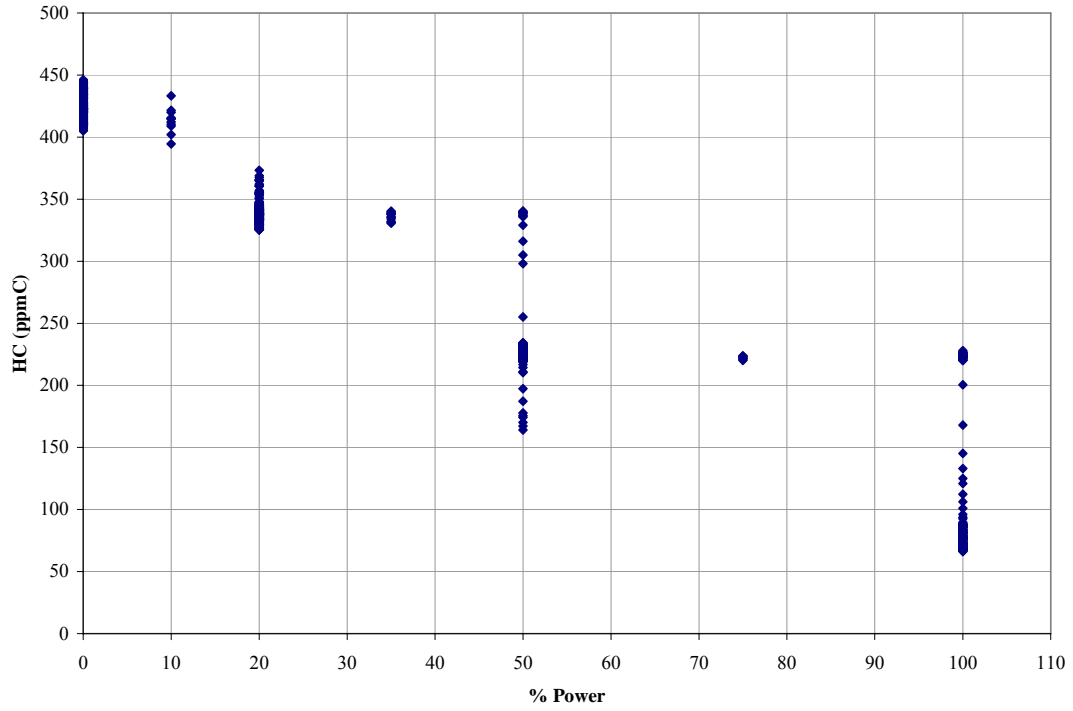


Figure 126: Hydrocarbon (Emission Run Two: ppmC Raw Data)

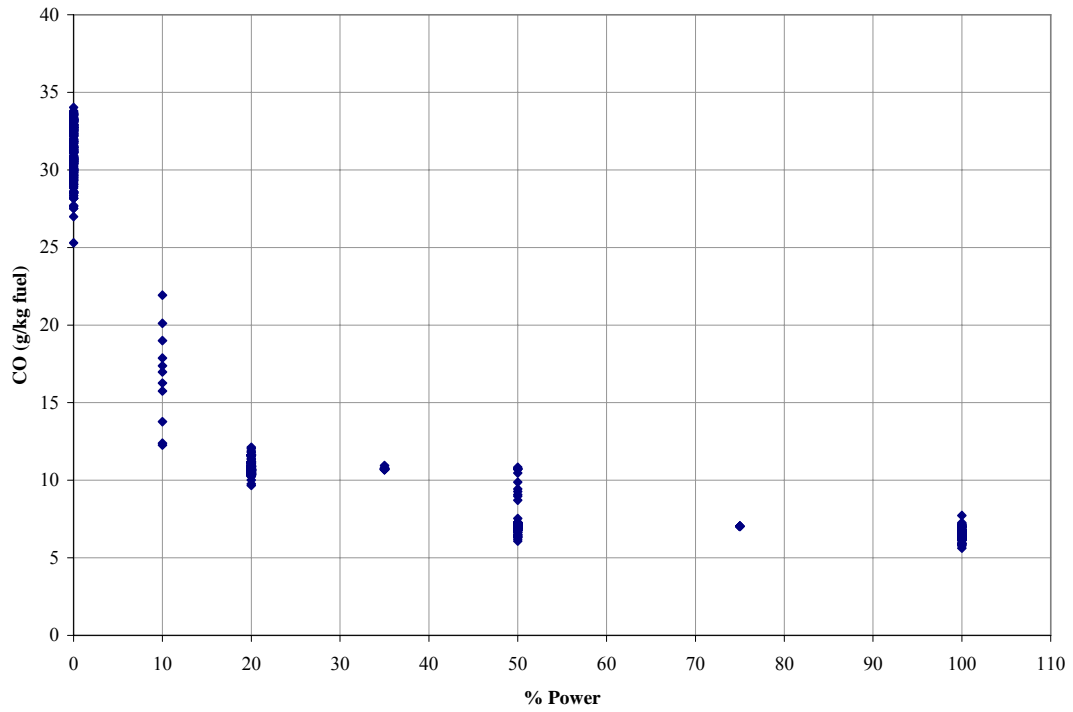


Figure 127: Carbon Monoxide (Emission Run Two: Mass Raw Data)

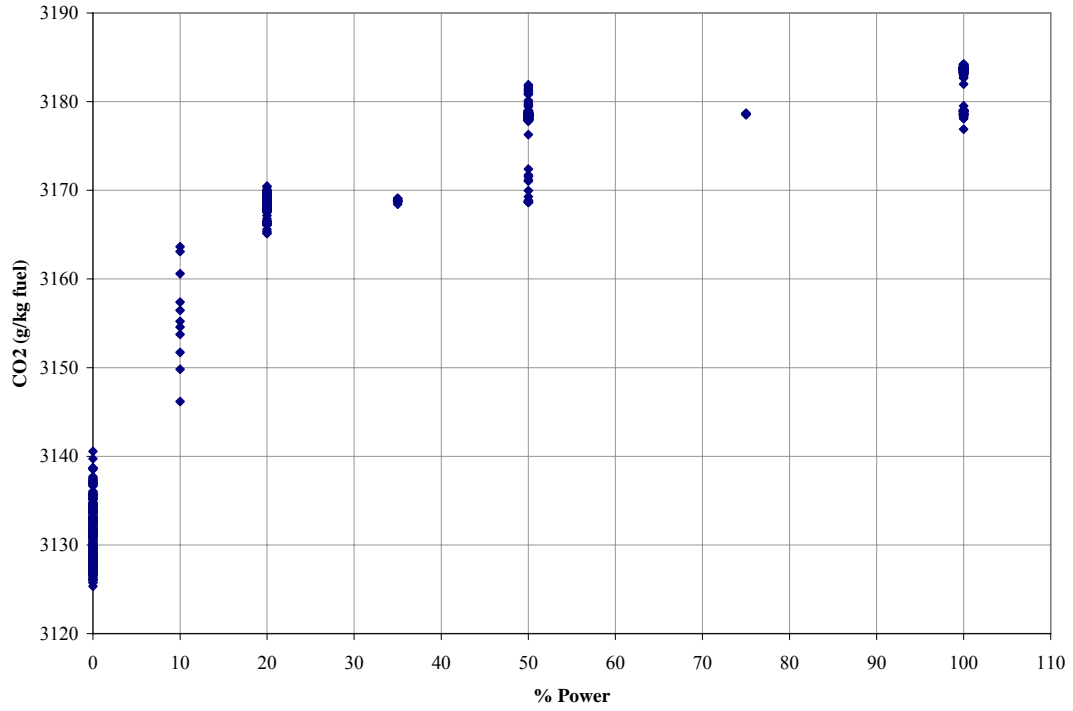


Figure 128: Carbon Dioxide (Emission Run Two: Mass Raw Data)

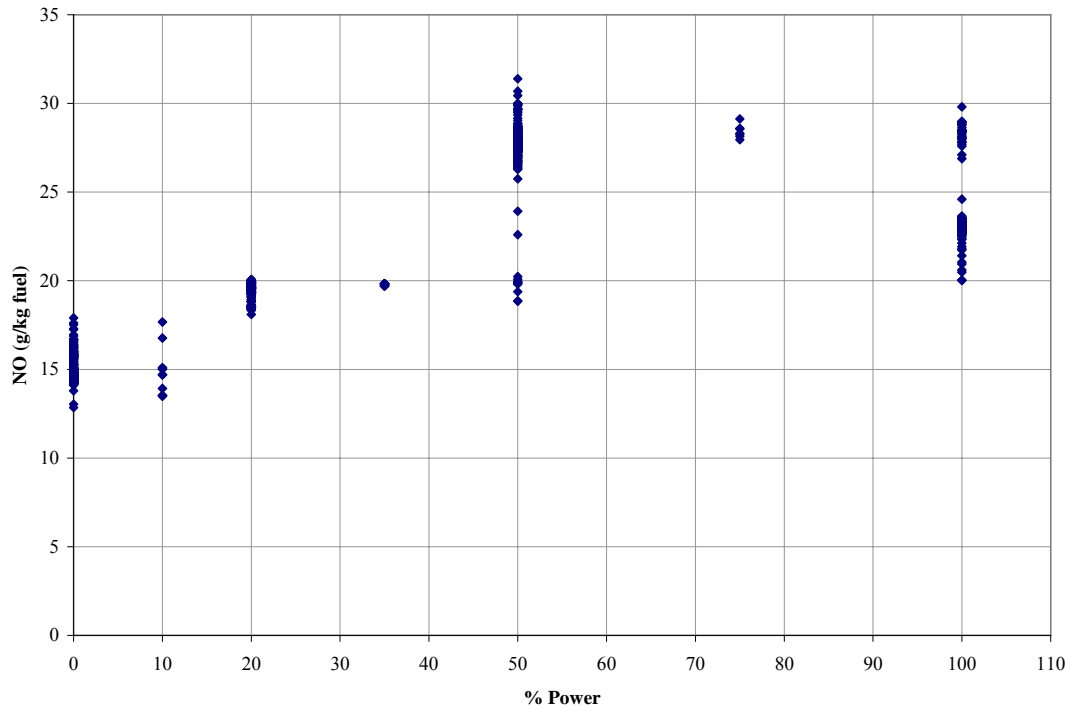


Figure 129: Nitric Oxide (Emission Run Two: Mass Raw Data)

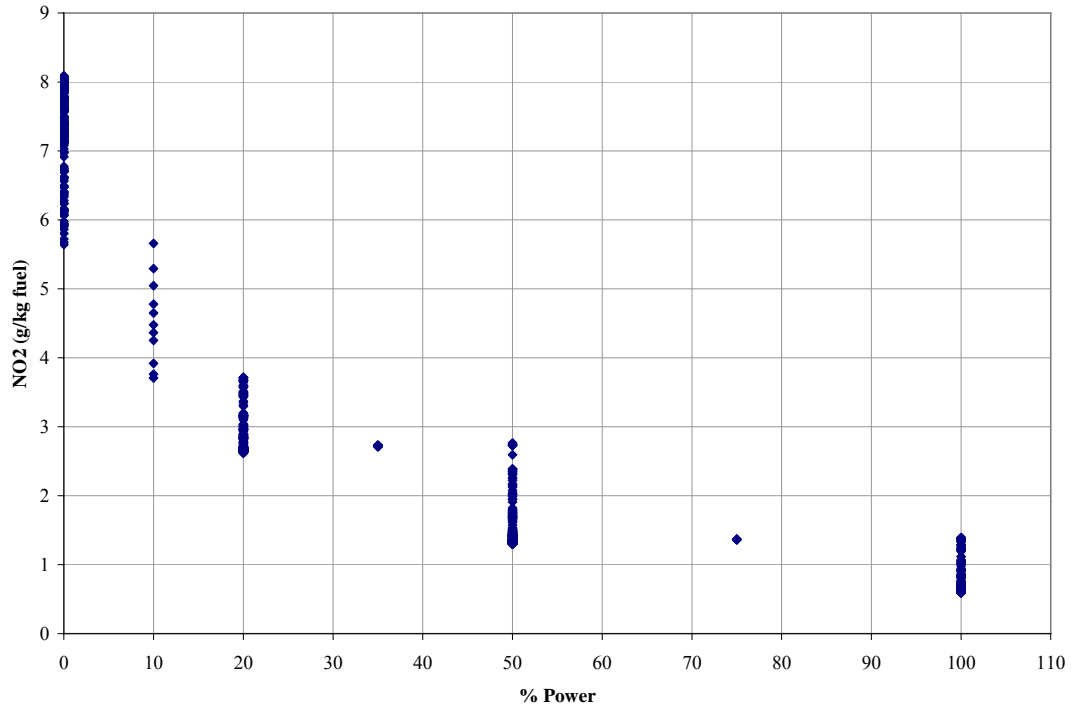


Figure 130: Nitrogen Dioxide (Emission Run Two: Mass Raw Data)

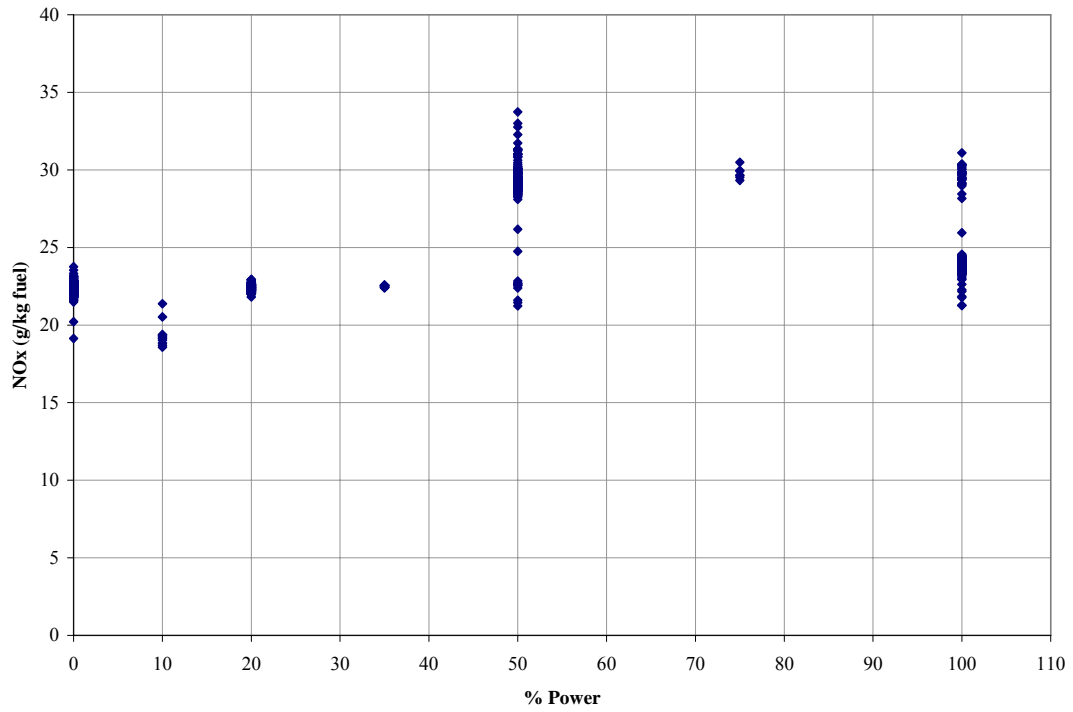


Figure 131: Nitrogen Oxides (Emission Run Two: Mass Raw Data)

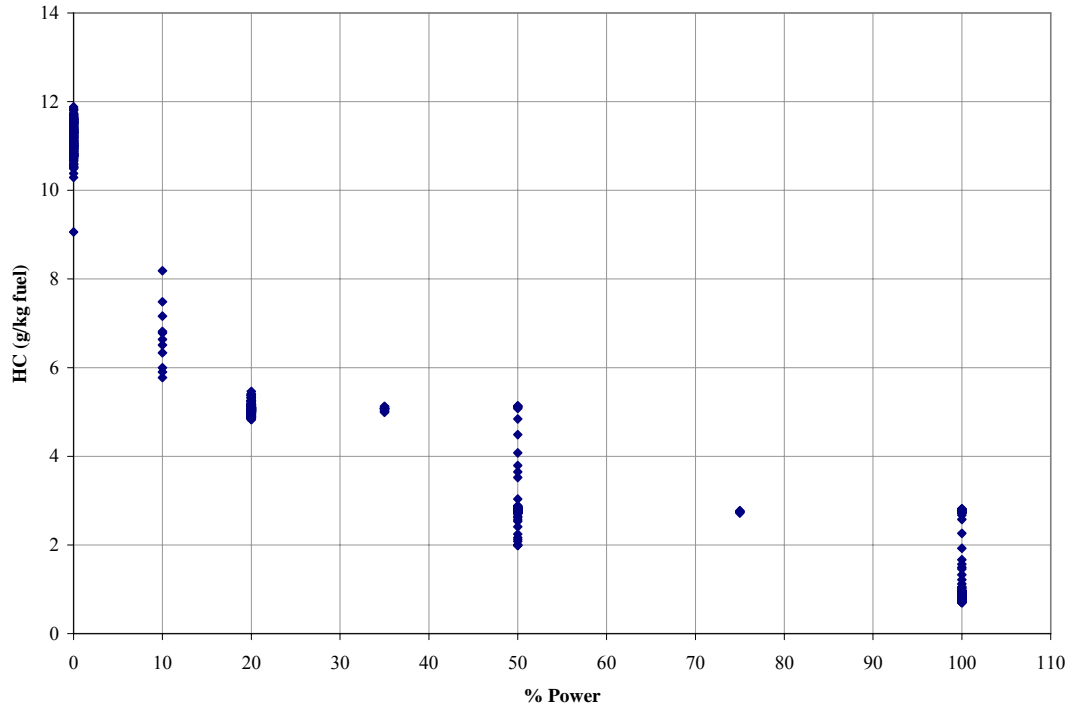


Figure 132: Hydrocarbon (Emission Run Two: Mass Raw Data)

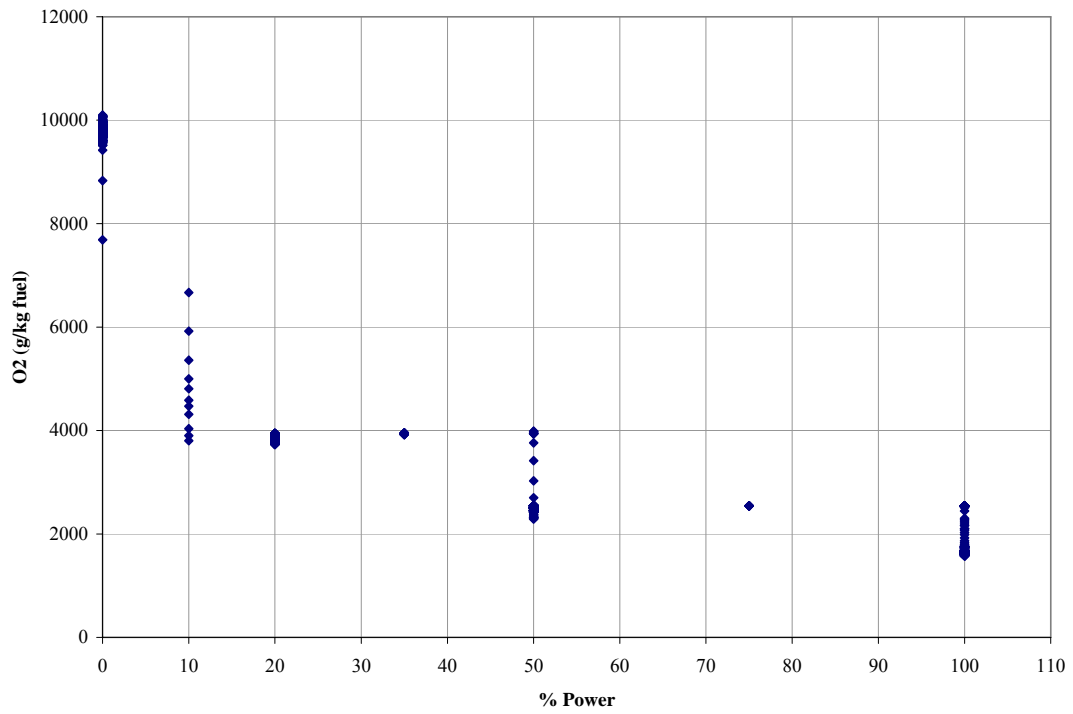


Figure 133: Oxygen (Emission Run Two: Mass Raw Data)

Table XLVIII: Engine Parameters (Emission Run Two)

CED Load	Engine	Prop	Fuel Flow	Exhaust Temperature	AFRs	AFR	Lambda
<i>%</i>	<i>RPM</i>	<i>RPM</i>	<i>l/hr</i>	<i>deg C</i>	<i>~</i>	<i>~</i>	<i>~</i>
0	1505.08	890.29	1.60	150.28	14.50	53.93	3.72
20	2397.38	1418.96	6.47	269.24	14.50	30.22	2.08
50	2949.93	1745.84	13.43	371.99	14.50	24.93	1.72
100	3679.46	2177.81	26.75	499.77	14.50	21.94	1.51

Table XLIX: Emission Data (Emission Run Two: % and PPM)

CED Load	CO2	CO	O2	H2O	NO	NO2	NOx	HC
<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>ppm</i>	<i>ppm</i>	<i>ppm</i>	<i>ppmC</i>
0	3.75	0.06	16.12	3.69	171.68	84.06	255.75	425.41
20	6.67	0.04	11.18	6.30	392.25	57.84	450.09	338.92
50	8.07	0.03	8.86	7.56	669.26	36.58	705.85	229.90
100	9.15	0.03	7.02	8.52	652.70	22.12	674.82	96.67

Table L: Emission Data (Emission Run Two: Mass)

CED Load	CO2	CO	NO	NO2	NOx	HC	O2
<i>%</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>
0	3131.33	31.28	15.03	7.36	22.39	11.17	9799.10
20	3168.72	10.71	19.51	2.88	22.38	5.06	3860.50
50	3178.09	7.15	27.56	1.51	29.07	2.86	2545.73
100	3182.95	6.48	23.86	0.82	24.68	1.09	1790.07

Appendix J: Engine Emission Data - Investigation III

(February 13, 2008)

Table LI: Atmospheric Condition (Emission Run Three)

Local Temperature	7 °C or 44.6 °F
Local Barometric Pressure	29.89 inHg

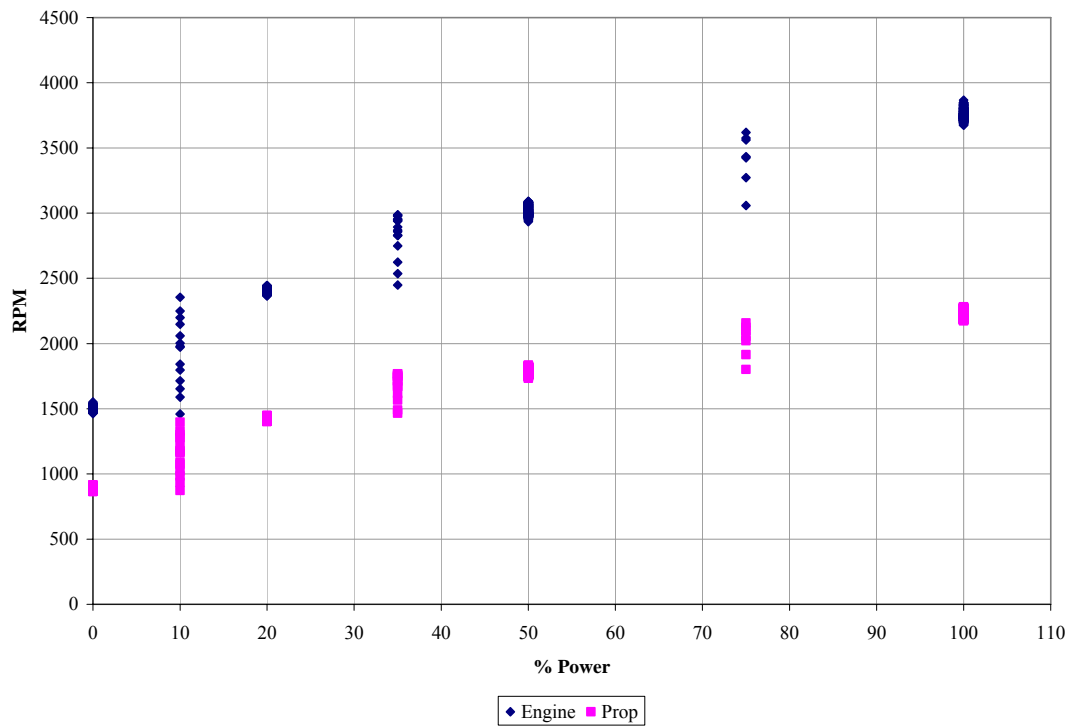


Figure 134: Engine/Prop RPM Data (Emission Run Three: Raw Data)

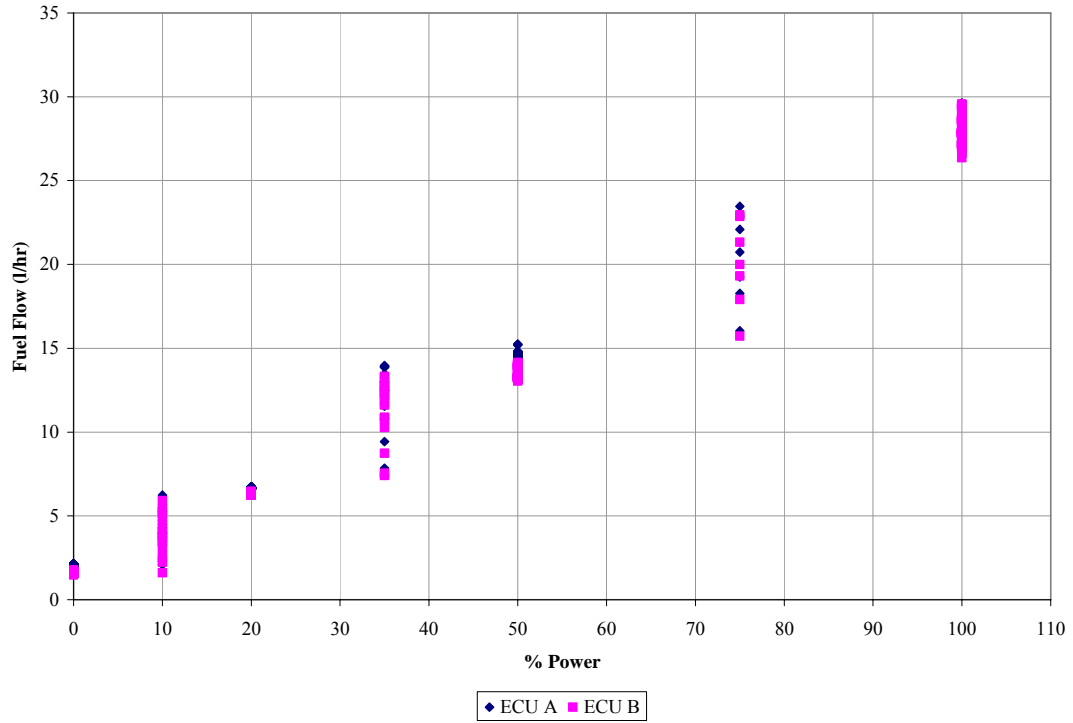


Figure 135: Fuel Flow (Emission Run Three: Raw Data)

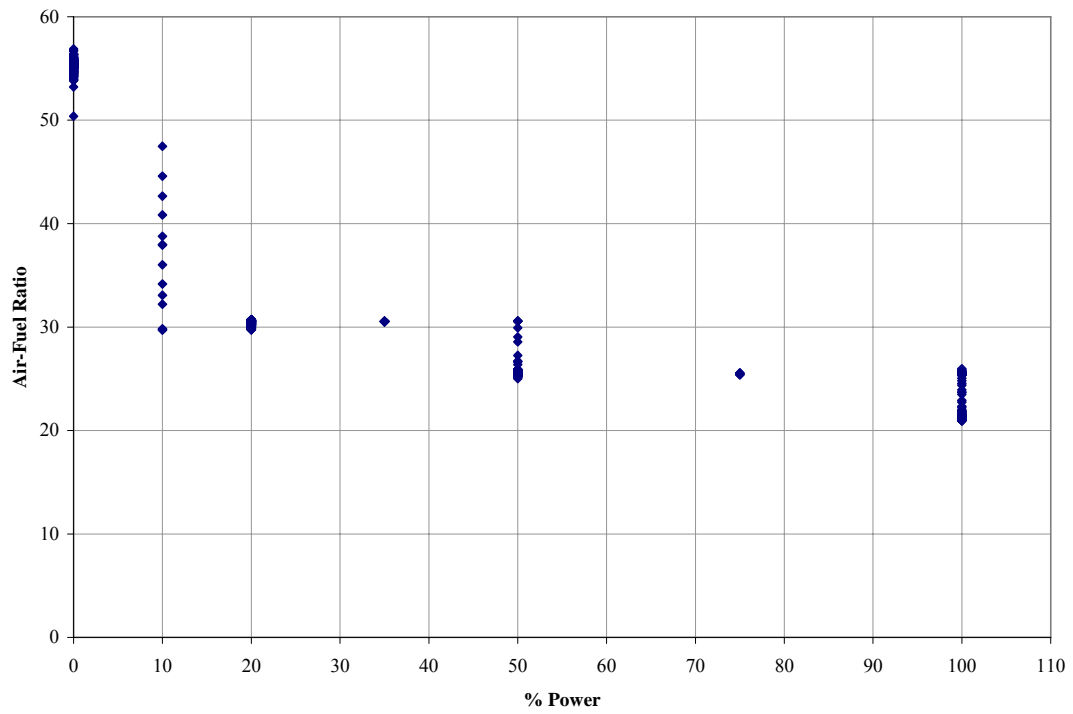


Figure 136: Air-Flow Ratio (Emission Run Three: Raw Data)

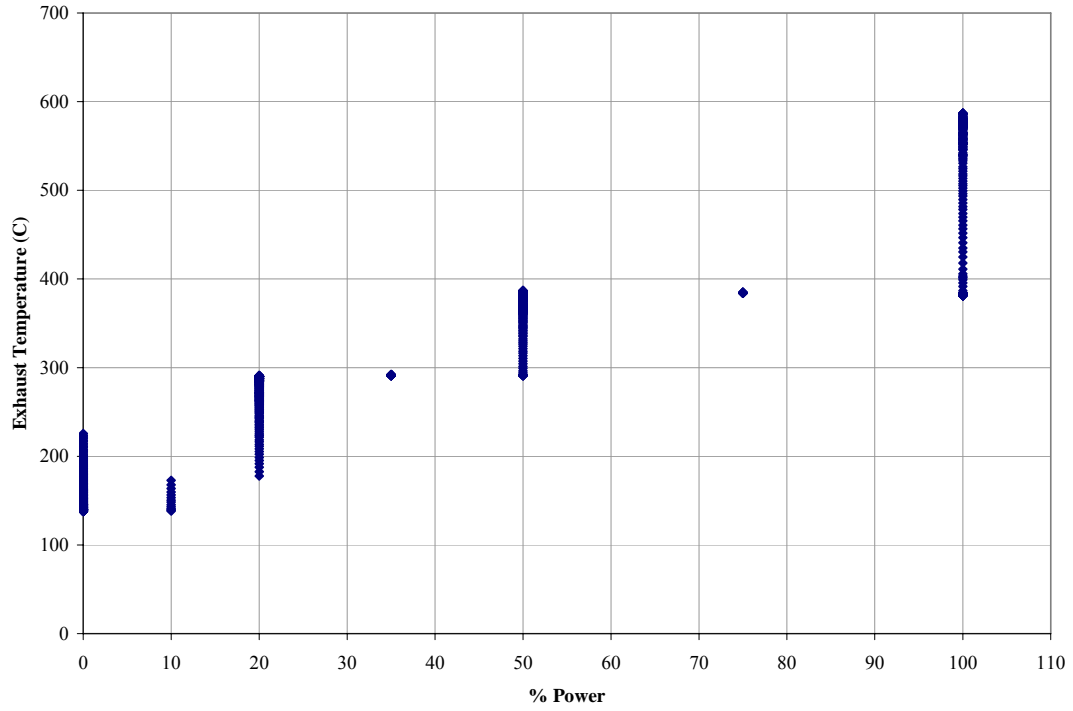


Figure 137: Exhaust Temperature (Emission Run Three: Raw Data)

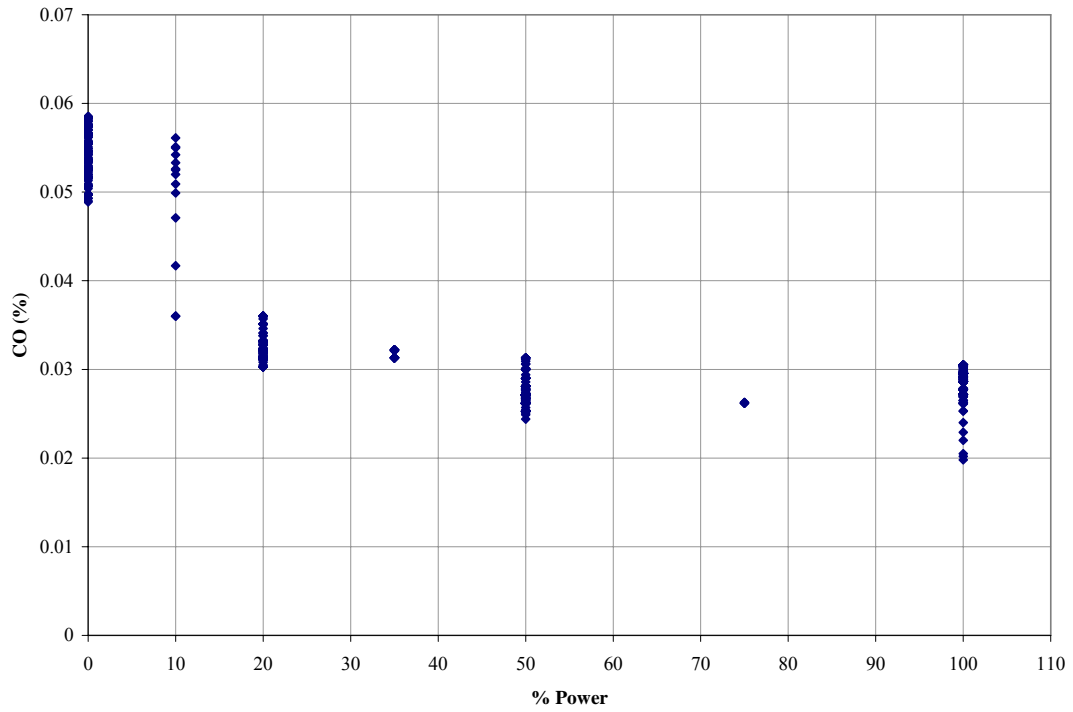


Figure 138: Carbon Monoxide (Emission Run Three: % Raw Data)

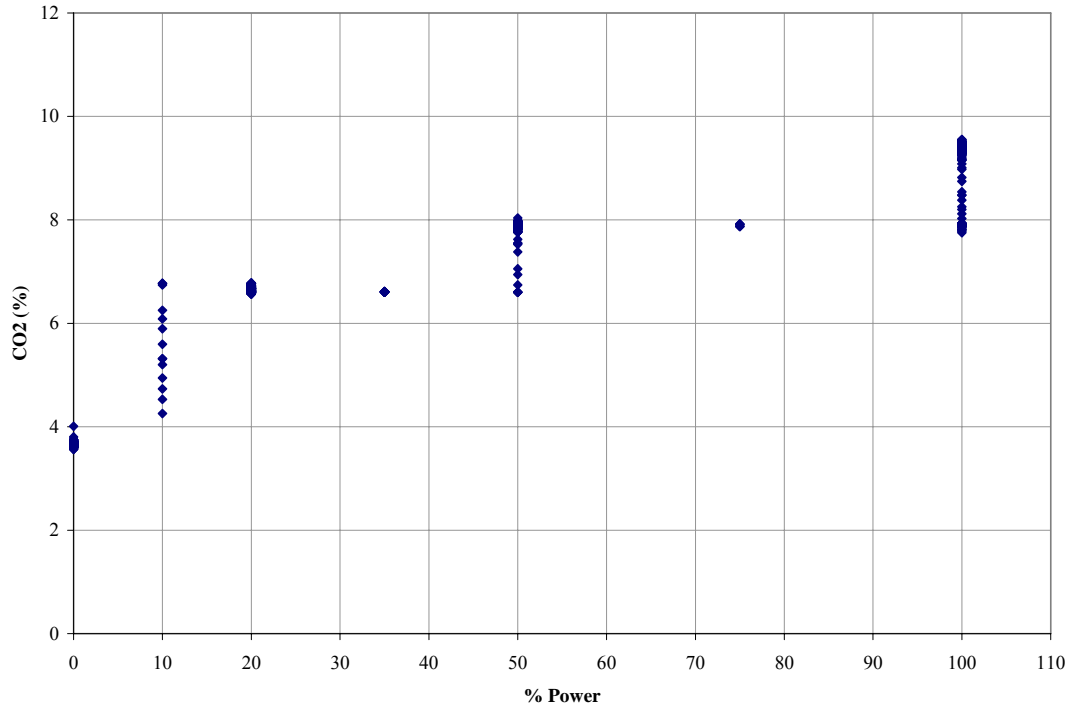


Figure 139: Carbon Dioxide (Emission Run Three: % Raw Data)

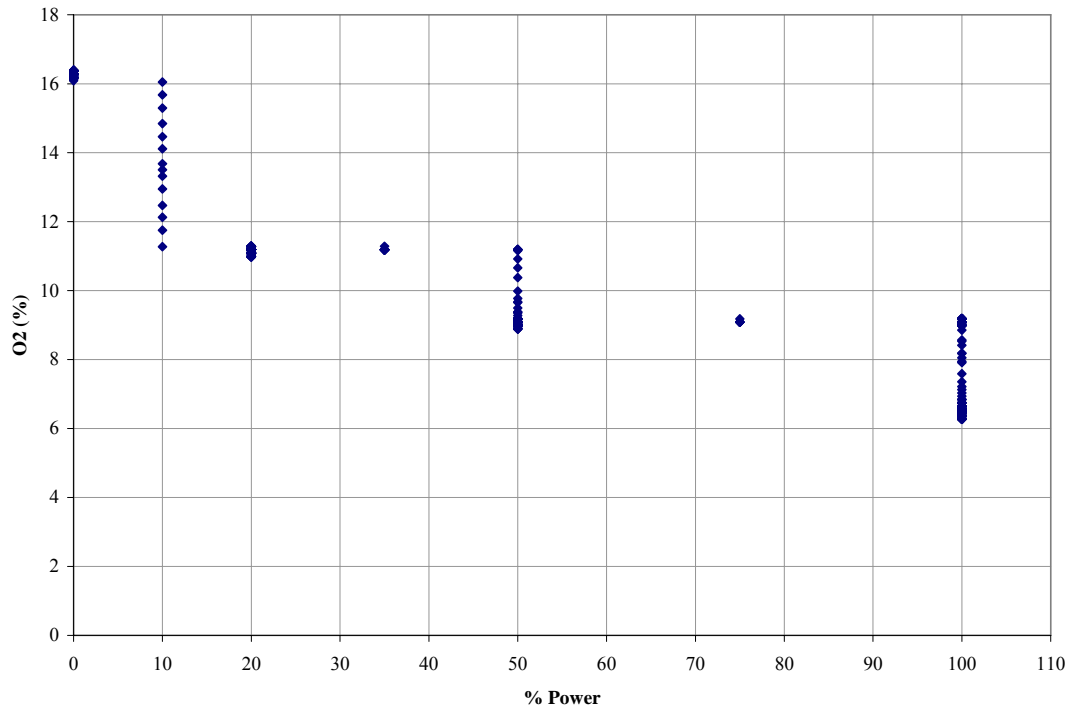


Figure 140: Oxygen (Emission Run Three: % Raw Data)

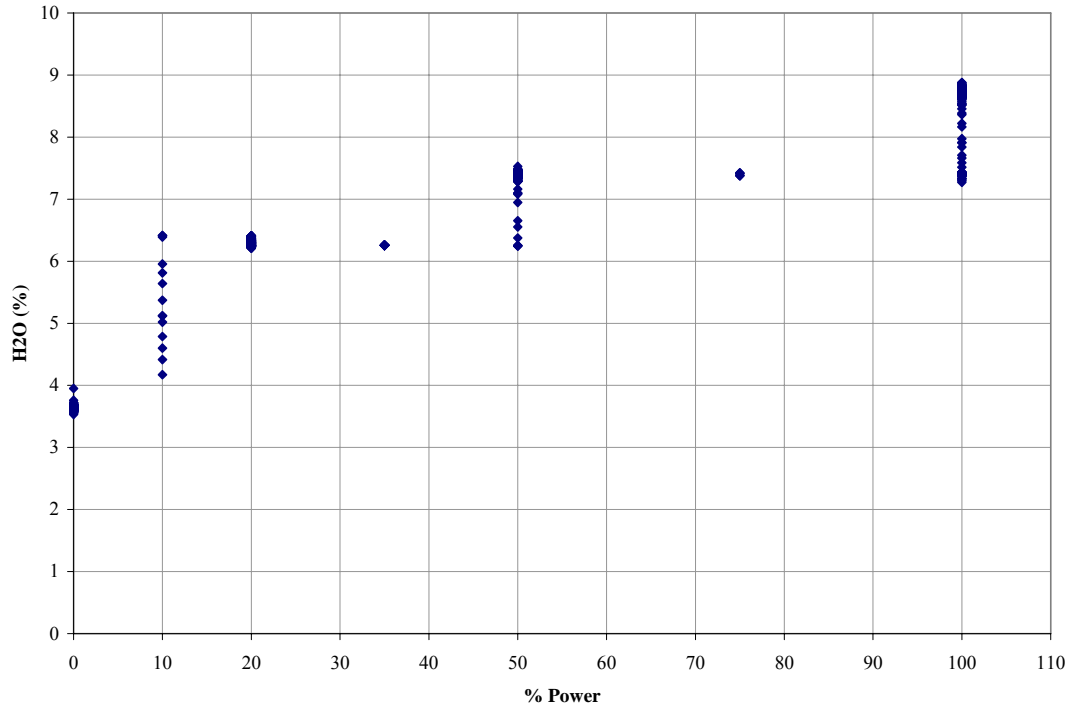


Figure 141: Water Vapor (Emission Run Three: % Raw Data)

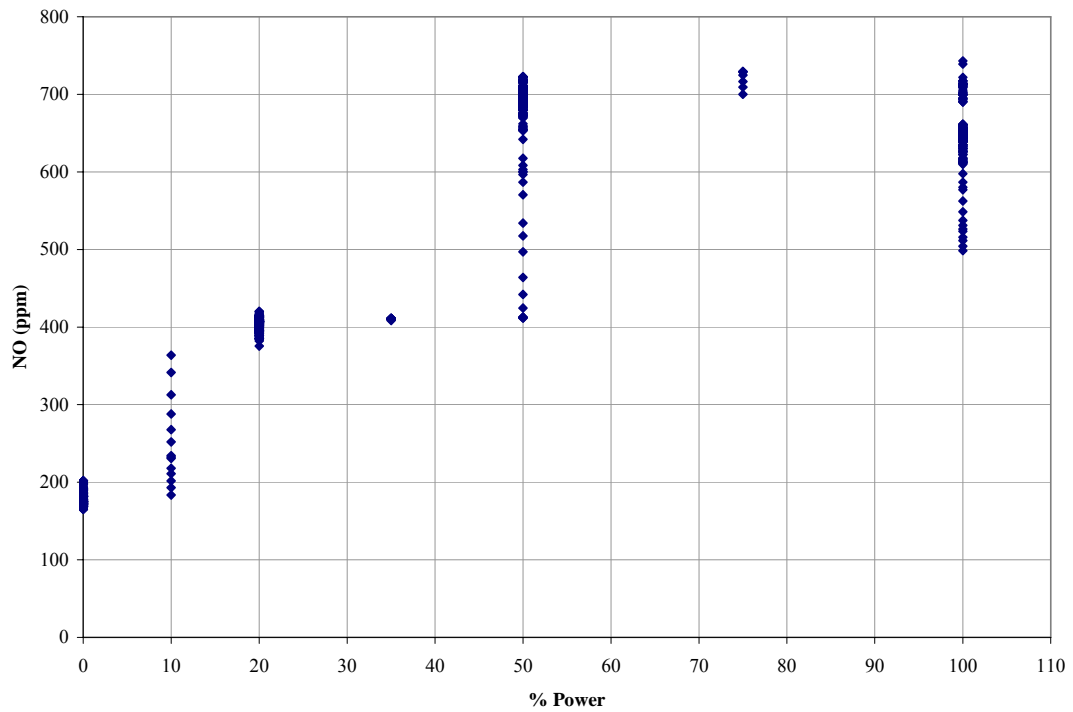


Figure 142: Nitric Oxide (Emission Run Three: PPM Raw Data)

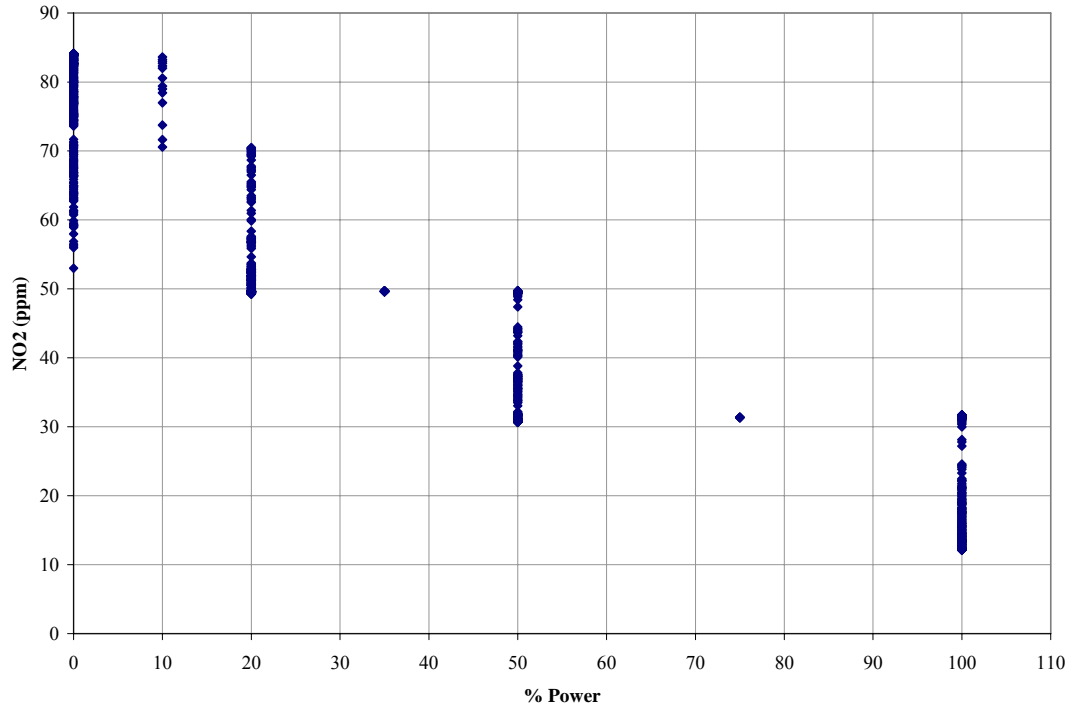


Figure 143: Nitrogen Dioxide (Emission Run Three: PPM Raw Data)

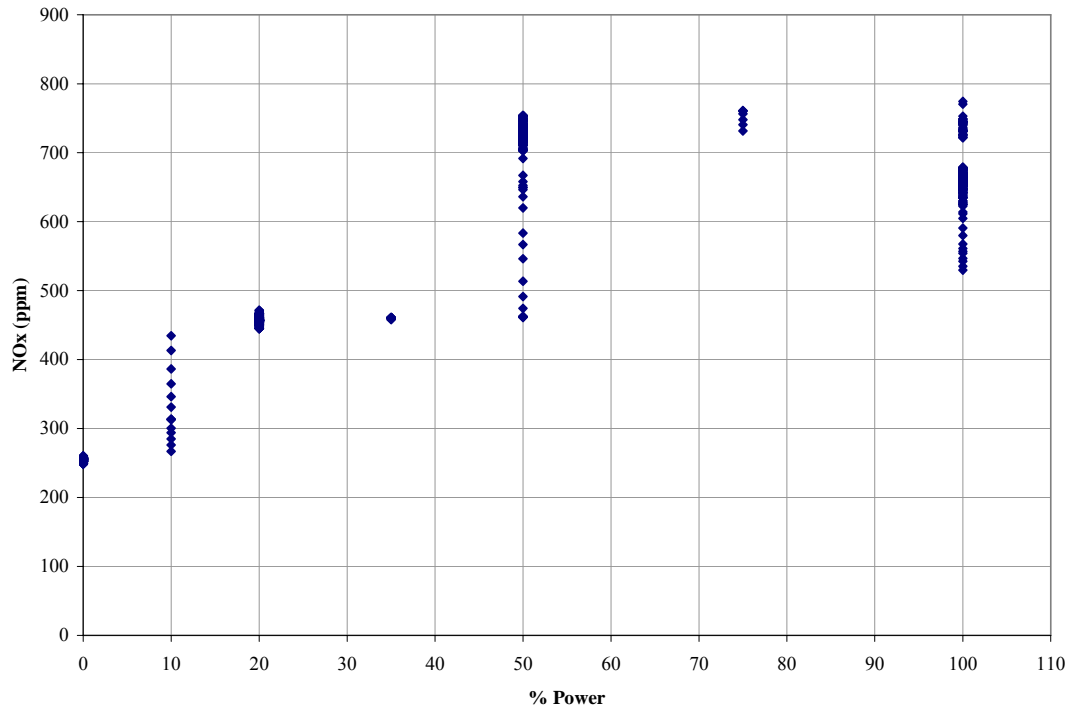


Figure 144: Nitrogen Oxides (Emission Run Three: PPM Raw Data)

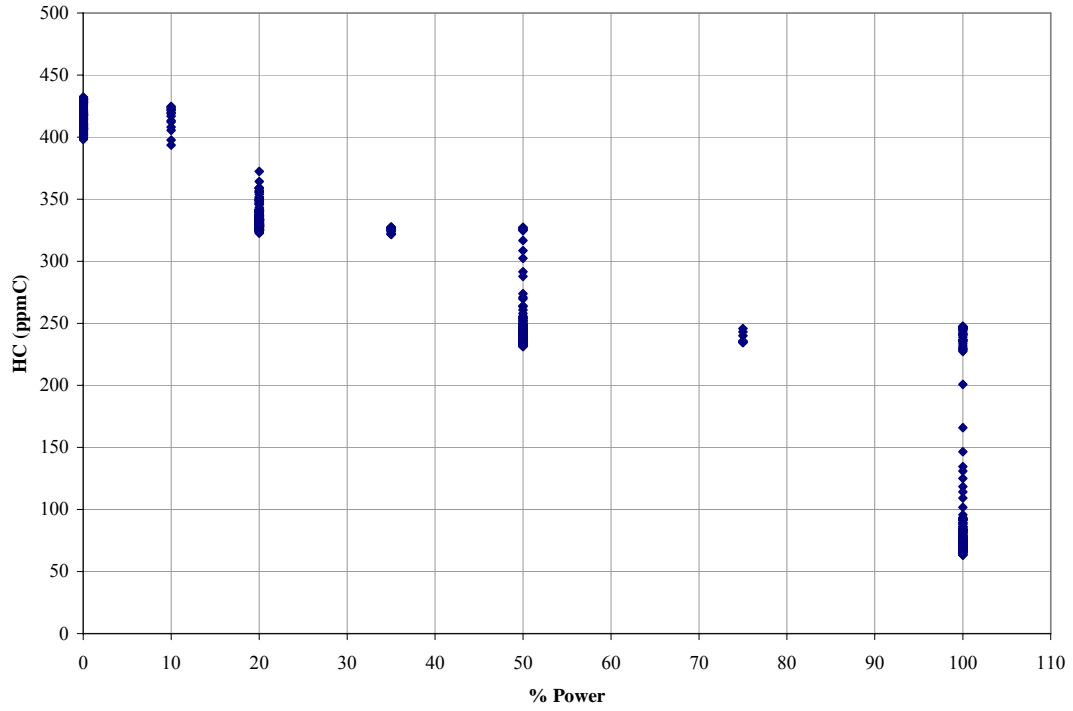


Figure 145: Hydrocarbon (Emission Run Three: PPM Raw Data)

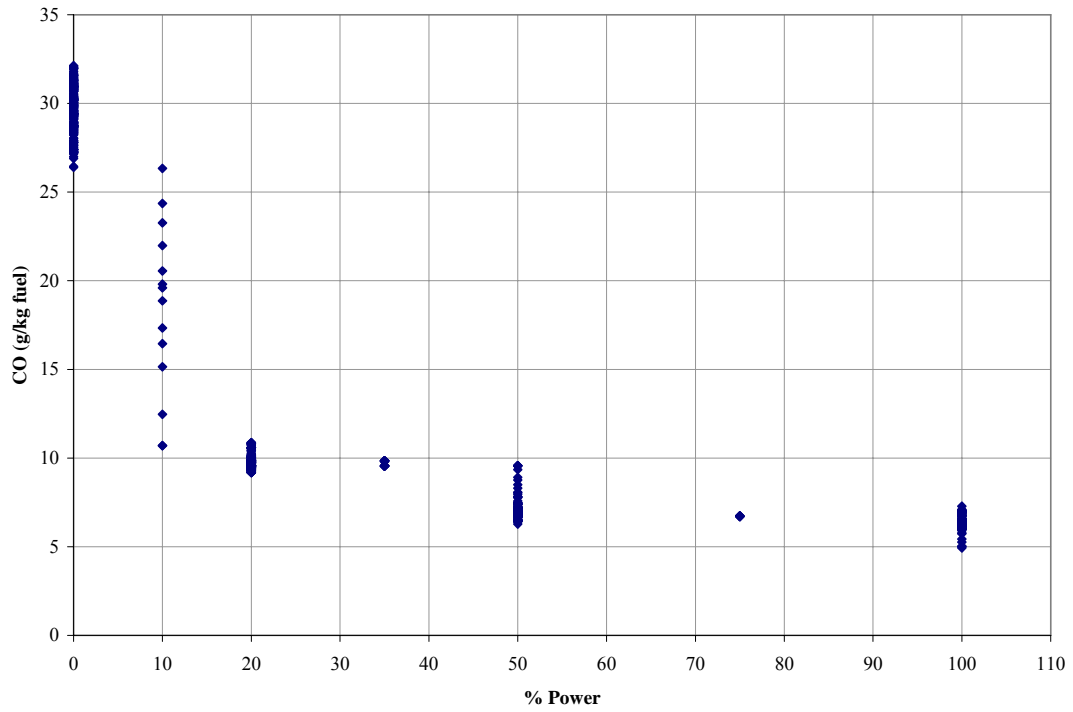


Figure 146: Carbon Monoxide (Emission Run Three: Mass Raw Data)

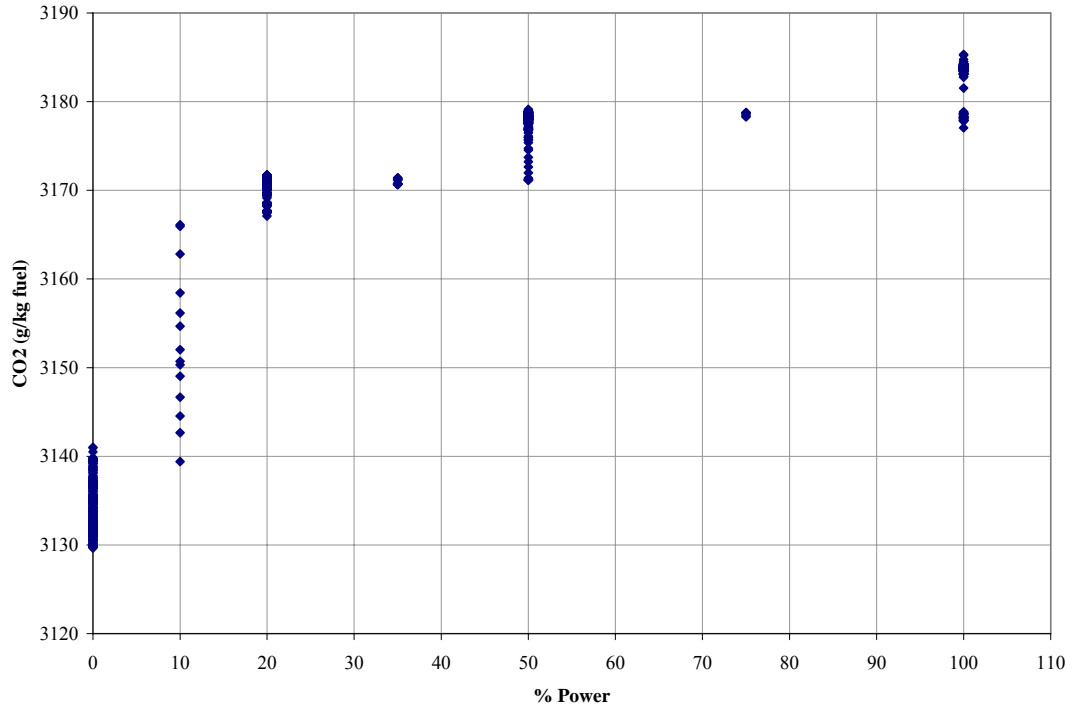


Figure 147: Carbon Dioxide (Emission Run Three: Mass Raw Data)

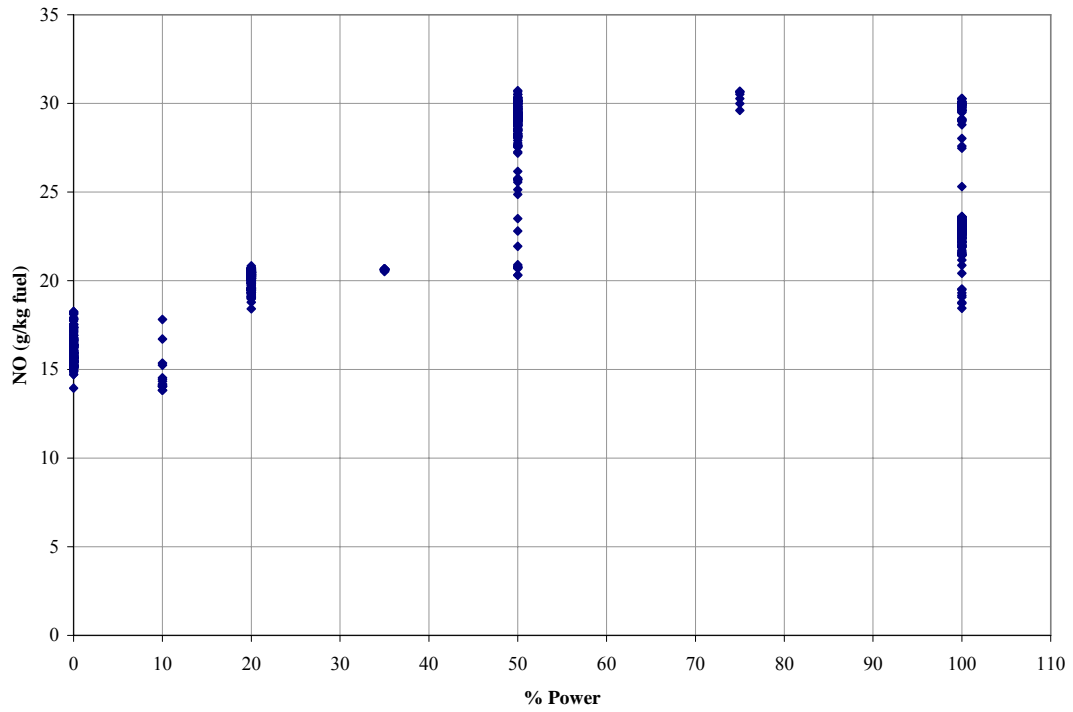


Figure 148: Nitric Oxide (Emission Run Three: Mass Raw Data)

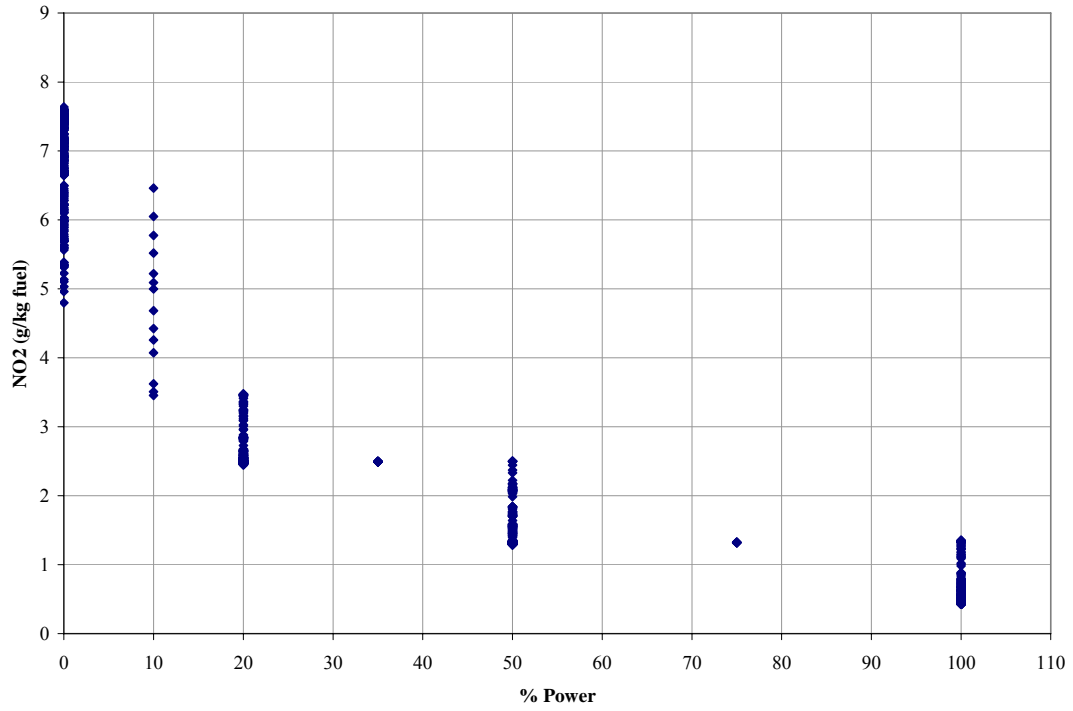


Figure 149: Nitrogen Dioxide (Emission Run Three: Mass Raw Data)

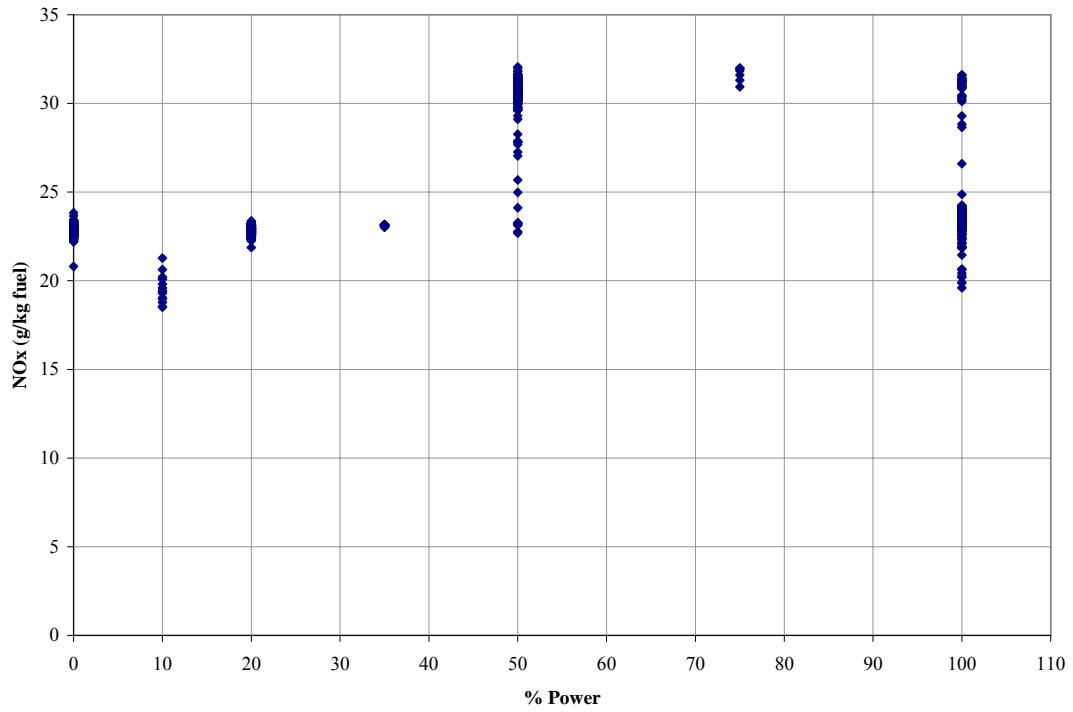


Figure 150: Nitrogen Oxides (Emission Run Three: Mass Raw Data)

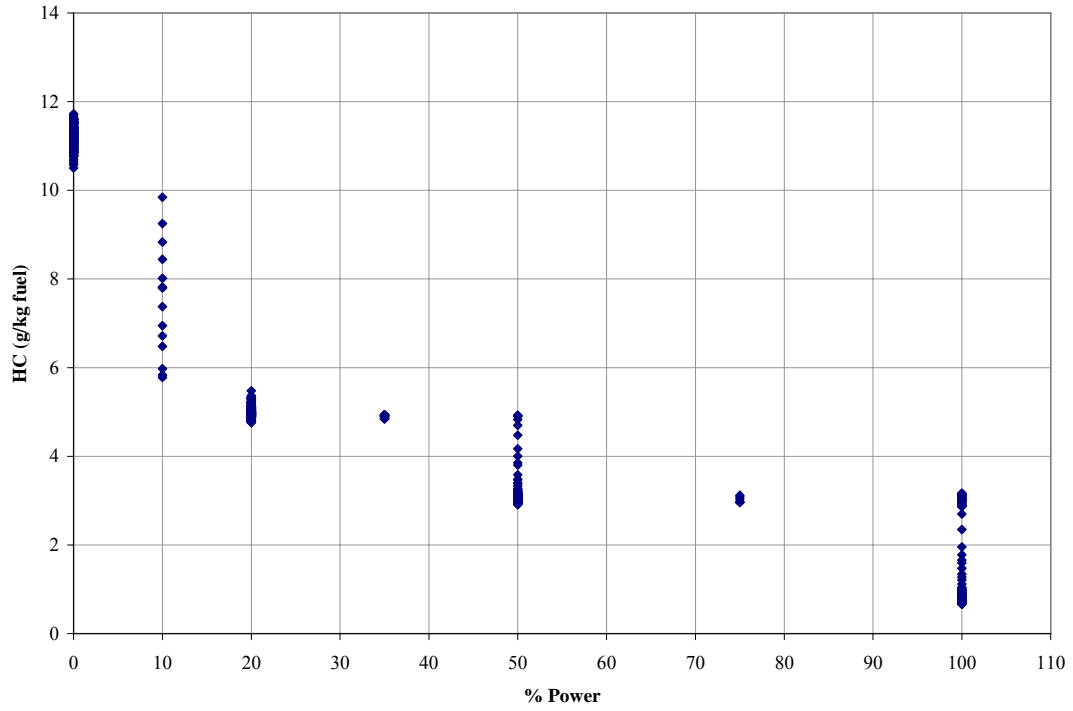


Figure 151: Hydrocarbon (Emission Run Three: Mass Raw Data)

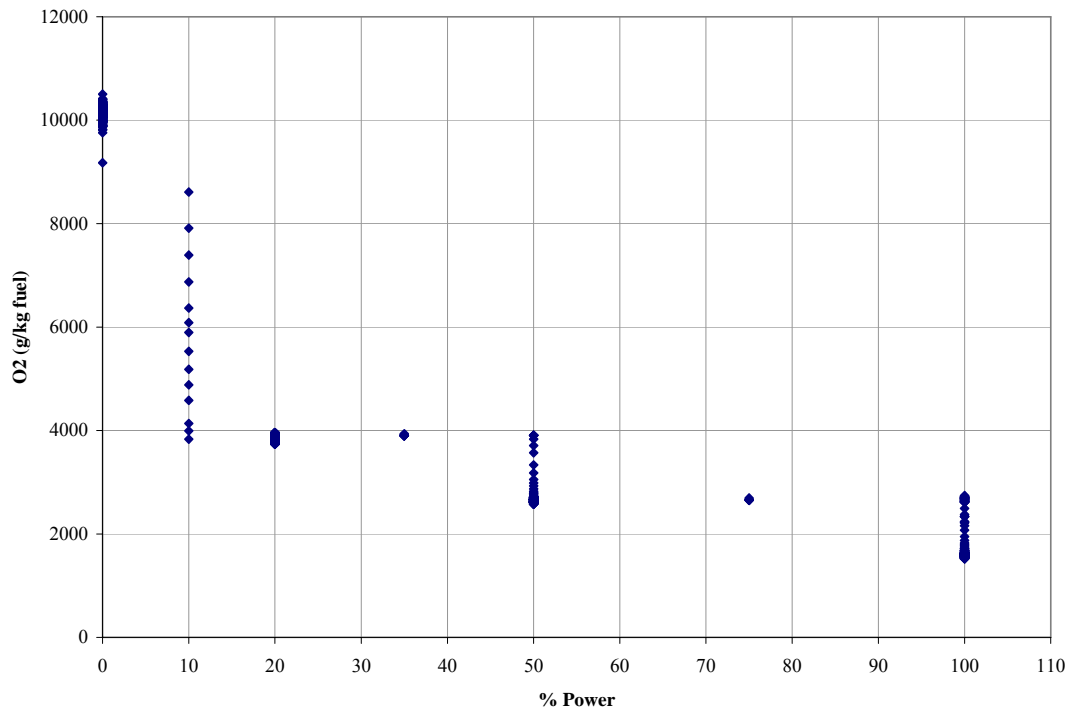


Figure 152: Oxygen (Emission Run Three: Mass Raw Data)

Table LII: Engine Parameters (Emission Run Three)

CED Load	Engine	Prop	Fuel Flow	Exhaust Temperature	AFRs	AFR	Lambda
<i>%</i>	<i>RPM</i>	<i>RPM</i>	<i>l/hr</i>	<i>deg C</i>	<i>~</i>	<i>~</i>	<i>~</i>
0	1502.19	888.48	1.83	157.18	14.50	55.30	3.81
20	2408.89	1425.58	6.50	274.86	14.50	30.35	2.09
50	3015.80	1785.05	13.96	368.70	14.50	25.67	1.77
100	3753.67	2222.59	28.02	528.11	14.50	21.95	1.51

Table LIII: Emission Data (Emission Run Three: % and PPM)

CED Load	CO2	CO	O2	H2O	NO	NO2	NOx	HC
<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>ppm</i>	<i>ppm</i>	<i>ppm</i>	<i>ppmC</i>
0	3.66	0.05	16.29	3.63	178.21	76.33	254.54	415.89
20	6.65	0.03	11.15	6.29	404.11	53.03	457.14	333.39
50	7.84	0.03	9.15	7.36	679.79	35.56	715.35	247.11
100	9.16	0.03	6.93	8.53	649.57	18.14	667.71	100.27

Table LIV: Emission Data (Emission Run Two: Mass)

CED Load	CO2	CO	NO	NO2	NOx	HC	O2
<i>%</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>
0	3134.58	29.69	16.00	6.85	22.85	11.20	10155.46
20	3170.50	9.75	20.18	2.65	22.83	4.99	3866.47
50	3177.82	7.00	28.80	1.51	30.31	3.15	2700.62
100	3182.98	6.37	23.78	0.68	24.46	1.14	1772.01

Appendix K: Engine Emission Data - Investigation IV
 (February 15, 2008)

Table LV: Atmospheric Condition (Emission Run Four)

Local Temperature	-1 °C or 30.2 °F
Local Barometric Pressure	30.42 inHg

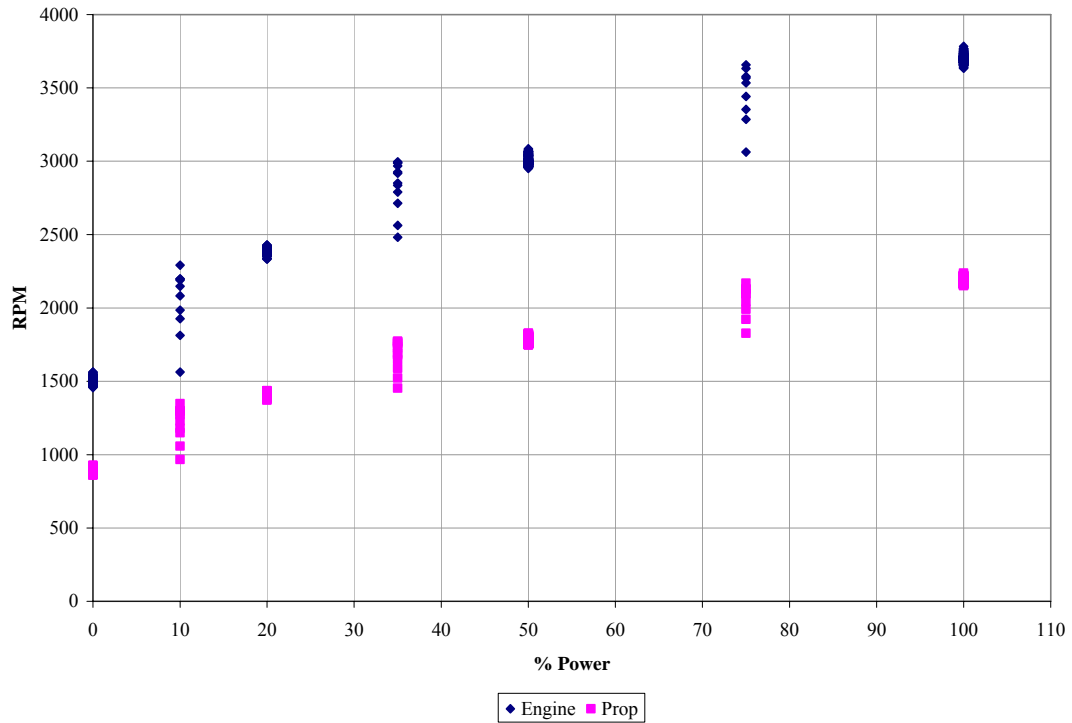


Figure 153: Engine/Prop RPM Data (Emission Run Four: Raw Data)

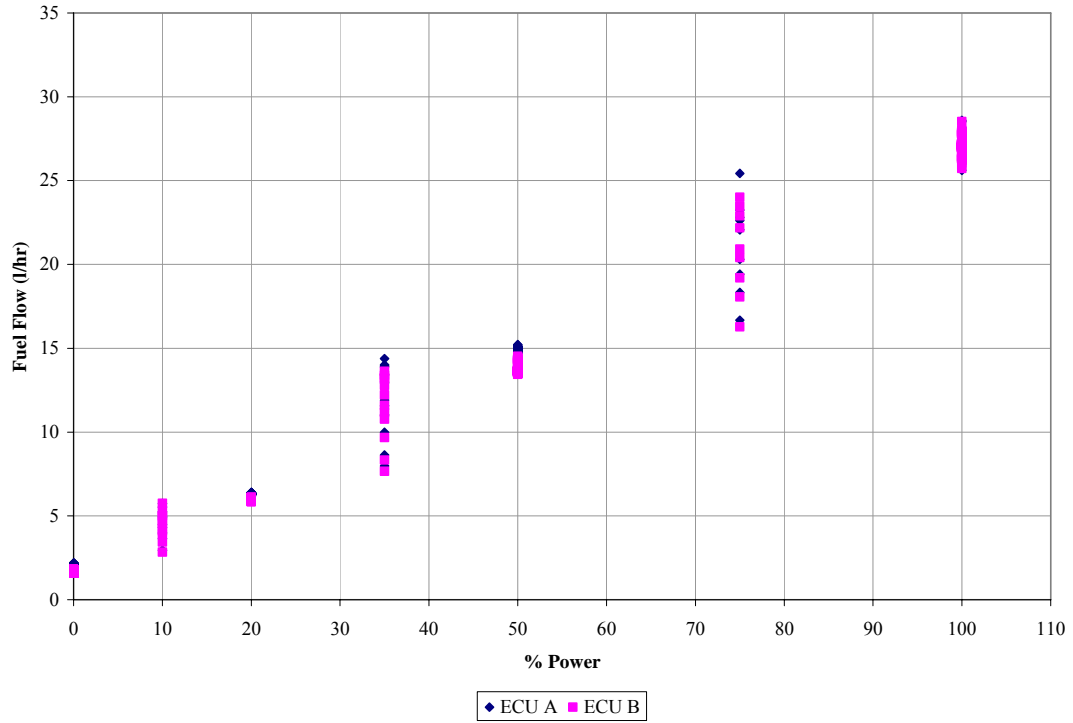


Figure 154: Fuel Flow (Emission Run Four: Raw Data)

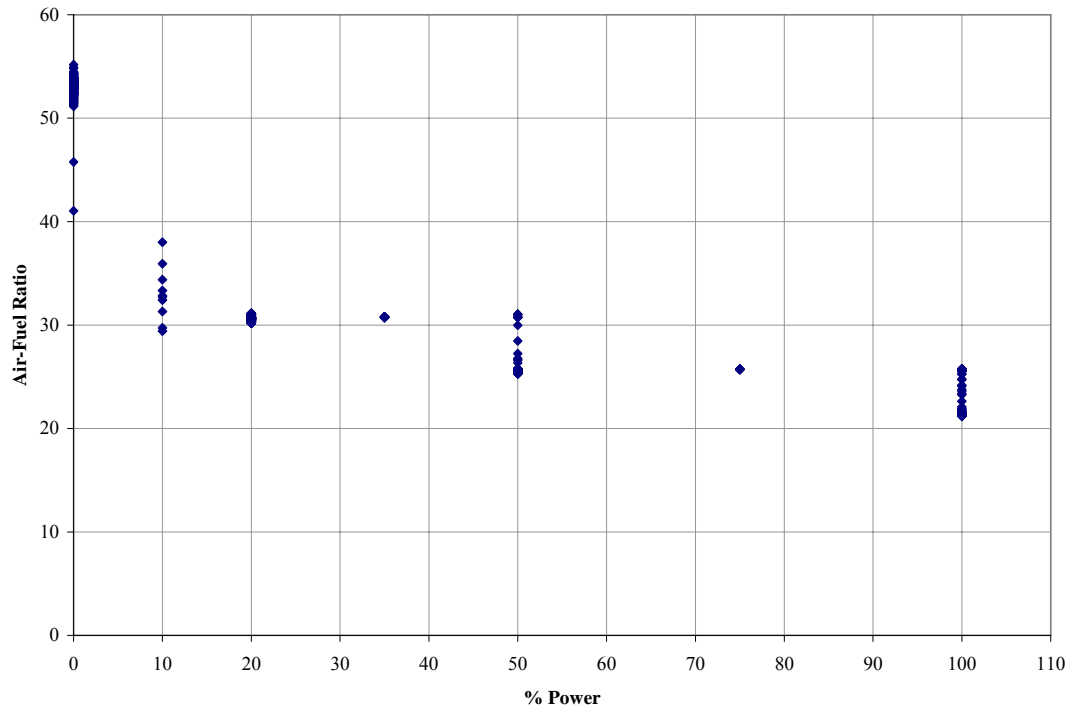


Figure 155: Air-Fuel Ratio (Emission Run Four: Raw Data)

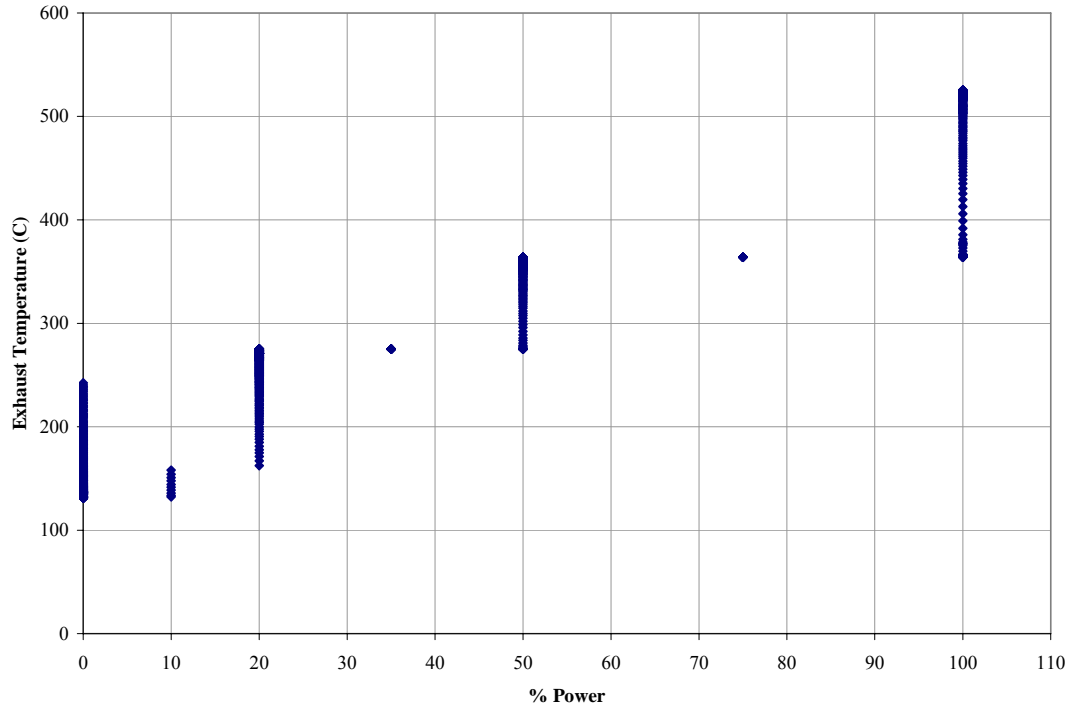


Figure 156: Exhaust Temperature (Emission Run Four: Raw Data)

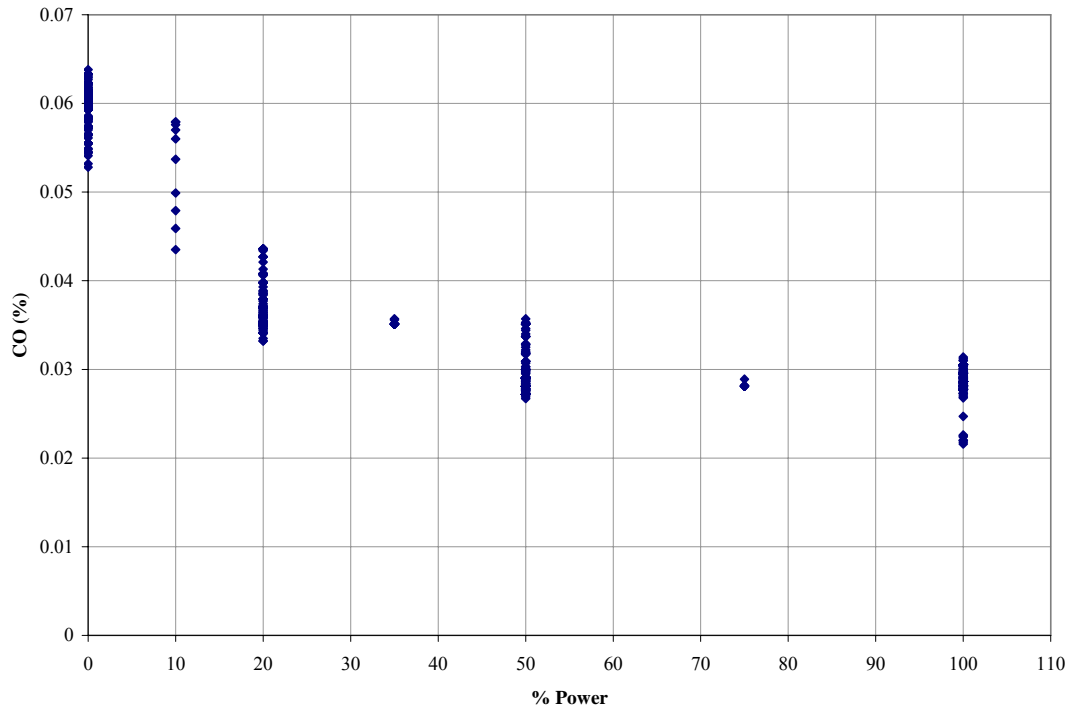


Figure 157: Carbon Monoxide (Emission Run Four: % Raw Data)

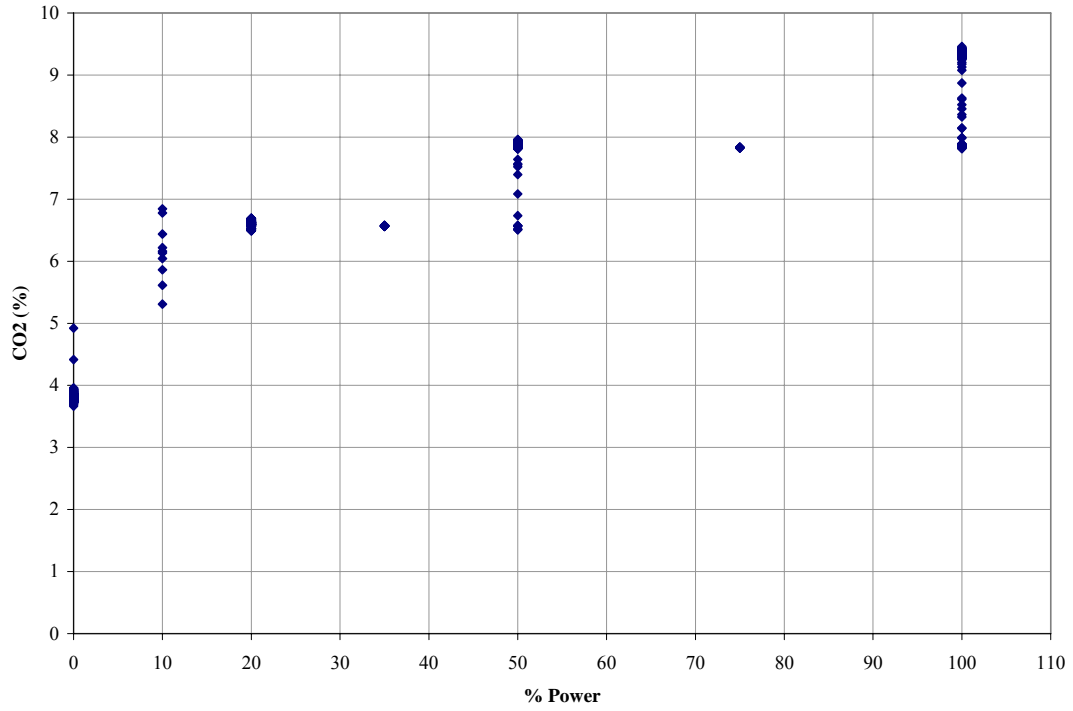


Figure 158: Carbon Dioxide (Emission Run Four: % Raw Data)

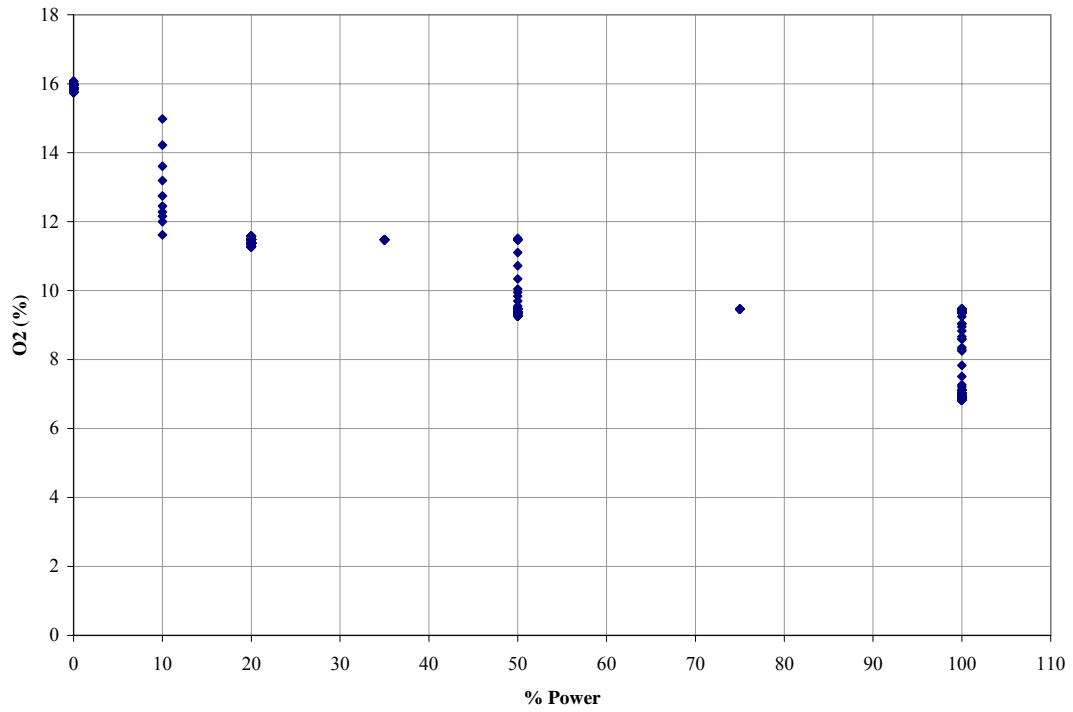


Figure 159: Oxygen (Emission Run Four: % Raw Data)

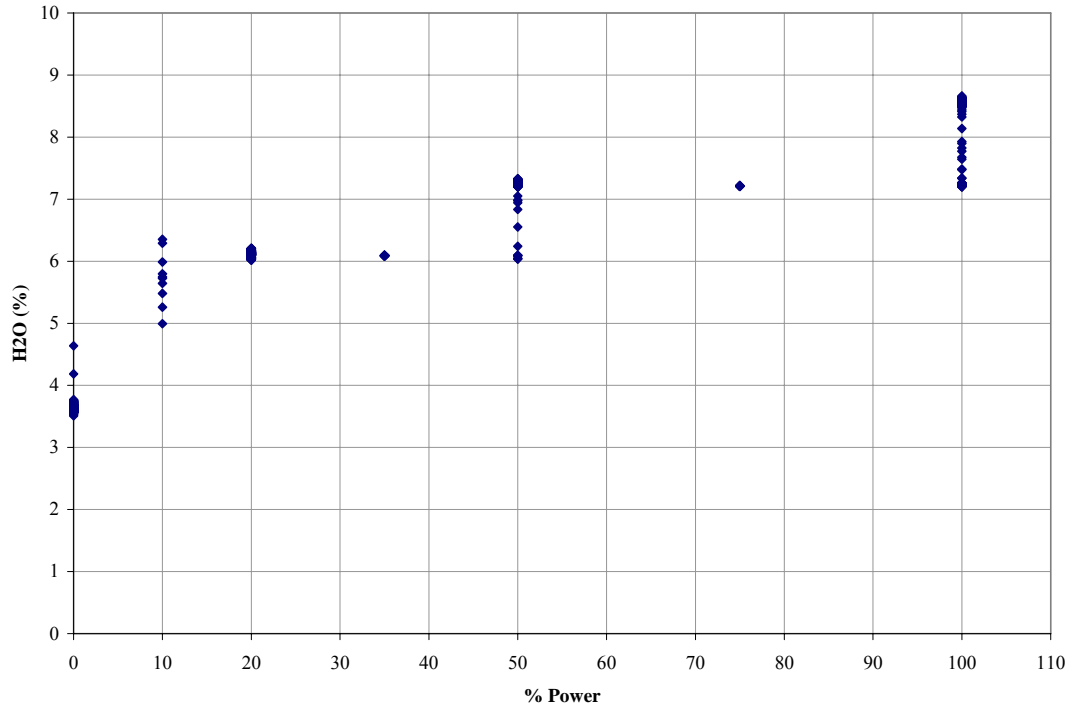


Figure 160: Water Vapor (Emission Run Four: % Raw Data)

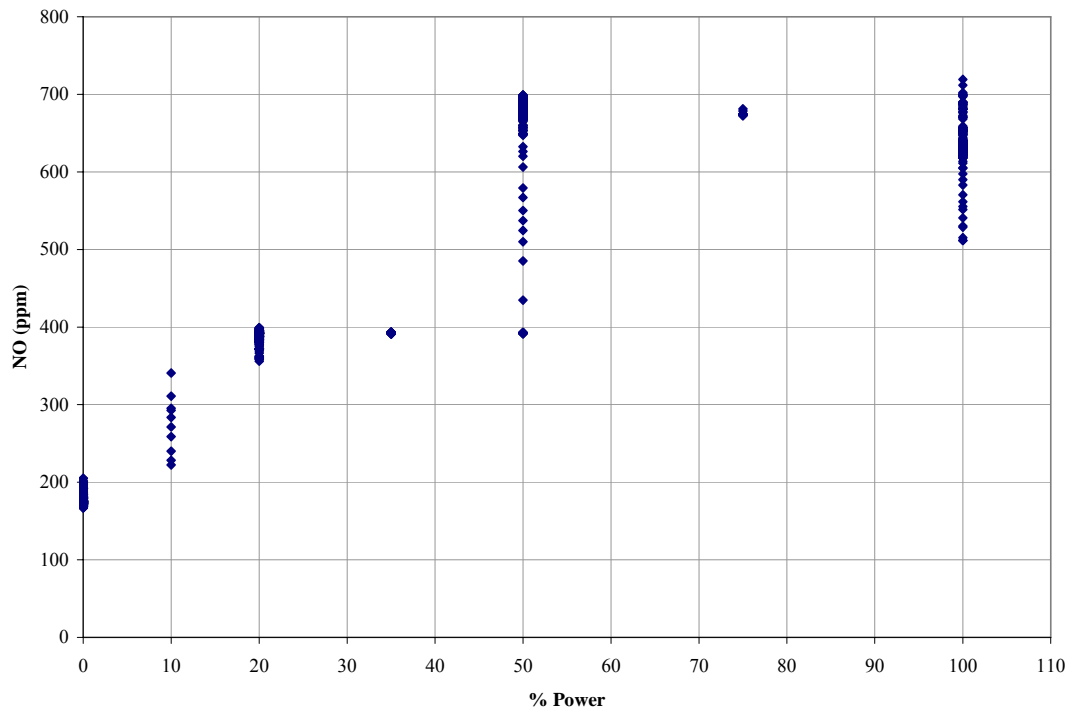


Figure 161: Nitric Oxide (Emission Run Four: ppm Raw Data)

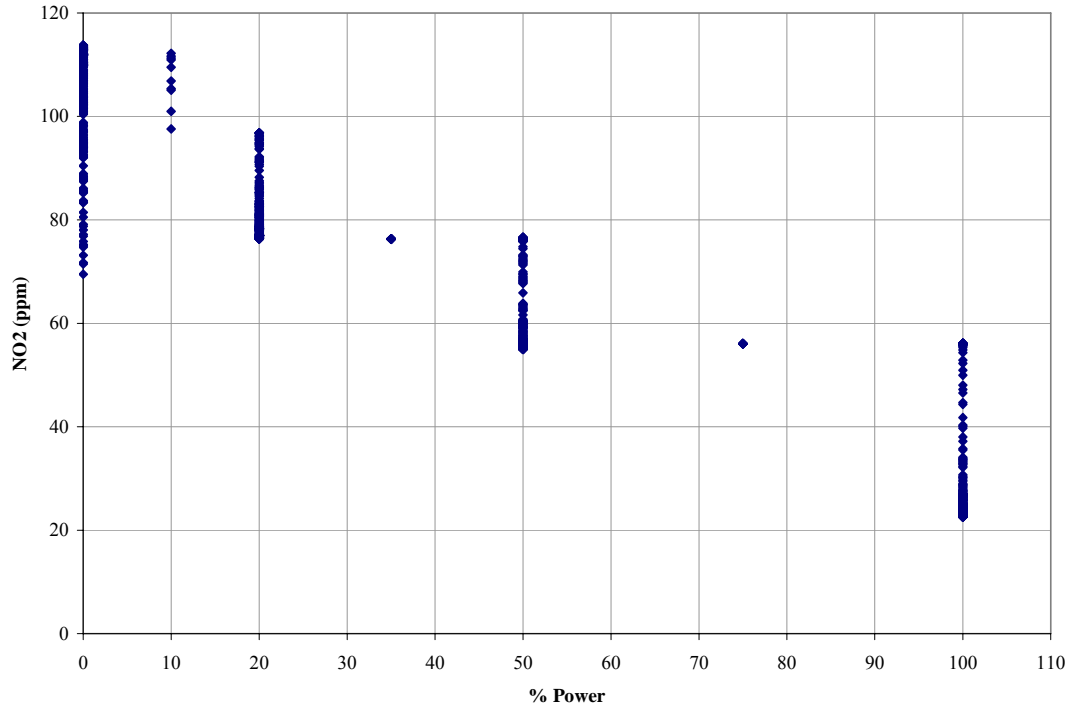


Figure 162: Nitrogen Dioxide (Emission Run Four: ppm Raw Data)

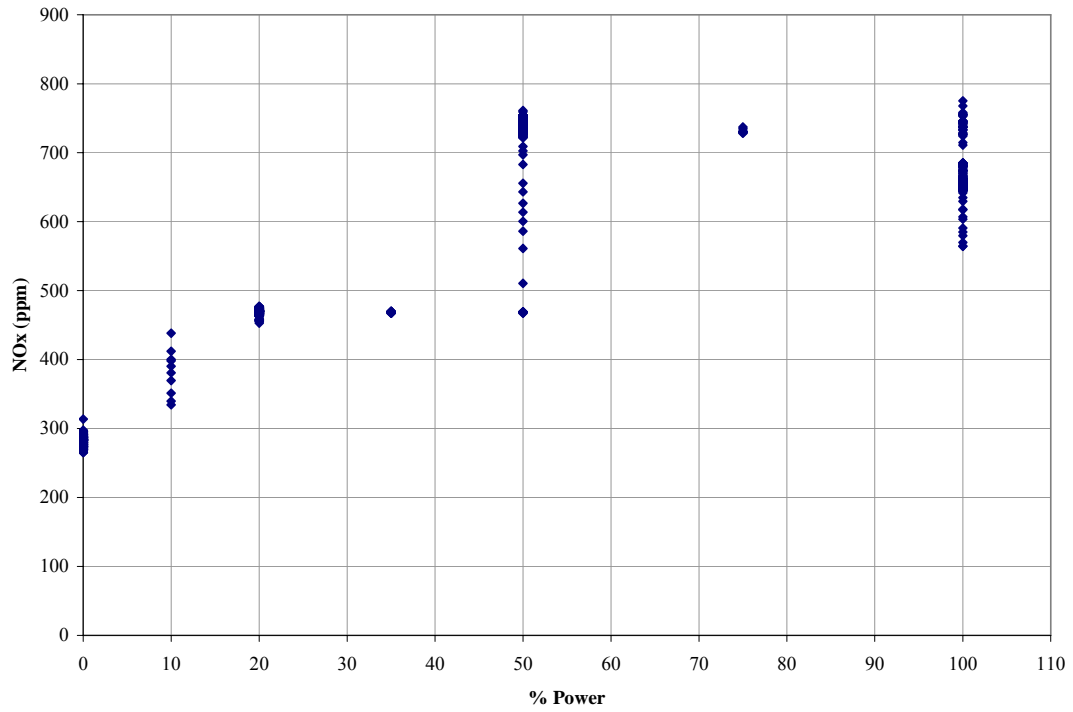


Figure 163: Nitrogen Oxides (Emission Run Four: ppm Raw Data)

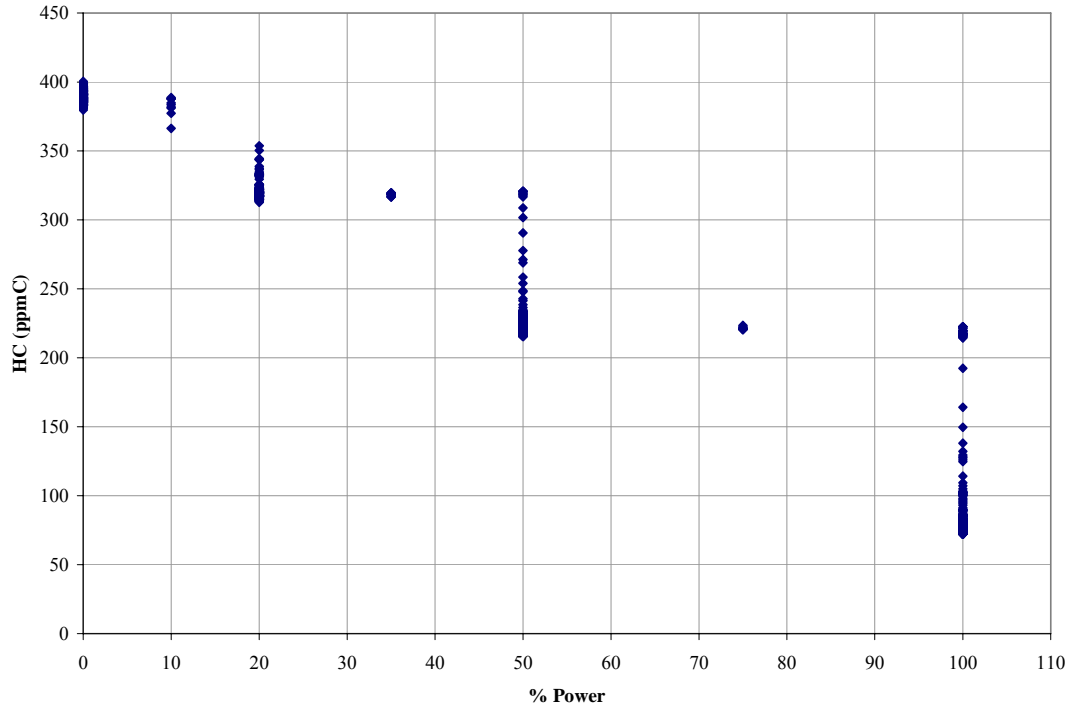


Figure 164: Hydrocarbon (Emission Run Four: ppmC Raw Data)

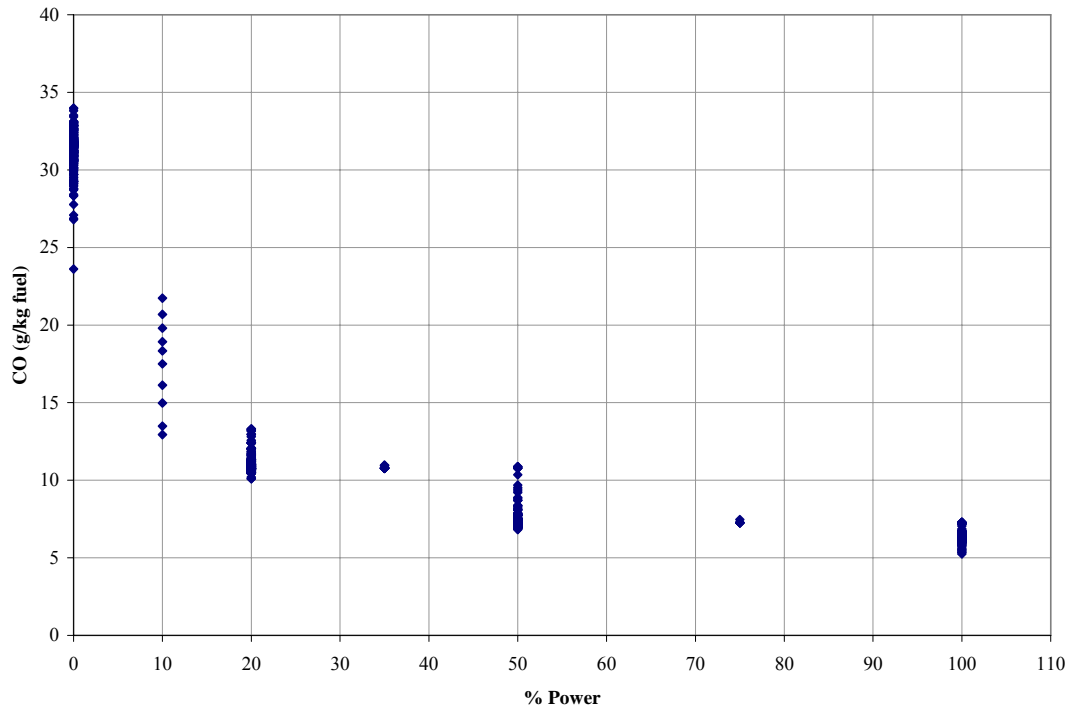


Figure 165: Carbon Monoxide (Emission Run Four: Mass Raw Data)

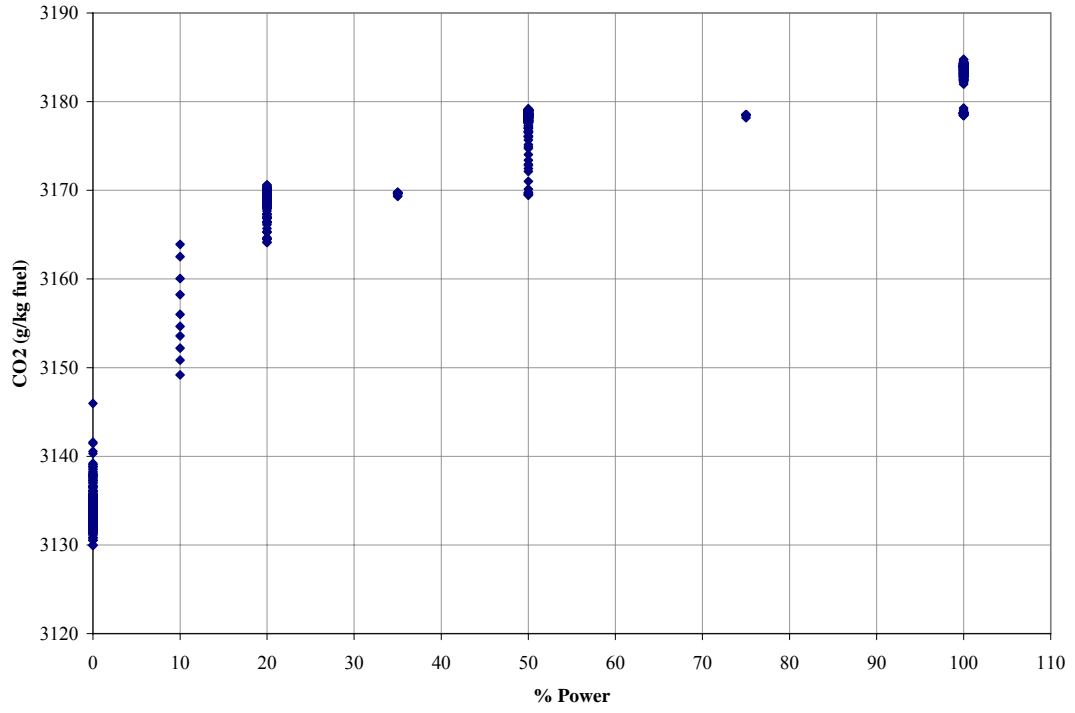


Figure 166: Carbon Dioxide (Emission Run Four: Mass Raw Data)

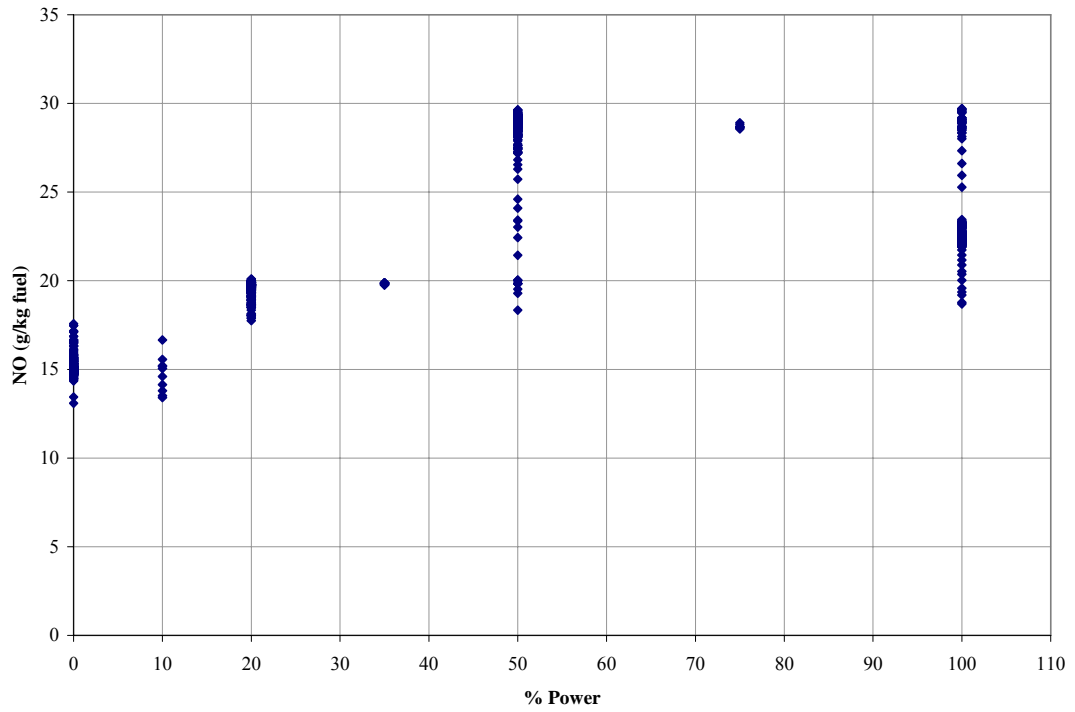


Figure 167: Nitric Oxide (Emission Run Four: Mass Raw Data)

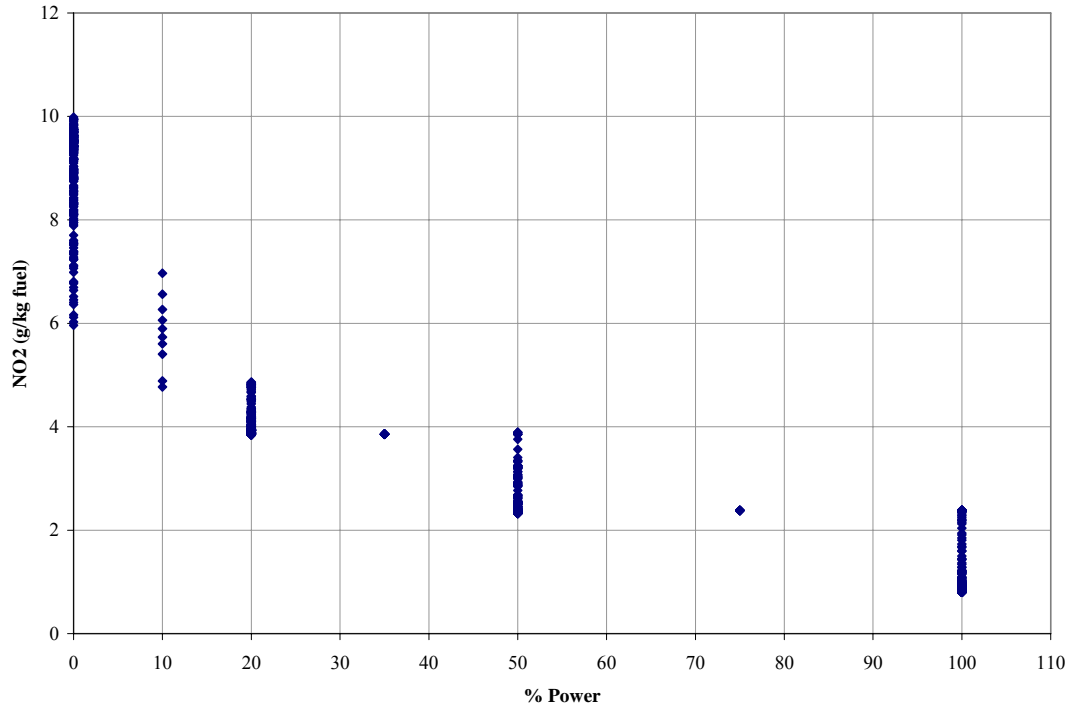


Figure 168: Nitrogen Dioxide (Emission Run Four: Mass Raw Data)

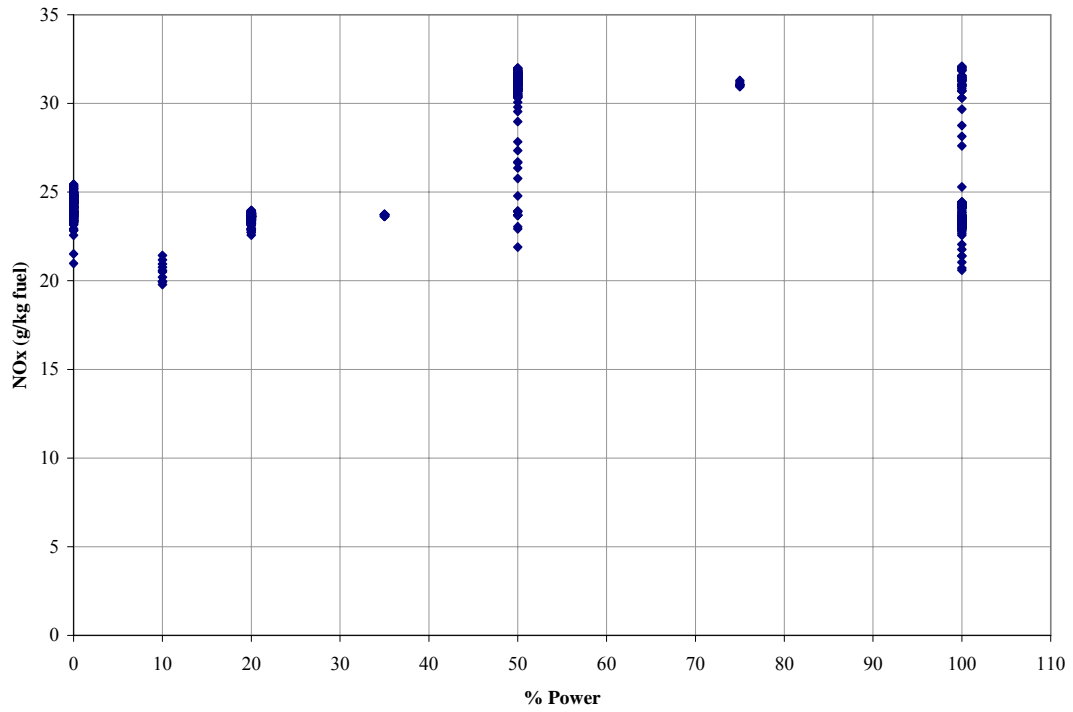


Figure 169: Nitrogen Oxides (Emission Run Four: Mass Raw Data)

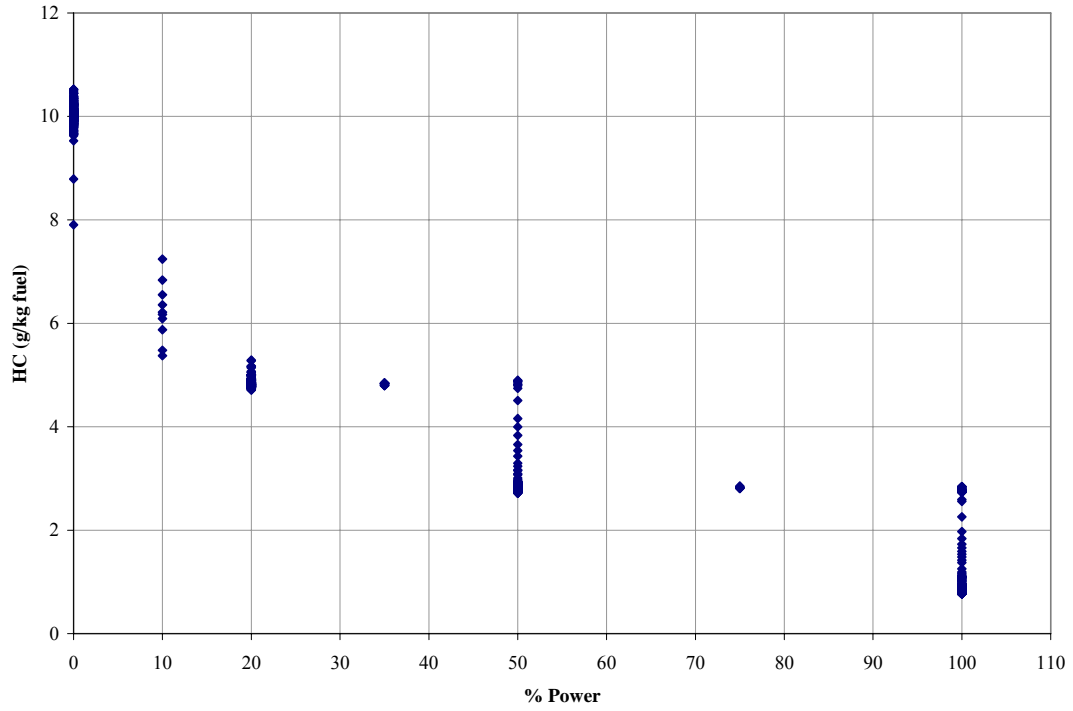


Figure 170: Hydrocarbon (Emission Run Four: Mass Raw Data)

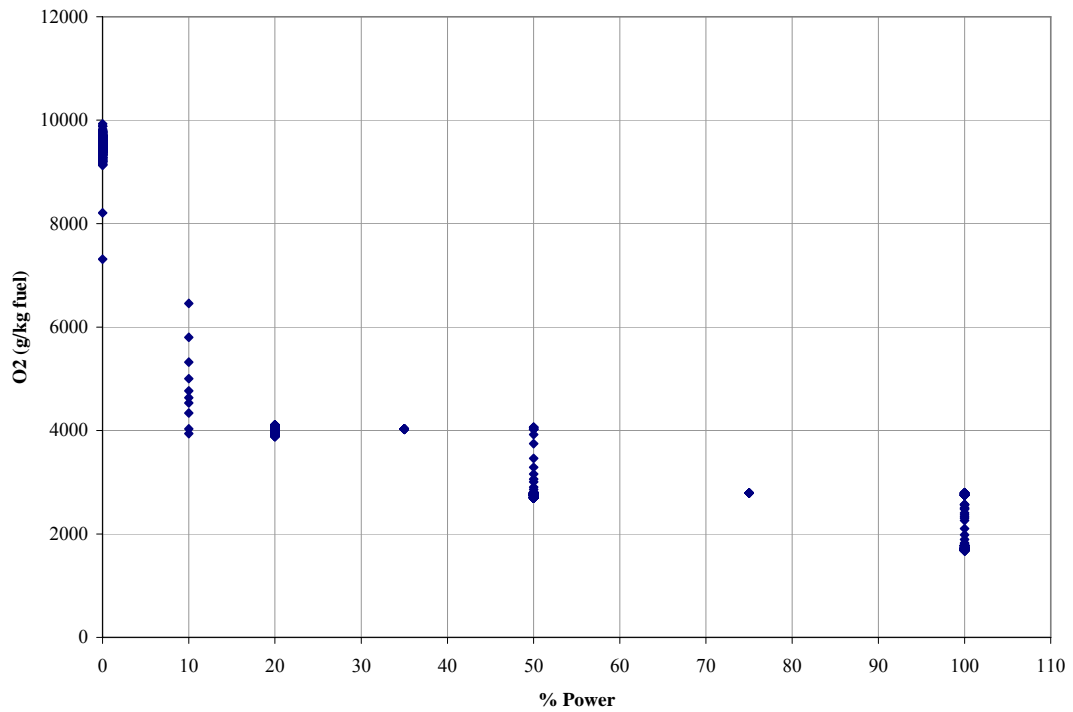


Figure 171: Oxygen (Emission Run Four: Mass Raw Data)

Table LVI: Engine Parameters (Emission Run Four)

	CED Load	Engine	Prop	Fuel Flow	Exhaust Temperature	AFRs	AFR	Lambda
	<i>%</i>	<i>RPM</i>	<i>RPM</i>	<i>l/hr</i>	<i>deg C</i>	<i>~</i>	<i>~</i>	<i>~</i>
Idle	0	1502.29	889.31	1.87	154.90	14.50	53.06	3.66
High Idle	20	2389.98	1414.75	6.16	257.13	14.50	30.61	2.11
Cruise	50	3000.22	1775.84	14.17	350.51	14.50	25.77	1.78
Max	100	3698.60	2187.86	27.06	486.54	14.50	22.03	1.52

Table LVII: Emission Data (Emission Run Four: % and PPM)

CED Load	CO2	CO	O2	H2O	NO	NO2	NOx	HC
<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>ppm</i>	<i>ppm</i>	<i>ppm</i>	<i>ppmC</i>
0	3.81	0.06	15.91	3.64	176.56	104.68	281.23	389.04
20	6.60	0.04	11.41	6.12	388.03	80.70	468.72	320.53
50	7.83	0.03	9.46	7.21	666.02	60.19	726.21	227.55
100	9.14	0.03	7.30	8.38	636.79	31.29	668.08	100.68

Table LVIII: Emission Data (Emission Run Four: Mass)

CED Load	CO2	CO	NO	NO2	NOx	HC	O2
<i>%</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>
0	3134.28	31.35	15.20	9.01	24.21	10.05	9507.95
20	3169.08	11.07	19.52	4.06	23.58	4.84	3985.22
50	3177.90	7.48	28.28	2.57	30.84	2.91	2800.84
100	3183.01	6.38	23.35	1.17	24.52	1.14	1870.83

Appendix L: Engine Emission Data - Investigation V
 (February 15, 2008)

Table LIX: Atmospheric Condition (Emission Run Five)

Local Temperature	0 °C or 32 °F
Local Barometric Pressure	30.39 inHg

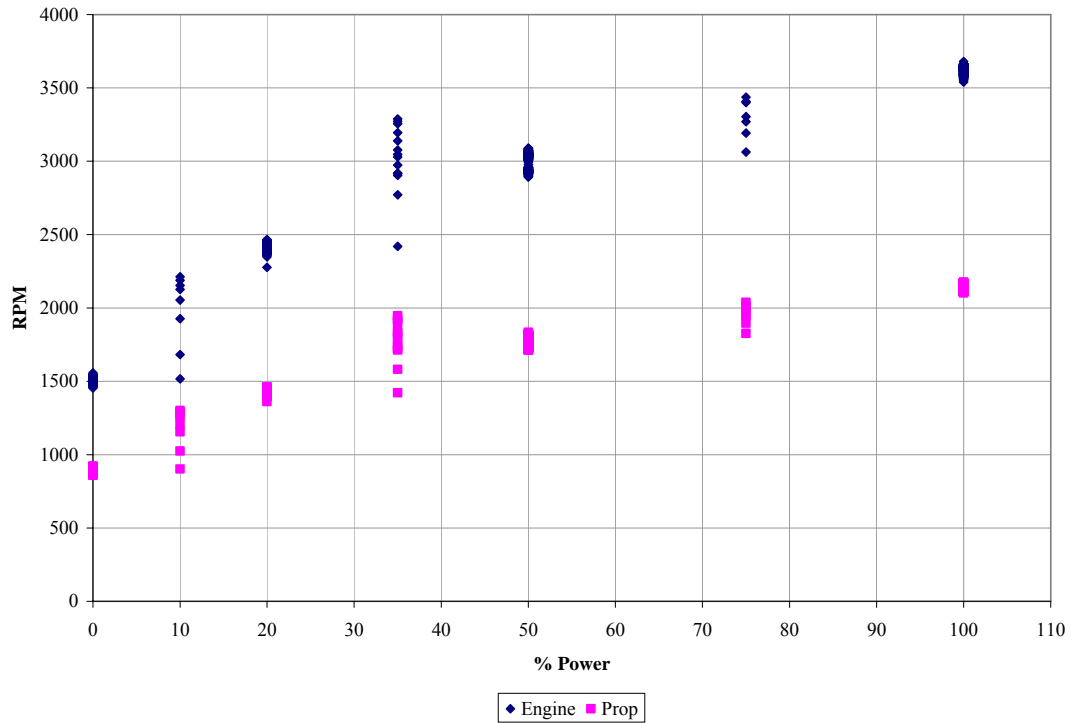


Figure 172: Engine/Prop RPM Data (Emission Run Five: Raw Data)

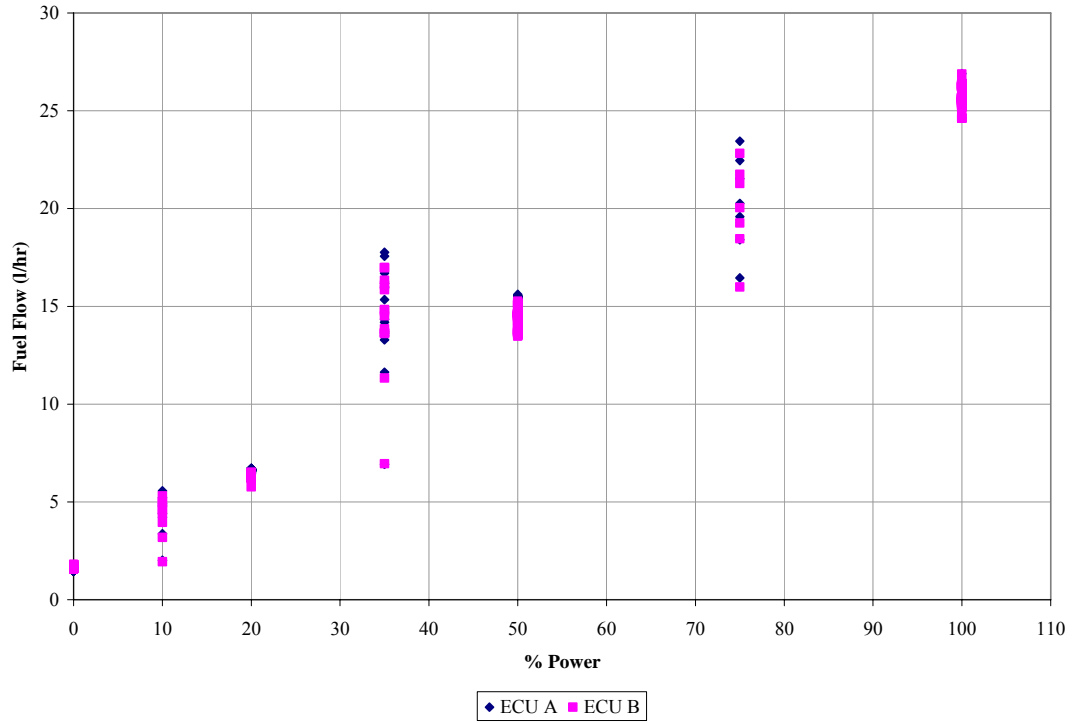


Figure 173: Fuel Flow (Emission Run Five: Raw Data)

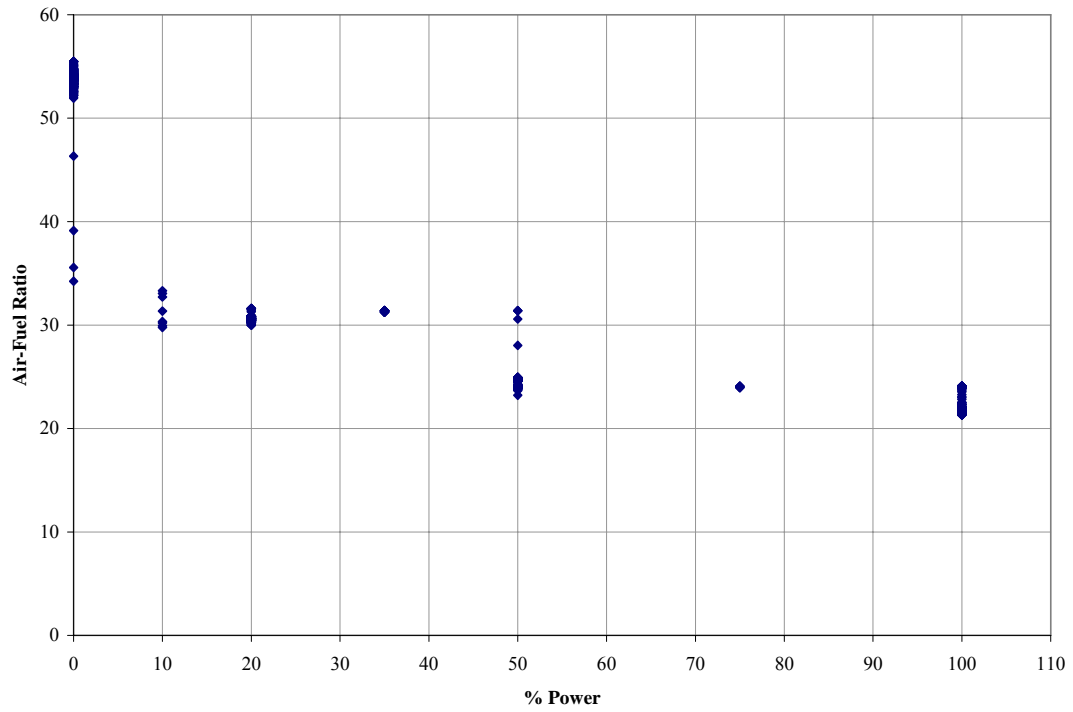


Figure 174: Air-Fuel Ratio (Emission Run Five: Raw Data)

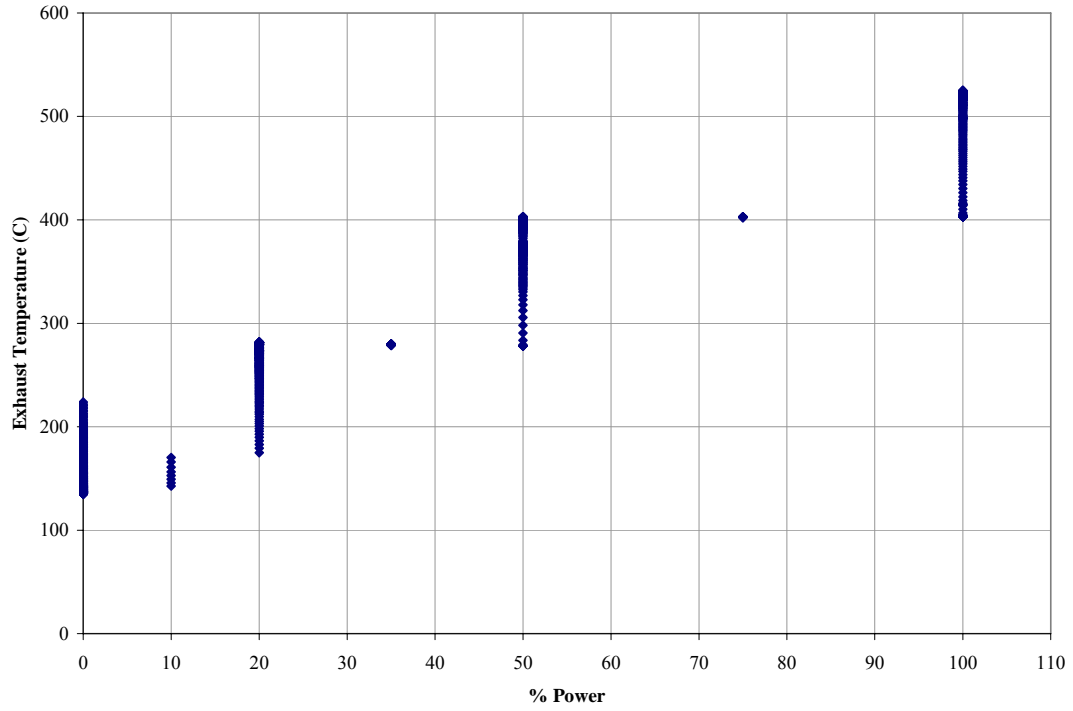


Figure 175: Exhaust Temperature (Emission Run Five: Raw Data)

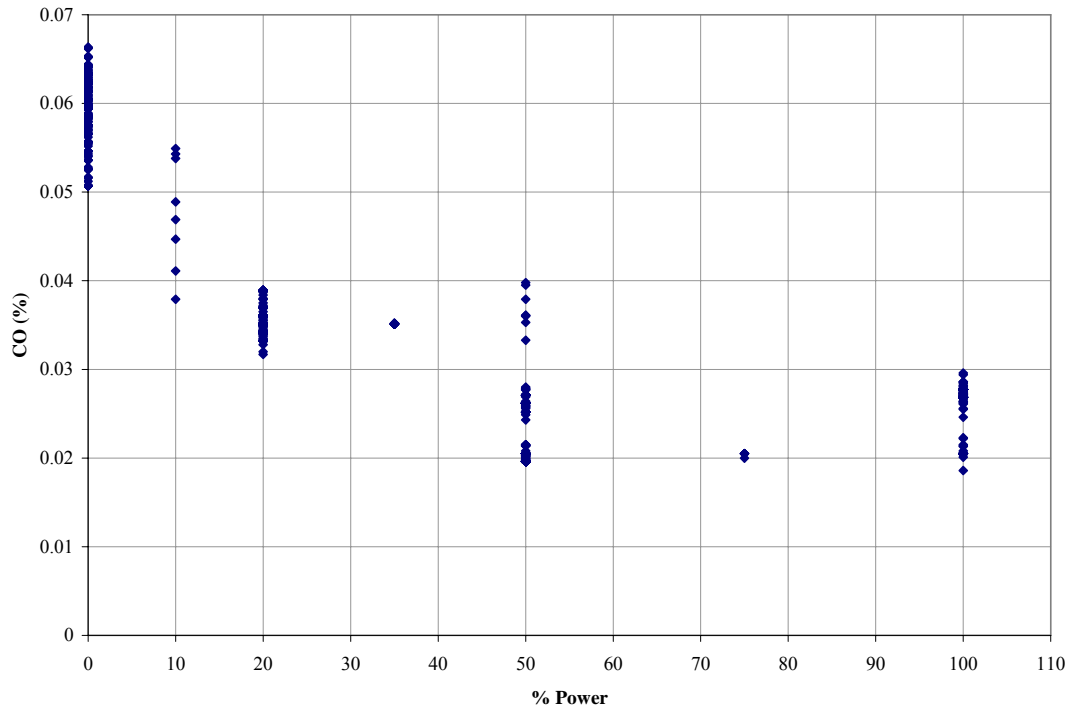


Figure 176: Carbon Monoxide (Emission Run Five: % Raw Data)

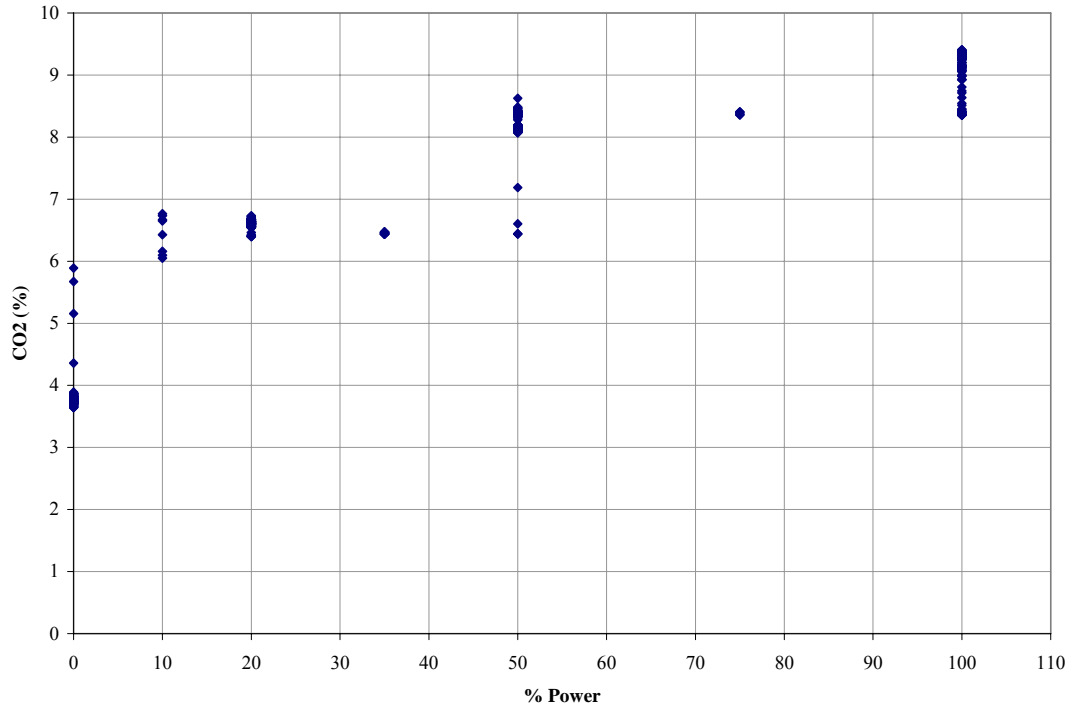


Figure 177: Carbon Dioxide (Emission Run Five: % Raw Data)

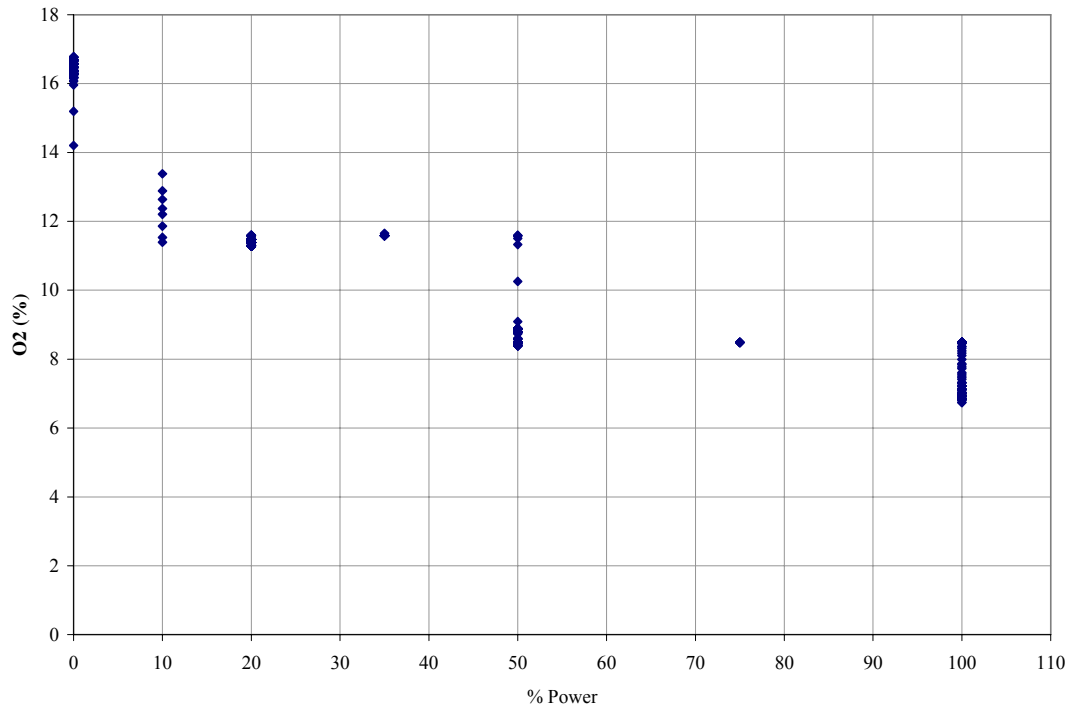


Figure 178: Oxygen (Emission Run Five: % Raw Data)

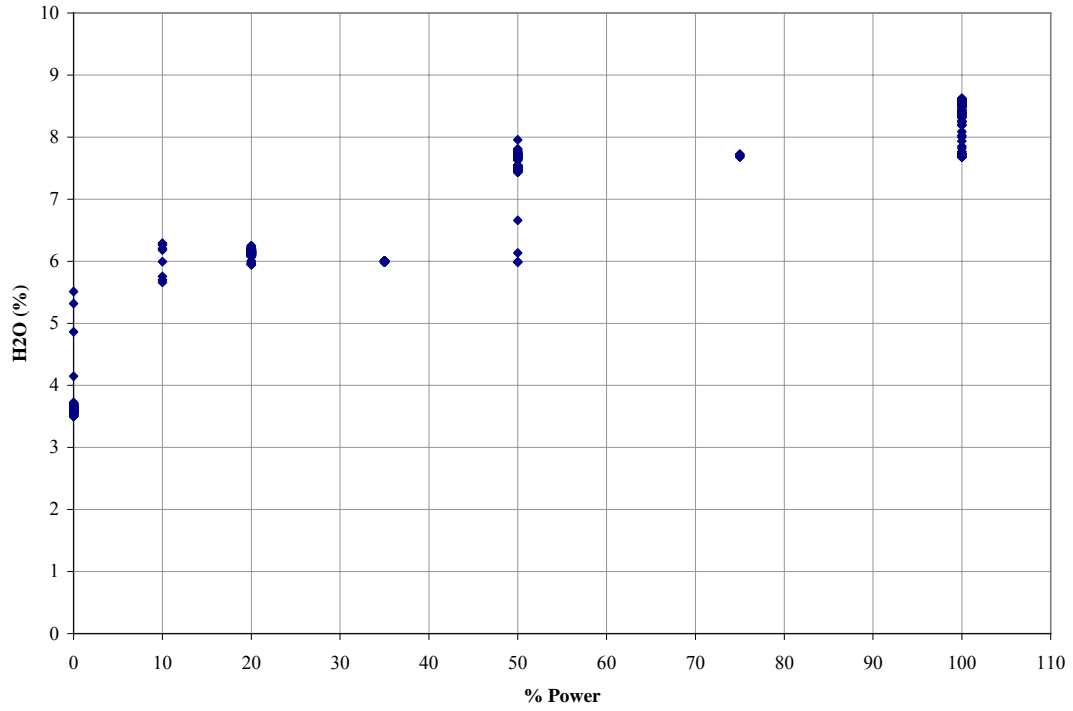


Figure 179: Water Vapor (Emission Run Five: % Raw Data)

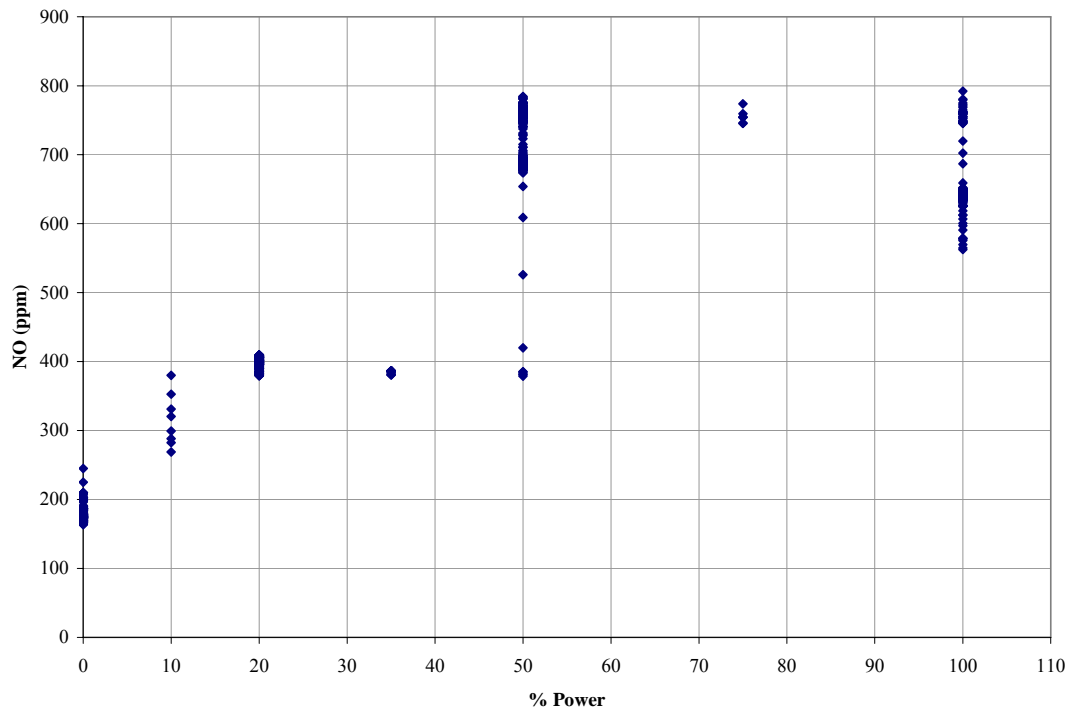


Figure 180: Nitric Oxide (Emission Run Five: ppm Raw Data)

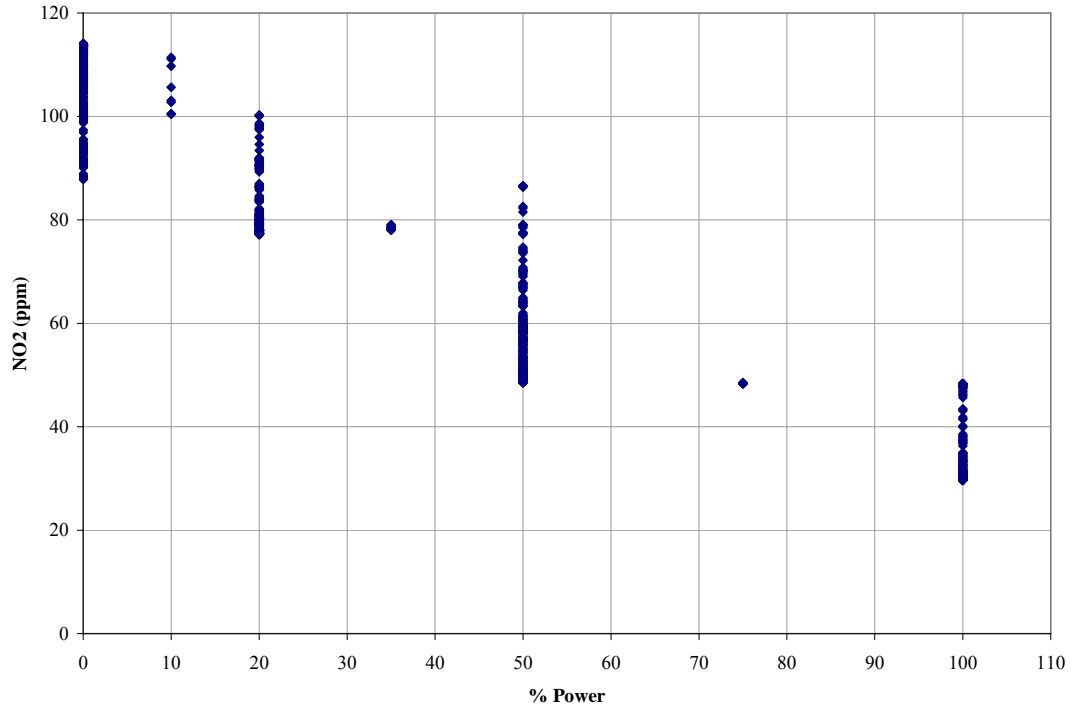


Figure 181: Nitrogen Dioxide (Emission Run Five: ppm Raw Data)

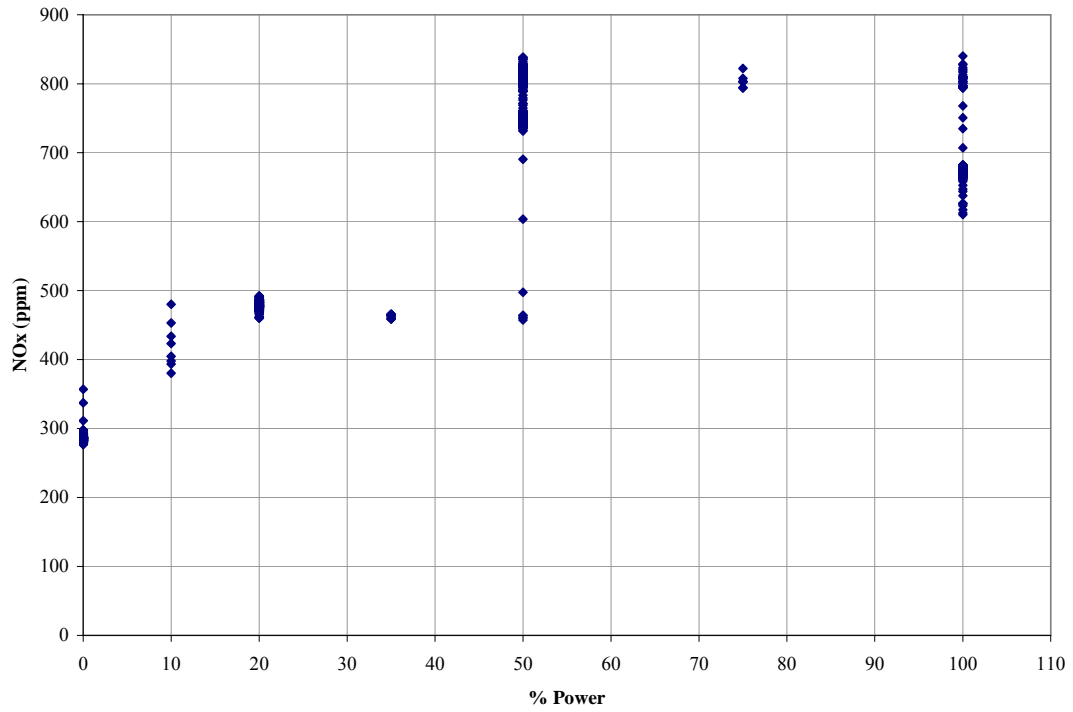


Figure 182: Nitrogen Oxides (Emission Run Five: ppm Raw Data)

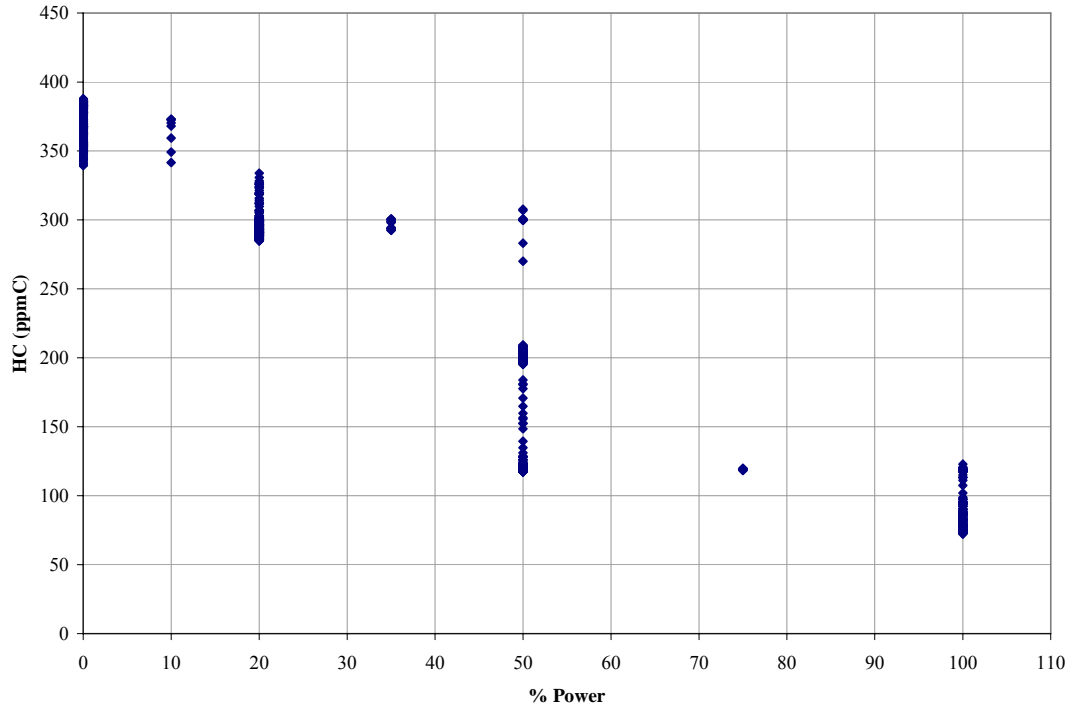


Figure 183: Hydrocarbon (Emission Run Five: ppmC Raw Data)

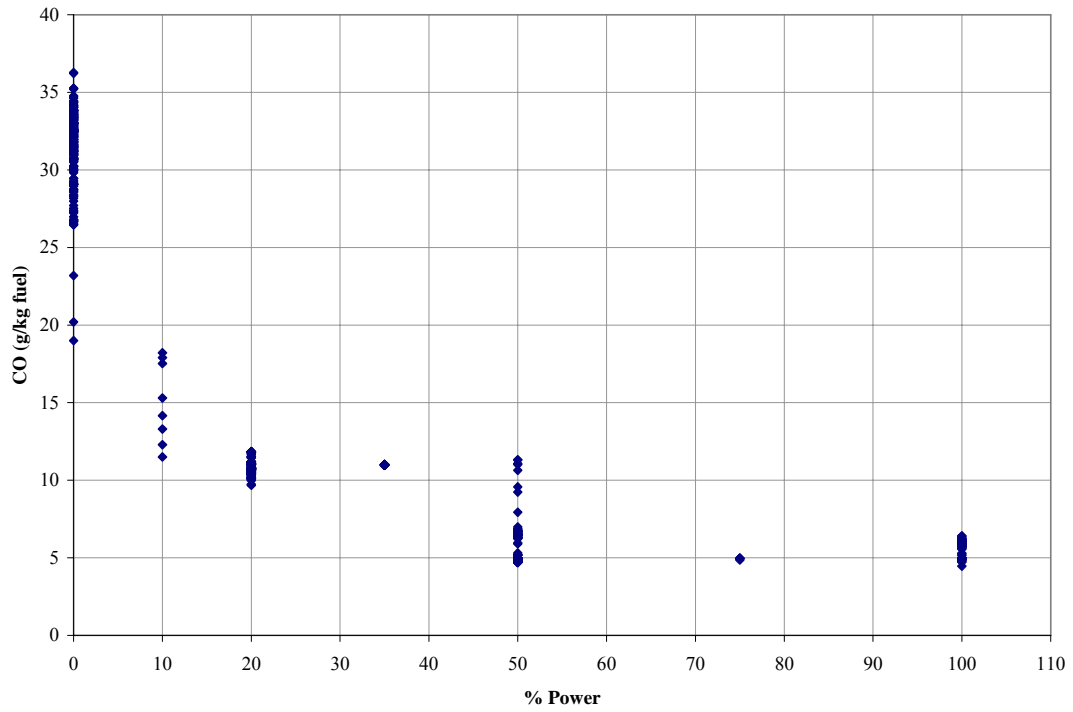


Figure 184: Carbon Monoxide (Emission Run Five: Mass Raw Data)

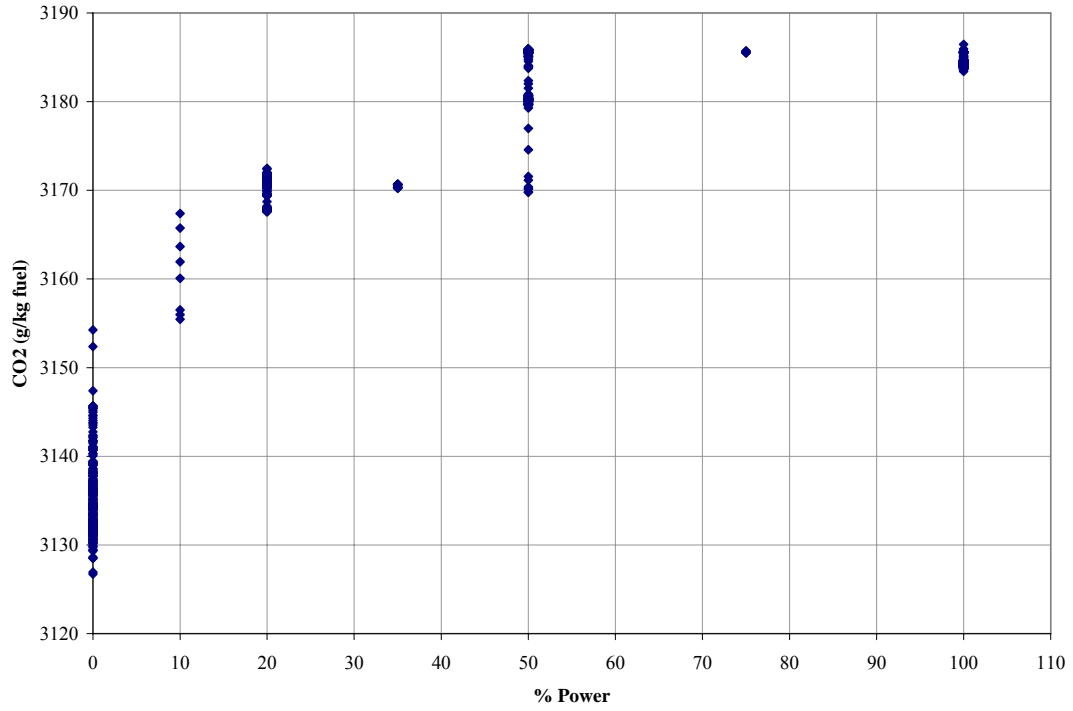


Figure 185: Carbon Dioxide (Emission Run Five: Mass Raw Data)

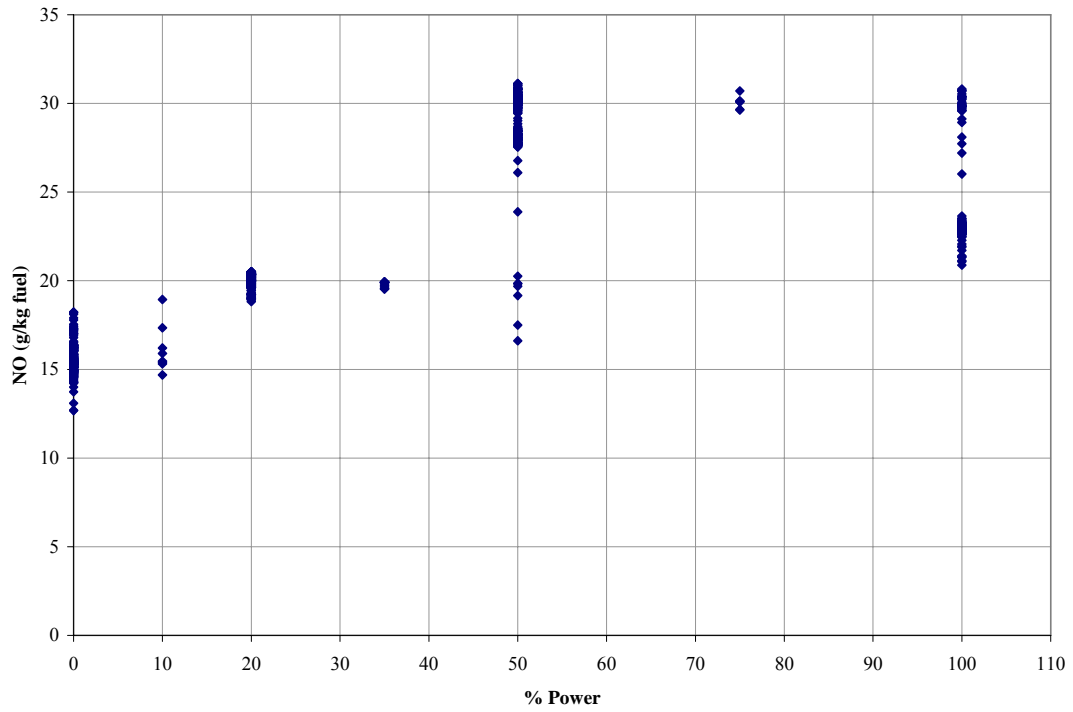


Figure 186: Nitric Oxide (Emission Run Five: Mass Raw Data)

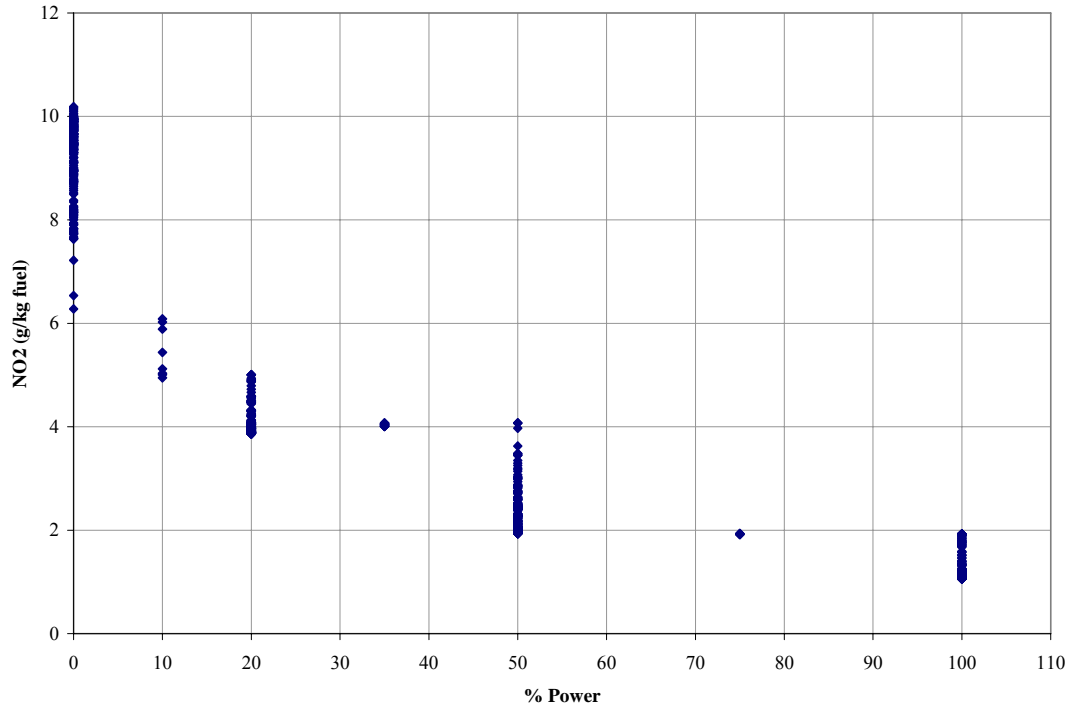
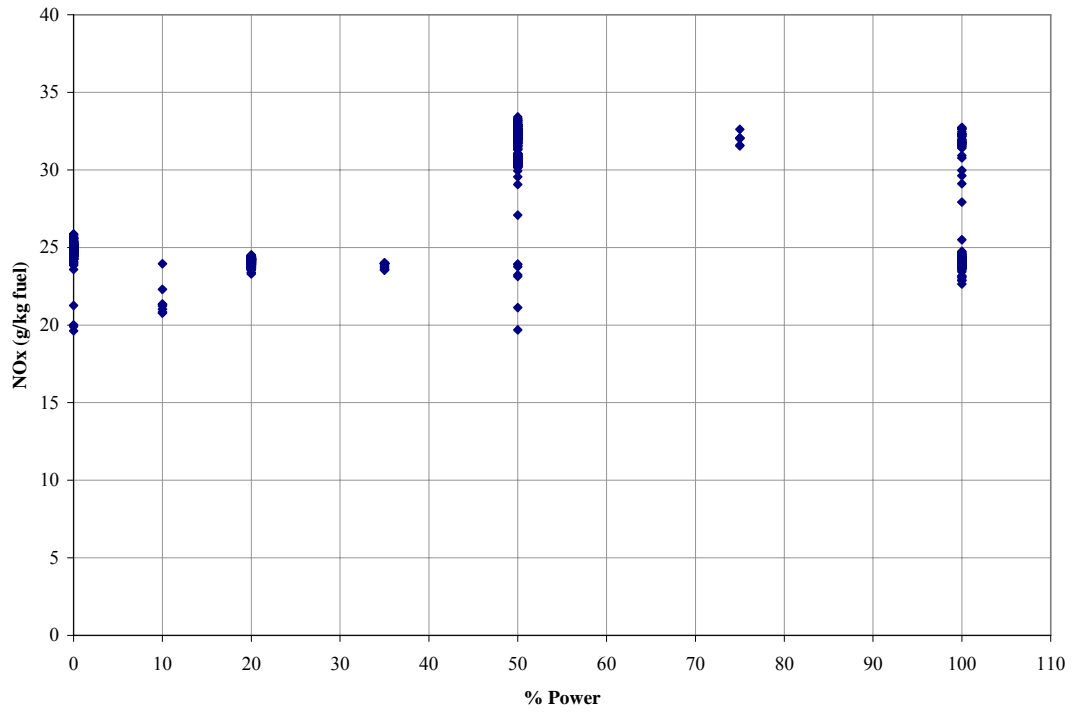


Figure 187: Nitrogen Dioxide (Emission Run Five: Mass Raw Data)



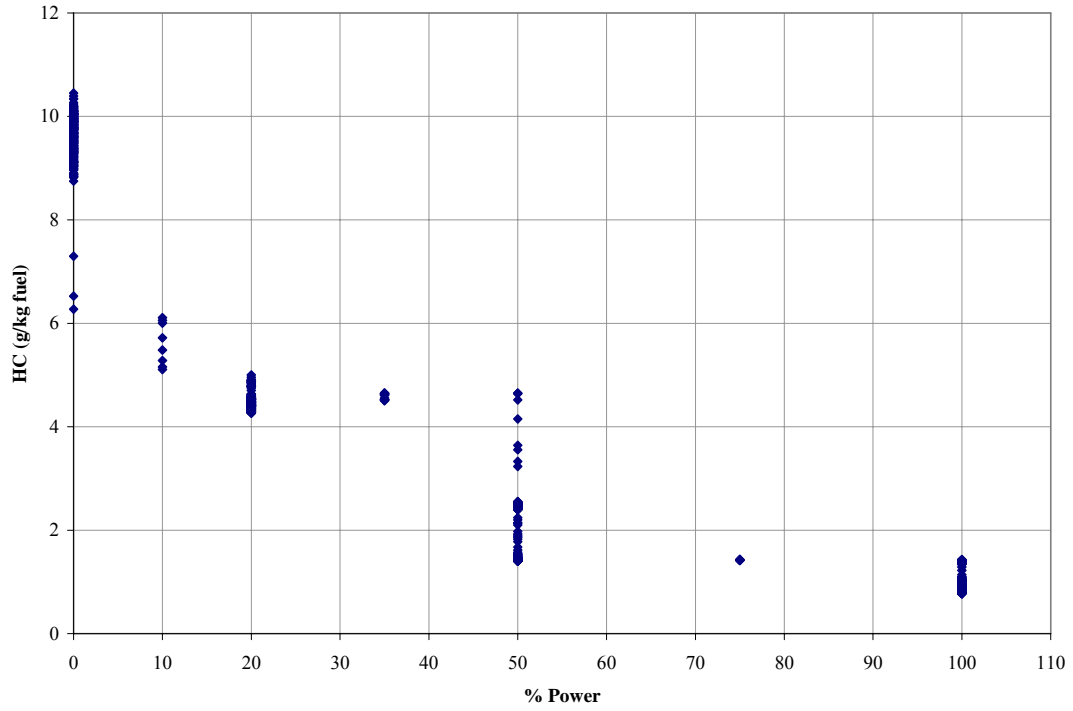


Figure 189: Hydrocarbon (Emission Run Five: Mass Raw Data)

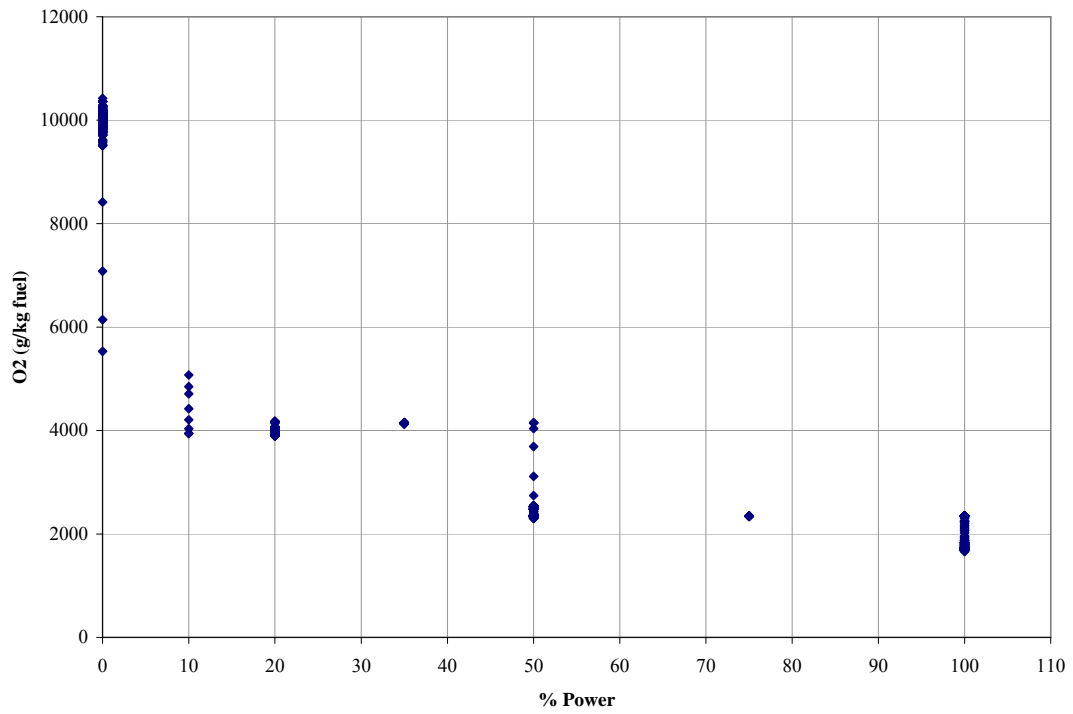


Figure 190: Oxygen (Emission Run Five: Mass Raw Data)

Table LX: Engine Parameters (Emission Run Five)

	CED Load	Engine	Prop	Fuel Flow	Exhaust Temperature	AFRs	AFR	Lambda
	<i>%</i>	<i>RPM</i>	<i>RPM</i>	<i>l/hr</i>	<i>deg C</i>	<i>~</i>	<i>~</i>	<i>~</i>
Idle	0	1504.08	889.67	1.62	155.46	14.50	53.63	3.70
High Idle	20	2401.24	1421.23	6.47	264.70	14.50	30.60	2.11
Cruise	50	3000.61	1774.99	14.65	378.78	14.50	24.43	1.68
Max	100	3621.40	2142.87	25.76	493.98	14.50	21.88	1.51

Table LXI: Emission Data (Emission Run Five: % and PPM)

CED Load	CO2	CO	O2	H2O	NO	NO2	NOx	HC
<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>ppm</i>	<i>ppm</i>	<i>ppm</i>	<i>ppmC</i>
0	3.78	0.06	16.48	3.62	178.89	106.63	285.52	368.52
20	6.60	0.04	11.42	6.13	398.26	80.90	479.17	296.51
50	8.25	0.02	8.70	7.59	718.04	58.29	776.32	161.56
100	9.18	0.03	7.17	8.42	653.31	34.54	687.85	85.38

Table LXII: Emission Data (Emission Run Five: Mass)

CED Load	CO2	CO	NO	NO2	NOx	HC	O2
<i>%</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>
0	3135.52	31.65	15.55	9.28	24.83	9.62	9958.92
20	3170.64	10.82	20.02	4.07	24.09	4.47	3984.80
50	3182.78	5.77	28.97	2.36	31.33	1.97	2448.71
100	3184.42	5.83	23.81	1.26	25.08	0.94	1816.07

Appendix M: Engine Emission Data - Investigation VI
 (February 15, 2008)

Table LXIII: Atmospheric Condition (Emission Run Six)

Local Temperature	0 °C or 32 °F
Local Barometric Pressure	30.39 inHg

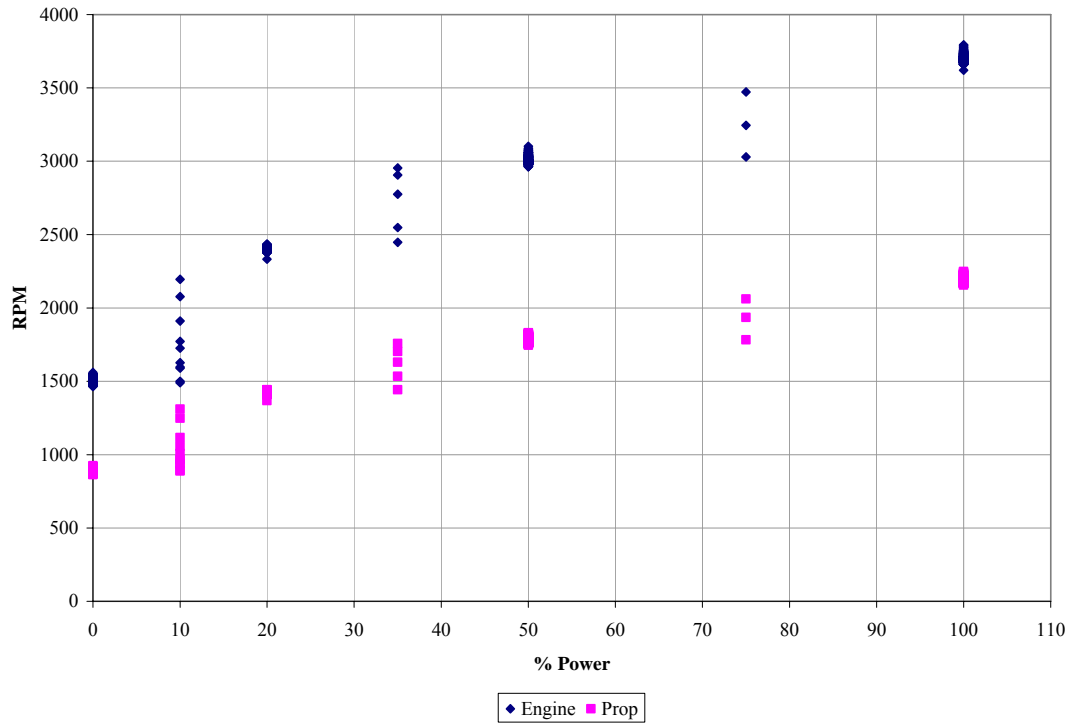


Figure 191: Engine/Prop RPM Data (Emission Run Six: Raw Data)

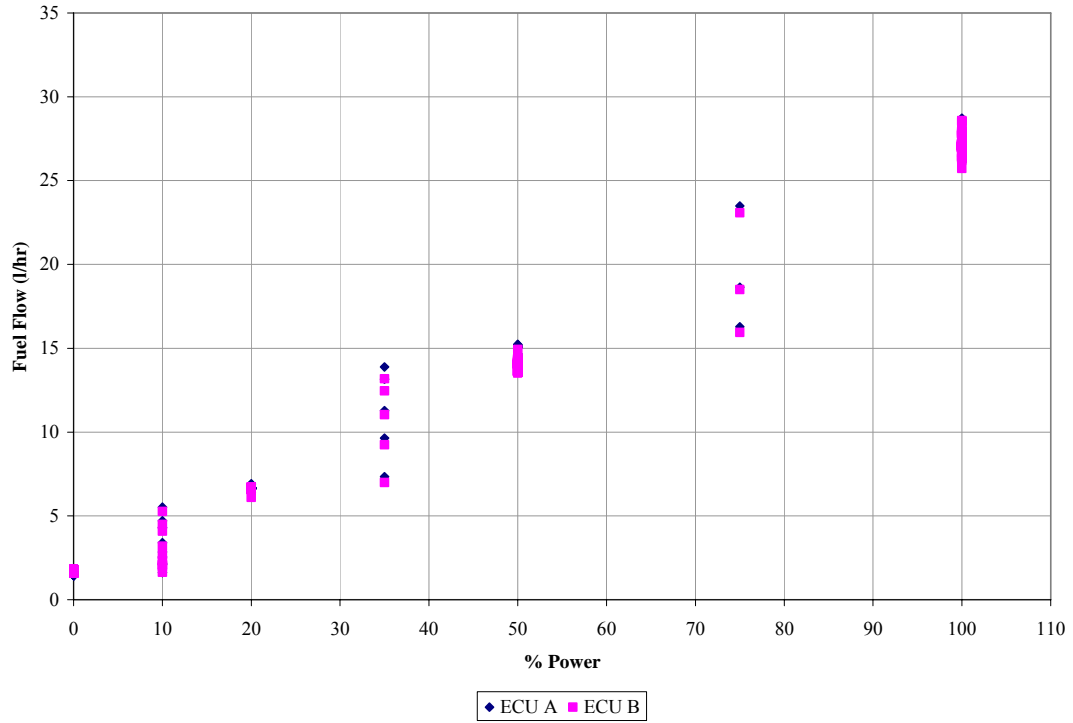


Figure 192: Fuel Flow (Emission Run Six: Raw Data)

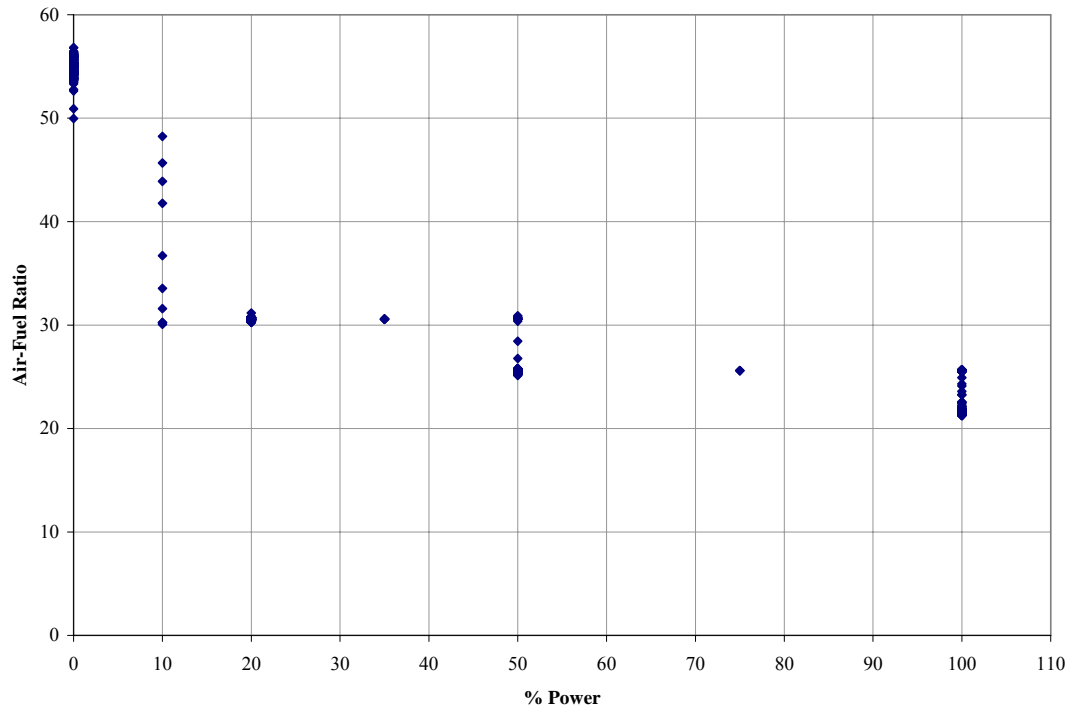


Figure 193: Air-Fuel Ratio (Emission Run Six: Raw Data)

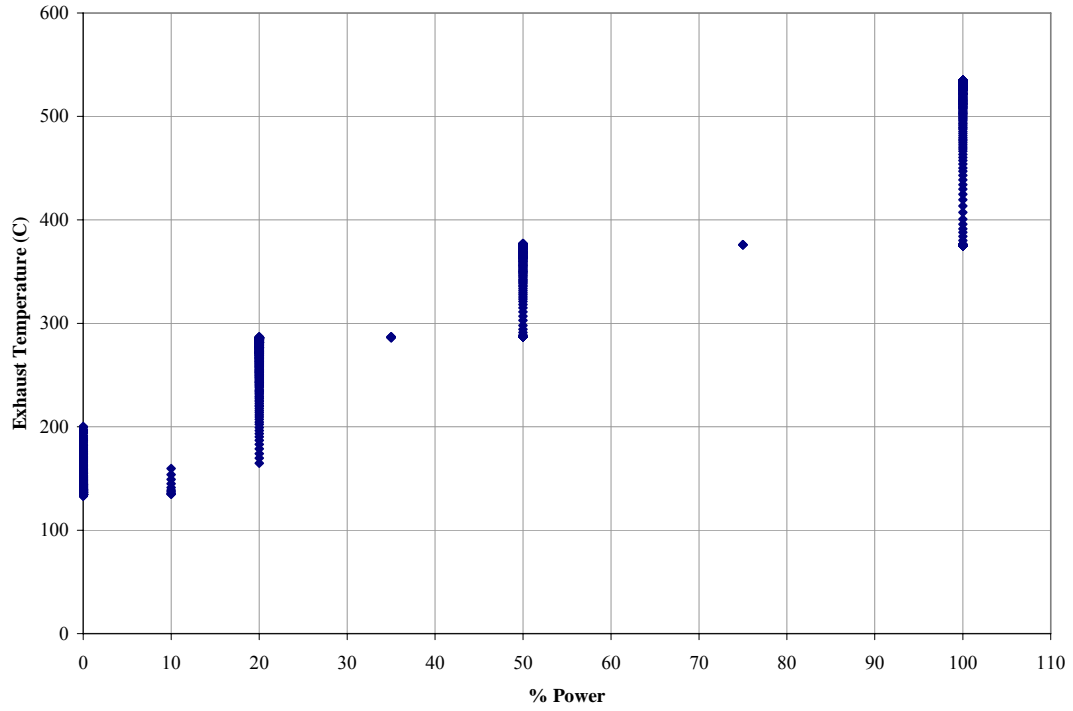


Figure 194: Exhaust Temperature (Emission Run Six: Raw Data)

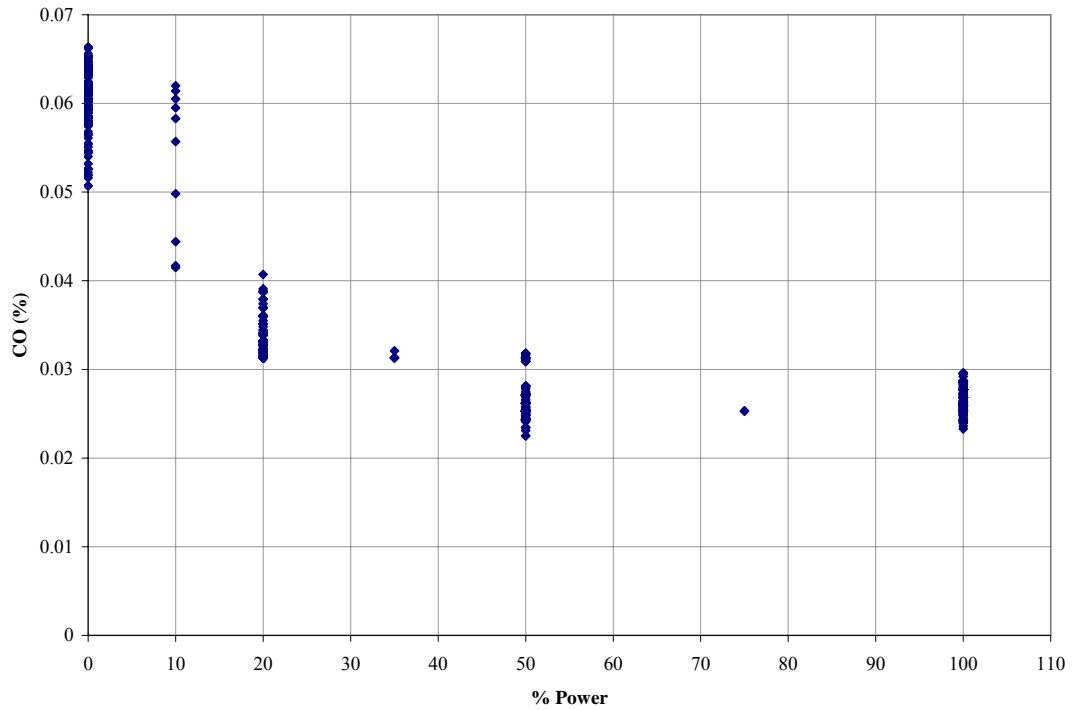


Figure 195: Carbon Monoxide (Emission Run Six: % Raw Data)

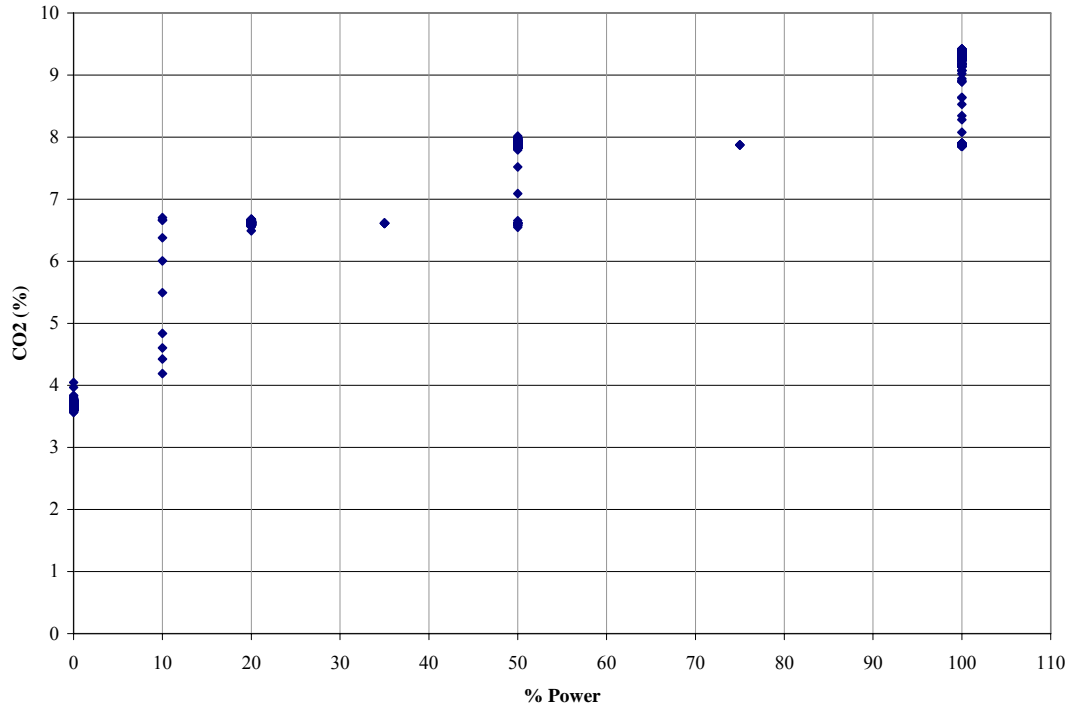


Figure 196: Carbon Dioxide (Emission Run Six: % Raw Data)

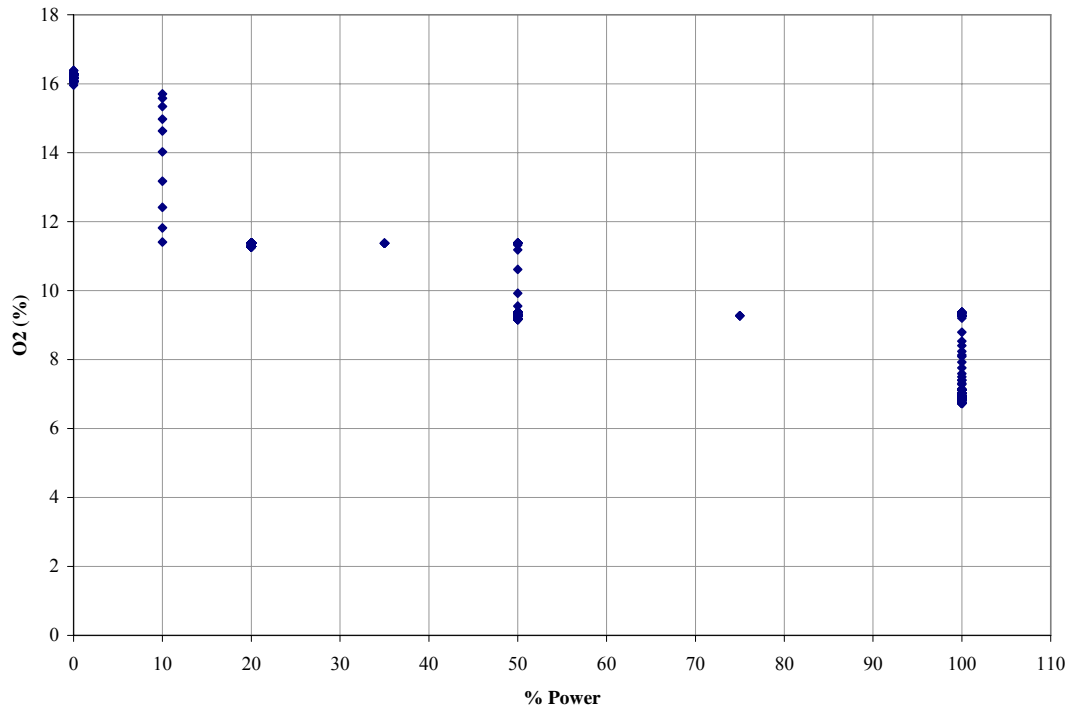


Figure 197: Oxygen (Emission Run Six: % Raw Data)

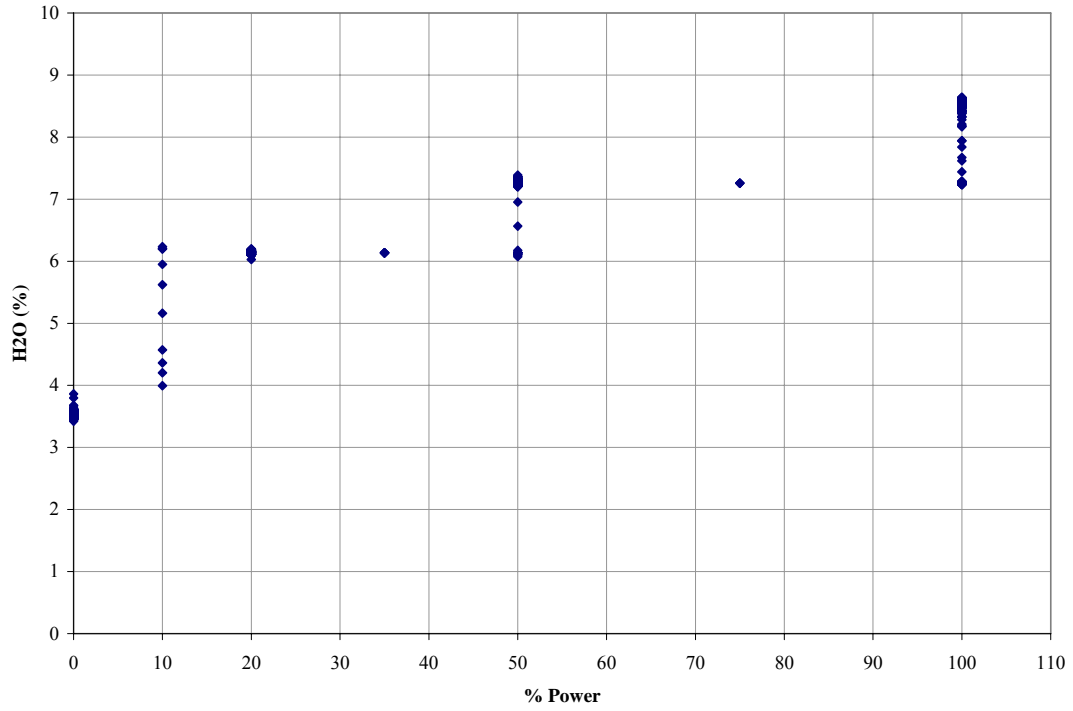


Figure 198: Water Vapor (Emission Run Six: % Raw Data)

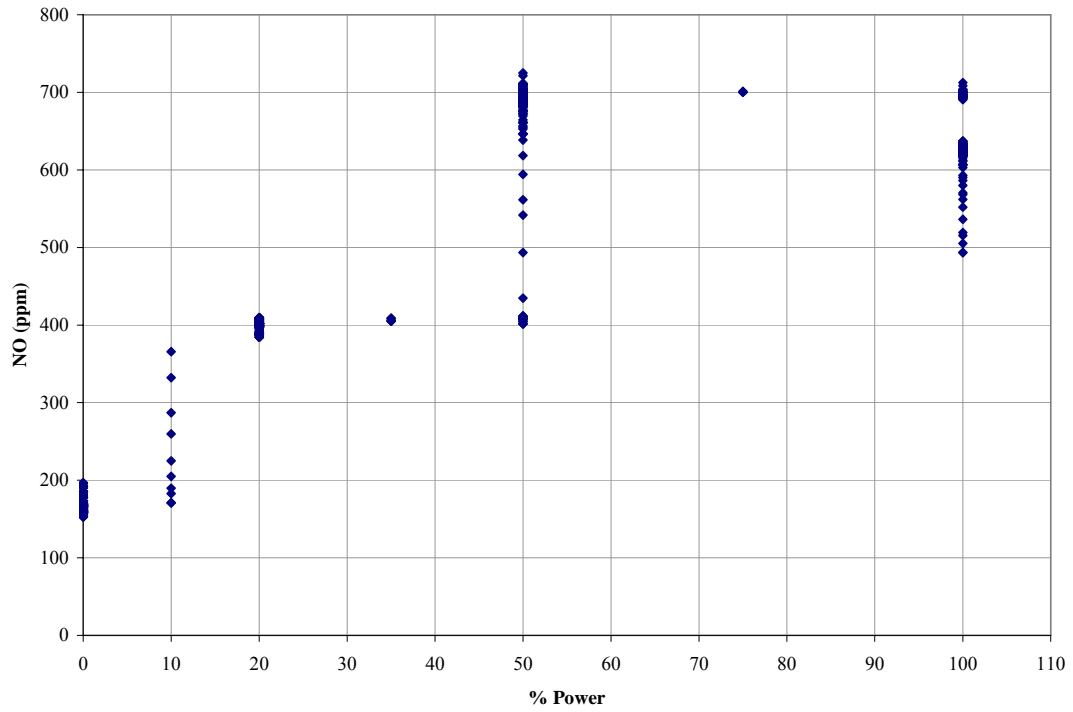


Figure 199: Nitric Oxide (Emission Run Six: ppm Raw Data)

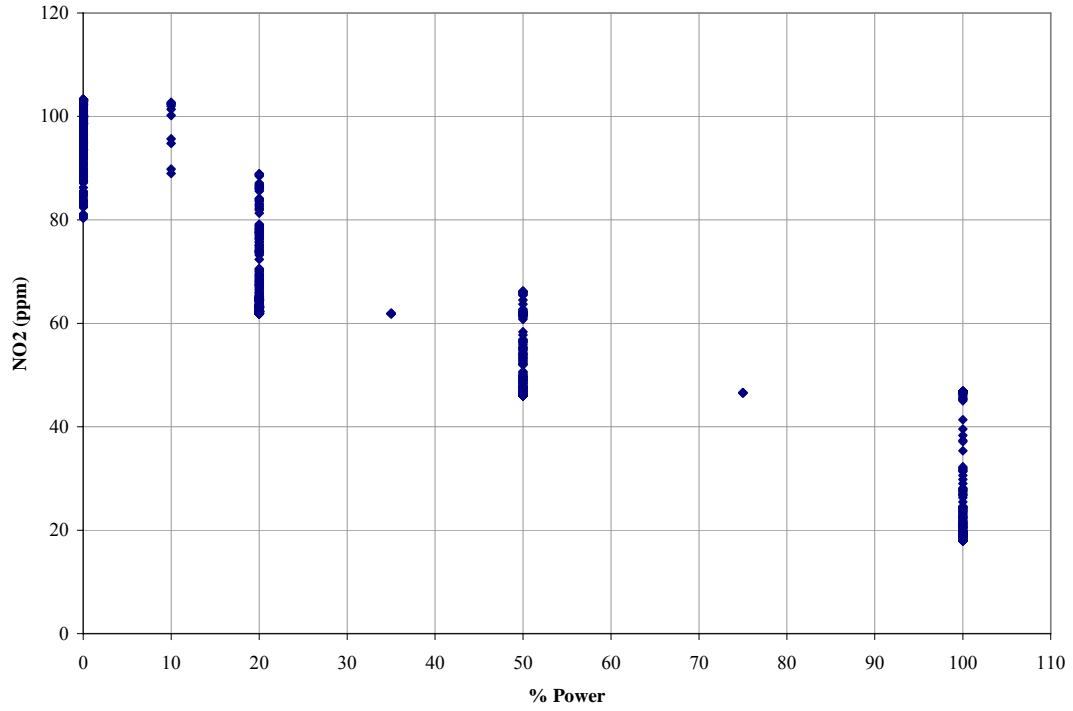


Figure 200: Nitrogen Dioxide (Emission Run Six: ppm Raw Data)

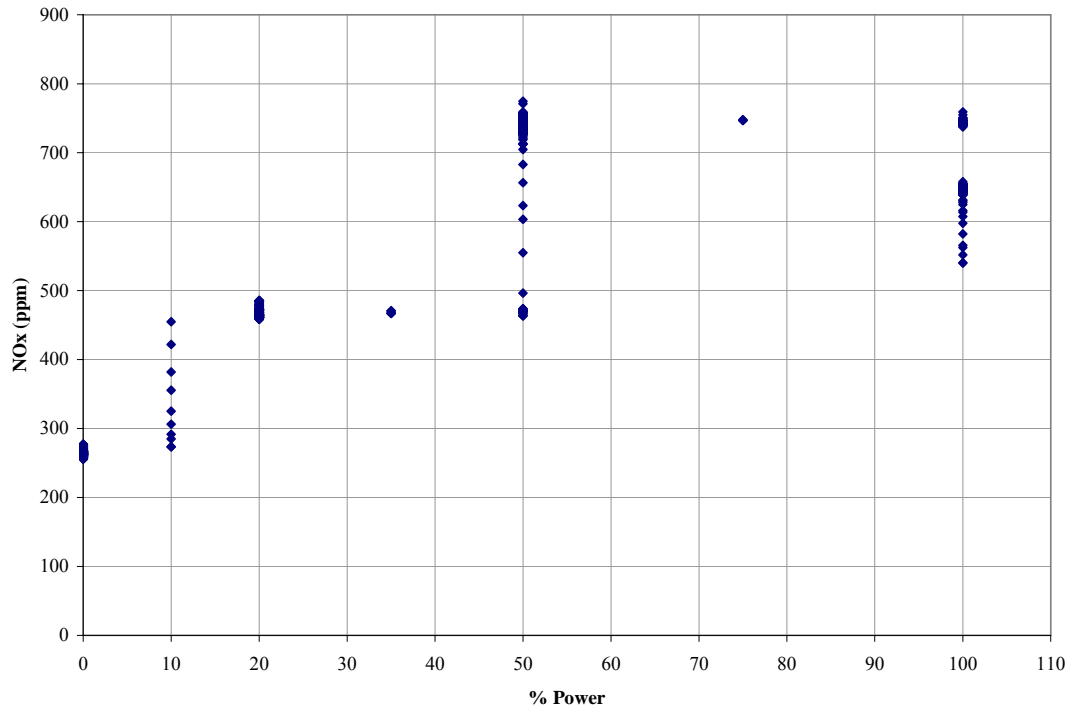


Figure 201: Nitrogen Oxides (Emission Run Six: ppm Raw Data)

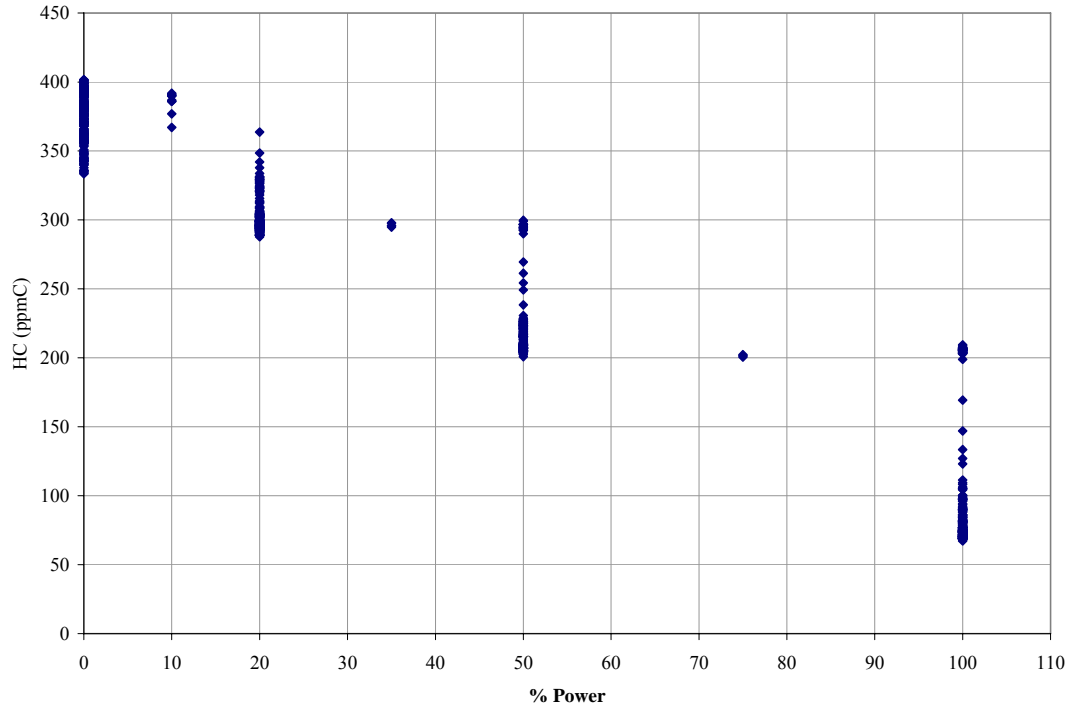


Figure 202: Hydrocarbon (Emission Run Six: ppmC Raw Data)

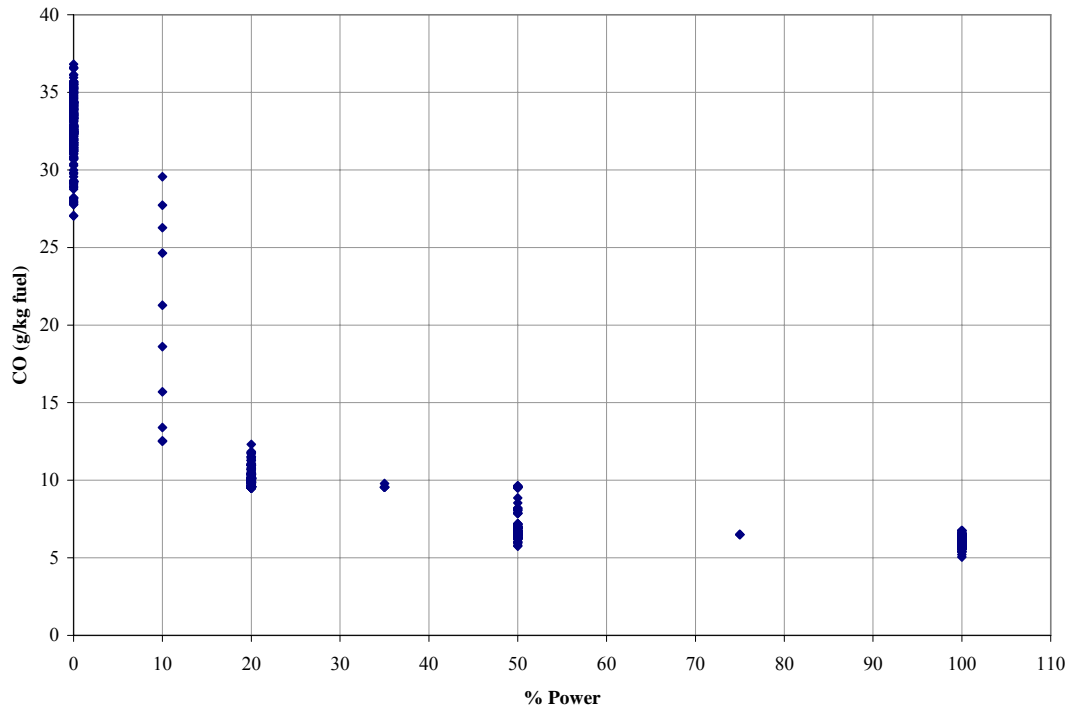


Figure 203: Carbon Monoxide (Emission Run Six: Mass Raw Data)

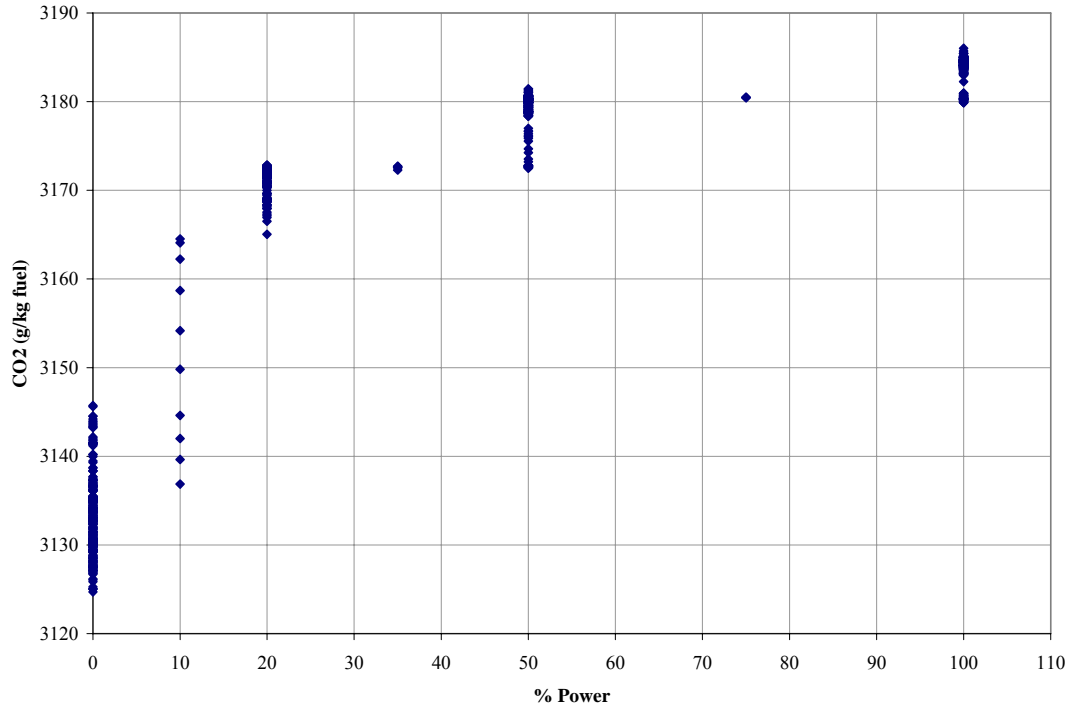


Figure 204: Carbon Dioxide (Emission Run Six: Mass Raw Data)

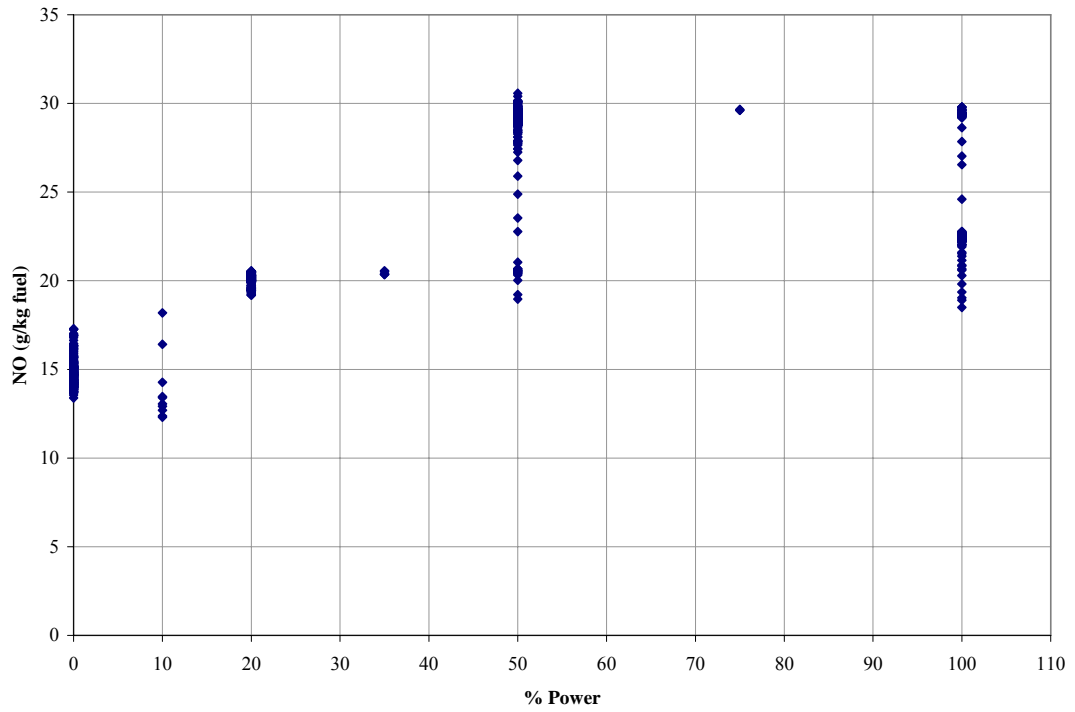


Figure 205: Nitric Oxide (Emission Run Six: Mass Raw Data)

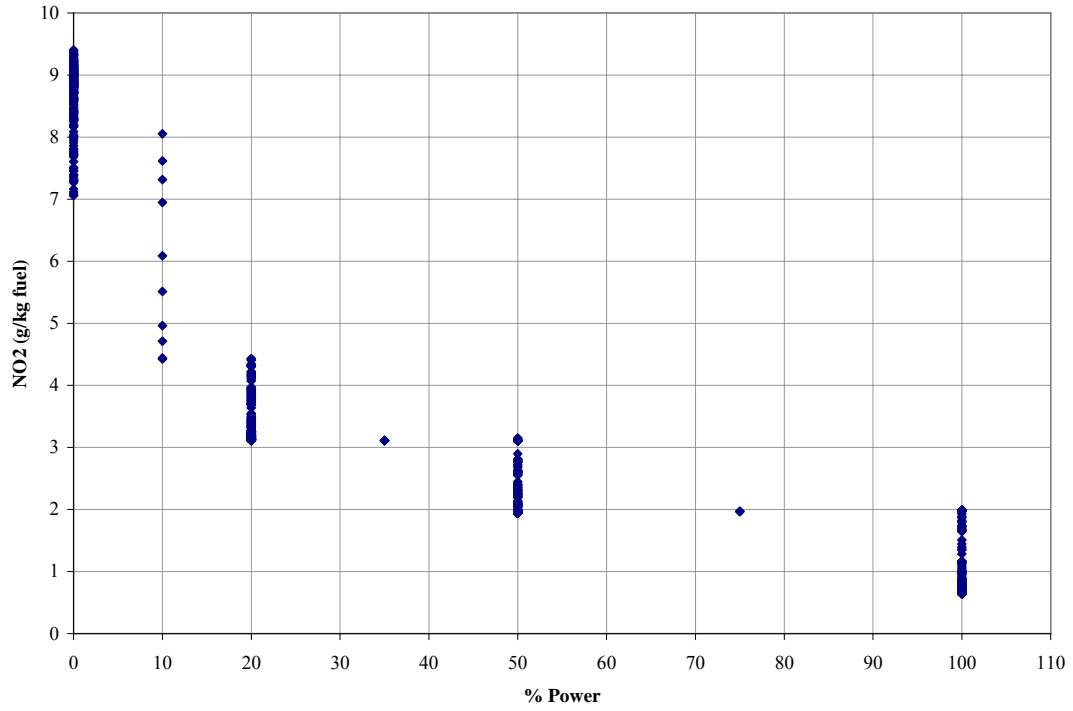


Figure 206: Nitrogen Dioxide (Emission Run Six: Mass Raw Data)

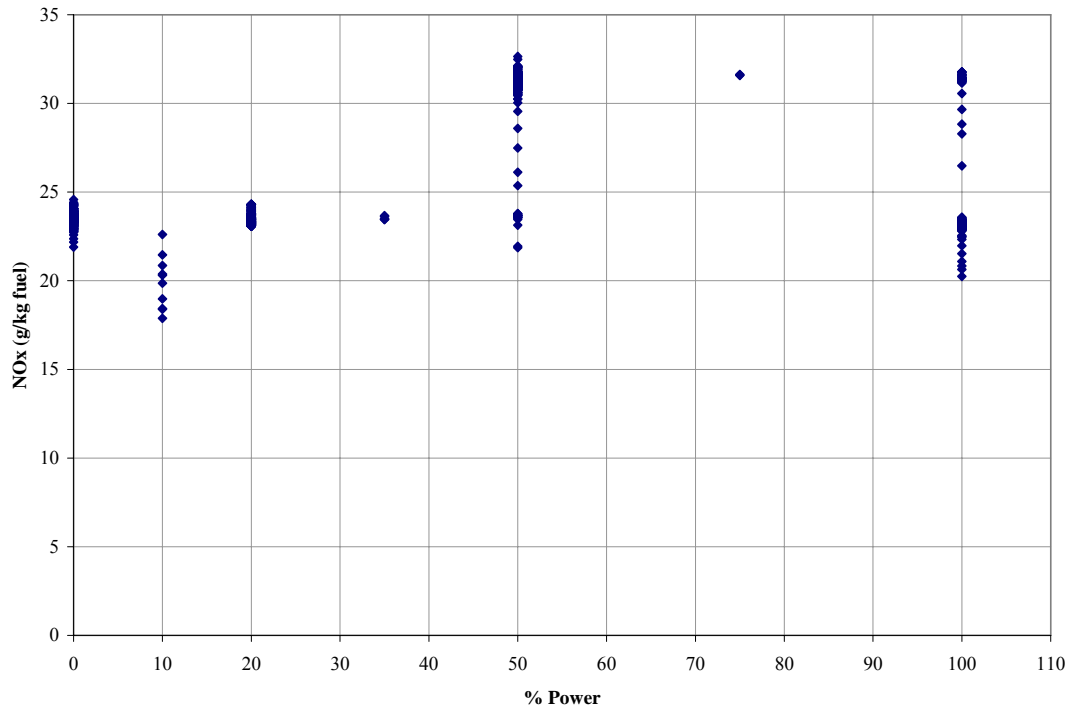


Figure 207: Nitrogen Oxides (Emission Run Six: Mass Raw Data)

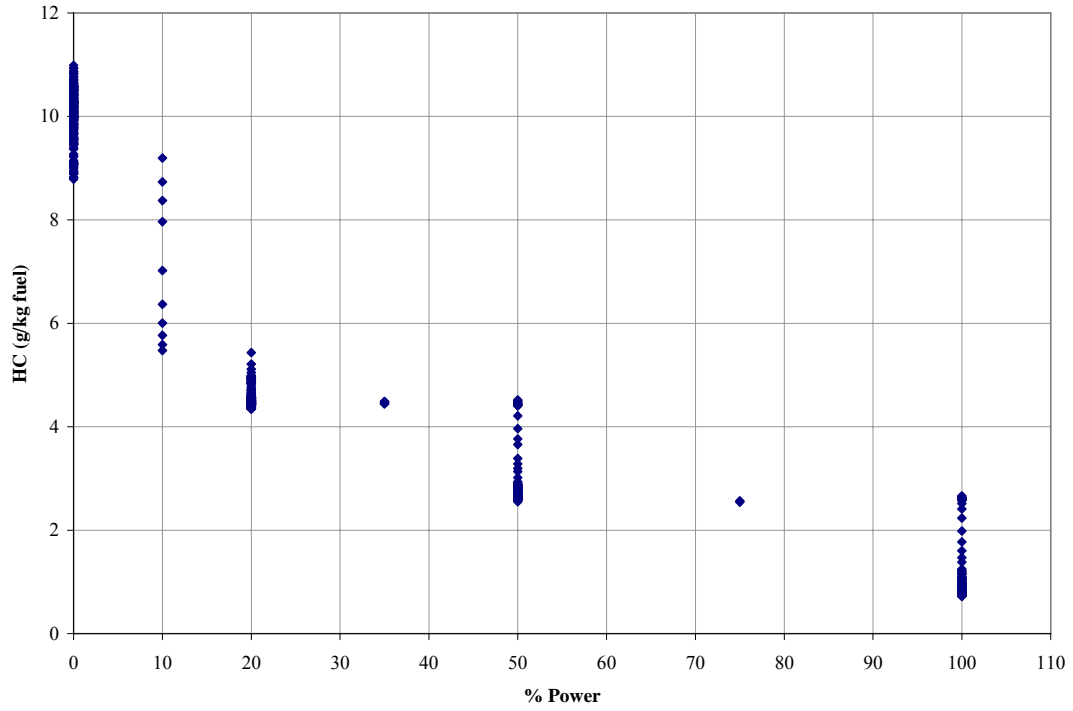


Figure 208: Hydrocarbon (Emission Run Six: Mass Raw Data)

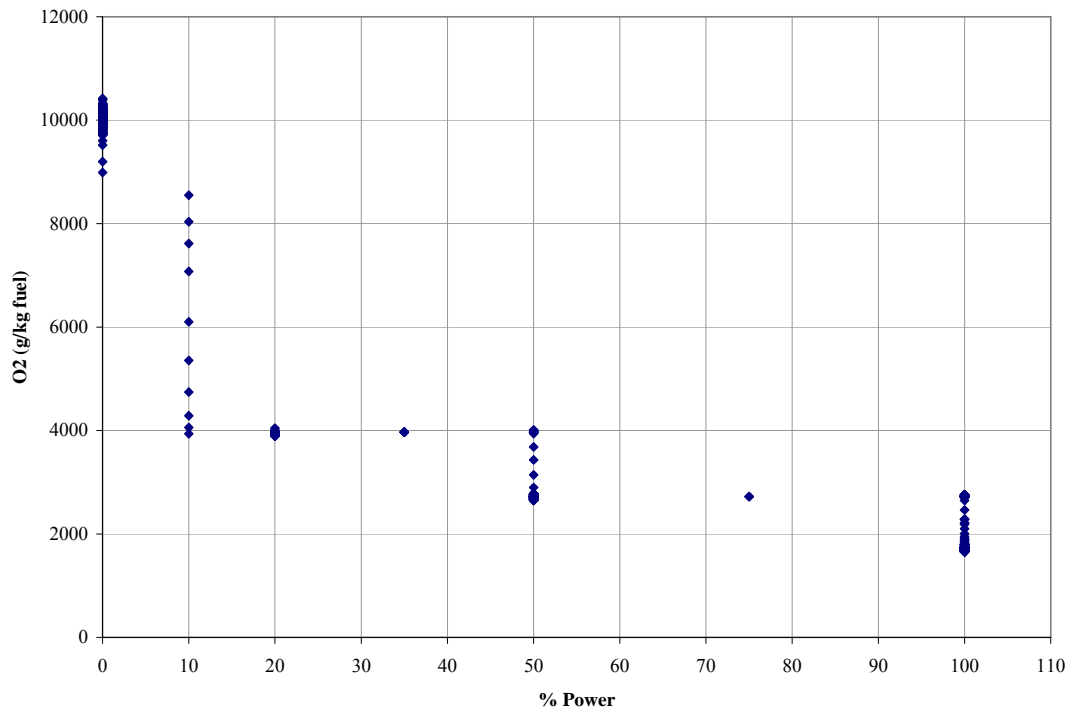


Figure 209: Oxygen (Emission Run Six: Mass Raw Data)

Table LXIV: Engine Parameters (Emission Run Six)

	CED Load	Engine	Prop	Fuel Flow	Exhaust Temperature	AFRs	AFR	Lambda
	<i>%</i>	<i>RPM</i>	<i>RPM</i>	<i>l/hr</i>	<i>deg C</i>	<i>~</i>	<i>~</i>	<i>~</i>
Idle	0	1506.29	891.24	1.60	147.82	14.50	54.93	3.79
High Idle	20	2404.99	1423.63	6.64	267.45	14.50	30.58	2.11
Cruise	50	3006.80	1779.81	14.22	362.48	14.50	25.83	1.78
Max	100	3700.34	2190.38	27.12	495.49	14.50	22.12	1.53

Table LXV: Emission Data (Emission Run Six: % and PPM)

CED Load	CO2	CO	O2	H2O	NO	NO2	NOx	HC
<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>%</i>	<i>ppm</i>	<i>ppm</i>	<i>ppm</i>	<i>ppmC</i>
0	3.68	0.06	16.20	3.54	166.39	97.66	264.05	375.85
20	6.61	0.03	11.35	6.14	400.12	67.08	467.19	301.52
50	7.81	0.03	9.39	7.21	672.60	49.97	722.56	218.60
100	9.10	0.03	7.27	8.35	633.10	25.61	658.71	96.47

Table LXVI: Emission Data (Emission Run Six: Mass)

CED Load	CO2	CO	NO	NO2	NOx	HC	O2
<i>%</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>	<i>g/kg fuel</i>
0	3133.20	32.77	14.82	8.70	23.52	10.04	10016.41
20	3171.58	10.06	20.10	3.37	23.47	4.54	3958.91
50	3179.32	6.82	28.58	2.14	30.72	2.81	2789.70
100	3183.79	6.01	23.33	0.96	24.29	1.09	1868.28