# Effects of Injection Timing on Exhaust Emissions of a Fuel Injected Spark Ignition Engine

**University of Michigan-Dearborn and NSF/REU Program**


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# *Table of Contents*

## *Abstract*

The purpose of this experiment was to observe the effects of changing various engine parameters, most importantly injection timing, on emissions (hydrocarbons, carbon monoxide, and nitrogen oxides) and thermal efficiency. The engine used was a Ford 1.6L four-cylinder DOHC multipoint port injected engine, modified to run on one cylinder. The equivalence ratio was set at 0.8 and 1 to represent stoichiometric and typical lean conditions. The lean equivalence ratio emitted significantly less specific emissions (SE) than the stoichiometric equivalence ratio. The engine was tested at loads of 200 kPa and 400 kPa. Carbon monoxide and hydrocarbon emissions improved when the load was increased because of the higher temperatures associated with a high load condition. Load's effect on NOx emissions was significant, but varied according to other variables. Engine speed had a varied effect on emissions. At low loads, as engine speed increased the NOx SE also increased due to the higher temperatures. At high load, this effect of changing engine speeds was minimal. Carbon monoxide specific emissions increased as the engine speed was increased from 1500 RPM to 2100 RPM because of a decrease in time for chemical reactions to take place. In contrast, engine speed had the opposite effect on hydrocarbon specific emissions because of the higher temperatures at 2100 RPM. Injection timing affected the hydrocarbon and carbon monoxide SE but did not affect NOx SE. Closed valve injection (CVI) timing generally resulted in a decrease in carbon monoxide and hydrocarbon SE over open valve injection (OVI) timing, with greater effects at low load and low engine speed. Thermal efficiency was affected by load, engine speed, and (to a lesser extent) injection timing. Higher load caused the thermal efficiency to increase, while higher engine speed caused it to decrease. CVI timing had a small positive effect on thermal efficiency at low speed over OVI timing.

# *Introduction and Background*

Hydrocarbons are formed by five modes: incomplete combustion, flame quenching, crevice volume, absorption of fuel vapor, and equivalence ratio. Incomplete combustion normally occurs during the expansion stroke, when the cylinder pressure drops therefore causing the unburned gas temperature to drop. This temperature drop causes a decrease in the burn rate. Flame quenching can be attributed to the relatively cold walls of the cylinder. The cooler walls form a boundary layer where the flame cannot penetrate, hence leaving some unburned HC molecules. Crevice volumes, such as the area between the piston and cylinder wall, can once again trap hydrocarbons in a region where the flame cannot enter. The absorption of fuel vapor into the thin oil layer occurs during the compression stroke. Once the pressure gets to a certain level, the fuel vapor can be absorbed into the oil layer. Upon expansion, the fuel vapors containing unburned HC are emitted from the oil layer and exit out through the exhaust. Hydrocarbons are also known to be sensitive to the equivalence ratio,$\phi$. When $\phi$ is greater than one, the fuel is rich and consequently HC emissions are high, conversely when $\phi$ is less than one, the fuel is lean and the HC emissions drop down (see Figure 14). It should be noted that with lean burning, HC emissions will be low as long as the combustion quality does not become poor, in which case HC emissions rise sharply due to incomplete combustion [1]. In general, HC emissions range from 1000-3000 ppm from an SI engine [1].

Carbon monoxide formation is mainly a function of the equivalence ratio. Similar to hydrocarbon formation, CO emissions will increase with a rich fuel mixture, and decrease with a lean fuel mixture (see Figure 14 in the appendix)[1]. The CO is formed when there is not enough oxygen present to form $CO_2$. Therefore, poor mixing and incomplete combustion also play a factor in increasing CO emissions [2]. Normally, CO emissions range from 0.2% to 5% in the exhaust of an SI engine[2].

The formation of oxides of nitrogen are caused mostly by high temperatures and large oxygen concentrations in the combustion chamber. The high temperatures cause the nitrogen to dissociate, and $NO/NO_2$ to form if there is oxygen present [2]. The main engine parameters that will then influence NOx production are spark timing, equivalence ratio, and EGR. Spark timing closer to TDC causes lower peak cylinder pressure [1]. These lower pressures cause lower cylinder temperatures, which reduce NOx emissions. Retarding spark timing has the opposite effect.

Equivalence ratio affects both oxygen content and temperature. Maximum temperature occurs at an equivalence ratio of 1.1, but oxygen concentration decreases as equivalence ratio rises, and is too low at $\phi$=1.1. The maximum amount of NOx emissions has been empirically found to be at approximately $\phi$=0.9 [1]. This is illustrated in Figure 14. Finally, exhaust gas recirculation has a very noticeable effect on NOx emissions. The already burned gases act as a diluent, and the temperature reached after combustion goes down as burned gas mass fraction goes up[1]. Therefore, as is shown in Figure 15, increasing the burned gas mass fraction through EGR causes NOx emissions to drop until combustion quality becomes poor. Also worthy of note is the fact that NO emissions far exceed $NO_2$ emissions in SI engines, and the $NO_2$ emissions are often neglected.

Now that it is known how the emissions are formed, the engine parameters were looked at to see how they affect the emission formation. As previously explained, the equivalence ratio has an effect on all three types of emissions. However, there are other engine parameters that affect the emissions.

Load, for instance has a large influence on NOx formations when running lean. As load increases, the NOx emissions will consequently increase. However, when the engine runs near stoichiometric air to fuel ratio, the effect of load becomes less significant. Tests have shown a moderate change of NOx emissions as load increased when $\phi$=1 [7]. It is important to note that the load has little effect on the molar percentage of HC in the exhaust when the speed and $\phi$ is fixed. Much of the HC emissions come from crevice volumes. For instance, if the load is increased then the pressure will increase. The amount of unburned HC molecules in the crevices will increase proportionally with the pressure, therefore having no effect on the overall percentage of unburned fuel [6].

Spark timing also has an effect on emissions. As mentioned above, NOx emissions are very dependent on the spark timing. Hydrocarbon emissions also change if a deviation from MBT timing is encountered[1]. As long as MBT timing is maintained, hydrocarbon emissions remain roughly constant. However, if spark timing deviates from MBT, combustion may not be as complete, causing more HC emission. Temperatures will also change, changing the amount of oxidation in the cylinder as well as in the exhaust, affecting the amount of HC that gets transported out of the exhaust. Spark timing has shown no significant effects on CO emissions.

Numerous tests have shown that the speed of the engine can affect the HC emissions [4,6]. These tests have shown that the HC emissions should decrease as the RPM increases. One theory is that when the engine runs at high speeds, there is not enough time for the HC to emanate from crevices. One recorded test shows that HC emissions dropped 20%-50% when the speed was increased from 1000 to 2000RPM[7]. Another factor is that the temperature increases therefore burning more HC and causing the HC emissions to decrease. This can also affect many aspects of emissions such as HC oxidation and NOx formation. However, higher speed also gives less time for NOx to form and increases the burned gas mass fraction, which will in many cases offset the higher temperatures, so engine speed may play a role in increasing or decreasing NOx emissions, depending on the exact conditions.

Injection timing has also shown the ability to affect the emission, especially HC, in an SI engine. There has been a fair amount of research done on this subject, however some is contradictory. The effects of injection timing seem to be very dependent of the geometrical facets of the system, such as the shape of the intake port and the angle of the injector spray; hence different setups correspond to different results. Many of the newer results have stated that closed valve injection (CVI) timing emits significantly less hydrocarbon emissions than open valve (OVI) timing [3-4,8]. This difference can be attributed to the different modes of fuel transport into the cylinder. For OVI timing, transport is dominated by direct fuel transport into the cylinder [3]. Direct fuel transport implies that the injector sprays the fuel directly into the cylinder. Depending on geometry and operating conditions, fuel can be deposited directly onto the wall in the form of a film on the cylinder liner [4]. This can have many effects. Firstly, the piston will push the fuel film and trap it in various crevices, most notably in the gap between the cylinder wall and piston. Secondly, more of the fuel will be inside the flame quench boundary layer, and will not get burned [4]. Third, this can make the in-cylinder A/F mixture less homogeneous, with a higher fuel concentration near the exhaust side cylinder wall. This, in turn, can lead to incomplete combustion. Direct fuel transport also tends to involve a higher number of fuel droplets [8]. This has been shown to decrease combustion quality, therefore increasing HC emission. The droplets are smaller than with CVI, but droplet size seems to have only small effects on emissions while the engine is warmed up [5]. Although OVI timing is dominated by direct transport, some of the fuel is deposited on the port wall (how much being dependent on manifold/port geometry), and then that fuel is governed by the same transport process as CVI timing. The CVI timing fuel transport process is called film atomization [5]. When the valve is closed, the fuel is sprayed directly against the intake port and valve. A fuel film is formed on the intake port wall. The fuel that is sprayed onto the relatively hot intake valve will start to vaporize. The rest of the fuel will stay as a film on the port wall. Then, the intake valve is opened and a large velocity difference between the film layer and the air velocity causes the fuel to break up and atomize while being driven into the cylinder [3]. Therefore, unlike OVI timing, evaporation of the film ensures that the amount of liquid fuel entering the cylinders of warm engines during intake would be small [9,10]. The atomization helps to make the mixture homogeneous, therefore increasing combustion quality while decreasing HC emissions [8]. The CVI timing usually results in less liquid fuel forming a film on the cylinder wall, which would result in less HC emissions than OVI timing.

## *Project Objectives:*

The main objective of this project was to gain experience in the performance of research for a nationally accredited university, as well as to improve communication and presentation skills. This specific project's objective was to experimentally investigate steady-state spark-ignition engine efficiency and exhaust emissions under varying operating conditions. Specifically, the effects of varying the following parameters was analyzed:

- Fuel-injection timing
- Engine load
- Engine speed
- Equivalence ratio

# *Methodology*

## Experimental Setup

The experiment used a 1.6-liter DOHC Ford Escort multipoint port fuel-injected engine that was modified to run off of a single cylinder. The output shaft of the engine was connected directly to the input shaft of a water-brake dynamometer. An engine control module can independently control injection timing, spark timing, and injection pulse width. Emissions analyzers, a thermocouple, and a wideband oxygen sensor are set to sample exhaust gas just before the catalytic converter. The exhaust gas thermocouple was connected to a display that output the temperature directly in degrees Fahrenheit. The oxygen sensor outputted to a digital readout of A/F ratio. A fuel tank (with 87 octane unleaded gasoline) was connected in line with a 50 mL fill burette, which was then connected to the fuel pump of the engine. Finally, a sensor was attached to the camshaft, and outputted a pulse for each camshaft revolution to a counter timer.

## Measurement Methods

Engine load was measured from a load cell that is connected to the water-brake dynamometer. The load cell outputs a voltage that reads out on a multimeter. The voltage is directly proportional to load, with 29.87 mV signifying 50 lbs of load. This load was controlled by a valve controlling the amount of water flowing through the dynamometer, and was adjusted to values that correspond to 200 and 400 kPa before beginning the run. However, due to fluctuations inherent in IC engines and dynamometers the actual load was recorded at regular intervals so that a more accurate BMEP value could be known.

Fuel flow rate was obtained using the metered fill burette and a stopwatch. The burette was filled with exactly 50 milliliters of fuel, and a stopwatch was used to measure the time required for the engine to consume the fuel in the burette. With knowledge of the density of the fuel, these two measurements can be combined to obtain the fuel mass flow rate.

Engine speed measurements were found through the use of the counter-timer and a handheld contacting tachometer. The counter-timer would measure the frequency of camshaft revolutions. This frequency was then recorded, to later be converted to engine speed. This method was suspected to not be entirely reliable due to intermittent noise mingling with the signal, so a handheld contacting tachometer was also used once for each run to verify that the signal was outputting the correct frequency.

Exhaust gas temperature was measured by the thermocouple in the exhaust piping.. Equivalence ratio was measured using the wideband oxygen sensor. A/F ratio could then easily be converted to equivalence ratio.

There are three separate emissions analysis machines, one each for CO, HC, and NOx. The machines all show the mole fraction of their respective gas (once multiplied by the scale they are currently operating in). These readings are recorded in parts per million.

An engine control module with rotary dial knobs set the injection timing, ignition timing, and pulse width. The dials showed numbers zero through ten, which were calibrated to mean different timings/pulse widths. The ignition timings were pre-calibrated and charted, so the ignition timing was recorded directly off of the chart. The pulse widths were not recorded, since they are implied by the equivalence ratio. The injection timing knobs were calibrated before beginning experimental runs. This calibration was done by using an oscilloscope that showed the pulse from the camshaft and the pulse from the opening of the fuel injector. The pulse from the camshaft sensor comes when the piston is at top dead center. Using that fact, the injection of fuel was set to two settings. The first setting, 360 degrees BTC, corresponds to when the intake valve opens (OVI timing). The second setting, 95 degrees BTC, corresponds to the middle of the compression stroke (CVI timing). These timings were calibrated for both engine speeds, since they were found to change with engine speed. These dial positions are shown in Figure 17.

**Setup Procedures**

To set up the experiment each day, a set of initial procedures was implemented. Since water molecules can condense inside the HC analyzer and consequently clog the tubing, the water molecules must be somehow removed from the exhaust gas. To accomplish this, the gas was passed through a cold chamber, forcing the water molecules to condense on the wall of the chamber. This process rids the exhaust gas of the water molecules. To keep the chamber at operating temperature, each day ice was placed into a bucket that surrounded the chamber. Next, given that the engine only runs on a single cylinder, the use of the alternator would take away a large portion of power produced by the engine. Hence, an alternator was not used and the battery was supplied with a charge via a battery charger that needed to be hooked up at the start of each day.

The emissions analyzers also needed to be calibrated at the start of the experiment. The analyzers needed two references, a *zero* and a *span*, to be properly calibrated. Since none of the analyzers detect nitrogen, pure nitrogen gas was passed through each of the emission analyzers as the zero gas. To calibrate the span for CO, premixed 0.995% CO gas was passed through the analyzer. The analyzer was then checked to make sure that it read roughly 1% CO. To calibrate the span for HC, premixed 1012 ppm HC gas was passed through the analyzer. The analyzer was again checked to make sure it had the proper reading. To calibrate the span for NOx, premixed 1005 ppm NOx gas was passed through the analyzer and checked. Finally, various other miscellaneous tasks were also performed, such as turning on the water for the dynamometer, hooking up the wide range oxygen sensor to the battery for power, and turning on the power for the other instruments.

**Experimental Procedure**

The engine was started up and allowed to warm up before any of the data is recorded. The engine speed, BMEP, and A/F ratio are then set to the desired values for the experiment. Since the emissions sensors are in a different room than the engine, two people were needed to take the required data. One person would record the dial positions for the injection and ignition timings. That person would also fill the 50 mL burette with gasoline and start timing the amount of time it takes for the engine to burn that quantity of gasoline. While the fuel was being consumed, the same person would take 3 separate measurements of the engine load (in mV) and camshaft frequency at regular intervals during the experiment. The EGT and tachometer were each measured once during the middle of the experiment. The second person would record the air to fuel ratio three times, and also record the HC, CO, and NOx emissions when they reach steady state value.

To optimize the amount of time to take data, each day a different RPM and A/F ratio were set and held constant while the injection timing and BMEP were varied. The injection timing was set to inject at both 95 and 360 degrees BTC and the BMEP was set to both 200 and 400kPa, making four runs necessary. Each day, the RPM was set to either 1500 or 2100 and the air to fuel ratio was set to either 14.6 for stoichiometric or 18.4 for lean operating conditions. In order to obtain enough data to do statistical analysis, each set of experiments was repeated three times, for a total of 12 runs per day. Finally, at the end of each day the engine was allowed to idle at very low load for a few minutes before being shut off.

**Analysis**

The data was collected and input into an excel spreadsheet. Equations were derived and entered into the spreadsheet in order to obtain the desired variables for analysis of emissions and thermal efficiency. Once all the data was compiled and calculated, charts such as the example shown in Figure 1 were created. This example chart includes visual aids to help understand the rest of the charts. Many equations had to be derived to adequately analyze the collected data. For example, the brake power was derived through the calibrated dynamometer output, which was 50 lbs per 29.87 mV. The moment arm was measured to be .375 feet. These values were combined with other measured parameters, voltage and RPM, to yield the power (see derivation in Figure 10). An equation for specific emissions from emissions as a mole fraction also had to be derived (shown in Figure 12). Specific emissions are emissions per unit power. This format allows the emissions to be compared to other engine sizes. These and other equations can be found in the appendices.

## *Results*

**Effects of Equivalence Ratio on Emissions:**

The lean gas mixture emitted considerably less emissions than the stoichiometric mixture. For instance, CO SE decreased an average of 77% when using a lean fuel mixture. Similarly, the HC SE reduced 40% and the NOx SE decreased 28%. These results coincided with previously accepted trends. These trends are illustrated in Figure 14; where all of the emissions increase as the equivalence ratio is changed from 0.8 to 1.

**Effects of Load on Emissions:**

Changing the load from 200 kPa to 400 kPa had a varied effect on the SE of all of the emission particles. For NOx, the load had negligible effect at stoichiometric conditions at 1500 RPM, however at 2100 RPM the SE increased 17% as the load was increased from 200kPa to 400kPa. When the engine was operating at lean conditions, the NOx SE (averaged across all engine speeds since they showed similar trends) increased 36% as the load increased. For CO, SE decreased by approximately 28% for all engine conditions. It should be noted that this corresponds to no change in nonspecific (in mole percentage) emissions. Hydrocarbon emissions also show no change with increased load on a molar percentage basis (note that, as with CO, this corresponds to approximately a 33% decrease in specific emissions). This corresponds to the findings of Henin and Patterson, who stated, "when spark timing is optimum, hydrocarbon emissions do not change significantly as load is varied, when speed and A/F ratio is fixed." [6].

**Effects of Spark Timing on Emissions:**

The effects of spark timing are already well known, as previously discussed. In our experiments, the timing was adjusted only to stay as close to MBT timing as possible without damaging the engine. This meant that in the majority of our runs, the ignition timing had to be retarded at high load in order to prevent excessive engine pre-detonation.

**Effects of Engine Speed on Emissions:**

Raising engine speed from 1500 RPM to 2100 RPM had the effect of increasing NOx and CO specific emissions in some cases. At stoichiometric conditions and low load, the NOx SE increased by 26%. At lean conditions and high load, the NOx SE decreased by 13% as the speed increased. The other two cases merely showed variations within standard error (which is fairly large), and based on mean values are assumed to not be affected greatly by engine speed. Carbon monoxide SE, however, seem to have a large dependence on engine speed. At stoichiometric conditions, CO SE increased by 56%; at lean conditions, CO SE increased by 28%. This is most likely because of the lack of time for the carbon to find sufficient oxygen to convert into $CO_2$. Conversely, hydrocarbon specific emissions showed an inverse relationship with engine speed. At stoichiometric conditions, HC SE decreased by 33 percent; at lean conditions, SE decreased by 38 percent. These HC values parallel Sher's experiment where the engine speed was raised from 1000 to 2000 RPM, and the HC emission decrease ranged from 20 percent to 50 percent [7]. This is most likely because of the higher temperatures at 2000 RPM. This increase in temperature will be marked by an increase in the amount of hydrocarbons that are oxidized before leaving the exhaust. It also may have a positive effect on mixture quality.

**Effects of Injection Timing on Emissions:**

The main purpose of this experiment was to investigate how the injection timing affected the emissions on the engine. The injection timing seemed to have an effect on the hydrocarbon formations as well as the carbon monoxide formations. By looking at Figure 4 in the appendix, it is evident that when the injection timing is changed from OVI to CVI there is no significant change in NOx formations. However, when looking at Figure 2 one can see that the injection timing has a profound effect on CO emissions. When the engine ran at low load (200 kPa), stoichiometric and 1500 RPM, the emissions reduced 36% when the injection timing was changed from OVI to CVI timing. At the same operating conditions, except with the lean A/F ratio, the CO SE dropped 22%. At the higher engine speed (2100 RPM) and/or at high load, the effect of injection becomes less noticeable, but the effects can still be seen. For instance, when the engine ran at high load (400kPa) and 1500 RPM, with the A/F ratio varying from stoichiometric to lean conditions, the CO SE dropped 10% and 11% respectively. At low load and 2100 RPM, when the A/F ratio was stoichiometric, the data had a very large statistical variation. It can be speculated from the averages that the CO SE decreased slightly, but due to the large statistical deviation a percentage was not calculated. One source of error that could have led to the deviation in the data can be attributed to the fact that the CO emissions analyzer had difficulty in staying calibrated on that day. At lean A/F ratio and low load, the CO dropped by 12% when the engine ran at 2100 RPM. When the engine ran at high load, stoichiometric A/F ratio, and 2100 RPM the emissions dropped 10% when the injection timing was changed from OVI to CVI. The only circumstances where the average emissions went up were when the injection timing was changed from OVI to CVI. This increase in CO SE occurred when the engine ran at high load, lean A/F ratio and 2100 RPM, and yielded an 8% increase. No previous reports on how the injection timing affects the CO emissions on engines could be obtained. However, one can speculate from these trends that the effects of injection timing on mixture quality are the reason for differences in CO emissions. Since the CO is formed due to a lack of oxygen present to make $CO_2$, a better mixture quality is essential to lowering the CO emissions. From already stated reports dealing with HC formations, it was found that OVI injection timing can cause a local stratified mixture in the cylinder, which would cause more CO emissions due to locally rich regions in the cylinder. Conversely, with CVI timing, the fuel is transported completely through atomization. Thus, less fuel becomes stuck near the cylinder wall, causing a more homogeneous mixture. At low speed, gas temperatures and air velocities are lower than for the high RPM case. At low load, the gas temperatures are less hot than at high load. Therefore, changing from low load/speed to high load/speed has an effect on fuel/air mixing properties. However, it can be speculated that the differences in mixture quality between OVI and CVI timing become smaller as speed/load are increased. The high temperatures in the cylinder help the fuel on the cylinder wall vaporize, and the high velocities will help the fuel mix with the air more effectively during OVI timing. Once these conditions were combined, such as in the case of high load and high rpm, the data actually showed a small increase in CO emissions for the CVI timing case.

Injection timing also had a significant effect on hydrocarbon emissions at low engine speeds. This is illustrated in Figure 6. In all cases at 2100 RPM, negligible differences in hydrocarbon SE were observed. However, at 1500 RPM marked differences were detected. Stoichiometric conditions were affected the most by injection timing. For instance, the HC specific emissions (with $\phi=1$) decreased approximately 30% at both load conditions. At lean conditions, the HC SE decreased 16% and 25% at loads of 200 kPa and 400 kPa, respectively. These results coincide with the findings of Arcoumanis et al [8] and Yang et al [4]. These changes occur for many of the same reasons mentioned in regards to CO emissions. The larger number of fuel droplets as well as the higher concentration of fuel near the cylinder wall from OVI timing decreases combustion quality, maximizing HC emissions. Once again, as shown in the CO data, the higher engine speed/temperatures at 2100 RPM quash all benefits inherent in CVI timing.

**Effects of Engine Parameters on Thermal Efficiency**

As can be viewed in Figure 8, some engine parameters had a significant impact on the thermal efficiency of the engine. Equivalence ratio did not have a measurable effect. Injection timing had a small effect at 1500 RPM, with CVI timing showing only a 3% higher thermal efficiency than OVI timing. At 2100 RPM, injection timing has no noteworthy influence on thermal efficiency. Solely changing the speed also has an effect on thermal efficiency. The efficiency goes down as engine speed increases in all cases, with speed changes at low load showing a higher degree of efficiency drop off than at high load. Load has the highest influence on thermal efficiency. The efficiency increases markedly at 400 kPa compared to 200 kPa, with a 36% increase in efficiency.

## *Conclusions:*

- An equivalence ratio of 0.8 showed superior emissions over the stoichiometric equivalence ratio of one.
- Carbon monoxide and hydrocarbon specific emissions both decreased as the load was increased because of the higher temperatures while NOx emissions had varied results.
- At low loads, as the engine speed increased the NOx SE also increased due to the higher temperatures. At high load, this effect of changing engine speeds was minimal. Carbon monoxide specific emissions increased as the engine speed was increased from 1500 RPM to 2100 RPM. The reason for this was a decrease in time for chemical reactions to take place. Conversely, engine speed had the opposite effect on hydrocarbon specific emissions because of the higher temperatures at 2100 RPM.
- Changing the injection timing from OVI to CVI generally resulted in a decrease in carbon monoxide specific emissions. The same effect was also observed for hydrocarbon specific emissions. These effects can be attributed to the differences in mixture composition at both injection timings. However, the injection timing had little influence for NOx specific emissions.
- Load had the largest impact on the thermal efficiency of the engine. Higher load corresponded to a higher efficiency. Changing injection timing from OVI to CVI caused a very small increase in thermal efficiency when the engine ran at 1500 RPM. Finally, the higher engine speed inversely affected the thermal efficiency.

## *Recommendations For Future Work*

Upon completing this research project, several questions arose: Is our data repeatable? What happens when the load and/or RPM is increased? What happens under cold or transient conditions? Since most of the experimental runs were done in one day, such as all of the 2100 RPM and lean conditions, it would be advantageous to repeat these experiments again in order to see if the tests get similar results, and for further statistical validity. One trend that was noticed is that the effect of injection timing on the emissions decreased as load and RPM increased, where eventually at high load and high RPM OVI timing had slightly better CO and HC SE. Therefore, it would be interesting to see if OVI timing continues to perform better or if the differences between OVI and CVI diminish as the load and speed is increased. Finally, upon reading the findings of Brehm et al, it would be beneficial to investigate the effects of cold starting conditions as well as engine transients on the emissions. Brehm et al speculated that CVI timing would have adverse effects under cold start conditions, since vaporization is poor. Also, OVI is likely to be advantageous for transient operating conditions where speed and load change quickly [9].

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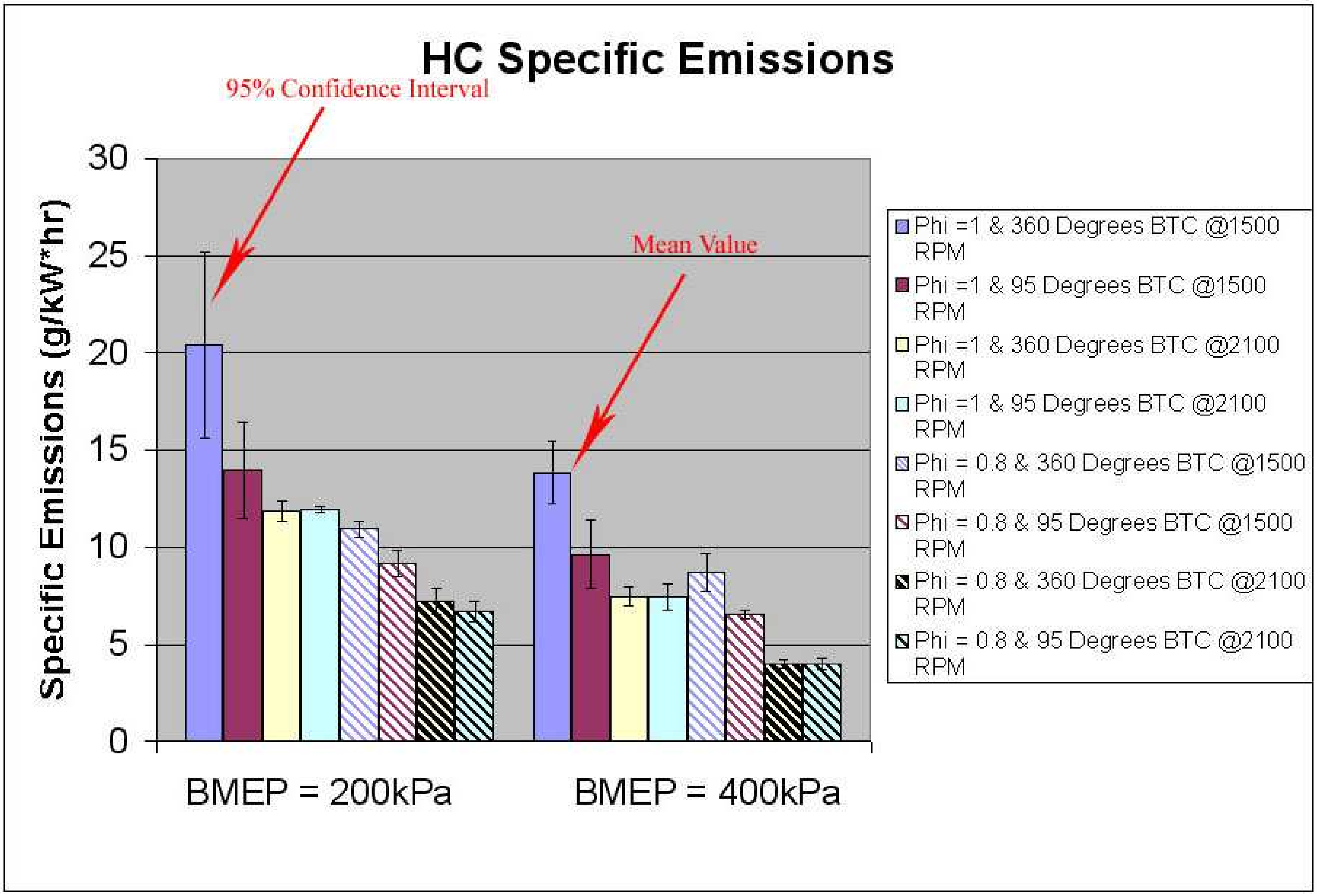
## *Nomenclature*

**A/F ratio-** Air to fuel ratio
**BMEP**-Brake mean effective pressure
**BTC-** Before top dead center
**CO-** Carbon monoxide
**CVI timing-** Closed valve injection timing
**DOHC-** Dual overhead cam
**EGR-** Exhaust gas recirculation
**EGT-** Exhaust gas temperature
**$\phi$–** Equivalence ratio
**HC-** Hydrocarbon
**IC engine-** Internal combustion
**MBT-** Maximum brake torque
**NOx-** NO and $NO_2$ (Oxides of Nitrogen)
**OVI timing-** Open valve injection timing
**ppm-** Parts per million
**RPM-** Revolutions per minute
**SE-** Specific emissions
**SI-** Spark ignition

# APPENDIX

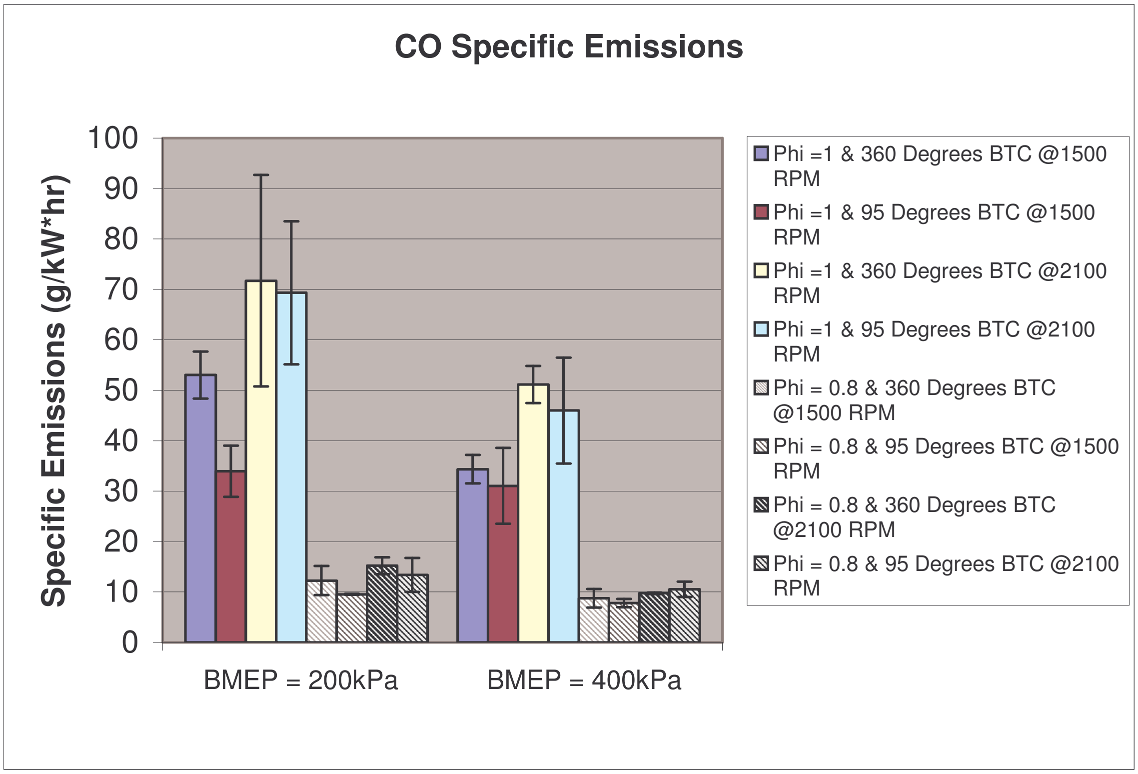
Example Chart




**TO AID IN UNDERSTANDING:**

The solid bars stand for stoichiometric A/F, while the striped bars represent the lean A/F ratio.
The bars alternate injection timing.
Every two bars represent a change in engine speed.
The first set of bars is at a BMEP of approximately 200kPa, while the second set is at a BMEP of approximately 400kPa.

**Figure 1: Example Chart**



CO Specific Emissions
Specific Emissions (g/kW*hr)
100
90
80
70
60
50
40
30
20
10
0
BMEP = 200kPa
BMEP = 400kPa
Phi =1 & 360 Degrees BTC @1500 RPM
Phi =1 & 95 Degrees BTC @1500 RPM
Phi =1 & 360 Degrees BTC @2100 RPM
Phi =1 & 95 Degrees BTC @2100 RPM
Phi = 0.8 & 360 Degrees BTC @1500 RPM
Phi = 0.8 & 95 Degrees BTC @1500 RPM
Phi = 0.8 & 360 Degrees BTC @2100 RPM
Phi = 0.8 & 95 Degrees BTC @2100 RPM


**Figure 2**

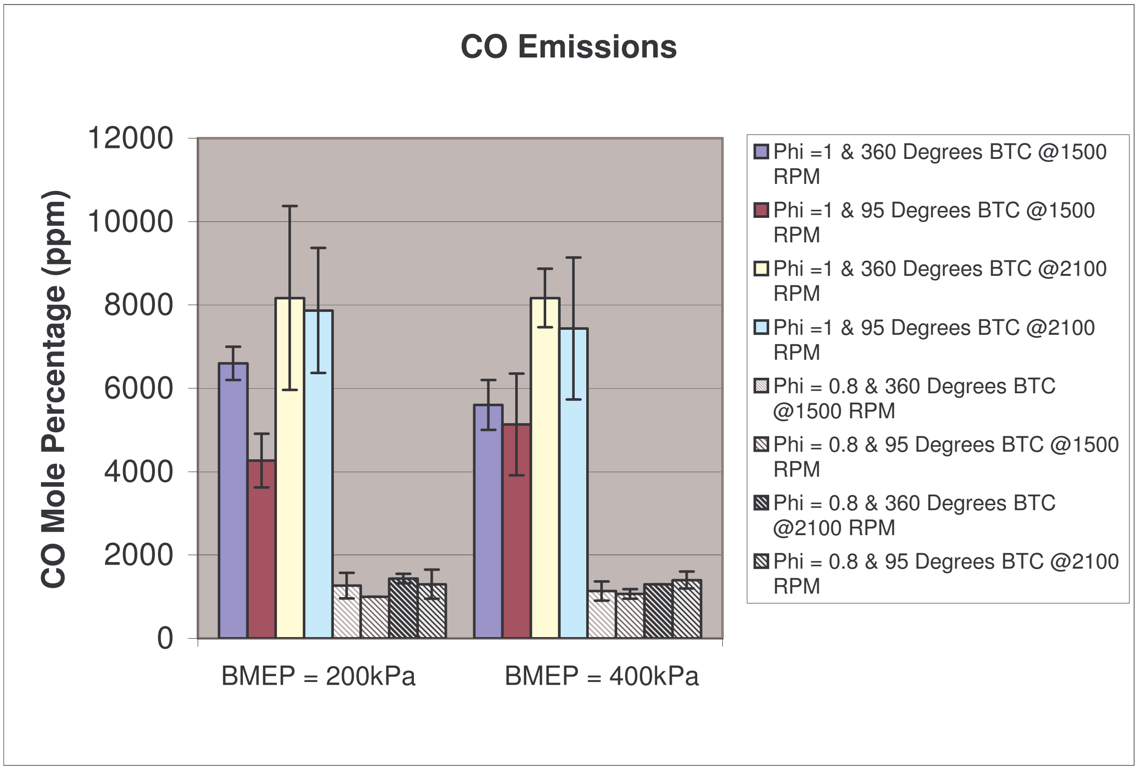

CO Emissions
CO Mole Percentage (ppm)
12000
10000
8000
6000
4000
2000
0
BMEP = 200kPa
BMEP = 400kPa
Phi =1 & 360 Degrees BTC @1500 RPM
Phi =1 & 95 Degrees BTC @1500 RPM
Phi =1 & 360 Degrees BTC @2100 RPM
Phi =1 & 95 Degrees BTC @2100 RPM
Phi = 0.8 & 360 Degrees BTC @1500 RPM
Phi = 0.8 & 95 Degrees BTC @1500 RPM
Phi = 0.8 & 360 Degrees BTC @2100 RPM
Phi = 0.8 & 95 Degrees BTC @2100 RPM

**Figure 3**

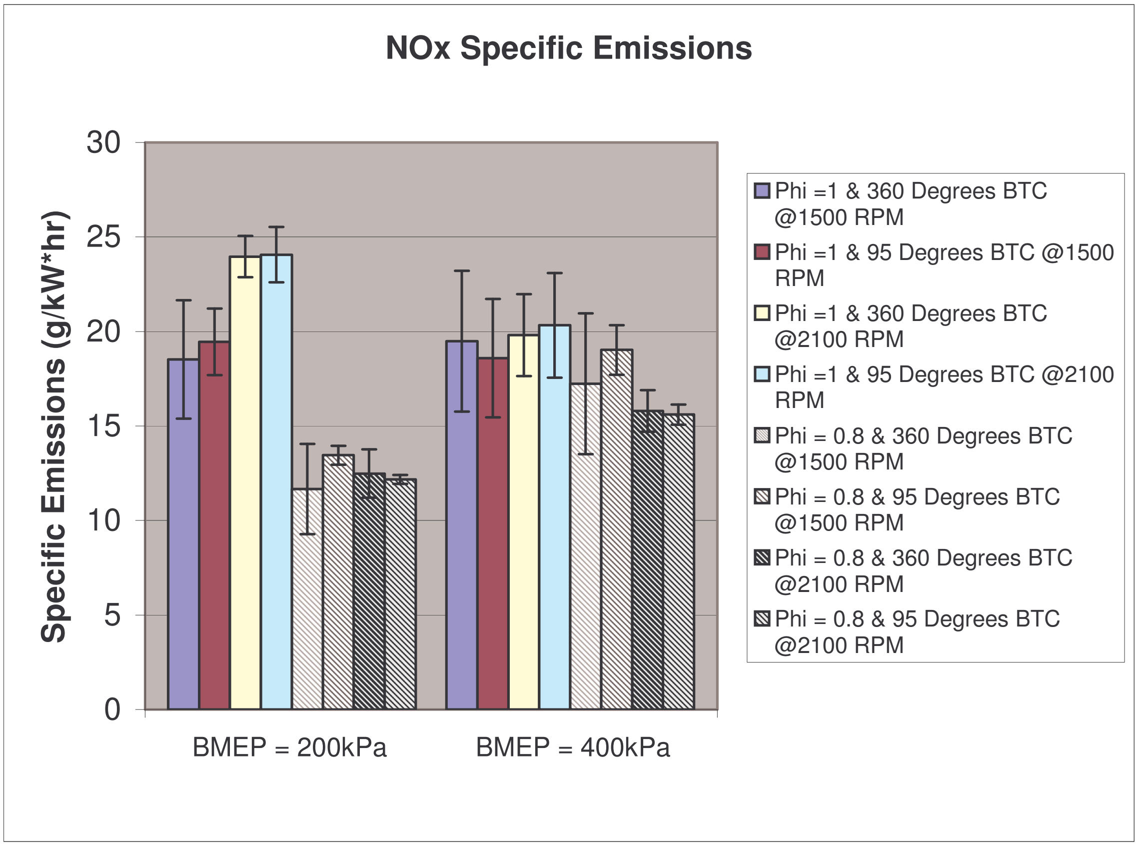

NOx Specific Emissions
Specific Emissions (g/kW*hr)
30
25
20
15
10
5
0
BMEP = 200kPa
BMEP = 400kPa
Phi =1 & 360 Degrees BTC @1500 RPM
Phi =1 & 95 Degrees BTC @1500 RPM
Phi =1 & 360 Degrees BTC @2100 RPM
Phi =1 & 95 Degrees BTC @2100 RPM
Phi = 0.8 & 360 Degrees BTC @1500 RPM
Phi = 0.8 & 95 Degrees BTC @1500 RPM
Phi = 0.8 & 360 Degrees BTC @2100 RPM
Phi = 0.8 & 95 Degrees BTC @2100 RPM

**Figure 4**

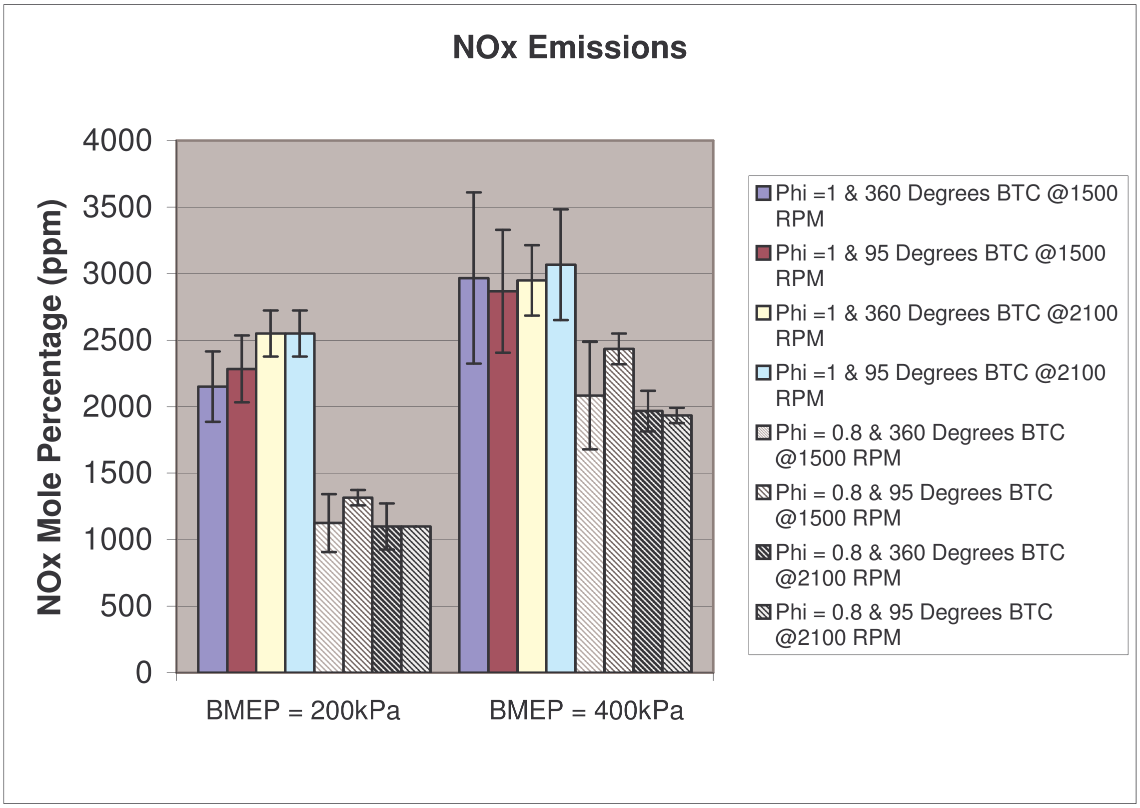

NOx Emissions
NOx Mole Percentage (ppm)
4000
3500
3000
2500
2000
1500
1000
500
0
BMEP = 200kPa
BMEP = 400kPa
Phi =1 & 360 Degrees BTC @1500 RPM
Phi =1 & 95 Degrees BTC @1500 RPM
Phi =1 & 360 Degrees BTC @2100 RPM
Phi =1 & 95 Degrees BTC @2100 RPM
Phi = 0.8 & 360 Degrees BTC @1500 RPM
Phi = 0.8 & 95 Degrees BTC @1500 RPM
Phi = 0.8 & 360 Degrees BTC @2100 RPM
Phi = 0.8 & 95 Degrees BTC @2100 RPM

**Figure 5**

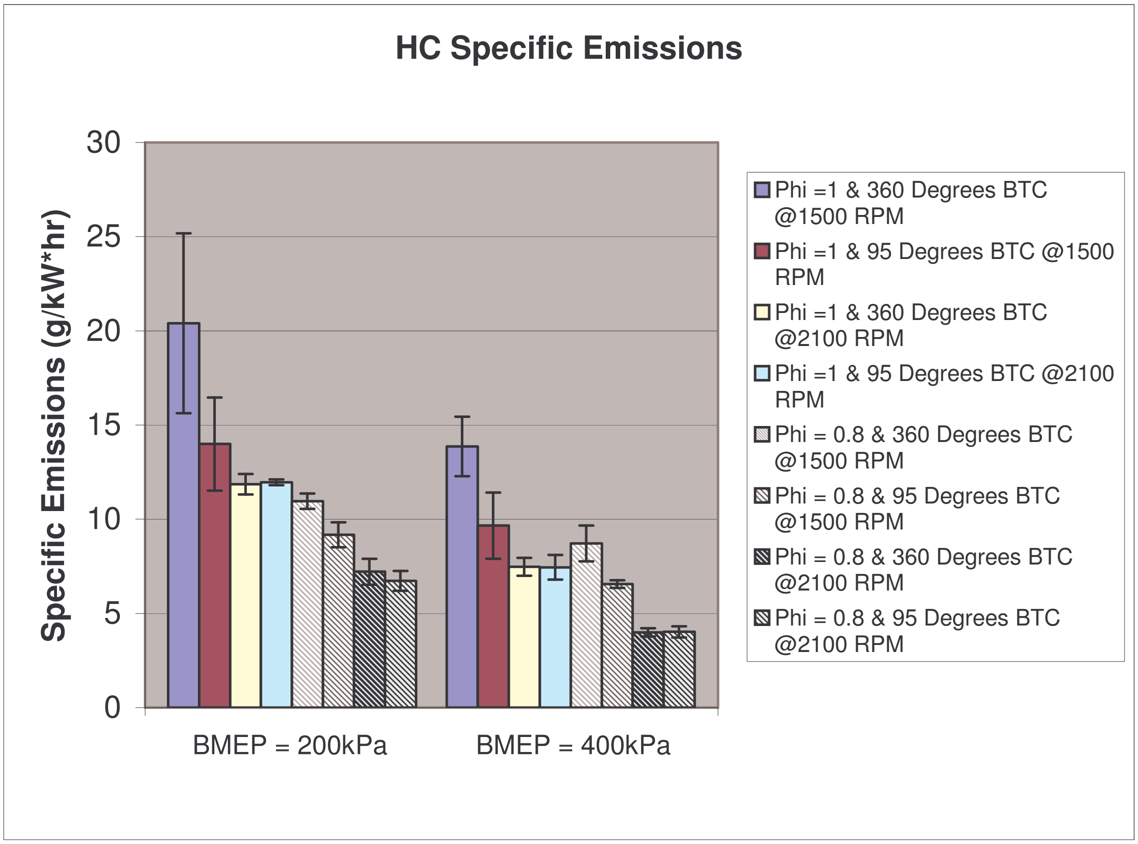

HC Specific Emissions
Specific Emissions (g/kW*hr)
30
25
20
15
10
5
0
BMEP = 200kPa
BMEP = 400kPa
Phi =1 & 360 Degrees BTC @1500 RPM
Phi =1 & 95 Degrees BTC @1500 RPM
Phi =1 & 360 Degrees BTC @2100 RPM
Phi =1 & 95 Degrees BTC @2100 RPM
Phi = 0.8 & 360 Degrees BTC @1500 RPM
Phi = 0.8 & 95 Degrees BTC @1500 RPM
Phi = 0.8 & 360 Degrees BTC @2100 RPM
Phi = 0.8 & 95 Degrees BTC @2100 RPM

**Figure 6**

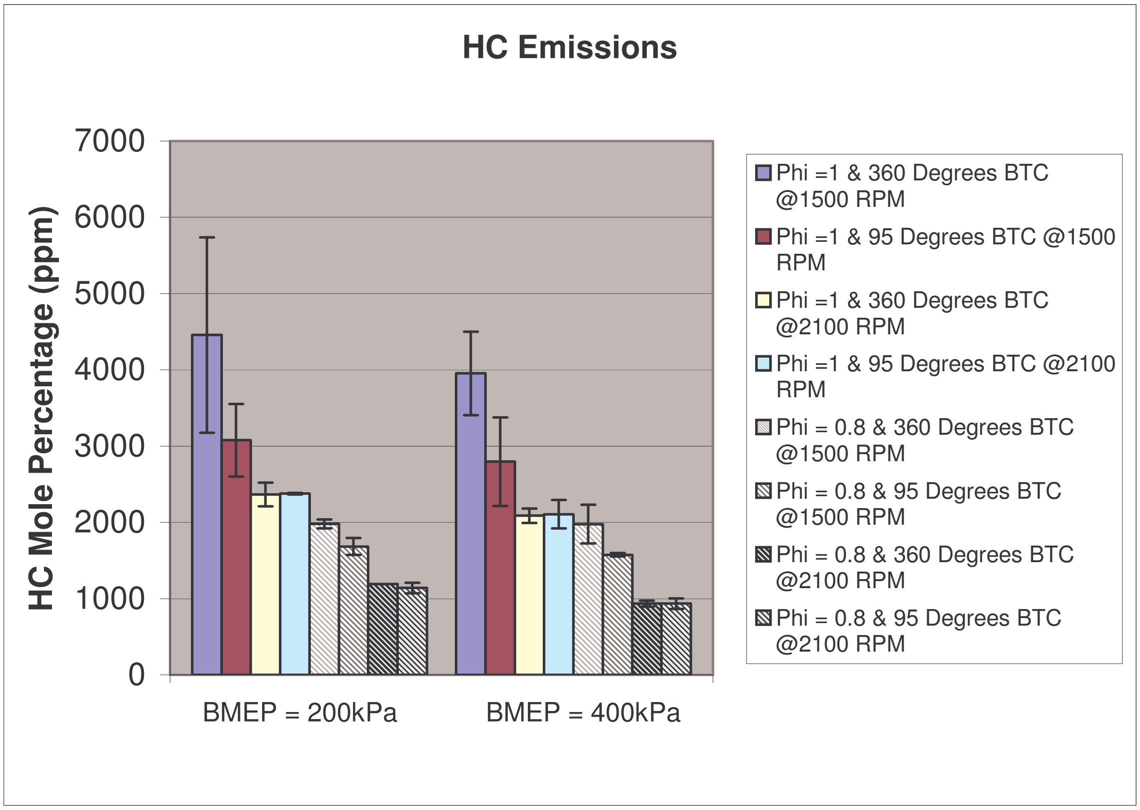

HC Emissions
HC Mole Percentage (ppm)
7000
6000
5000
4000
3000
2000
1000
0
BMEP = 200kPa
BMEP = 400kPa
Phi =1 & 360 Degrees BTC @1500 RPM
Phi =1 & 95 Degrees BTC @1500 RPM
Phi =1 & 360 Degrees BTC @2100 RPM
Phi =1 & 95 Degrees BTC @2100 RPM
Phi = 0.8 & 360 Degrees BTC @1500 RPM
Phi = 0.8 & 95 Degrees BTC @1500 RPM
Phi = 0.8 & 360 Degrees BTC @2100 RPM
Phi = 0.8 & 95 Degrees BTC @2100 RPM

**Figure 7**

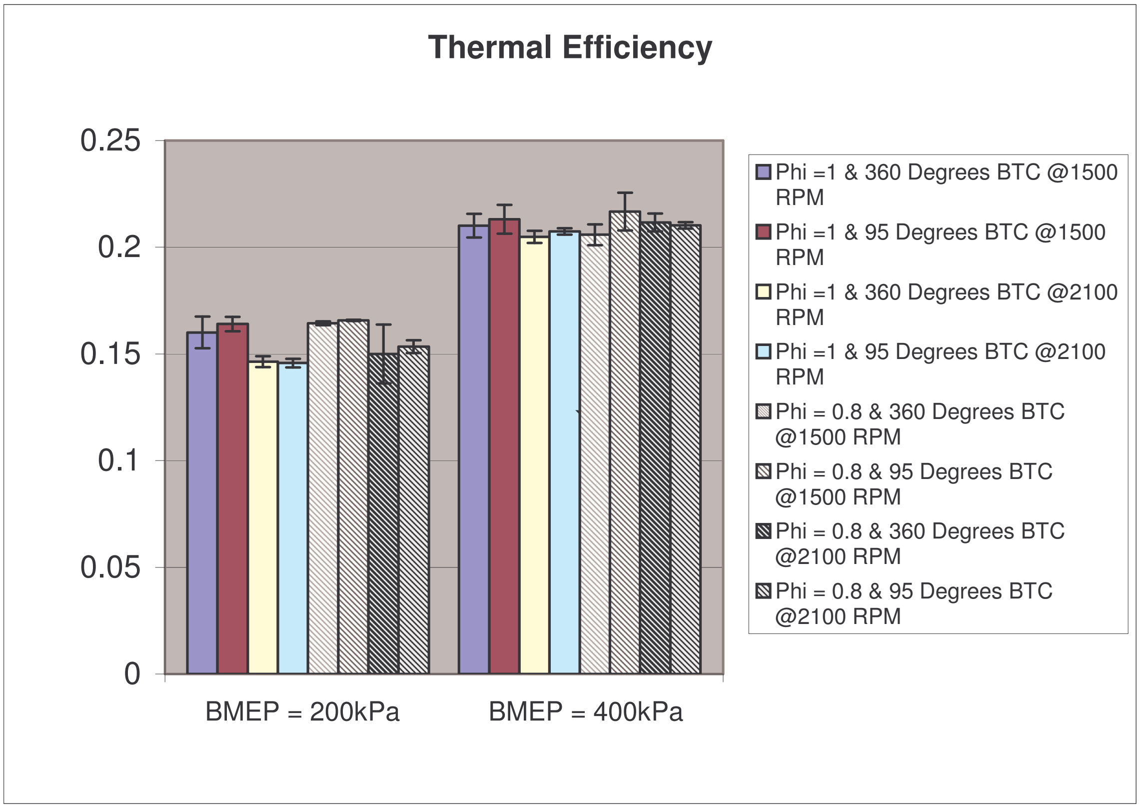

Thermal Efficiency
0.25
0.2
0.15
0.1
0.05
0
BMEP = 200kPa
BMEP = 400kPa
Phi =1 & 360 Degrees BTC @1500 RPM
Phi =1 & 95 Degrees BTC @1500 RPM
Phi =1 & 360 Degrees BTC @2100 RPM
Phi =1 & 95 Degrees BTC @2100 RPM
Phi = 0.8 & 360 Degrees BTC @1500 RPM
Phi = 0.8 & 95 Degrees BTC @1500 RPM
Phi = 0.8 & 360 Degrees BTC @2100 RPM
Phi = 0.8 & 95 Degrees BTC @2100 RPM

**Figure 8**

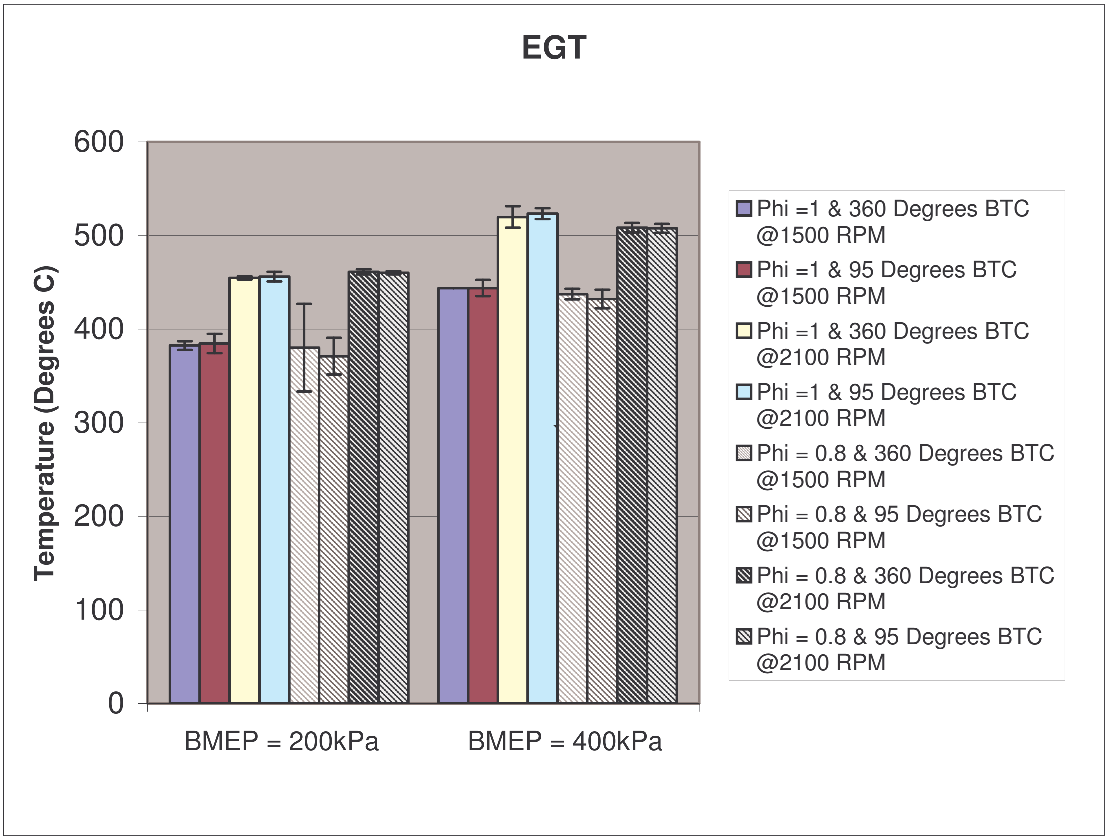



**Figure 9**

$$F = Voltage(\frac{50lb}{29.87mV})$$
$$T = F * (moment\ arm)$$
$$T = F(.375ft)$$
$$Power = 2\pi NT$$

**Figure 10: Brake Power Derivation**

$$BMEP = \frac{P(2\frac{rev}{cycle})}{V_{sw}N}$$

**Figure 11: Equation for Brake Mean Effective Pressure [1]**

$$\beta\left(\frac{g}{kW*hr}\right)=\frac{\left[\beta(ppm)*10^{-6}\right]\left[Molecular\,Weight\left(\frac{g}{mol}\right)\right]\left[\frac{\dot{m}_f\left(\frac{14.6}{\phi}+1\right)}{28.8-0.2\phi}\right]\left[3600\frac{s}{hr}\right]}{Brake\ Power}$$

**Figure 12: Equation for Specific Emissions (where β is the chemical compound of interest)**

$$Specific\ Fuel\ Consumption\ (sfc)=\frac{\dot{m}_f}{BP}$$

$$Lower\ Heating\ Value=43\frac{MJ}{kg}$$

$$Thermal\ Efficiency\ or\ Fuel\ Conversion\ Efficiency=\eta_{th}\ or\ \eta_f$$

$$\eta_f=\frac{3600}{sfc*LHV}$$

**Figure 13: Derivation of Thermal Efficiency [1]**

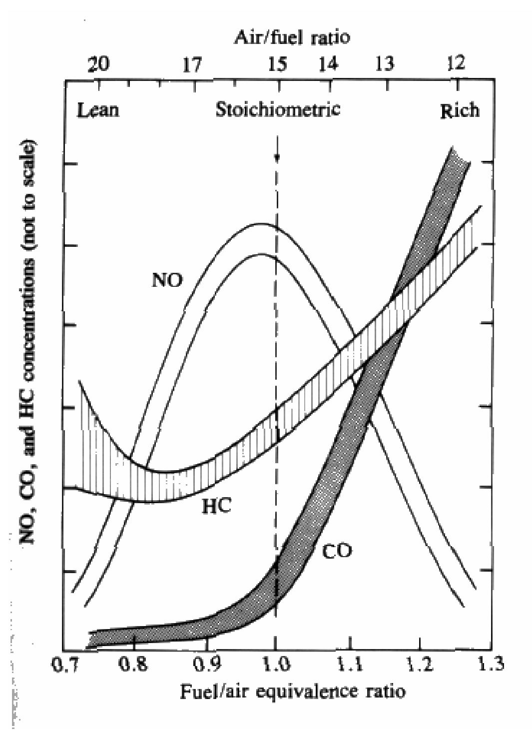



**Figure 14:Effects of Equivalence Ratio on Emissions**

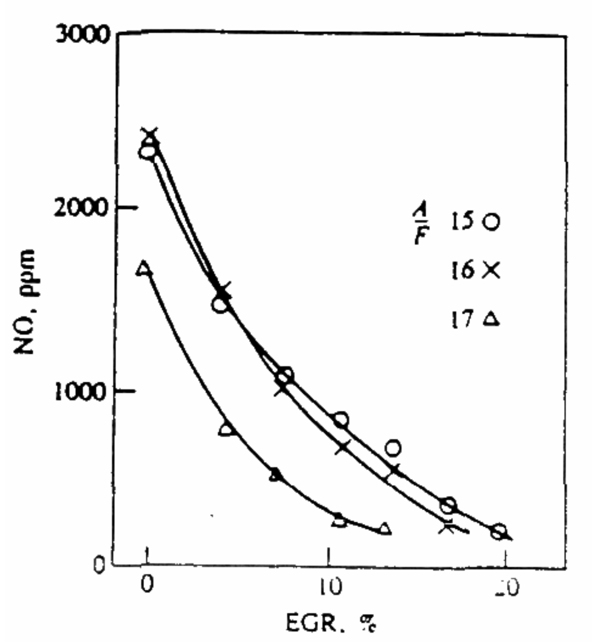



**Figure 15: Effects of EGR on NO Emissions**

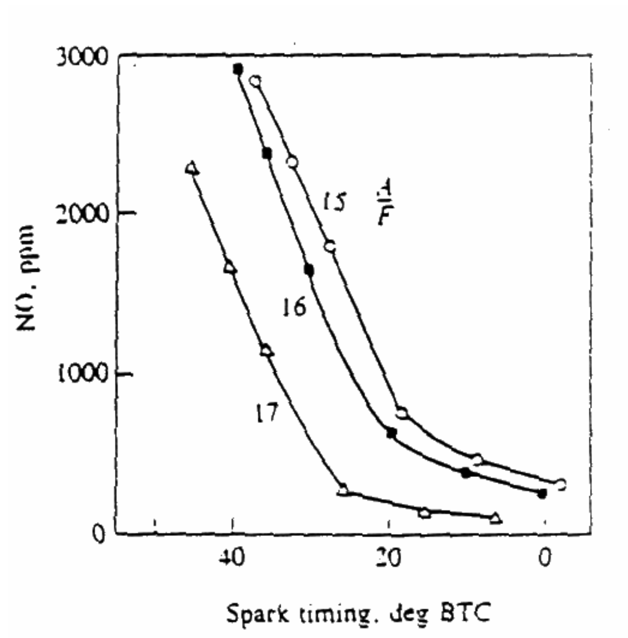



**Figure 16: Effects of Spark Timing on NO Emissions**

| | OVI (360° BTC) | CVI (95° BTC) |
|---|---|---|
| ***1500 RPM*** | 6 | 9.5 |
| ***2100 RPM*** | 5.2 | 8 |

Figure 17: Injection Timing Dial Positions