Analysis of various fuels in DISI and PFI engines: Separating mixing effects from crevice and quench layer effects

by

Sareena Avadhany

Submitted to the Department of Mechanical Engineering
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Abstract

The United States consumes billions of gallons of gasoline per year, threatening national security and causing environmental problems. Research in automotive research aims to resolve such problems. Solutions include turbocharged direct injection, spark ignition (DISI) engines for higher output and efficiency. But this comes at the cost of greater concentrations of unburned hydrocarbons (UBHC) in the exhaust during cold start, when the catalytic converter is further away from the engine. The time the catalytic converter takes to heat to an optimum efficiency is longer. UBHC can also accumulate in the cylinder chambers and can be caused by quenching effects or poor mixing. A system was set up to determine the significance of mixing in producing high concentrations of UBHC. A GM 2009 LNF Ecotec was modified to run PFI and DISI under operating conditions representative of cold start for isopentane, and gasoline with varying concentrations of ethanol. Results were inconclusive, indicating no relationship between neither the UBHC count in the exhaust of increasing ethanol concentration, nor differences between PFI and DISI. To make test results more reliable, more ethanol containing fuel types should be tested, and a sweep of spark times should be assessed. The set up does provide a good foundation for further studies in mixing research.

Thesis Supervisor: Sanjay Sarma
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Chapter 1

Introduction

Every year, the United States consumes approximately 213.7 billion gallons of gasoline [7]. The country's dependence on fuel gives rise to national security, environmental and financial problems. The U.S. government in 2011 implemented stricter fuel economy standards for passenger and truck vehicles. The Environmental Protection Agency (EPA), a federal administration responsible for emissions regulations, recently announced that passenger vehicles in 2022 must reach an average of 48.8 miles per gallon [1]. To reach this goal, U.S. car companies must increase fuel economy for their vehicles every year.

A variety of solutions that meet these requirements increase power output and decrease the amount of unburned hydrocarbons (UBHC). These include:

- Different fuel types: higher ethanol content, isopentane, compressed natural gas (CNG). Isopentane is currently not being considered by automakers.
- Downsized, turbocharged, direct injection, spark ignition (DISI) engines
- Hybrid vehicles
- Electric vehicles

In addition to raising the fuel economy standards, the federal government requires that "use of renewable fuels in light-duty vehicles and heavy trucks increase from 15.2

billion gallons in 2012 to 36 billion gallons annually by 2022." [6] Fuel blends containing ethanol qualify. It is thought that since ethanol is a "partially oxidized" hydrocarbon and a smaller molecule, it burns more completely than gasoline. Since oxygen is required for combustion, more fuel can burn, reducing the UBHC content in the exhuast.

This paper studies DISI and port fuel injection (PFI) engines. Injectors for DISI engines spray fuel directly into the cylinder. For PFI engines, injectors spray fuel into the manifold, and an air-fuel mixture enters the cylinder. DISI engines reach higher compression ratios than PFI engines, and thus the power output is greater. This is not true for turbo DISI engines, however (see Table 1.1). Lower compression ratios for turbocharged DI engines reduce knock. Fuel economy benefits from downsizing because of favorable scaling of heat transfer and friction. Turbocharging is used to boost the downsized engine's power to match that of larger engines. But this doesn't necessarily result in greater heat transfer or friction losses. On the contrary, such losses are smaller for downsized turbocharged DI engines. Overall, vehicles with downsized turbocharged DISI engines consume less gas.

However, this comes at the cost of greater emissions of UBHC, especially during cold start, since the air-fuel mixture in DISI engines is not well mixed. Our study examines the reasons for UBHC emissions in both PFI and DISI engines during cold start.

Table 1.1: Compression Ratios for PFI and DISI engines

Engine Type	Compression Ratio (r_c)
Naturally aspirated PFI	10-11
Naturally aspirated DISI	11-13
Turbocharged DISI	9-10.5

Chapter 2

Background

Increasing fuel economy requirements spur interest in downsized turbo-DISI engines. These engines are more efficient for equal performance. However, they also present emissions challenges. The catalytic converter is responsible for converting CO, HC, NO_x to CO_2, H_2O and N_2. It is attached to and inline with the exhaust manifold and sits close to the engine in the exhaust system to heat up quickly. Unfortunately, at temperatures below 250°C, the catalytic converter is incapable of operating efficiently [2]. During a standard federal test procedure (FTP) 23 test cycle over which cumulative HC emissions are measured, approximately 90% of UBHC are exhausted during this period, which can last between 15 to 60 seconds as the catalytic converter temperature rises to a normal operating state.

If the engine is turbocharged, the warm up time is longer. The catalytic converter is installed further away from the engine to make room for the turbocharger. Cold cylinders are an additional reason why most of the UBHC are exhuasted during cold-start. In DISI engines, liquid fuel is injected directly into the cylinder. The low temperature of the engine does not force the fuel to vaporize, and fuel mixing is worse. Conventional PFI engines have liquid fuel injected into the air intake path, so only pre-evaporated, pre-mixed fuel and air enter the combustion chamber.

The mechanisms by which UBHC can escape the cylinder are [4]:

- Fuel absorbed by oil layers along cylinder walls

- Fuel seeping in between the cylinder walls and piston (crevices)
- Fuel quenched by colder chamber surfaces
- Incomplete combustion due to an excessive amount of fuel

UBHC found from these four types of mechanisms can escape the chamber during the exhaust stroke. Figure 2-1 depicts the different mechanisms by which fuel can escape combustion in a PFI engine [4]. Very similar phenomena are observed for DISI engines, but since the fuel is sprayed directly into the chamber, it is more likely that fuel will hit the walls and remain in liquid phase. Crevice and quench layer effects are a result of the geometry of the piston and cylinder unit.

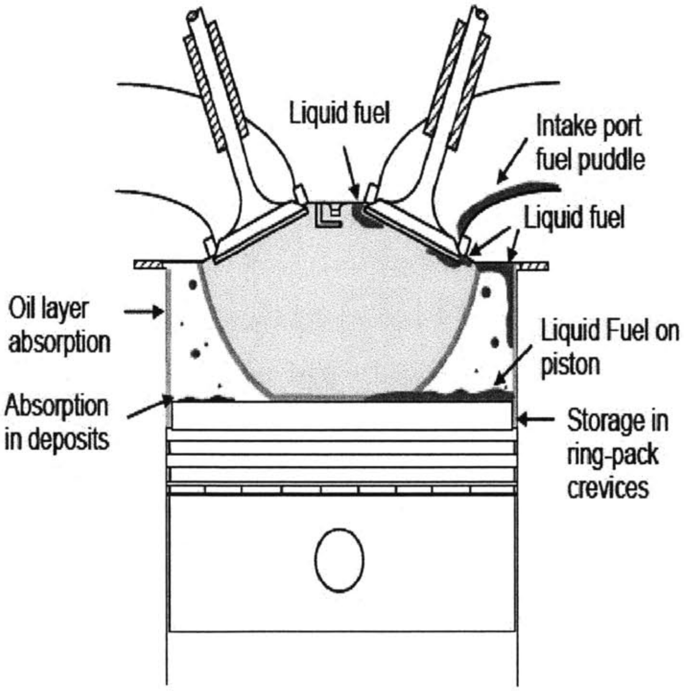

Figure 2-1: The various mechanisms by which fuel goes unburned in the combustion chamber.

We attempted to isolate the effects of mixing by adapting a turbocharged DISI engine for both port fuel and direct injection.

Chapter 3

Experimental Design

3.1 Engine Specifications

Experiments were conducted on a turbocharged, DISI engine (GM 2009 LNF Ecotec, 2.0L inline 4 cylinder engine).

Table 3.1: Specifications

Engine Specifications		Operating Conditions	
Displacement volume (cc)	1998	Engine Speed (rpm)	1200
Clearance volume (cc)	61	NMEP (bar)	2.0
Bore (mm)	86	Coolant/Oil Temperature (°C)	20
Stroke (mm)	86	Ambient pressure (kPa)	100
Connecting rod (mm)	145.5	Intake Air Temperature (°C)	25
Wrist pin offset (mm)	0.5	Intake Air Vapor Pressure (kPa)	1
Compression ratio	9.2:1	Exhaust Back Pressure (kPa)	0.5
Firing order	1-3-4-2		
Valve configuration	16V DOHC		

Data acquisition is conducted using National Instruments LabView. Table 3.2 indicates particular data collected once per crank angle degree (CAD) and once per cycle.

Fuel injection pulse duration data is collected 100,000 times per second. The data collected helps to monitor engine operating conditions that are typical of cold start after the transient speed flare. Various spark times were implemented to determine the influence of early and late spark in the UBHC count in the exhaust. Late spark

Table 3.2: Data Points Collected

Once per CAD	Once per Cycle
Engine cylinder pressure	Fuel temperature
Intake manifold pressure	Intake air temperature
Exhaust manifold pressure	Intake air temperature
Hydrocarbon concentration	Exhaust temperature
Air-Fuel equivalence ratio (λ)	Intake and exit oil temperature
	Intake and exit engine coolant temperature
	Ambient air temperature

time is representative of cold start because the less work output heats up the engine quicker. For this experiment, spark time was set to TDC

3.2 Design of Port Fuel Injection Manifold

We purchased an LNF manifold for the PFI runs. Figure 3-1 shows the completed manifold. The author modified engine's existing fuel to supply the PFI fuel system, and updated the control electronics to interface with both PFI and DI injectors.

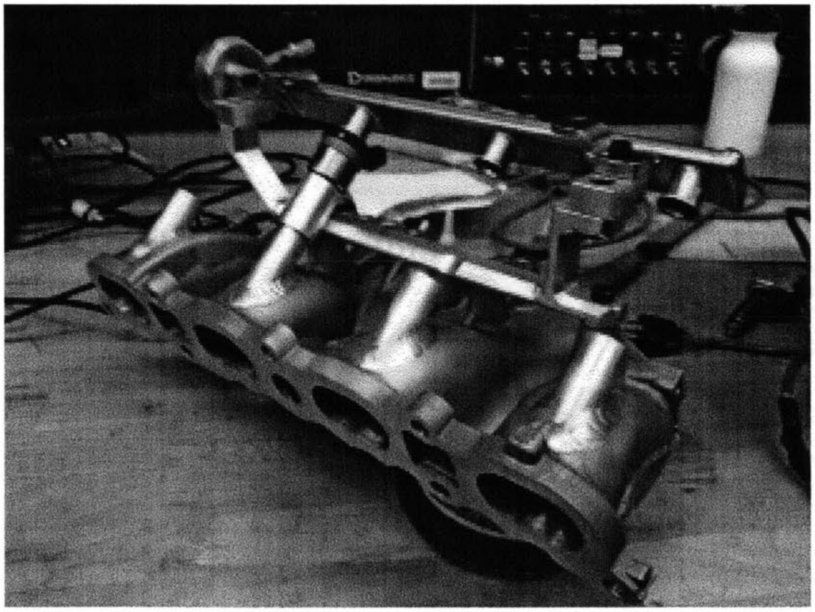

Figure 3-1: LNF Ecotec manifold with welded bosses to mate PFI injectors with the manifold.

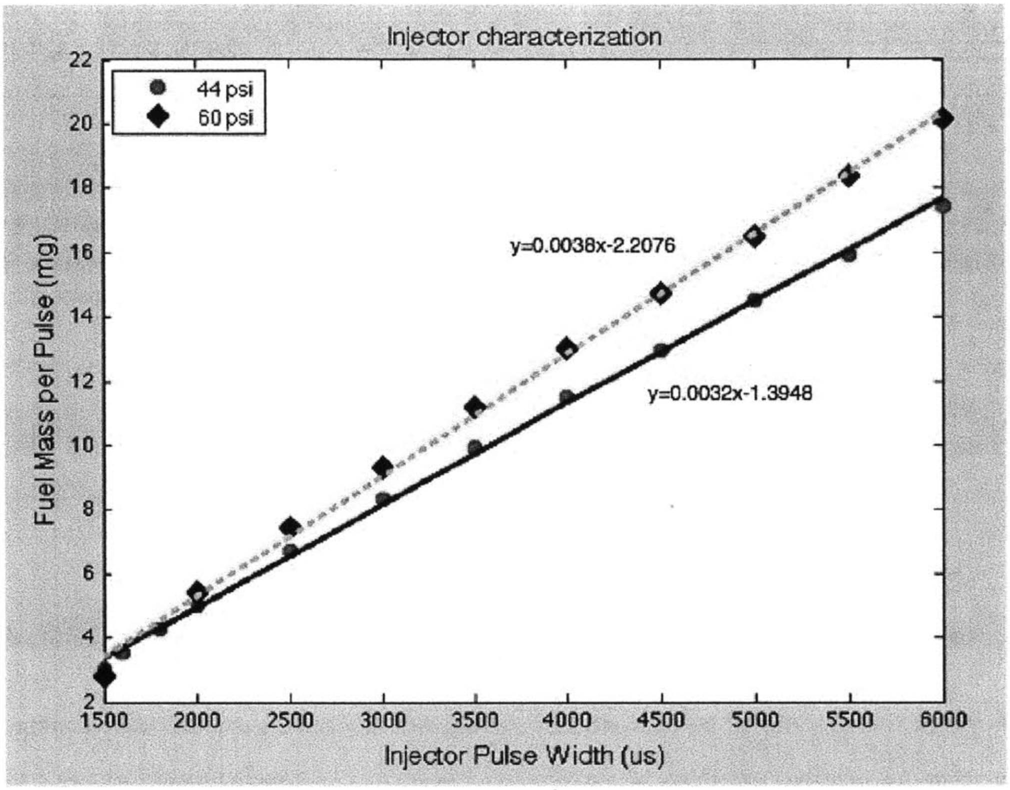

Figure 3-2: Fuel mass per pulse width as a function of increasing injection pulse width duration. The longer the duration, the more mass ejected.

3.3 Injector Characterization

The PFI injectors were characterized to determine the fuel mass ejected as a function of fuel supply pressure and pulse width duration from the control computer. Figure 3-2 shows that the fuel mass per pulse linearly increases with injection duration. Additionally, for a given duration, the amount of fuel mass per pulse rises for higher ΔP values. In fact, two different pressures scale with $\sqrt{\Delta P}$ (i.e. $m_2=m_1\sqrt{\frac{\Delta P_2}{\Delta P_1}}$)

3.4 Selected Fuels

We used four different fuels for this experiment (see Table 3.3). Ethanol enriched fuels are denoted by percentage. For instance, E10 is 10% ethanol and 90% gasoline by volume. These fuels are of interest for cold start studies because of their wide range of evaporative and mixing properties. For turbocharged, DISI engines, two problems exist:

- Cold start produces UBHC. Fuels with low h_{fg} values (e.g. gasoline) are desirable. Less energy is needed to vaporize the fuel, thus less heat is transferred from the engine to the air-fuel mixture. This shortens the amount of time needed for the catalytic converter to reach a normal operating temperature.

- At high loads, the engine builds up heat, which is a cause of engine knocking. To prevent knock, the engine can have a late spark time, or the fuel could be rich. But these conditions can ruin the vehicle's efficiency (the concentration of UBHC increases). To prevent knock without lowering efficiency, fuels with high h_{fg} and octane values (e.g. E85) are desirable. Engines exploit the evaporative properties to cool. This is known as charge cooling. The downside to fuels like E85 is the lower heating value. More fuel is needed to get the same amount of energy during combustion. Additionally, E85's availability is poor and the cost is high.

We used isopentane because this fuel is chemically similar to gasoline but thermally different (higher h_{fg} value and lower T_b value). Isopentane instantly evaporates. Ethanol-containing fuels are chemically and thermally different. Comparing all these fuels to gasoline will determine whether the results are due to chemical or thermal differences.

$$\Delta T = \frac{m_f \cdot h_{fg}}{(m_f + m_a) c_{p,ave}} = \frac{h_{fg}}{c_{p,ave}(1 + \lambda \cdot AFR_{stoich})} \tag{3.1}$$

Table 3.3: Fuel Types for LNF Ecotec Engine

Fuel	T_b at 1 atm (°C)	h_{fg} (kJ/kg)	LHV (MJ/kg)	AFR_{stoich} (kg/kg)	ΔT of air-fuel mixture at TDC (K)
E0	$T_{10}=38$ $T_{50}=80$ $T_{90}=127$	289	43.8	14.6	35
E20	$T_{10}=38$ $T_{50}=71$ $T_{90}=127$	402	40.8	13.5	52
E85	78	769	31.1	9.8	133
Isopentane	27.7	342	45.2	15.2	41

3.5 UBHC detection

Fully combusted fuel cotains solely CO_2 and H_2O. For incomplete combustion, HC compounds will exit into the exhaust. A Fast-Response Flame Ionization Detector (FFID) is a commonly used instrument to measure HCs in internal combustion engine research. Two FFIDs were used for this experiment, one measure the exhaust exiting cylinder 4, and the other measuring the exhaust after the turbocharger (comprised of a mixture of all four cylinders). Since this paper studies UBHC for turbocharged engines, the FFID placed after the turbocharger is of primary interest.

FFIDs ionize the hydrocarbons using hydrogen flame. The ions are collected, and the charge across the electrode is measured. Oxygen-containing fuels (like ethanol) give interesting, less reliable results however. When ethanol partially combusts and the species in the exhaust contain carbon to oxygen bonds, those UBHC are not accounted for [3]. Therefore the measurements for ethanol-containing fuels will be less accurate.

Chapter 4

Results and Discussion

4.1 Unburned Hydrocarbons

4.1.1 Direct Injection Spark Ignition

Emissions between four fuel types and two injection types were compared. Multiple operating points of 100 cycles (or approximately 10 seconds) were recorded. The data that most represented operating conditions for NIMEP, λ, and RPM.

DISI experimental results indicated generally increasing UBHC content in exhaust as the ethanol concentration increased (see Figure 4-2), even though FFID results for E0 were lower than expected. Fuels with higher h_{fg} values like those of ethanol-containing fuels are more difficult to vaporize during cold start (see Table 3.3).

We hypothesized a linearly increasing total hydrocarbon (THC) count as the concentration of ethanol in the fuel increased for DI. The THC value plateaus at E20, however. Possible reasons for this would include faulty readings of the FFID. Results of fuels containing oxygen are more uncertain than that of gasoline because the FFID does not count hydrocarbons that are bonded to oxygen [3]. Alternatively, a saturation point might exist, whereby with any increase in the concentration of ethanol, the FFID is unable to detect higher UBHC content. More trials should be conducted for operating points of E20 and E85, as well as concentrations inbetween to determine whether a relationship exists between THC and ethanol concentration.

As indicated in Figure 4-1, isopentane's UBHC value is similar to that of gasoline (501.99 ppmC1 ± 6% vs. 888.2 ppmC1 ± 3% respectively). This suggests that both gasoline and isopentane's chemical similarities were contributing factors. In DISI engines, higher compression ratios exist because less mass enters the chamber. During cold start, gasoline is a better fuel because of its low h_{fg}, but isopentane has a noticeably higher heat of vaporization (342 kJ/kg compared to 289 kJ/kg). Additionally, isopentane boils at 27.7 °C. This might explain why isopentane fuel vaporizes easily at high temperatures resulting in low total hydrocarbon (THC) count at the exhaust.

4.1.2 Port Fuel Injection

PFI results showed a linear response to increasing ethanol concentration in the fuel. E85 had 41% lower UBHC emissions than E0 (see Figure 4-1 and 4-2). The UBHC count decreases in PFI engines because ethanol is an organic fuel that contains oxygen. Since oxygen is necessary for combustion, more oxygen molecules present in the fuel increases the probability of combustion. This should not apply for DISI engines because of poor mixing effects. Fuel is better mixed in PFI engines because it is injected into the manifold before entering the chamber. However, results in Figure 4-1 show that PFI data for gasoline and isopentane have higher THC counts than that of DISI. Poor combustion quality of the fuel in the PFI engine could have resulted in higher UBHC. During the expansion stroke, the cylinder pressure drops and the temperature of the flame drops as well. This can reduce the burning rate of the fuel. If the temperature and pressure fall too quickly, the flame can be extinguished and the fuel quenched [5]. Crank angle degrees of the expansion stroke were measured (see Figure 4-3). The expansion stroke for the PFI runs were 10 degrees fewer than that of the DISI runs, which means that pressure and thus temperature fell more rapidly. Quench effects could have occured in the chambers of the PFI runs which would affect the THC readings. This effect might not be noticeable for ethanol containing fuels because of the higher oxygen content.

4.1.3 CAD and Burn Duration

Measuring percent of fuel burned with crank angle degrees is useful and accurate. Figures 4-4 and 4-6 indicate that the number of CADs for 10% to 90% of the fuel to burn overall decreased as ethanol content increased for both PFI and DISI runs.

4.2 Exhaust Species

In addition to measured counts of UBHC in the exhaust, O_2, CO_2 and CO species were all measured as well. Figure 4-7 shows a signifcantly higher concentration of O_2 for the E85 fuel in PFI. The burn duration for E85 for PFI was shorter than PFI runs of E0 and E20. Additionally, E85 had a lower THC than the DISI run (see Figure 4-1).

But overall, exhaust species and UBHC don't overlap predictably. Figure 4-2 shows a decrease and increase for UBHC for PFI and DISI, respectively. Low numbers of UBHC in the exhaust should indicate that the combustion was of high quality - or higher CO_2 and lower O_2 concentrations in the exhaust. O_2 exhaust readings are not entirely accurate, however, because we did not ensure the meter was calibrated.

Carbon monoxide concentrations significantly decreased from E20 to E85 in the PFI runs (see Figure 4-10). CO values are a function of both global and local mixing effects. No trends seem noticeable in DISI data. Carbon monoxide concentrations are alarmingly for E0 and E20. This surfaces concerns that the lambda sensor, was damaged, which would lead to increased pollutant emissions.

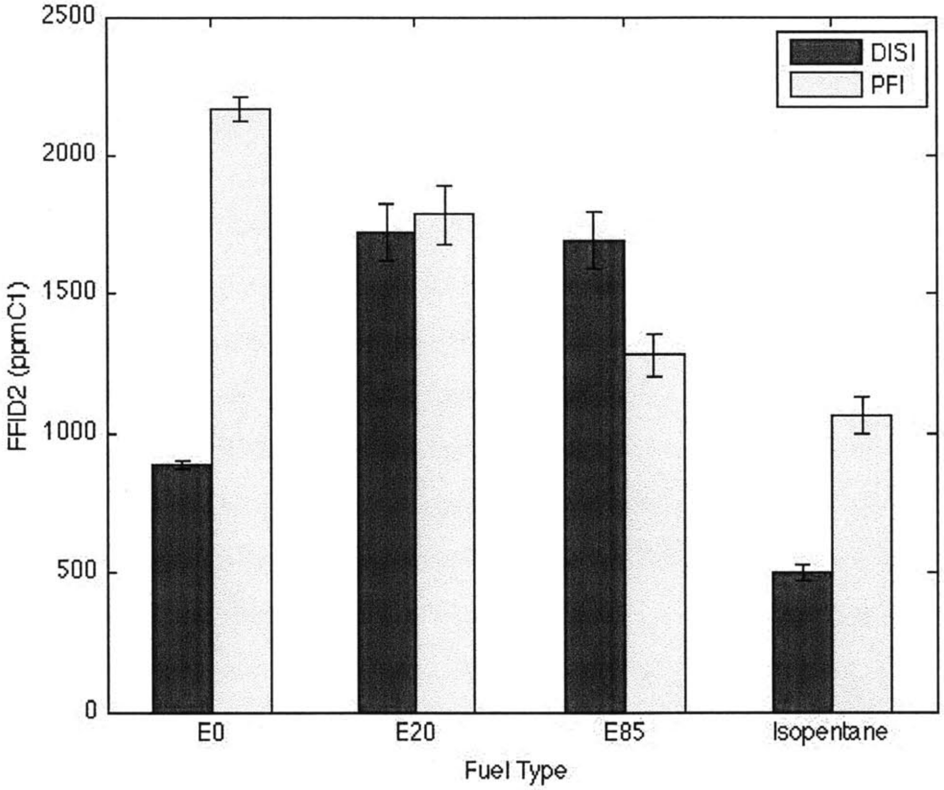

Figure 4-1: Unburned Hydrocarbons in Exhaust for Different Fuel Types.

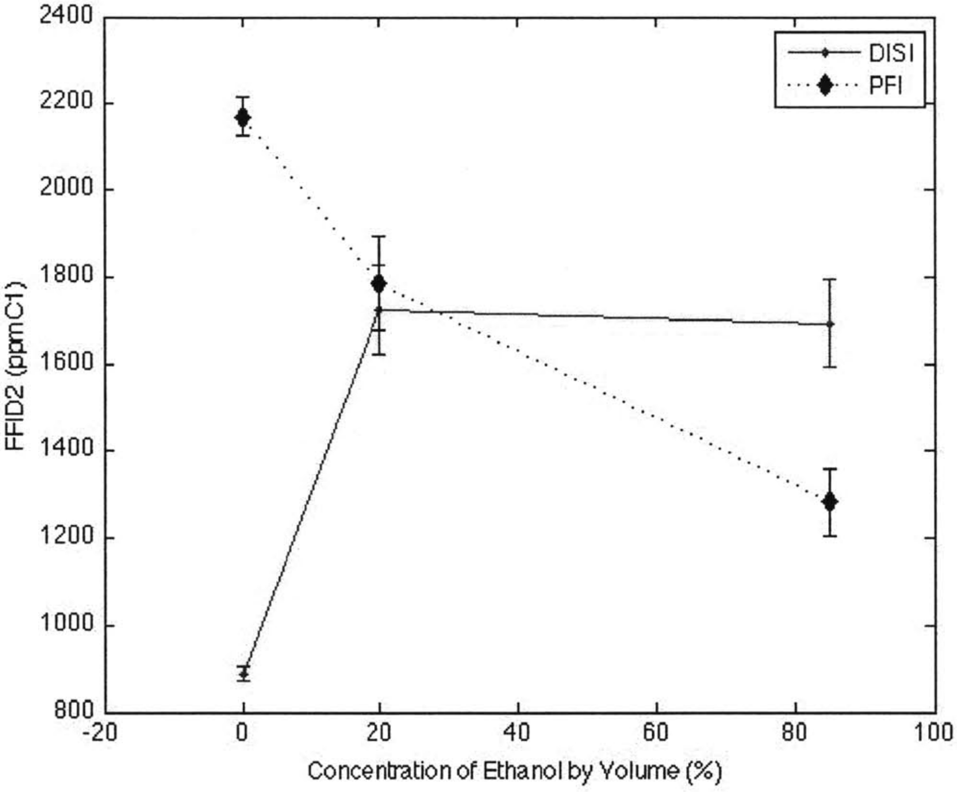

Figure 4-2: Unburned Hydrocarbons in Exhaust for Different Fuel Types.

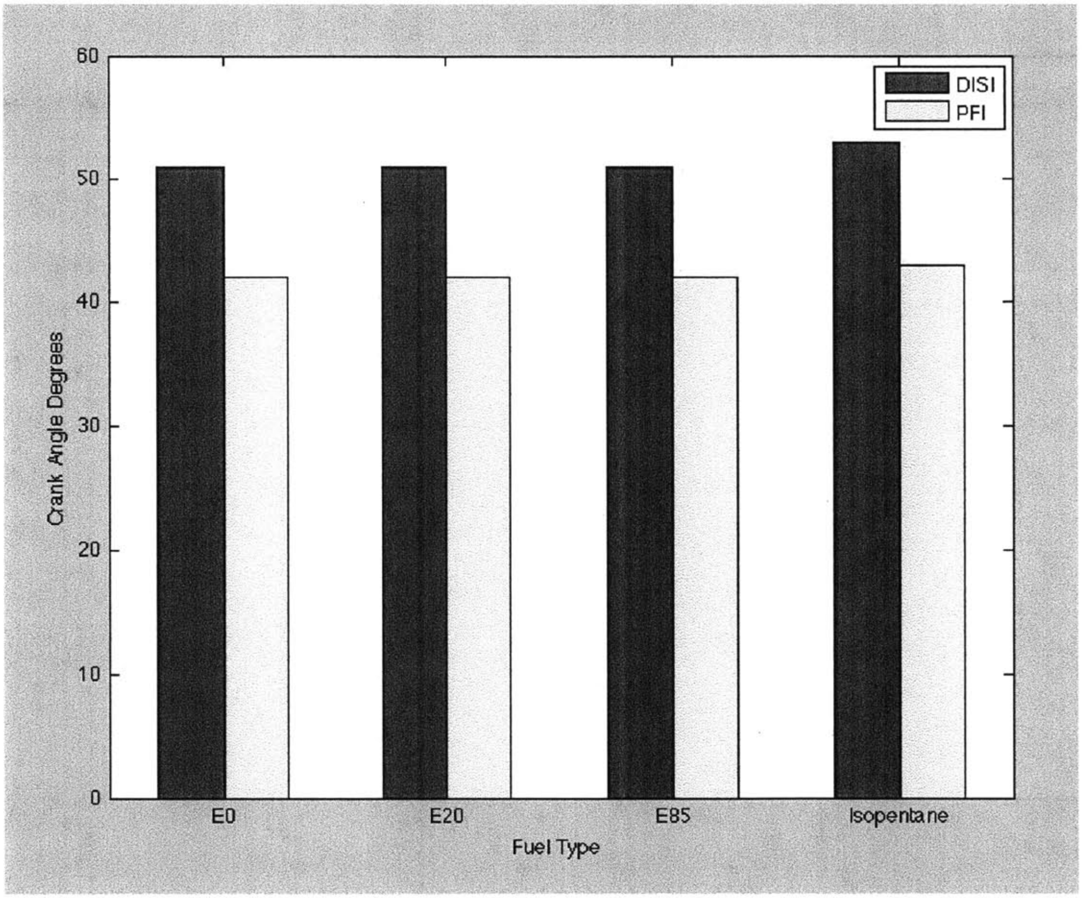

Figure 4-3: Number of crank angle degrees for the exhaust valve opening. This is during expansion, before BDC.

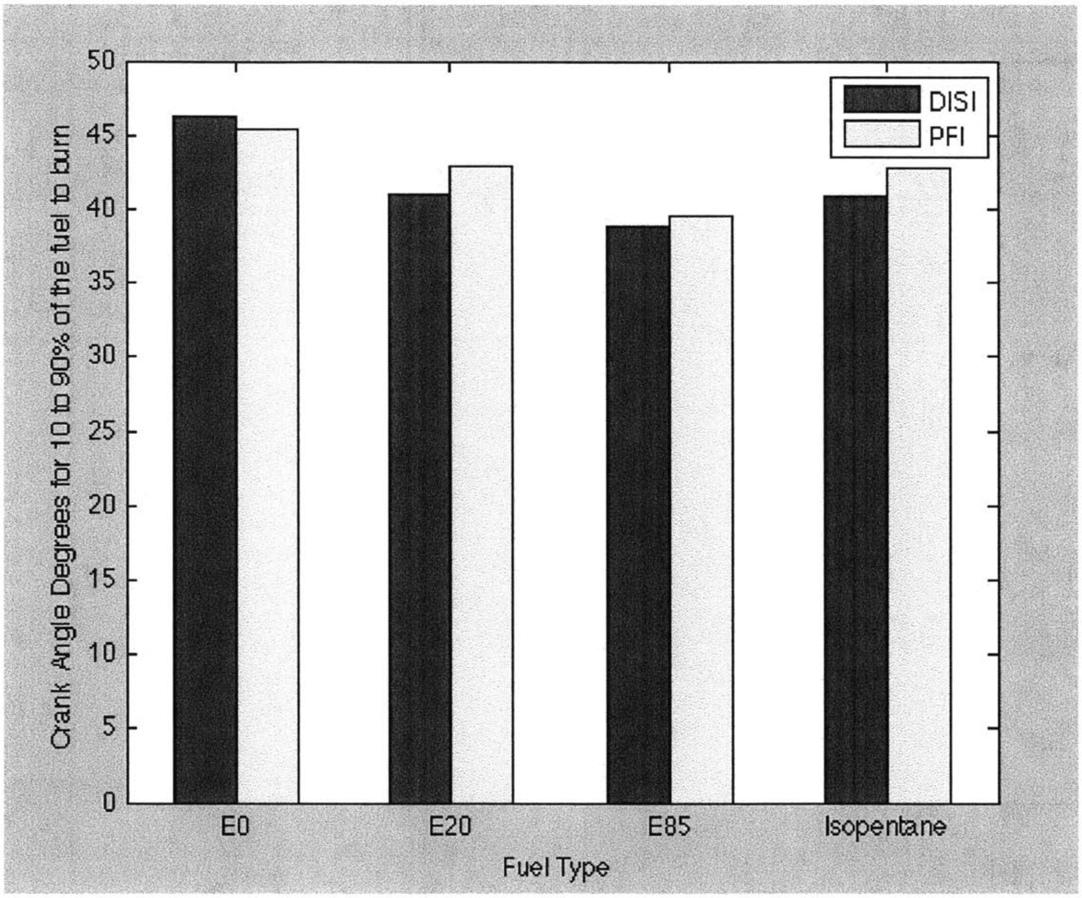

Figure 4-4: Burn Duration: number of crank angles for 10% to 90% of the fuel to burn.

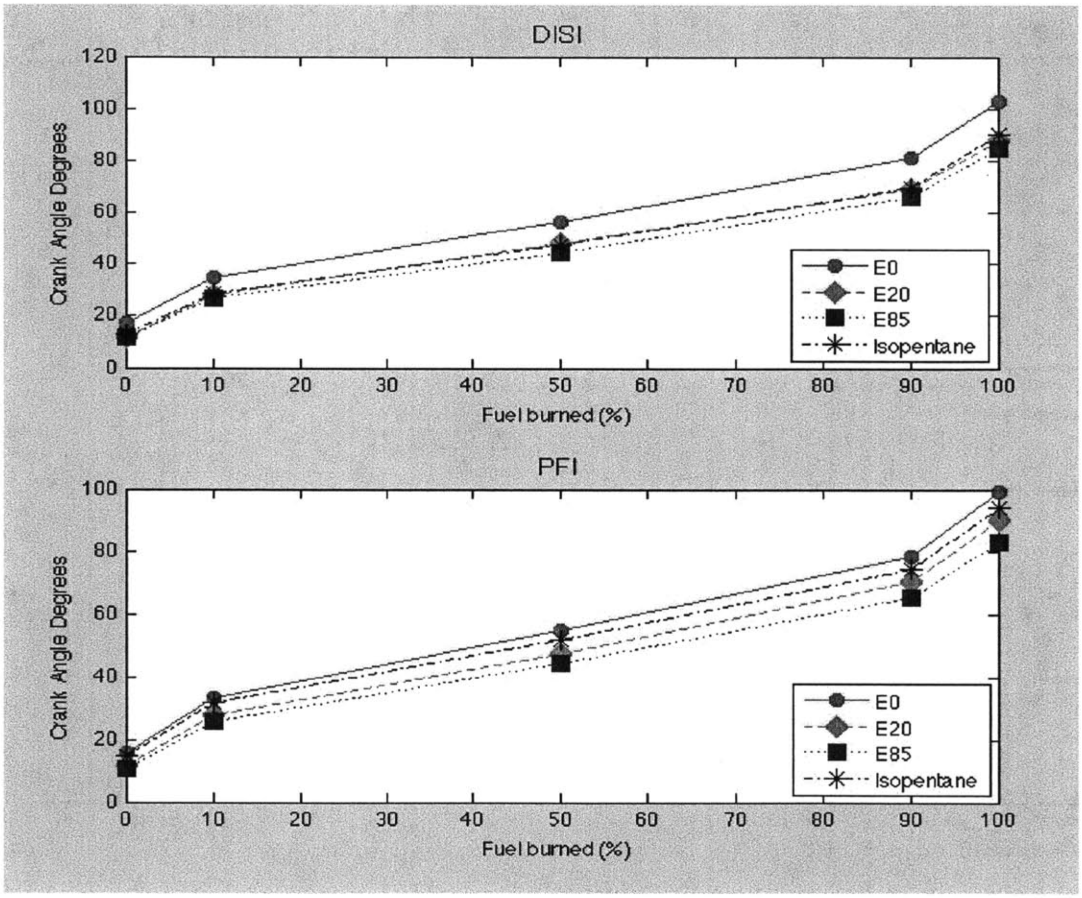

Figure 4-5: Number of crank angles for percent burn of fuel.

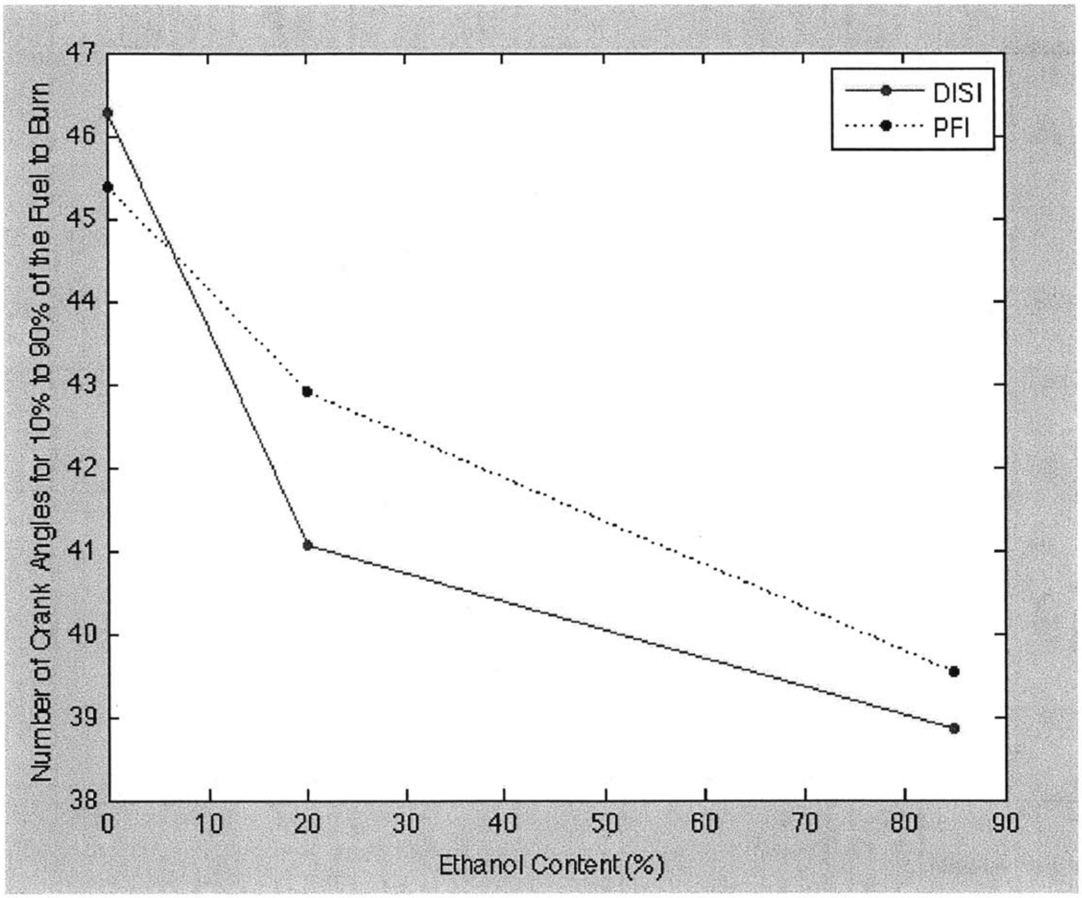

Figure 4-6: The influence of ethanol content in burn duration of fuel.

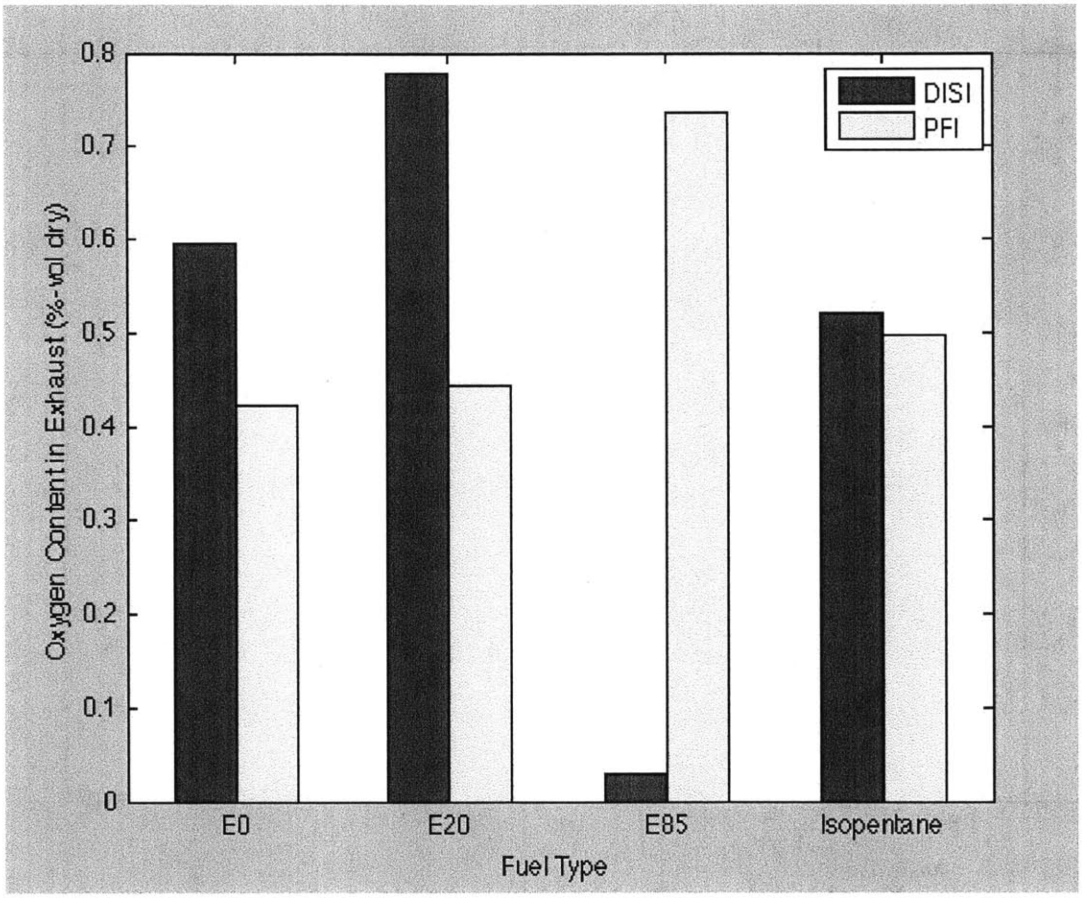

Figure 4-7: Oxygen concentration in the exhaust for different fuel types.

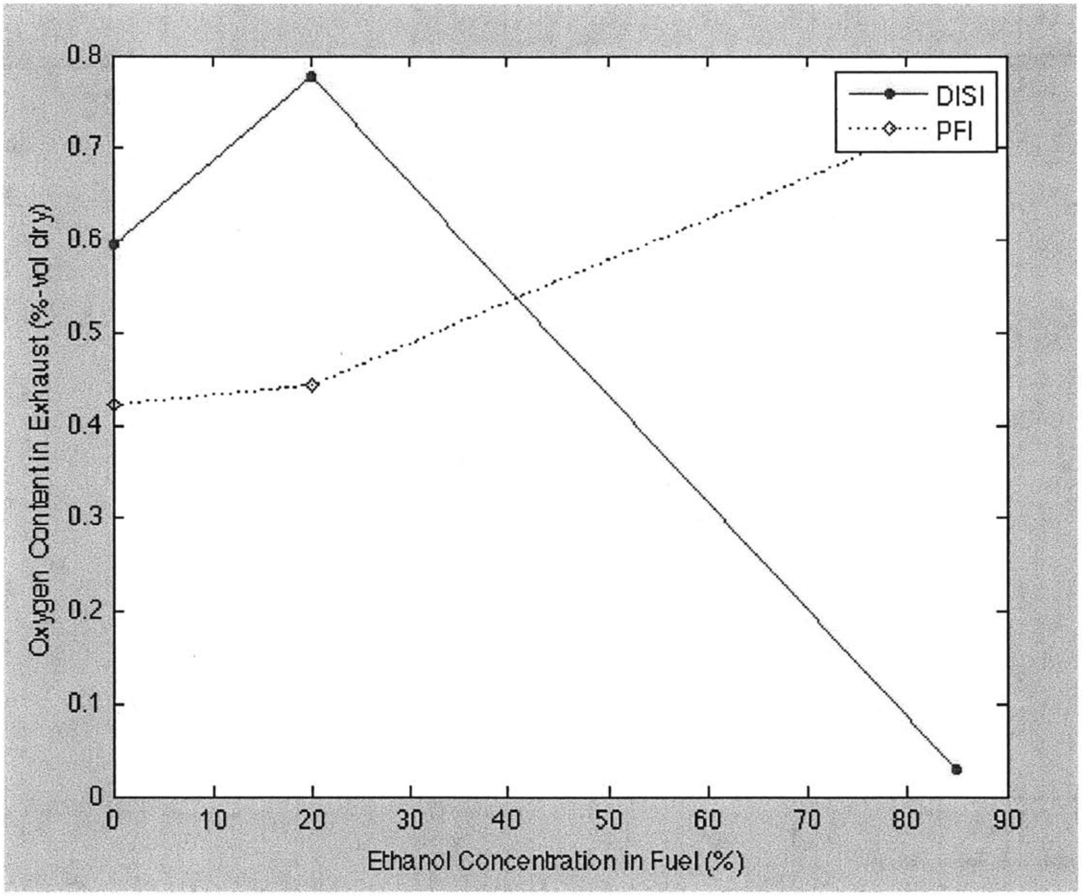

Figure 4-8: Oxygen concentration in the exhaust as a function of increasing ethanol concentration in fuel.

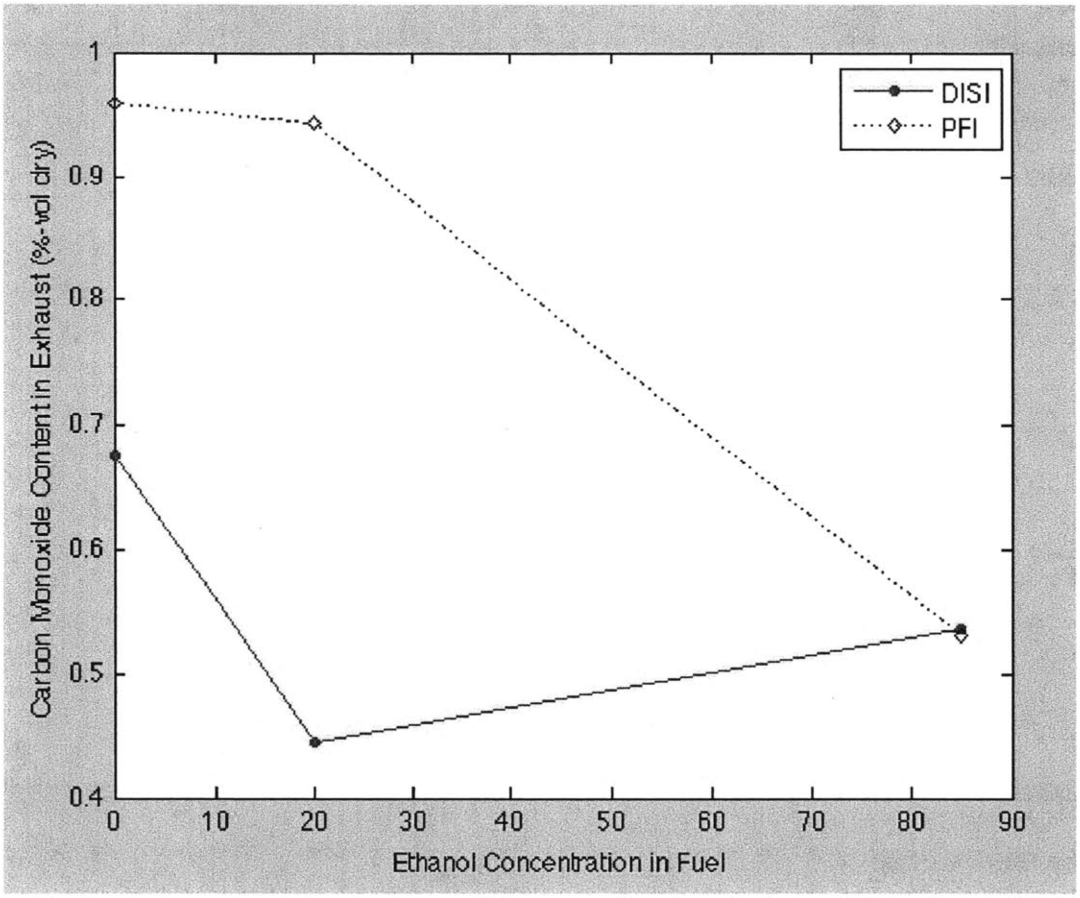

Figure 4-9: Carbon Monoxide concentration in exhaust for different fuel types.

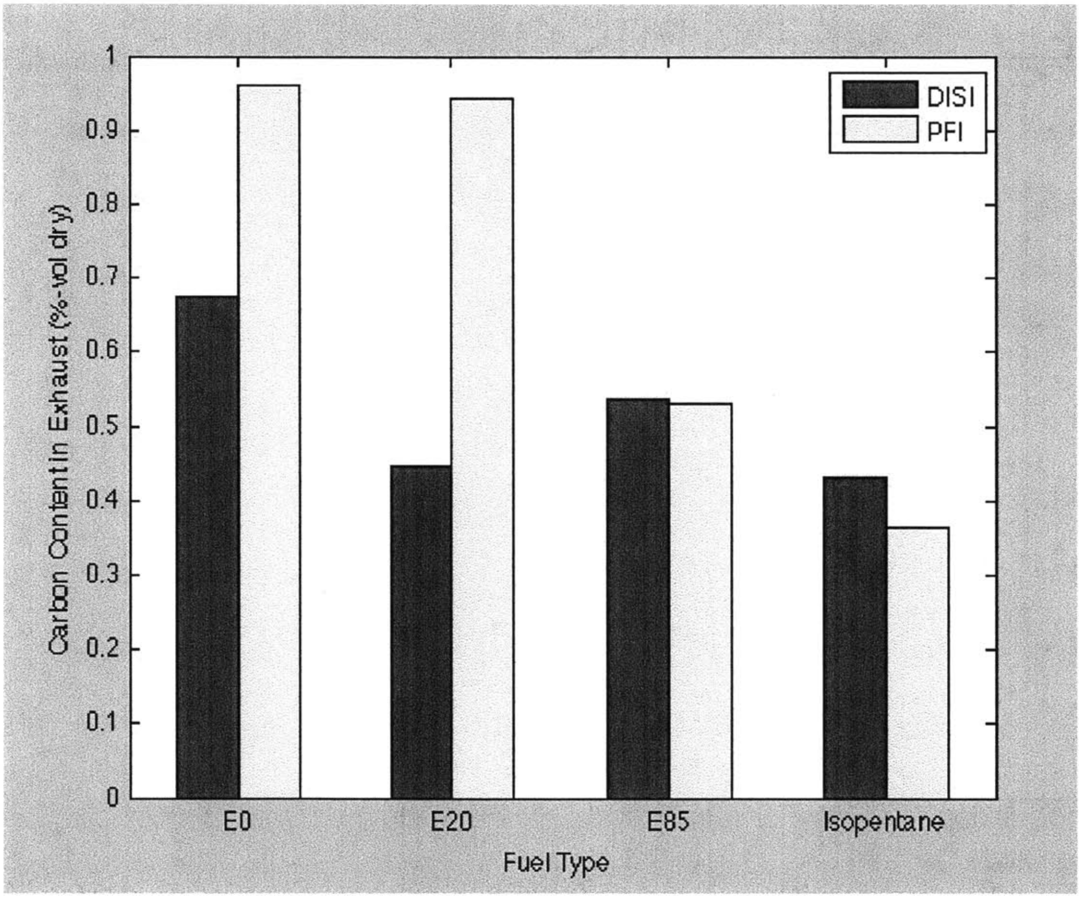

Figure 4-10: Carbon monoxide concentration in the exhaust as a function of increasing ethanol concentration in fuel.

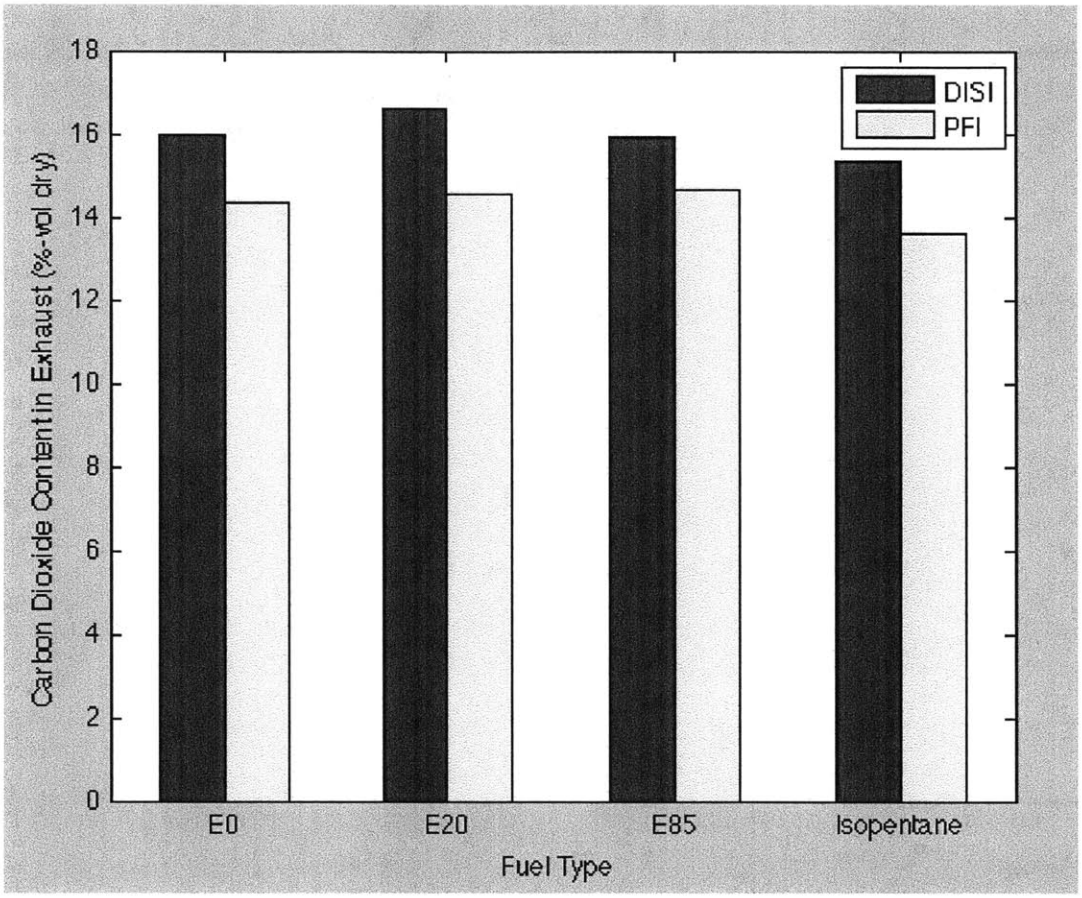

Figure 4-11: Carbon dioxide concentration in the exhaust as a function of increasing ethanol concentration in fuel.

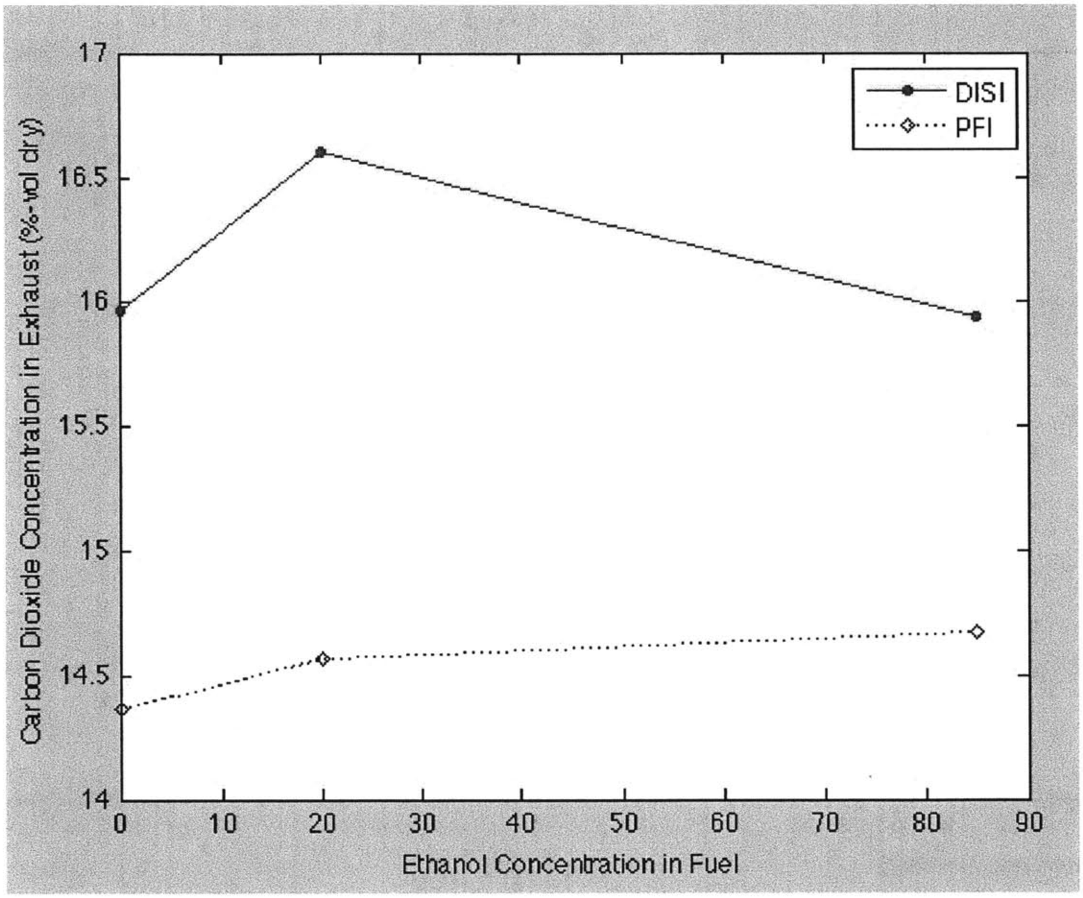

Figure 4-12: Carbon dioxide concentration in the exhaust as a function of increasing ethanol concentration in fuel.

Chapter 5

Conclusion

Research in cold start conditions have shown that 90% of UBHC emitted from vehicles occur during this 15 to 60 second period. Our particular setup removed geometry as a variable by testing two injection types on the same engine. This allowed us to study how mixing affects the concentration of UBHC in exhaust emissions for both DISI and PFI. Isopentane is chemically similar to gasoline but thermally different, whereas ethanol based fuels are both thermally and chemically different. We studied a variety of fuels to give us a better understanding of whether the quality of the mixing is due to chemical or thermal differences.

Results were inconclusive, however. We had reasonable predictions about trends for PFI and DISI as ethanol concentrations increased. But the data did not follow such behaviors, and neither the physical nature of the fuels nor the system used to run these fuels explain why. Sample operating points were observed for PFI and DISI data. We discovered some irregularities between FFID2 numbers of the same fuel but for two different operating points. We conjectured that throttling issues could have affected the results by changing the AFR. Additionally, for DISI runs, we ran the fuels lean because of the high CO levels being read by the lambda sensor. We speculate a faulty lambda sensor.

Trends were also difficult to observe because of the limited variety of fuels used for the experiment. This study only observed the behaviors of E0, E20 and E85 for DISI and PFI. A more robust study would test not only these fuels but also E10, E30, E40, etc. This would essentially flesh out the data for both runs and give a better picture of how UBHC concentrations are affected by increasing ethanol concentrations in the fuel.

The data evaluated was for a spark time at TDC. However, spark times representative of cold start are approximately 15 to 20 CAD after TDC. With later spark, the power stroke is smaller. The energy from the combustion is then used to heat up the engine, a process in cold start that is important for emissions. A variety of spark times were tested during data collection. A more valid analysis for this experiment would be to observe how a sweep of spark times affect the emissions across the tested fuels.

Although the data were inconclusive, the experiment is not entirely moot. Selecting data from the same runs that do not have irregularities between data of the same fuel would elminiate the potential throttling issues. Significant differences in the UBHC concentrations for PFI and DISI would give us insight into the UBHC left in the chamber. The dual PFI, DISI system provides a strong foundation for future studies on mixing.

Chapter 6

Definitions, Acronyms, Abbreviations

λ: The actual AFR divided by the stoichiometric AFR. λ greater than indicates a rich mixture, whereas λ less than 1 indicates a lean mixture.

AFR: Air to Fuel Ratio

BDC: Bottom Dead Center

DISI: Direct Injection Spark Ignition

CAD: Crank Angle Degree

CNG: Compressed Natural Gas

E0: Gasoline, Haltermann HF0437 Tier II EPA certified

E20: 20% Ethanol, 80% Gasoline

E85: 85% Ethanol, 15% Gasoline

EPA: Environmental Protection Agency

EVO: Exhaust Valve Opening

FFID: Fast response flame ionization detector

FTP: Federal Test Procedure

$\mathbf{h_{fg}}$: Heat of vaporization

NIMEP: Net Indicated Mean Effective Pressure. A measure of the engine's ability to do work

PFI: Port Fuel Injection

TDC: Top Dead Center

THC: Total Hydrocarbons

UBHC: Unburned hydrocarbons

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