

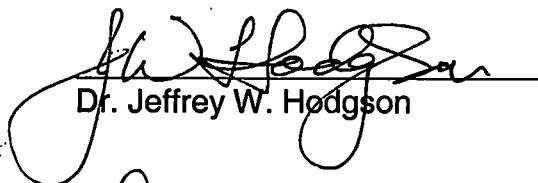
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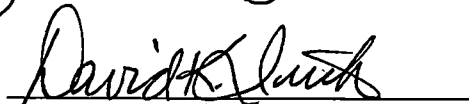


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**Study of NO_x and Loading of a Soot Filter versus EGR
for a 2.4-L Diesel Engine**

A Thesis

Presented for the

Masters of Science

Degree

The University of Tennessee, Knoxville

Palak Kirendra Patel

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This thesis is dedicated to my parents, Kirendra and Jyoti Patel, who never stopped encouraging me and for giving me the strength to persevere.

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ABSTRACT

The Environmental Protection Agency (EPA) has set forth strict diesel emissions regulations that will take effect in 2004 and be totally phased in by 2007. For this action, the automotive industry has been compelled to assess new and current technologies to reduce diesel engine tailpipe emissions. Particulate matter (PM) and oxides of nitrogen (NO_x) are the emissions of major distress. Both emissions are linked to cause damage to plant and animal ecosystems and adversely affect human health.

For many years, several methods have been employed to reduce PM and NO_x . Currently, the most widely used techniques to reduce these emissions are exhaust gas recirculation (EGR) and the particulate filter. NO_x formation is heavily dependent on temperature and EGR reduces peak temperatures in the combustion chamber. PM emitted by diesel engines is primarily trapped by particulate filters and are removed from the filter by combustion or other similar methods.

The purpose of this study is to investigate the dependence of NO_x and PM emissions on EGR at various engine loads (0%, 25%, 50%, and 75% rated engine torque) and engine speed of 2000 rpm. The test cell used in this study employs a water brake dynamometer with a 2.4-L, five cylinder inline diesel engine. A vacuum driven system was implemented to control the EGR flow rate manually. For the purpose of this study, EGR rate was determined

by the ratio of CO_2 in the intake and exhaust. The measurements of the various exhaust quantities were determined by using the appropriate emission analyzers. The loading of the Microwave Regenerable Particulate Trap used in this study was expressed by the efficiency of the filter, which was determined by the measurement of smoke before and after the filter by the use of a smoke meter.

This study shows that high levels of EGR are an effective method for the reduction of NO_x , but increases the amount of PM emissions. For 75% engine load, NO_x was lowered by 46% over the respective EGR range. Particulate emissions increased as EGR increased and for all loads and these emissions started to spike at "critical" EGR levels. PM spiked at 7% EGR for 75% engine load with appropriate increases for 25% and 50% engine loads. For the particulate trap used in the study, the effectiveness increased as EGR increased. Again, for 75% load, the efficiency of the filter varies from 50% at 0% EGR to 74.2% at roughly 10% EGR with the majority of the efficiency increase occurring beyond the "critical" EGR level.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION	1
Background.....	2
Oxides of Nitrogen	2
Formation of Oxides of Nitrogen in Compression Ignition Engines	2
Environmental Concerns of Oxides of Nitrogen	4
Health Effects of Oxides of Nitrogen	7
Reduction Methods of Oxides of Nitrogen.....	7
Particulate Matter	15
Formation of Particulate Matter in Compression Ignition Engines	15
Environmental Concerns of Particulate Matter	16
Health Effects of Particulate Matter	19
Reduction Methods of Particulate Matter	20
Statement of Problem	22
Approach	23

CHAPTER 2

EQUIPMENT	25
Engine and Engine Peripherals.....	25
Engine Control	27
Microwave Regenerative Particulate Filter.....	27
EGR Control System.....	30
Exhaust Analysis.....	31

CHAPTER 3

PROCEDURE.....	40
Venturi Tube Evaluation.....	40
EGR Variation Tests	44
Initial Setup	44
Testing	45
Testing Procedure.....	49
Testing Discussion	50
Data Recording	53

CHAPTER 4

RESULTS AND DISCUSSION	54
------------------------------	----

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS.....	83
--------------------------------------	----

BIBLIOGRAPHY	86
--------------------	----

APPENDIX	89
----------------	----

Engine Specifications.....	90
----------------------------	----

VITA.....	91
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LIST OF TABLES

Table 1.1 – Types of oxides of nitrogen.....	3
Table 1.2 – Typical composition of diesel exhaust PM	16
Table 1.3 – Typical components of soluble organic fraction	17
Table 2.1 – Exhaust constituents measured.....	32
Table 3.1 – Pressure data from intake line	43
Table 4.1 – Recorded data from two test runs for 0% and 25% engine loads. Engine operated at 2000 rpm	55
Table 4.2 – Recorded data from two test runs for 50% and 75% engine loads. Engine operated at 2000 rpm	56

LIST OF FIGURES

Figure 1.1 - Effect of injection timing on nitrogen oxides emissions in DI and IDI engines.....	9
Figure 1.2 – General trend on emissions due to the influence of EGR.....	10
Figure 1.3 –Trend on particulate matter accumulation and NO _x concentration due to the influence of EGR	12
Figure 1.4 – NO _x -storage catalyst operation under oxidizing and reducing conditions	14
Figure 1.5 – SFR (self-supported filter regeneration) system	22
Figure 2.1 – Alfa Romeo 2.4-liter diesel engine	26
Figure 2.2 - Original cooling and intercooler setup	28
Figure 2.3 - Updated cooling and intercooler setup	28
Figure 2.4 – Schematic of Microwave Regenerative Particulate Filter.....	29
Figure 2.5 – Schematic of EGR control system	30
Figure 2.6 – EGR Varying system control panel.....	32
Figure 2.7 – Exhaust after treatment setup.....	34
Figure 2.8 – Particulate concentration versus Bosch smoke number	37
Figure 2.9 – Alignment chart of relationships between various particulate-smoke measurements.....	38
Figure 2.10 – Emissions test bench.....	39
Figure 3.1 – Experimental setup for pressure and temperature measurements	41
Figure 3.2 – Intake manifold sampling tube	46
Figure 3.3 – Intake manifold sampling tube orientation in experimental setup.....	47

Figure 3.4 – Sample probes for smoke measurement.....	48
Figure 3.5 – Illustration of experimental setup	51
Figure 3.6 – Actual experimental setup	52
Figure 4.1 – NO _x versus EGR for 0% Load. Engine operated at 2000 rpm.....	57
Figure 4.2 – NO _x versus EGR for 25% Load. Engine operated at 2000 rpm.....	58
Figure 4.3 – NO _x versus EGR for 50% Load. Engine operated at 2000 rpm.....	59
Figure 4.4 – NO _x versus EGR for 75% Load. Engine operated at 2000 rpm.....	60
Figure 4.5 – Exhaust opacity versus EGR for 0% Load. Engine operated at 2000 rpm.....	62
Figure 4.6 – Exhaust particulate concentration versus EGR for 0% Load. Engine operated at 2000 rpm	63
Figure 4.7 – Exhaust opacity versus EGR for 25% Load. Engine operated at 2000 rpm.....	64
Figure 4.8 – Exhaust particulate concentration versus EGR for 25% Load. Engine operated at 2000 rpm	65
Figure 4.9 – Exhaust opacity versus EGR for 50% Load. Engine operated at 2000 rpm.....	66
Figure 4.10 – Exhaust particulate concentration versus EGR for 50% Load. Engine operated at 2000 rpm	67
Figure 4.11 – Exhaust opacity versus EGR for 75% Load. Engine operated at 2000 rpm	68
Figure 4.12 – Exhaust particulate concentration versus EGR for 75% Load. Engine operated at 2000 rpm	69

Figure 4.13 – NO _x versus exhaust opacity for 50% Load and both test runs. Engine operated at 2000 rpm	71
Figure 4.14 – NO _x versus exhaust particulate concentration for 50% Load and both test runs. Engine operated at 2000 rpm	72
Figure 4.15 – NO _x versus exhaust opacity for 75% load. Engine operated at 2000 rpm.....	73
Figure 4.16 – NO _x versus exhaust particulate concentration for 75% load. Engine operated at 2000 rpm	74
Figure 4.17 – NO _x versus Pre-Filter exhaust opacity for all loads and both test runs. Engine operated at 2000 rpm. Smoke units in opacity (%)	75
Figure 4.18 – NO _x versus Post-Filter exhaust opacity for all loads and both test runs. Engine operated at 2000 rpm. Smoke units in opacity (%)	76
Figure 4.19 – NO _x versus Pre-Filter exhaust particulate concentration for all loads and both test runs. Engine operated at 2000 rpm. Smoke units in concentration (mg/m ³)	77
Figure 4.20 – NO _x versus Post-Filter exhaust particulate concentration for all loads and both test runs. Engine operated at 2000 rpm. Smoke units in concentration (mg/m ³)	78
Figure 4.21 – Effect of EGR and EGR cooling on NO _x and Particulates	80
Figure 4.22 – NO _x and smoke measurements for different loads and EGR ..	81

CHAPTER 1

INTRODUCTION

Globally, diesel engines play an important role in transportation and power generation. They are used in both mobile and stationary applications. Mobile diesels include automobiles, trucks, buses, trains, boats, and many types of heavy machinery. Major uses of stationary diesel engines are in oil and gas exploration and production as well as for base-load and standby-load electricity generation. Diesels, compared to gasoline spark ignition engines, typically operate with much higher compression ratios and they do not throttle the intake air to control their torque output. Both of these contribute to their higher fuel economy. However, diesel engines produce emissions of oxides of nitrogen and particulate matter, which are major contributors to air pollution. Because of this, various techniques have been employed to reduce these emissions, including exhaust gas recirculation (EGR) and exhaust gas after treatment.

In this study, the impact of exhaust gas recirculation on the oxides of nitrogen and particulates was investigated and documented for a 2.4-liter diesel engine. The variation of the exhaust gas recirculation was accomplished by controlling the vacuum actuated EGR valve. Particulates were collected with a microwave regenerable particulate filter. The collection efficiency was determined by the measurement of smoke upstream and

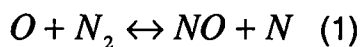
downstream of the filter.

Background

Oxides of Nitrogen

Formation of Oxides of Nitrogen in Compression Ignition Engines

There are seven types of oxides of nitrogen [1]. These are included in Table 1.1. The major air pollutants of these seven are nitric oxide (NO) and nitrogen dioxide (NO₂). Nitrogen oxides are formed during the combustion process by the primary method of high temperature thermal fixation of the molecular oxygen (O₂) and nitrogen (N₂) present in the combustion air [2]. The widely accepted mechanism for this method of NO_x formation is the *thermal* or *Zeldovich mechanism*. The Zeldovich mechanism consists of two chain reactions:



which can be extended by adding the following reaction:



This three-reaction set is referred to as the *extended Zeldovich mechanism*.

The first reaction is relatively slow, while the other two are relatively fast.

Increased combustion temperature increases the rate of the forward reaction 1

Table 1.1 – Types of oxides of nitrogen [1].

Constituent	Formula
Nitric oxide	NO
Nitrogen dioxide	NO ₂
Nitrogen trioxide	NO ₃
Nitrous oxide	N ₂ O
Nitrogen trioxide	N ₂ O ₃
Nitrous tetroxide	N ₂ O ₄
Nitrous pentoxide	N ₂ O ₅

as well as the concentration of O atoms, thus favoring the formation of NO and N [4]. The forward and reverse rate of reaction coefficients are listed below [3].

$$\begin{aligned}
 K_{(1)f} &= 1.8 \cdot 10^{11} \exp[-38,370/T(K)] & [=] \text{ m}^3/\text{kmol-s} \\
 K_{(1)r} &= 3.8 \cdot 10^{10} \exp[-425/T(K)] & [=] \text{ m}^3/\text{kmol-s} \\
 K_{(2)f} &= 1.8 \cdot 10^7 T(K) \exp[-4680/T(K)] & [=] \text{ m}^3/\text{kmol-s} \\
 K_{(2)r} &= 3.8 \cdot 10^6 T(K) \exp[-20820/T(K)] & [=] \text{ m}^3/\text{kmol-s} \\
 K_{(3)f} &= 7.1 \cdot 10^{10} \exp[-450/T(K)] & [=] \text{ m}^3/\text{kmol-s} \\
 K_{(3)r} &= 1.7 \cdot 10^{11} \exp[-24560/T(K)] & [=] \text{ m}^3/\text{kmol-s}
 \end{aligned}$$

N can further react to form additional NO via reactions 2 and 3. The higher the combustion reaction temperature, the more diatomic nitrogen, N₂, will dissociate to monatomic nitrogen, N, which leads to greater formation OF NO_x

[5]. This dependence on temperature can also be seen in the initial formation rate of NO. The initial formation rate of NO is taken as

$$\frac{d[NO]}{dt} = \frac{6 \cdot 10^{16}}{T^{1/2}} \exp\left(\frac{-69090}{T}\right) [O_2]_e^{1/2} [N_2]_e \quad \text{mol/cm}^3 \cdot \text{s} \quad [6].$$

where,

T = temperature of reaction

$[O_2]$ = concentration of oxygen

$[N_2]$ = concentration of nitrogen

Heywood [6] states that there is a strong dependence of $d[NO]/dt$ on temperature in the exponential term. This reliance on temperature results in high NO formation rates. The formation of NO_x becomes an obvious problem since compression ignition engines have high compression ratios that produce higher cylinder temperatures.

Environmental Concerns of Oxides of Nitrogen

Oxides of nitrogen are of importance because they affect the environment. The effects on the environment include the formation of photochemical smog, global warming, and acid rain. Photochemical smog is a brownish-gray hazed air pollution caused by a complex chemical reaction of solar ultraviolet radiation in the atmosphere polluted by hydrocarbons and oxides of nitrogen [2]. In an atmosphere consisting of only NO_x pollution and no reactive hydrocarbons, the conversion of NO_2 and oxygen into ozone (O_3)

and NO is balanced by the conversion of NO back to NO₂. The latter conversion consumes ozone so the net result of the cycle is no more than a slight warming of the air from the energy of the absorbed light [7]. When certain hydrocarbons are present in the atmosphere, however, this balance is disrupted. These hydrocarbons convert NO back to NO₂, without converting an equivalent amount of ozone back to oxygen. This reaction permits the accumulation of ground level ozone and nitrogen dioxide that are the principal features of photochemical smog. This pollution has also been shown to damage plants if the concentration is sufficiently high.

Global warming is produced by the ability of certain trace gases to trap radiant energy in the earth's atmosphere. These greenhouse gases (primarily carbon dioxide, but also including water vapor, chlorofluorocarbons (CFC's), methane and others) are nearly transparent to the visible and near-infrared wavelengths in sunlight, but they absorb and re-emit downward a large fraction of the longer infrared wavelengths emitted by the earth [8]. Another contributing factor to global warming is the eradication of the stratospheric ozone layer. This destruction is primarily credited to the release of CFC's from aerosol cans and refrigeration systems, but this ozone can also be consumed by nitric oxide (NO) as discussed previously. Because the ozone layer serves to protect the earth from some of the sun's ultraviolet radiation, as it is depleted more radiant energy is allowed to enter the earth's atmosphere where it can be absorbed by greenhouse gases [8].

Acid rain is produced by the absorption of the primary pollutants sulfur dioxide (SO_2) and nitrogen oxides (NO_x) in atmospheric water to form sulfuric acid (H_2SO_4) and nitric acid (HNO_3) [2]. NO_x are attributed to vehicle emissions, while SO_2 is produced via volcanoes and the oxidation of sulfur gases produced by the decomposition of plants. Coal power plants are also major sources of both NO_x and SO_x . Acid rain is formed high in the clouds where sulfur dioxide and nitrogen oxides react with water, oxygen, and oxidants. This creates a mild solution of sulfuric acid and nitric acid. Sunlight often increases the speed at which the reactions occur. Rainwater, snow, fog, and other forms of precipitation containing these new solutions of sulfuric and nitric acids fall to earth as acid rain [9]. When this acid rain returns to the earth, it can adversely affect the ecosystems of the planet. Aluminum that is present in soil is freed by the acid rain and in turn is absorbed by the roots of trees. This deprives trees of vital nutrients such as calcium and magnesium, and is causing whole forests to disappear [9]. The aquatic ecosystem is also heavily affected by acidic precipitation. In the spring, many aquatic species reproduce, and some of these species lay their eggs in the water to hatch. The sudden pH change can cause serious deformities in their young or even kill off the whole species since the young spend a lot of their crucial primary life cycle in the water [9].

Health Effects of Oxides of Nitrogen

There are several different types of health effects caused by the oxides of nitrogen. These effects can be directly linked to the environmental effects that are brought about by NO_x . In the case of photochemical smog, irritation of the eyes has become an issue where this type of pollution is common, such as large metropolitan areas like Los Angeles and New York. With global warming, in which the ozone layer is being depleted, the increasing penetration of ultraviolet radiation can promote skin cancer and other DNA-related problems [10].

With these affects aside, oxides of nitrogen themselves are capable of causing varying levels of damage to human health. Health risks brought about by NO_x range from irritation of the eyes, as mentioned above, to the damage of the lungs, liver and the heart [10]. In low concentrations, oxides of nitrogen may produce only mild upper respiratory tract symptoms, but long-term exposure to low concentrations can lead to chronic lung damage [10]. Because NO_2 is not very soluble, it is a deep lung irritant that may reach the bronchioles and alveoli. The inhaled gas dissolves in the aqueous epithelial lining of the nasal and pharyngeal passages where it rapidly forms nitrous and nitric acids [2]. The latter involves acute exposure to NO_x .

Reduction Methods for Oxides of Nitrogen

The control of NO_x in compression ignition engines is usually achieved

in one or both of the following, during the combustion process or exhaust treatment. Control of oxides of nitrogen during the combustion process can be accomplished by various methods. Two of the most practiced are the retard of injection timing and exhaust gas recirculation. The retard of injection has been found to be very effective in the reduction of NO emissions in both direct injection (DI) and indirect injection (IDI) diesel engines. This is mainly due to the reduction in the residence time and in the maximum temperatures in the combustion chamber [11]. The effect of injection retard is shown in Figure 1.1 below. As the figure shows, the effect of injection timing in the reduction of NO_x is sufficient in both DI and IDI engines, although it is more effective in direct injection engines.

The other method used to reduce NO_x during the diesel combustion process is *Exhaust Gas Recirculation* (EGR). Since the formation of NO_x is greatly dependent on high temperatures, EGR has been used as a means to reduce peak temperatures during combustion. Since the exhaust gas does not participate in the combustion process, it absorbs some of the energy and hence, lowers the peak temperature and reduces NO_x formation. When the gas is introduced into the intake manifold, it displaces some of the oxygen of the intake charge. Because of this reduction of oxygen, EGR is commonly used at part load, or when the fuel-air ratio is sufficiently high so as not to cause a dramatic increase in other emissions [2]. This increase is illustrated in Figure 1.2. The engine used to generate the graph is a Ford prototype 1.8-

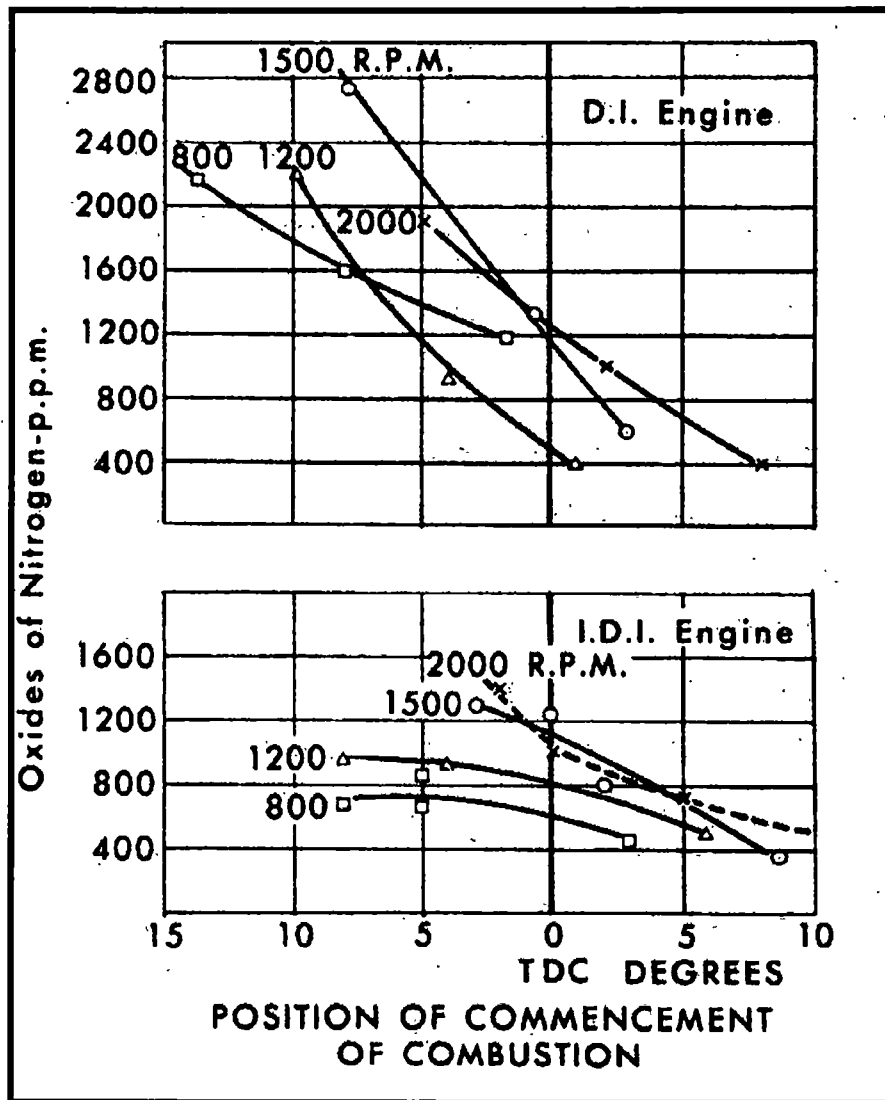


Figure 1.1 - Effect of injection timing on nitrogen oxides emissions in DI and IDI engines [11].

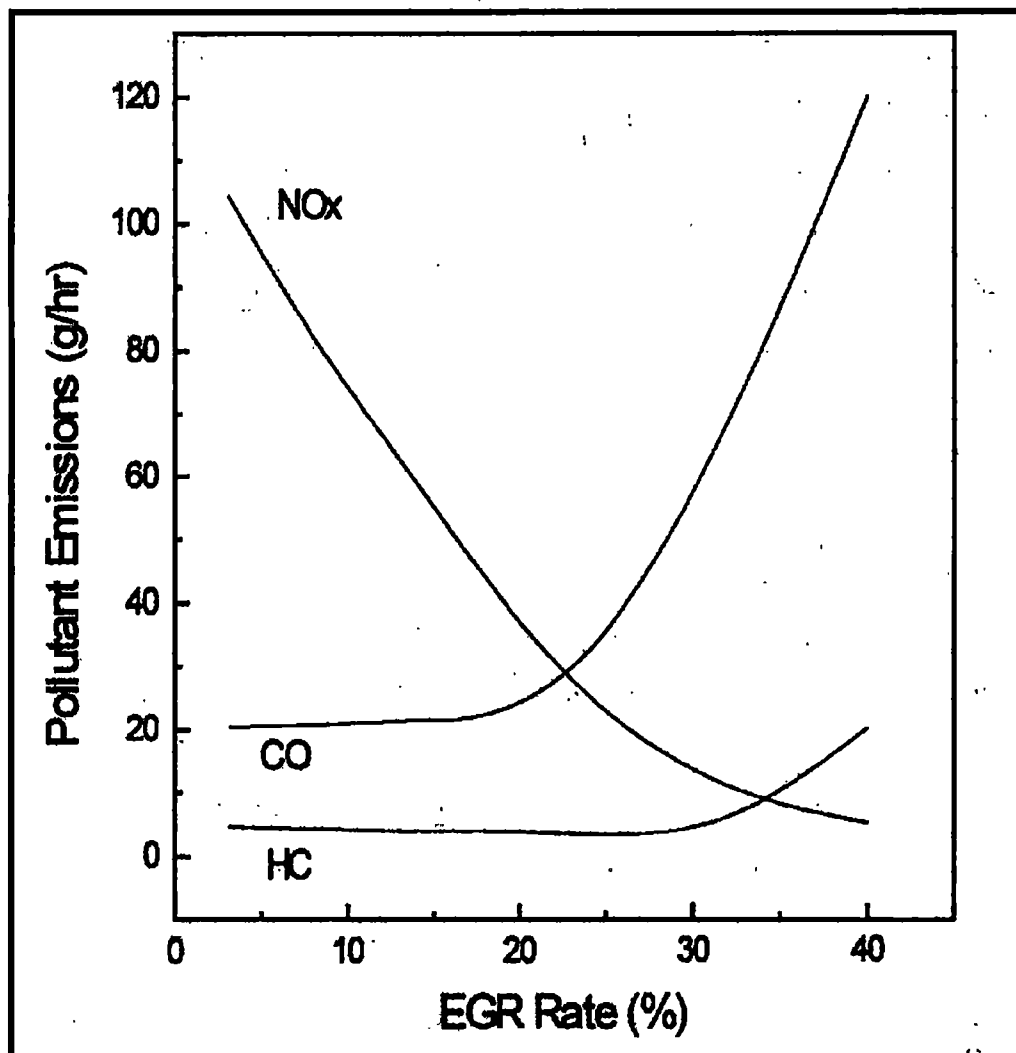


Figure 1.2 – General trend on emissions due to the influence of EGR [2].

liter DI engine [2]. As can be seen in the figure, as the EGR rate increases, the amount of NO_x produced decreases, while the amounts of carbon monoxide (CO) and hydrocarbons (HC) increase. It should also be noted that CO and HC are not the only emissions that are affected by the increase of EGR. Particulate matter also increases in an inverse manner as EGR increases. This relationship is demonstrated in Figure 1.3. The graph shows the particulate matter accumulation rate and concentration of NO_x versus increasing EGR rates for a Volkswagen 1.9-liter DI, turbocharged engine [12]. As can be seen, as with the CO and HC emissions, the particulate accumulation rate increases as NO_x decreases. This is a very pertinent detail to notice when deciding the rate of EGR to use at certain points during engine operation. Too much EGR can lead to excellent NO_x reduction whereas particulate matter emissions would increase in an almost inverse fashion. Excessive EGR will also lead to lower engine power output and decreased fuel economy.

Exhaust treatment is also employed to lower nitrogen oxide emissions from compression ignition engines. There are strategies under research such as lean NO_x catalysts, *Selective Catalytic Reduction* (SCR), and NO_x storage traps. The challenge in reducing NO_x emissions from diesel engines with a catalyst stems from the fact that the engines run lean, and hence, there is excess O_2 in the exhaust stream. The key to catalytically reducing NO_x emissions is a reducing, not an oxidizing reaction [13]. Lean NO_x catalysts

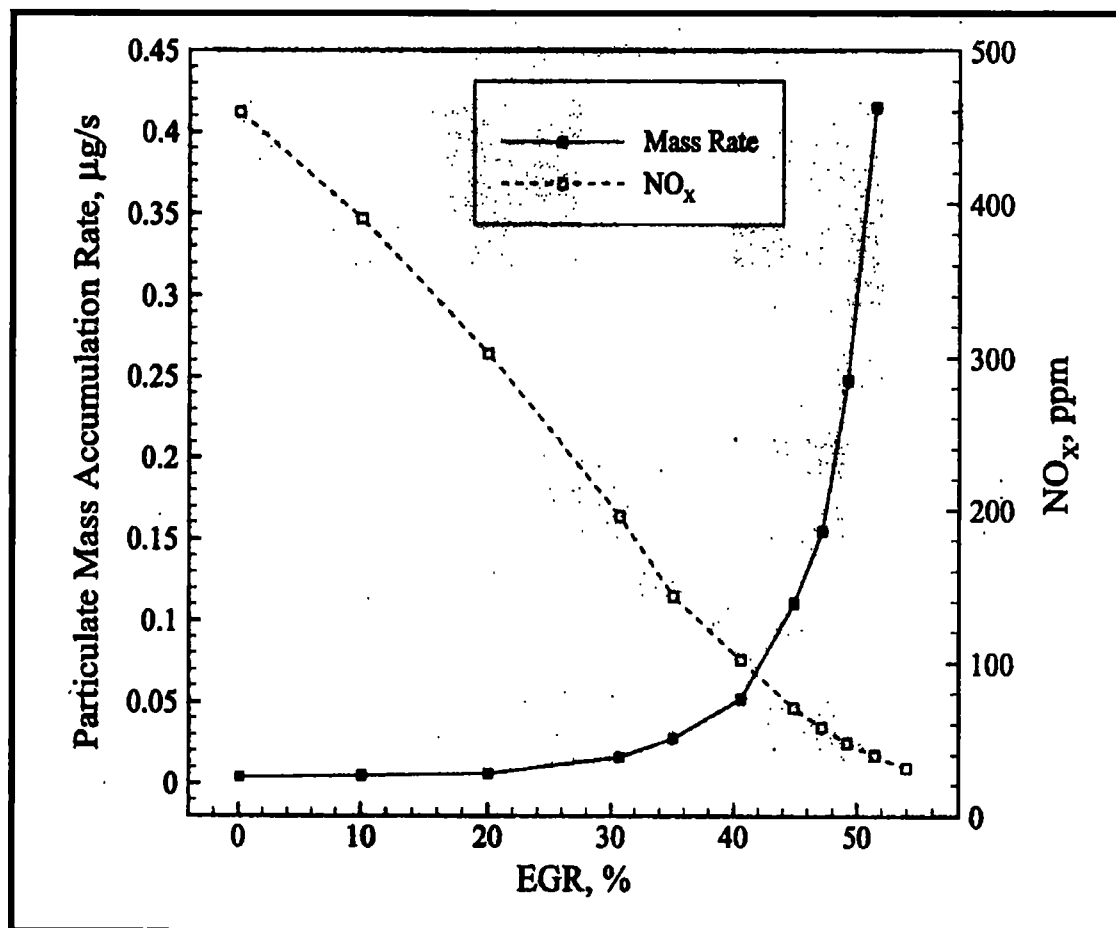


Figure 1.3 – Trend on particulate matter accumulation and NO_x concentration due to the influence of EGR [12].

employ base metals and/or precious metals contained on zeolitic structures [13]. The zeolitic structure acts to provide a local reducing environment, essentially creating a rich environment where the catalyst promotes the reaction of NO_x and other emissions such as HC and CO to form N_2 , O_2 , and water [13].

NO_x storage traps and SCR are new and emerging technologies in the reduction of oxides of nitrogen. NO_x storage catalysts employ a high Pt content catalyst for oxidation of NO to NO_2 . The NO_2 is then stored, using one of a number of barium compounds, such as barium nitrate. For approximately 2- second durations every 2 minutes, diesel fuel is either sprayed into the exhaust or injected into the cylinder after combustion to provide the necessary hydrocarbons to remove the NO_x from the storage components. The NO_x is then reduced over a standard three-way catalytic converter [14]. A generalized schematic of the operation of this device is shown in Figure 1.4 [14]. The NO_x reduction potential for this technology over the Federal Test Procedure (FTP) driving cycle is 50% to 75%, with a fuel consumption penalty of approximately 3% to 5% [14]. SCR is currently available for stationary diesel engines and is proposed for mobile light- and heavy-diesel applications. SCR uses a reductant that is added to the exhaust stream to convert NO_x to nitrogen and oxygen. The reductant can be ammonia, but urea is normally used in mobile source applications. Exhaust gases then pass over a catalyst of either metallic or ceramic substrate. NO_x reductions of 70% to 90% over a

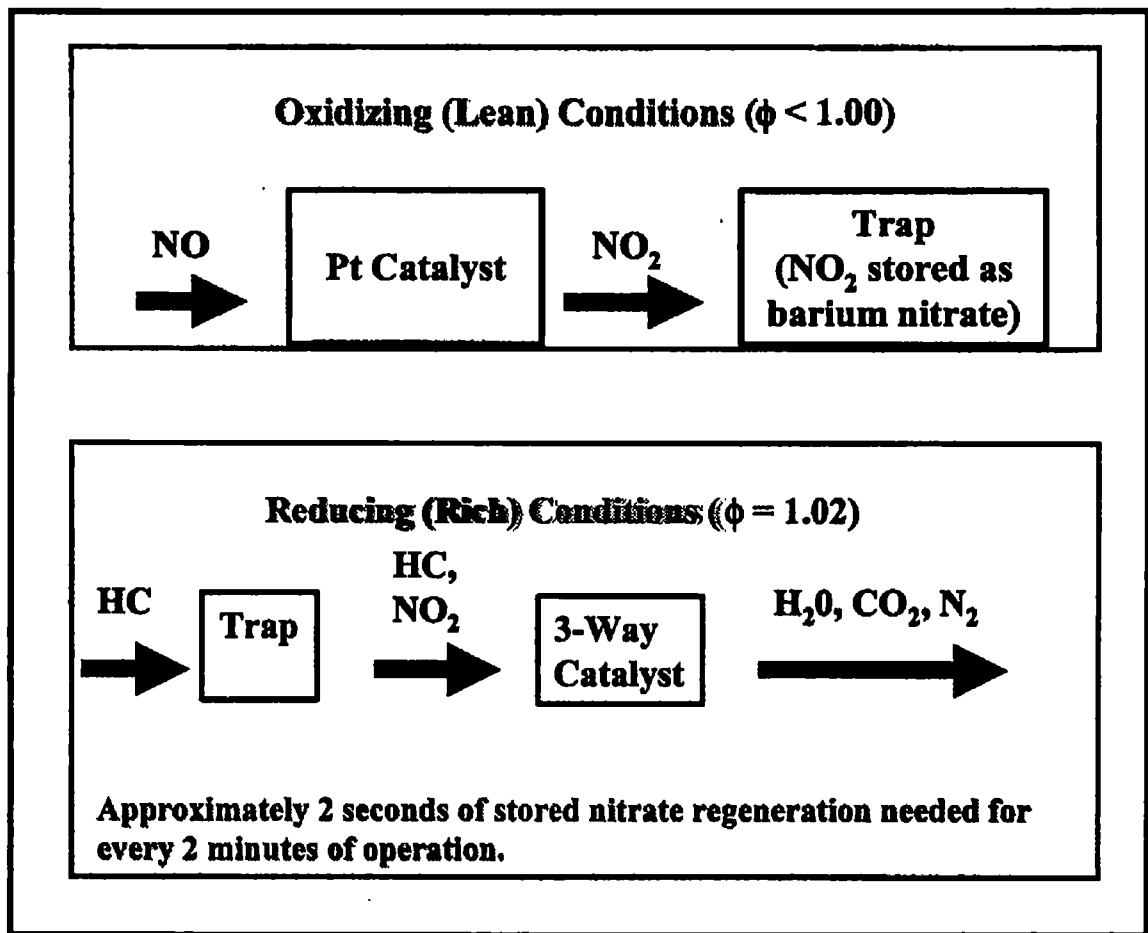


Figure 1.4 – NO_x-storage catalyst operation under oxidizing and reducing conditions [14].

broad range of operating conditions are possible using such systems [14].

SCR can also reduce the characteristic odor produced by a diesel engine.

Particulate Matter

Formation of Particulate Matter in Compression Ignition Engines

Particulate matter from diesel engines is derived from various sources. The majority of PM is either hydrocarbons from unburned fuel or soot emitted as a product of incomplete combustion [11]. Further particulate matter is added by the oxidation of sulfur in the fuel to form sulfur dioxide (SO_2) and sulfates, which bind with water on the carbon nuclei [2]. These particles can constitute as much as 20% of the total PM produced. Another major source is lubricating oil, which finds its way into the combustion chamber and is partially burned. This form of PM is dependent on the effectiveness of the piston ring pack and to a degree on the valve stem sealing [2]. Particulates from lubricating oil can make up as much as 40% of the total makeup. Table 1.2 shows a typical composition of diesel exhaust PM. Composition of PM is dependent on the conditions in the engine exhaust. At temperatures above 500°C , the individual particles are principally small spheres or spherules of carbon (with a small amount of hydrogen) with individual spherule diameters of about 15 to 30 nm [6]. At temperatures below 500°C , the particles absorb, condense, and are coated with high molecular weight organic compounds,

Table 1.2 – Typical composition of diesel exhaust PM [2].

Constituent	Percentage of PM Makeup
Carbon	31%
Unknown	8%
Sulfate and water	14%
Unburned fuel	7%
Unburned oil	40%

which include unburned hydrocarbons, oxygenated hydrocarbons (ketones, esters, ethers, organic acids), and polynuclear aromatic hydrocarbons [6].

The condensed material also includes inorganic species such as the aforementioned sulfur dioxide and sulfates and nitrogen dioxide. The organic portion can further be broken into seven different categories as follows: basics, acidics, paraffins, aromatics, transitionals, oxygenates, and ether insolubles. These seven categories are known as the *Soluble Organic Fraction (SOF)* of diesel particulate emissions. Table 1.3 indicates the types of components in each fraction and the estimated percentages.

Environmental Concerns of Particulate Matter

The effects of PM on the environment are not widely known. Research is being conducted to further understand the full contribution to the

Table 1.3 – Typical components of the soluble organic fraction [6].

Fraction	Components of fraction	Percent of total
Acidic	Aromatic or aliphatic Acidic functional groups Phenolic and carboxylic acids	3-15
Basic	Aromatic or aliphatic Basic functional groups Amines	< 1-2
Paraffin	Aliphatics, normal and branched Numerous isomers from unburned fuel and/or lubricant	34-65
Aromatic	From unburned fuel, partial combustion and recombination of combustion products; from lubricants Single ring compounds Polynuclear aromatics	3-14
Oxygenated	Polar functional groups but not acidic or basic Aldehydes, ketones, or alcohols Aromatic phenols and quinines	7-15
Transitional	Aliphatic and aromatic Carbonyl functional groups Ketones, aldehydes, esters, ethers	1-6
Insoluble	Aliphatic and aromatic Hydroxyl and carbonyl groups High molecular weight organic species Inorganic compounds Glass fibers from filters	6-25

environment. One effect is certain, and that is decreased visibility in many locations across the planet. This reduction in visibility is caused by various manners by particulate matter. One is the increase in frequency or duration of fog. Because the particles in the air help moisture condense to fog, a typical area has close to double the amount of foggy weather in winter and nearly a third more in summer [7]. Another mode of reduced visibility is by the introduction of a haze that is often light gray, bluish-white, or even a little yellowish-brown. This haze is caused by more than just visible particulate pollutions emitted directly from sources. It also involves very small particles that are formed in the air from gaseous pollutants [7]. The latter particles are the smallest in size, less than 1 micron in diameter. These smaller particles affect visibility by scattering light rather than absorbing it like larger particles. The absorption of the light leads to blurriness rather than darkening, and an observer's reaction is generally a blinking and straining of the eyes rather than the urge to turn on lights.

Another major environmental concern of PM is the effect that it has on the mortality of animals and plants in selected ecosystems. This concern has been studied extensively through experimentation. These investigations show that the lung function of many of the animals tested decreased dramatically and would lead to a premature life span. The deterioration of lung function leads to the irregularities in the circulatory and immune systems. For plants, the effects lead to decreased mortality. Plants absorb PM mixed with

rainwater. The absorption of the solution leads to abnormal metabolism and the process of photosynthesis cannot be carried out in the proper fashion. Once again, this leads to lower mortality rates. If this sort of exposure to PM were on a wider scale, the extinction of whole ecosystems could be a possibility.

Health Effects of Particulate Matter

In humans, PM affects primarily the lungs. Larger particles do not affect lung function as much as the smaller particles, those less than 2.5 microns in diameter. These particles do not settle as quickly from the atmosphere and cannot be efficiently filtered by the lungs. The respiratory tract is not necessarily the only organ affected by inhaled particulates. Following deposition in the airways of the lungs, the particulates can reach other parts of the body via the bloodstream and the lymphatics, as well as by mucociliary clearance to the digestive tract [15]. Other health effects include the aggravation of asthma and allergic rhinitis. Studies in England reported that children under the age of five years were more likely to be hospitalized for asthma than for other reasons if they lived in an area of high traffic flows [16]. A positive correlation was reported between the prevalences of wheezing and allergic rhinitis and traffic density among adolescents in German cities [16]. PM is also thought to lead to more serious consequences. Short-term tests have shown that diesel particulates can be mutagenic and are potentially

carcinogenic. It is feared that this characteristic of PM can lead to various forms of cancer. Also long term exposure to diesel particulates can lead to *Chronic Obstructive Pulmonary Disease (COPD)* and premature mortality [15].

Reduction Methods for Particulate Matter

The reduction of PM can be effectively achieved by exhaust after treatment. The method of after-treatment is often the particulate trap, also referred to as trap oxidizers [6] and particle storage reactors [2]. A temperature-tolerant filter or trap removes the particulate material from the exhaust gas and then the filter is "cleaned off" by oxidizing the accumulated particulates [6]. Although this technology is effective, it is often difficult to implement. The difficulty comes in these aspects:

- (1) the filter, even when clean, increases the pressure in the exhaust system;
- (2) this pressure increases as the filter collects particulate matter;
- (3) under normal diesel engine operating conditions, the collected PM will not ignite and oxidize; and
- (4) once ignition of the particulate occurs, the burn-off process must be carefully controlled to prevent excessively high temperatures and trap damage or destruction [6].

Traps have been put into production for construction and mining equipment and are starting to be applied to light-duty automobile diesel

engines. The use of this type of system for heavy-duty engines creates more difficult issues due to higher particulate loading and lower exhaust temperatures. Types of particulate filters include ceramic monoliths, alumina-coated wire mesh, ceramic foam, ceramic fiber mat, and woven silica-fiber rope wound on a porous tube. All of these types of filters have different intrinsic pressure losses and trapping efficiencies. When a trap is full, regeneration of the trap by burning the filtered PM can be achieved by raising its temperature to the ignition point, while providing oxygen-containing exhaust gas to support combustion and carry away the heat released [6]. Since diesel PM ignites at about 500°C to 600°C, temperatures that are higher than those typically encountered in diesel exhausts during urban driving diesel exhaust temperatures, the implementation of catalytic materials have become necessary. Catalytic coatings on the trap reduce the ignition temperature by up to 200°C [6]. Studies of the emissions of one light-duty diesel passenger car by Volkswagen showed that the release of particulates was reduced by a particulate trap by at least 80% during the collection phase and by about 60% during the regeneration phase, with a reduction of 80% for the whole cycle [17].

Emerging technologies like the patented SFR (self-supported filter regeneration) are making their way into the forefront. This system is illustrated in Figure 1.5. A small amount of additive is added to the fuel, which after combustion makes the particulates reactive for low-temperature oxidation in

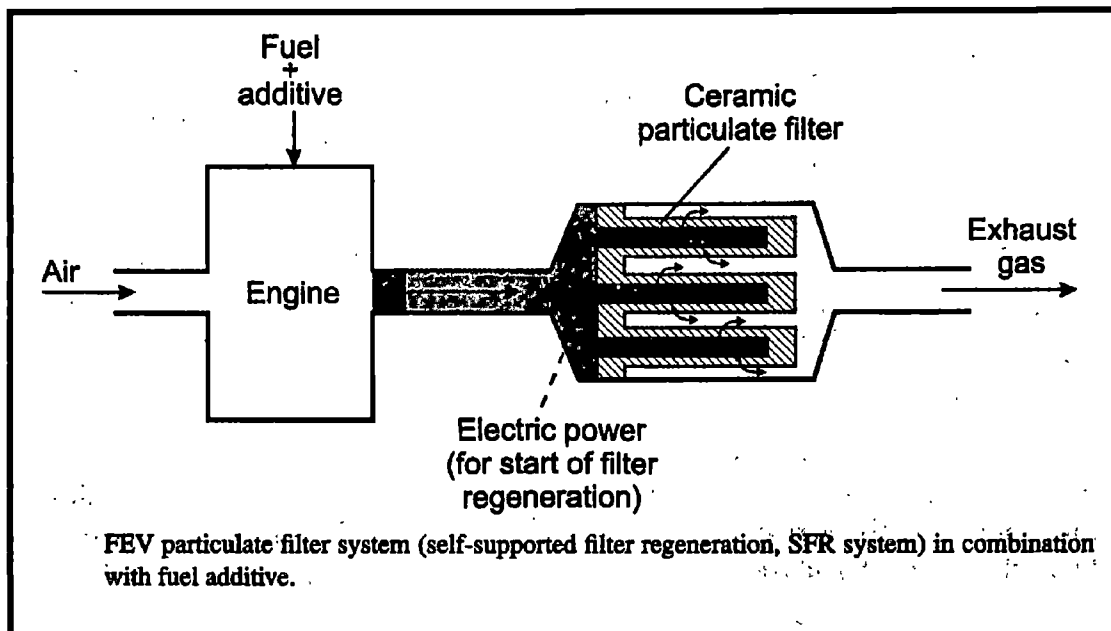


Figure 1.5 – SFR (self-supported filter regeneration) system [2].

the trap. The additive can be carried as a lifetime supply or can be added into future diesel fuel in the refinery. Electric flame initiation is also combined with the additive method for situations where exhaust temperatures would not be able to support the burning of the trapped PM. With such a regenerative trap, particulate emissions can be reduced by more than 80% [2].

Statement of Problem

It was the objective of this study to document the dependence of the oxides of nitrogen (NO_x) and particulates on the amount of exhaust gas recirculation (EGR). The premise of the study is that if an effective particulate filter could be implemented, then increased EGR could be tolerated to

decrease the formation of NO_x . Along with those quantities, the loading of a particulate filter was also documented. Loading on the filter refers to the amount of particulate matter that is trapped by the filter. A vacuum driven system was implemented to control the EGR flow rate manually. The EGR rate was determined by the ratio of CO_2 in the exhaust and intake. The measurement of those values was determined by using the appropriate gas analyzers. The loading of the particulate trap was expressed by the efficiency of the filter, which was determined by the measurement of smoke before and after the filter by the use of a smoke meter. In addition to the other aspects of the study, an investigation of the use of a venturi tube for the augmentation of exhaust gas recirculation flow was investigated. Pressures were taken at various locations along the intake and exhaust lines and that data was analyzed to determine the feasibility of the venturi tube. Further information on the development of the test setup and procedures will be presented in detail in Chapter 3.

Approach

The first step in the documentation of this thesis is a description of the equipment used in this study (Chapter 2). The next step is to describe the tests and testing procedures involved with the gathering of data (Chapter 3). In this study, the engine was operated at a constant speed (2000 RPM) and at

four different loads (0%, 25%, 50%, and 75%). The exhaust gas recirculation was varied at each of these loads and the resulting amounts of NO_x and particulates were measured and recorded. Chapter 4 documents the results of the tests. Finally, conclusions are drawn and recommendations are suggested in Chapter 5.

CHAPTER 2

EQUIPMENT

Engine and Engine Peripherals

The engine used in this investigation is a 2.4-liter, five-cylinder inline, turbocharged and intercooled, common rail, direct injection diesel manufactured by Alfa Romeo. The cylinders have a bore of 82 mm, a stroke of 90.4 mm, and the engine has a compression ratio of 18.5. The engine is equipped with a variable geometry turbocharger manufactured by Garret and a module controlled EGR system. Fuel transfer was accomplished using a Walbro 10-psi auxiliary external fuel pump. Figure 2.1 shows the engine. Detailed specifications for the engine are listed in Appendix A.

The engine was coupled to an engine dynamometer to conduct an experimental investigation, but modifications had to be made to this setup for proper operation. The modifications involved the coolant system and the intercooler setup. The coolant system had been preliminarily implemented with a conventional automotive radiator with cooling provided by an appropriately sized cooling fan. This setup could not adequately provide enough cooling to the engine when running at high speed and high load. Therefore, the dynamometer cell was equipped with an external coolant tower that alleviated this setback. The coolant used was tap water and the cooling

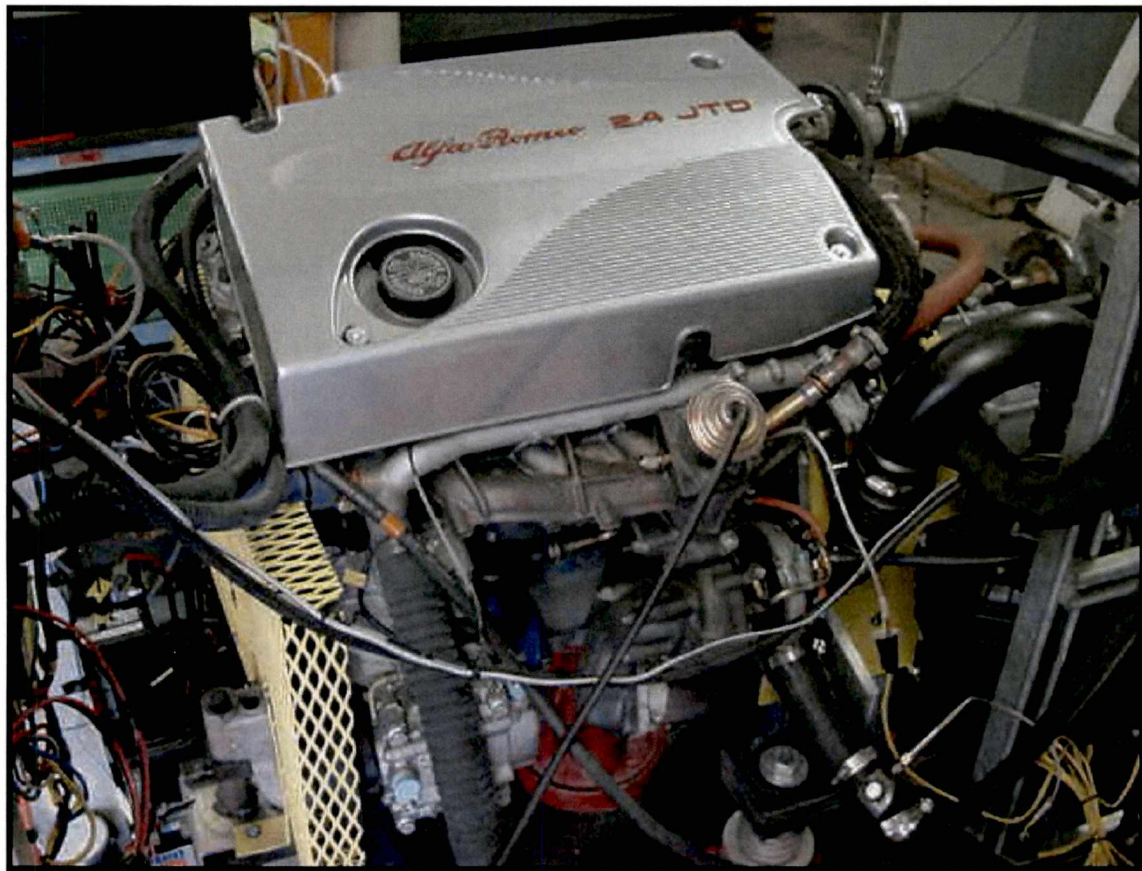


Figure 2.1 – Alfa Romeo 2.4-liter diesel engine.

system was set to circulate cool water at 175°F.

Further modifications were undertaken for the intercooler setup also. Initially, the stock intercooler cooled the boosted intake air in a similar manner as the engine coolant in that it utilized an ordinary cooling fan. This arrangement was insufficient in cooling the boosted intake air especially during engine operation at high speeds and loads. An improvement was made to replace the stock intercooler with a larger capacity intercooler and a more effective method of cooling was introduced. The cooling technique used was

to continuously spray water onto the fins of the intercooler. Figures 2.2 and 2.3 show the original and updated cooling and intercooler setups.

Engine Control

Engine speed was measured by an optical sensor, model FS-M1H, manufactured by Keyence. The sensor detected engine speed from a pattern affixed to the crank pulley of the engine. The output signal was displayed on an Omega model DPF700 rate meter that displays the speed to ± 1 rpm.

The engine dynamometer used is a water brake manufactured by Clayton Manufacturing Company. The dynamometer is equipped with a torque arm (length = 28.73 inches) and Omega model LCCB-500 load cell. The output signal was displayed on an Omega model DP25-S strain gauge panel meter that displays the torque to ± 1 ft-lb.

Microwave Regenerative Particulate Filter

The particulate trap used is designed by Industrial Ceramic Solutions of Oak Ridge, TN. The schematic in Figure 2.4 shows the setup of the system. This system could periodically apply microwave energy to the trap at idle conditions to heat and burn off the particulate matter trapped in the filter. The filter cartridge consists of ceramic paper media that consists of 25% silicon carbide fibers and 75% alumino-silicate fibers [18]. The silicon carbide fibers

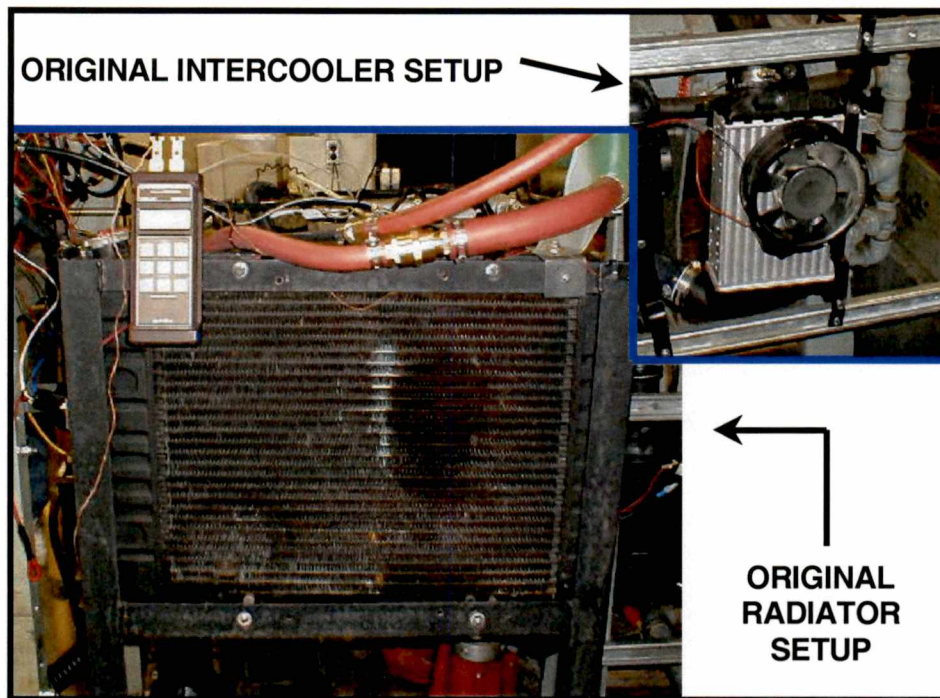


Figure 2.2 - Original cooling and intercooler setup.

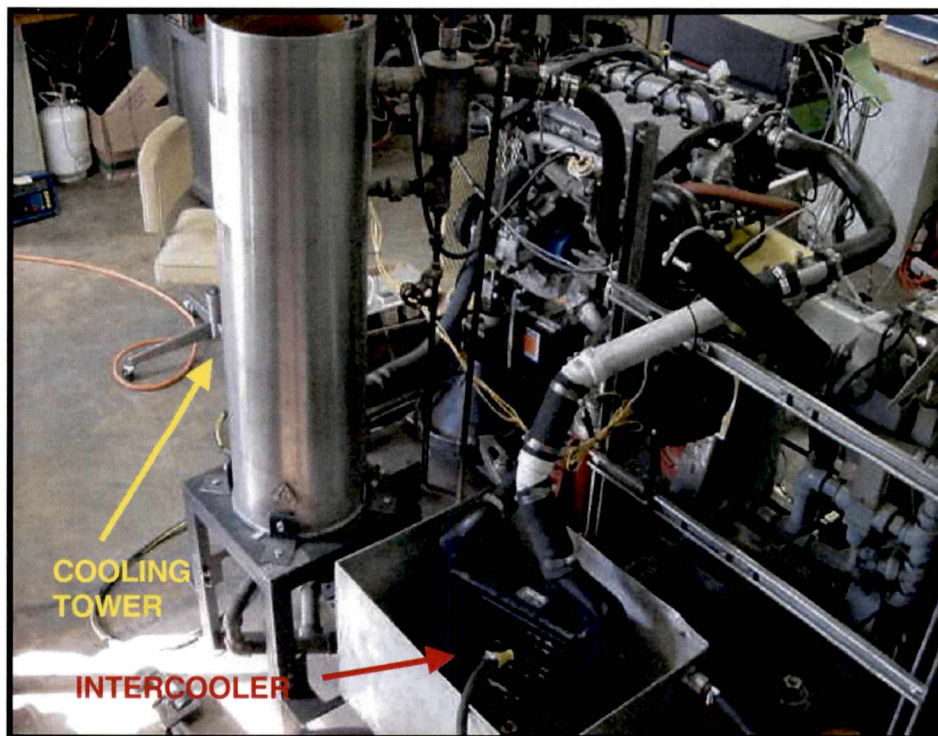


Figure 2.3 - Updated cooling and intercooler setup.

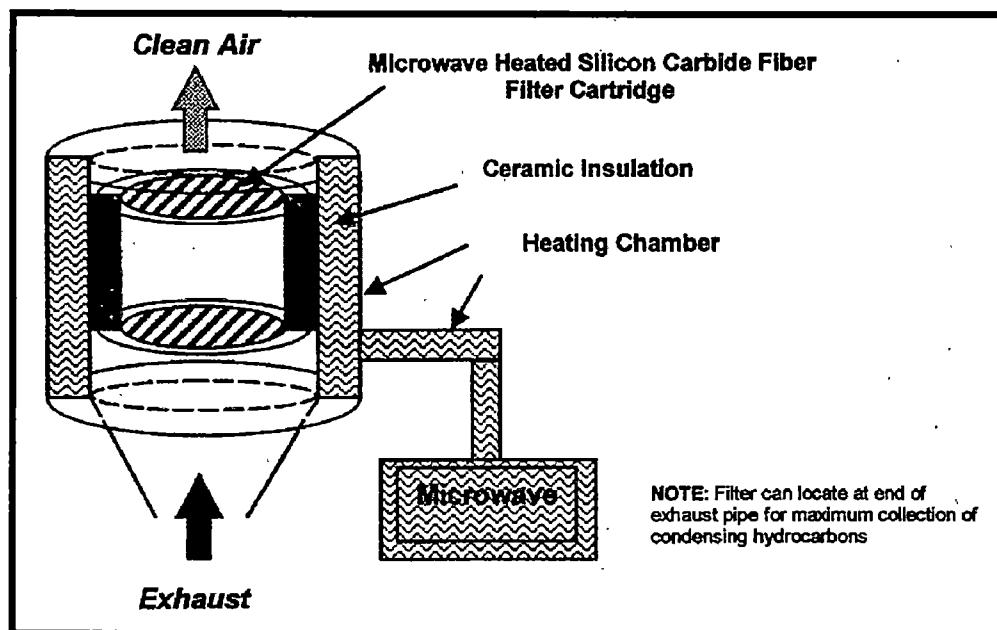


Figure 2.4 – Schematic of Microwave Regenerative Particulate Filter [18].

are unique in that they have the ability to convert microwave energy almost perfectly to thermal energy. The fibers can reach 800°C, under low exhaust flow conditions, in a common 2.4 GHz microwave field in less than one minute [18]. At idle conditions, the fibers are able to heat the cartridge faster than the exhaust gases can remove the heat. This means that the filter can achieve carbon combustion temperatures under certain exhaust flow constraints. These flow constraints require that the filter must be regenerating at idle conditions. These idle conditions are 100°C to 150°C exhaust temperature and 10 to 15 cfm exhaust flows [18]. Another advantage that this device offers is that the pressure drop across the filter is small, due to the high surface area and open structure of the fibrous paper media.

EGR Control System

The EGR valve on the engine is vacuum actuated. To vary the EGR rate, as shown schematically in Figure 2.5, an external vacuum pump was connected to the EGR valve with two valves inline to vary the amount of vacuum applied to the EGR unit. A ball valve was used for coarse adjustments, whereas the needle valve was used for fine adjustments. A vacuum gauge was also used to observe the level of vacuum applied to the EGR valve. With the use of this system, the EGR valve opening could be varied to control the amount of EGR entering the intake manifold. Also incorporated in this system was the ability of the engine vacuum pump to

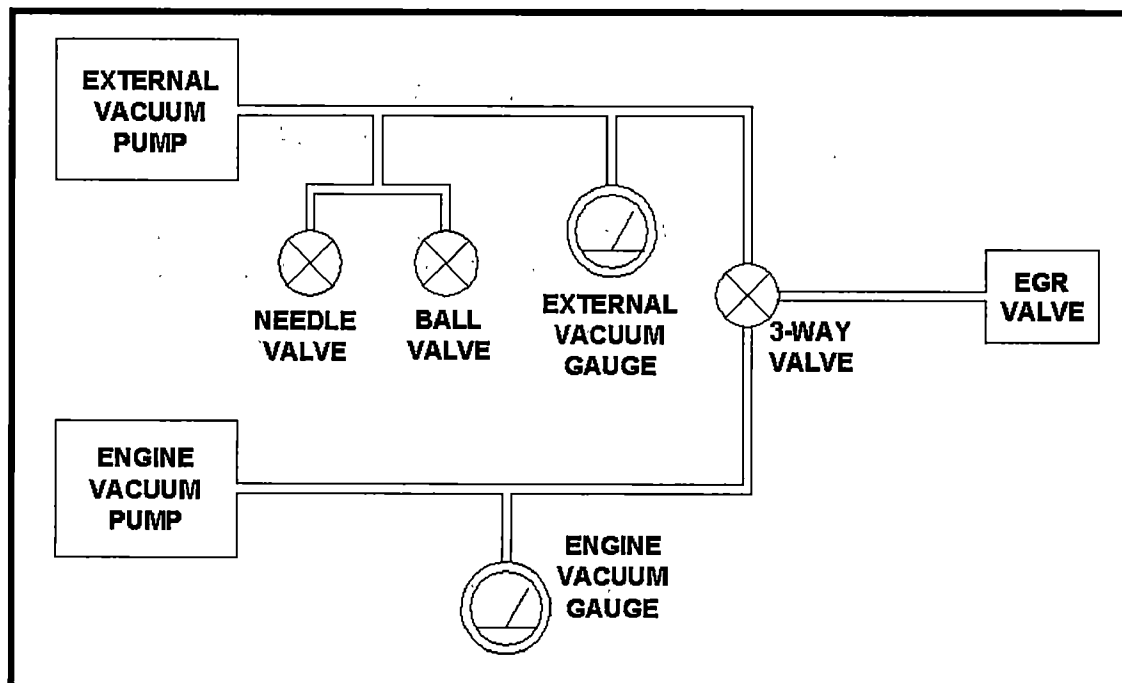


Figure 2.5 – Schematic of EGR control system.

control the EGR valve. This was done so the EGR valve could operate without the external vacuum pump during engine warm-up procedures and experimental setup shakedowns. The ability to switch from the external to the engine vacuum pumps was made possible by a three-way valve. A vacuum gauge was also implemented inline to the engine vacuum pump to determine the level of vacuum delivered. The ball, needle, and three-way valves including the two vacuum gauges were situated into a control panel. The control panel for this system is illustrated in Figure 2.6.

Exhaust Analysis

The exhaust constituents measured in the study were CO_2 in the intake and exhaust for evaluation of EGR ratio, NO_x in the exhaust, and smoke measurements before and after the particulate trap. These constituents are listed with the appropriate units in Table 2.1. A sample of the engine exhaust was extracted and passed through a heated filter to remove particulates, a heated line to prevent condensing, and then through a California Analytical Model 1100 chiller to reduce the water vapor content of the sample before feeding it to the analyzers. The water content in the exhaust sample is kept evaporated in the heated line and then the sample is led into the chiller. The sample gas is circulated through approximately 10 feet of 1/4-inch stainless steel tubing with an external 3/8-inch tube containing coolant surrounding it. The coolant condenses the water vapor contained in the sample and an

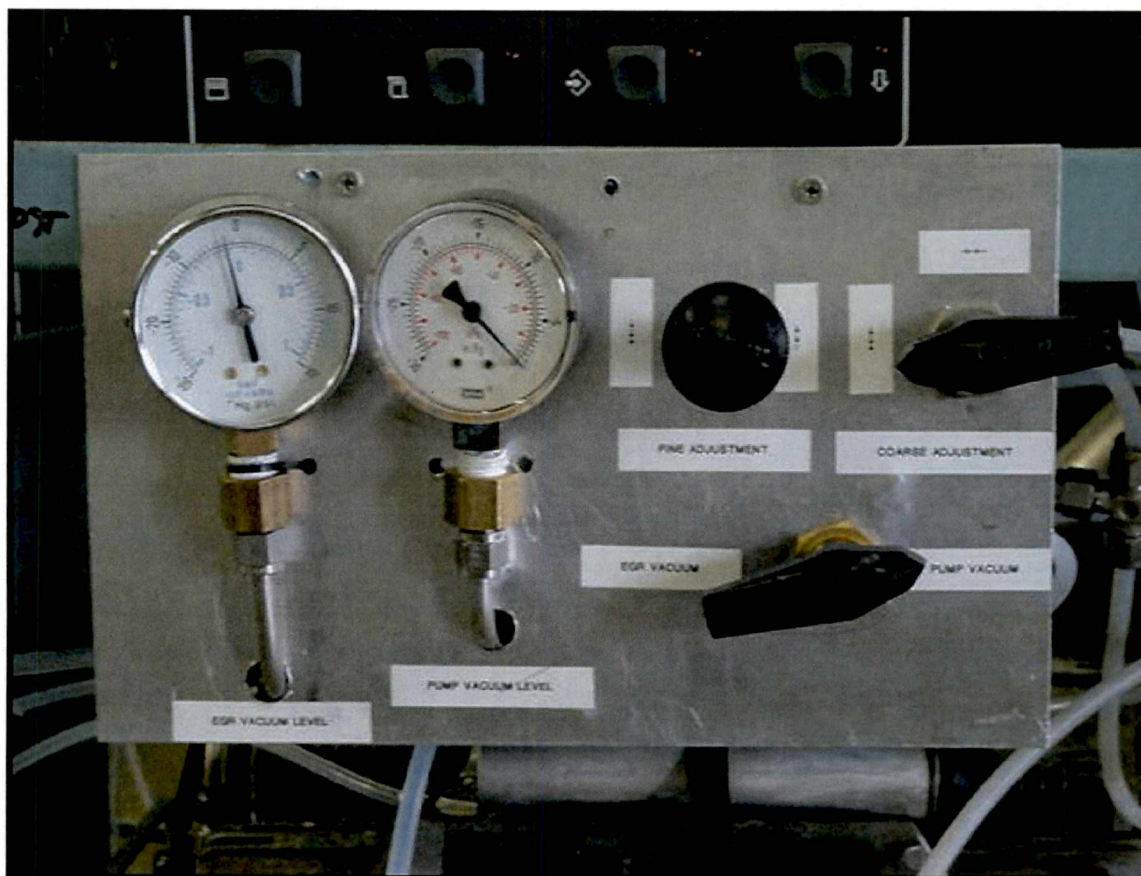


Figure 2.6 – EGR Varying system control panel.

Table 2.1 – Exhaust constituents measured.

Exhaust Constituents	Units of Measure
CO ₂ , exhaust	% volume
CO ₂ , intake	% volume
NO _x	ppm
Smoke	opacity (%) & mg/m ³

aspirator valve then removes the condensate. This exhaust treatment setup is illustrated in Figure 2.7. The intake sample was withdrawn from the intake manifold through a vacuum pump and handled in a similar fashion as the exhaust sample.

The oxides of nitrogen were measured using a Beckman model 951 NO/NO_x analyzer. This analyzer utilizes a photo chemiluminescent method of detection. This method of detection of nitric oxide (NO) is based on its reaction with ozone (O₃) to produce nitrogen dioxide (NO₂) and oxygen (O₂) [19]. Ozone produced by an internal generator is mixed with the exhaust sample in a reaction chamber, and the ensuing chemiluminescent reaction produces light emission that is directly proportional to the concentration of NO. This emission is measured by a photomultiplier tube and associated electronic circuitry. The NO_x determination is identical to the NO determination, except that, prior to entry into the reaction chamber, the sample is routed through a converter where the NO₂ component is dissociated to NO [19]. Instrument response is proportional to the total NO in the converted sample, that is, to the sum of the NO originally present in the sample plus the resulting dissociation of NO₂ [19]. This combination of NO and NO₂ is commonly designated NO_x. There are several ranges to be chosen from on this analyzer and the 1000-ppm scale was chosen. The analyzer was zeroed and span checked using reference gases. Spanning was conducted using 1000 ppm NO gas. NO₂ span was not conducted due to the lack of the gas, but the error percentage in

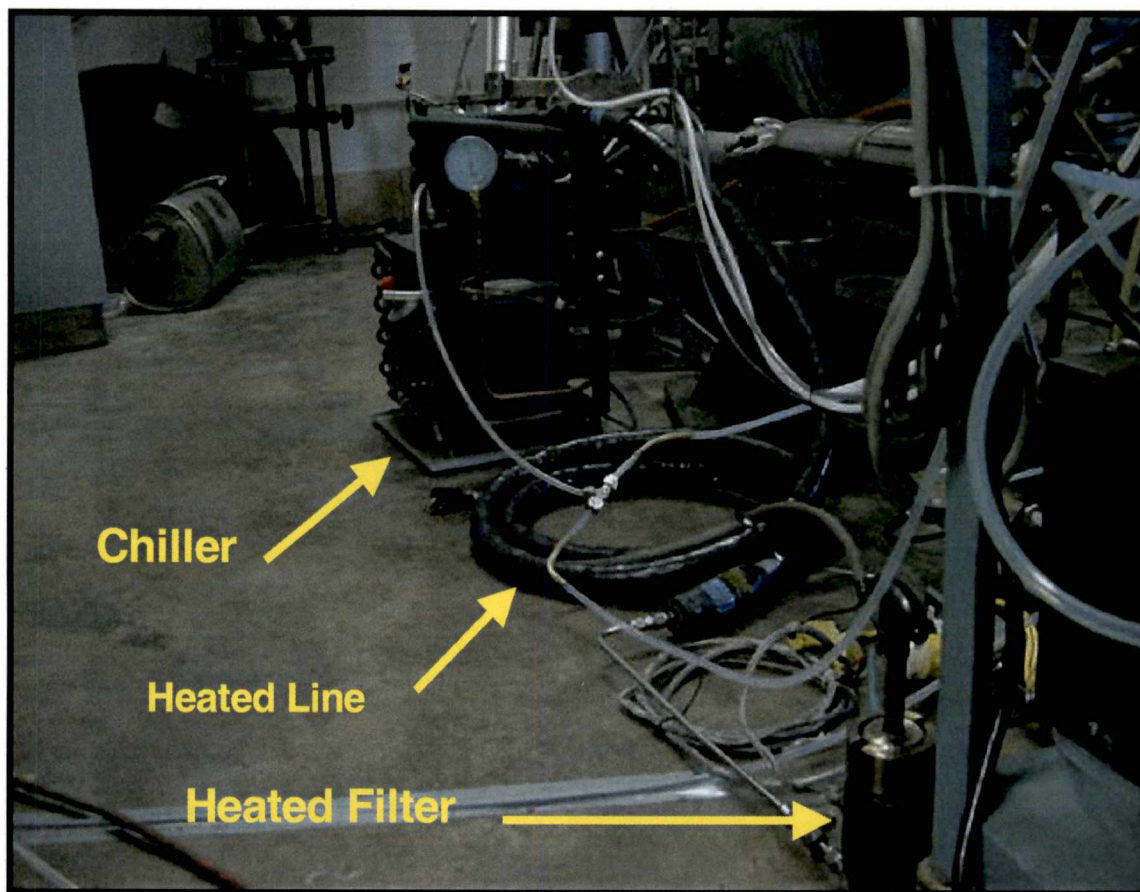


Figure 2.7 – Exhaust after treatment setup.

the analyzer's measurement of NO_x due to this calibration is low. This is due to the fact that the NO_2 measured is converted to NO in the analyzer itself.

The carbon dioxide concentration from the intake was determined using a Horiba model PIR-2000 infrared analyzer with a range of 0-20% CO_2 by volume. This analyzer is a nondispersive infrared (NDIR) analyzer and measurement is based on the premise that most molecules absorb infrared radiation of a specific wavelength and the degree of absorption is proportional to the concentration at constant pressure [20]. Nondispersive infrared

analyzers detect the infrared absorption difference between two different gas-filled columns. One column contains the sample to be analyzed and the other column contains a nonabsorbing gas. At the other end of the sample and reference columns is the detector cell that most commonly consists of two identical chambers, separated by a flexible metal diaphragm. As each chamber in the detector cell receives infrared radiation, the pressure rises [10]. As the pressure rises, the diaphragm is flexed which produces an electrical output. This electrical output is amplified and directed to a meter and/or recording device. The concentration of CO₂ for the exhaust was determined using a Horiba model MEXA-554GE, 5-gas automotive emission analyzer. This analyzer employs the same method of measurement as the PIR-2000 CO₂ analyzer. These analyzers were zeroed and span checked using reference gases.

To measure the efficiency of the particulate trap, the amount of smoke before and after the filter was measured. A Bosch Smoke Opacimeter model RTT 100 was used to accomplish this. The method to measure smoke used by this meter is similar to that of the Horiba CO₂ analyzers. The difference is that a halogen light source is used instead of infrared radiation. Sample gas is passed through a collection chamber with a light source on one end and a light detector on the other. As the sample passes through the chamber, the detector measures the light allowed through the sample. This measurement is converted to an electric signal and is conditioned, amplified and directed to a

digital display. Smoke was measured in two different units with the use of the meter. The first method is visual opacity with a range of 0 to 100% and a resolution of 0.1% and the other is mass concentration in units of mg/m^3 with a range of 0 to 1966 mg/m^3 with a resolution of 1 mg/m^3 . The Bosch smoke meter can measure smoke in these units through particulate-smoke correlations. Previous researchers measured smoke in various units and developed these correlations. For instance, Alkidas [21] performed a study on the relationships of smoke measurements. A relationship from this study between Bosch smoke number and particulate concentration is illustrated in Figure 2.8. It should be noted that several relationships have been defined to relate different units of particulate-smoke measurements. An example of this is shown in Figure 2.9. All emission analyzers were situated into a test stand and are displayed in Figure 2.10.

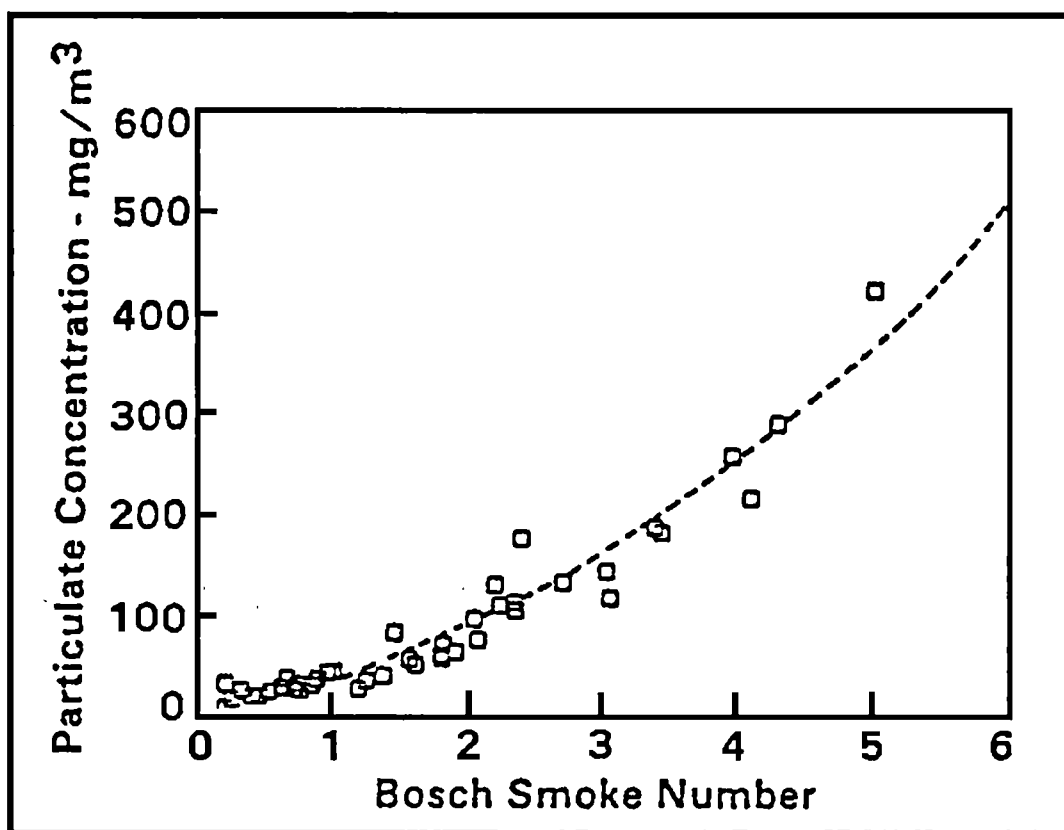


Figure 2.8 – Particulate concentration versus Bosch smoke number [21].

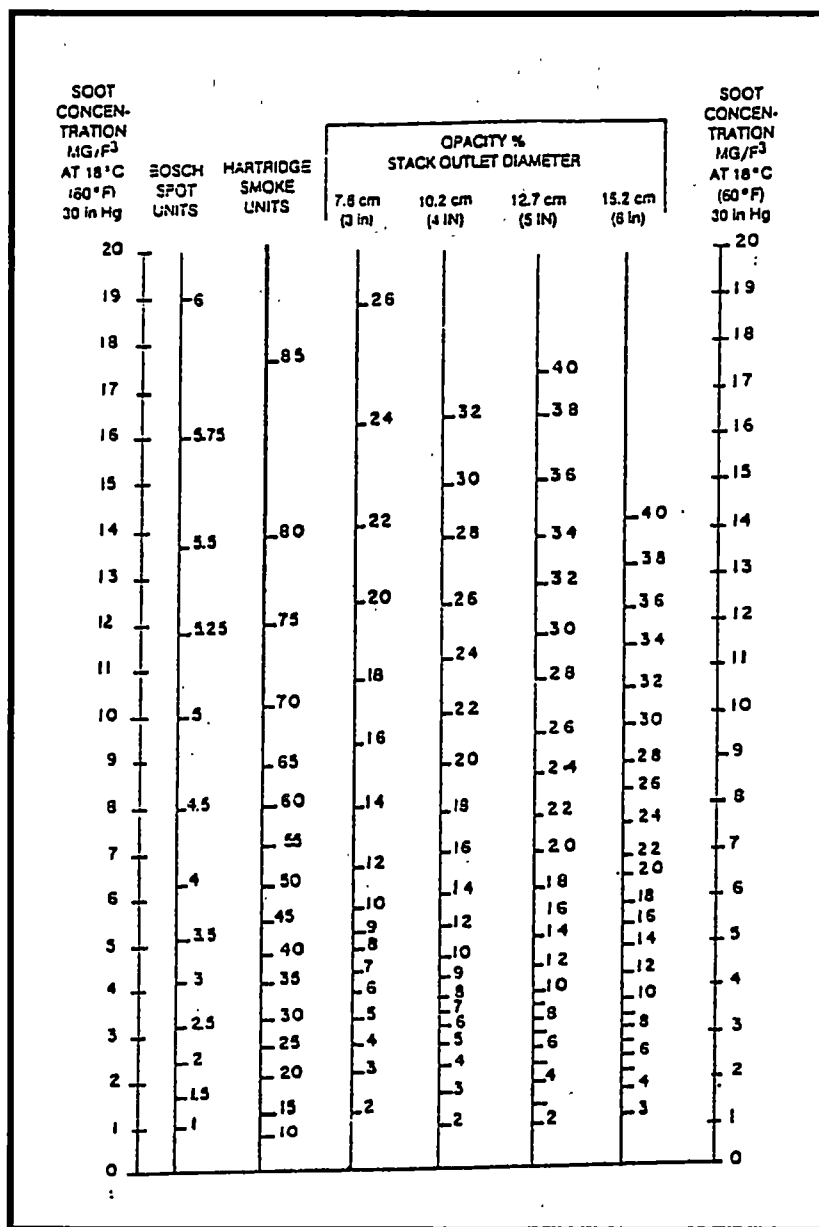


Figure 2.9 – Alignment chart of relationships between various particulate-smoke measurements [22].

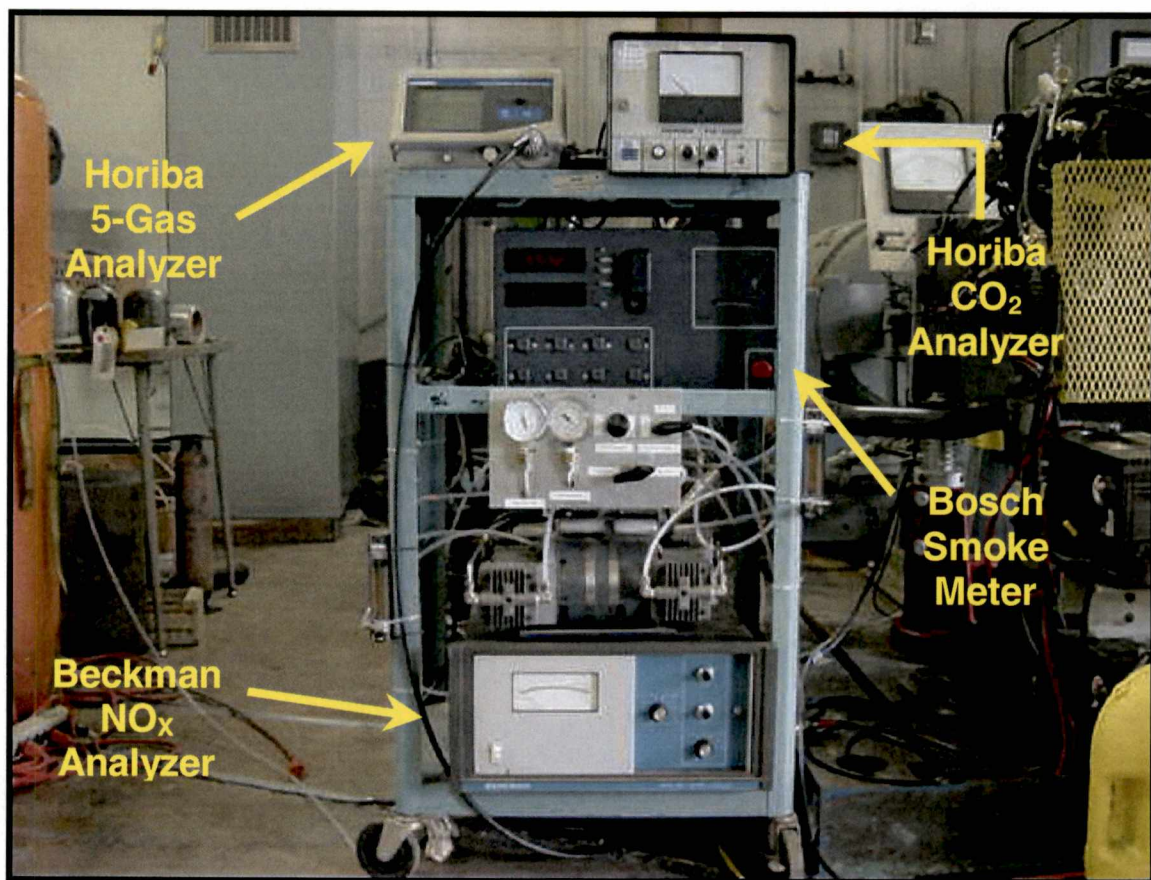


Figure 2.10 – Emissions test bench.

CHAPTER 3

PROCEDURE

The overall procedure in this study was to examine and document the relationship of NO_x and smoke emissions with exhaust gas recirculation, when a diesel particulate trap was applied. Investigations included the evaluation of a venturi tube for EGR introduction to the engine, the setup of experimental system, and the actual testing and data recording. These steps are discussed in detail in this chapter.

Venturi Tube Evaluation

As mentioned in the Statement of Problem in Chapter 1, an implantation of a venturi tube was considered to augment EGR introduction into the intake manifold. A series of pressure and temperature measurements were taken along the intake and exhaust systems of the engine to determine if a sufficient pressure differential existed to warrant a venturi tube.

Temperature data was taken for diagnostic purposes. Three possible locations were considered for the venturi tube, which were before the compressor of the turbocharger unit, after the compressor and before the intercooler, and after the intercooler. An illustration of the experimental setup is shown in Figure 3.1. The first two locations were considered risky because introduction of EGR at those locations could cause damage to compressor

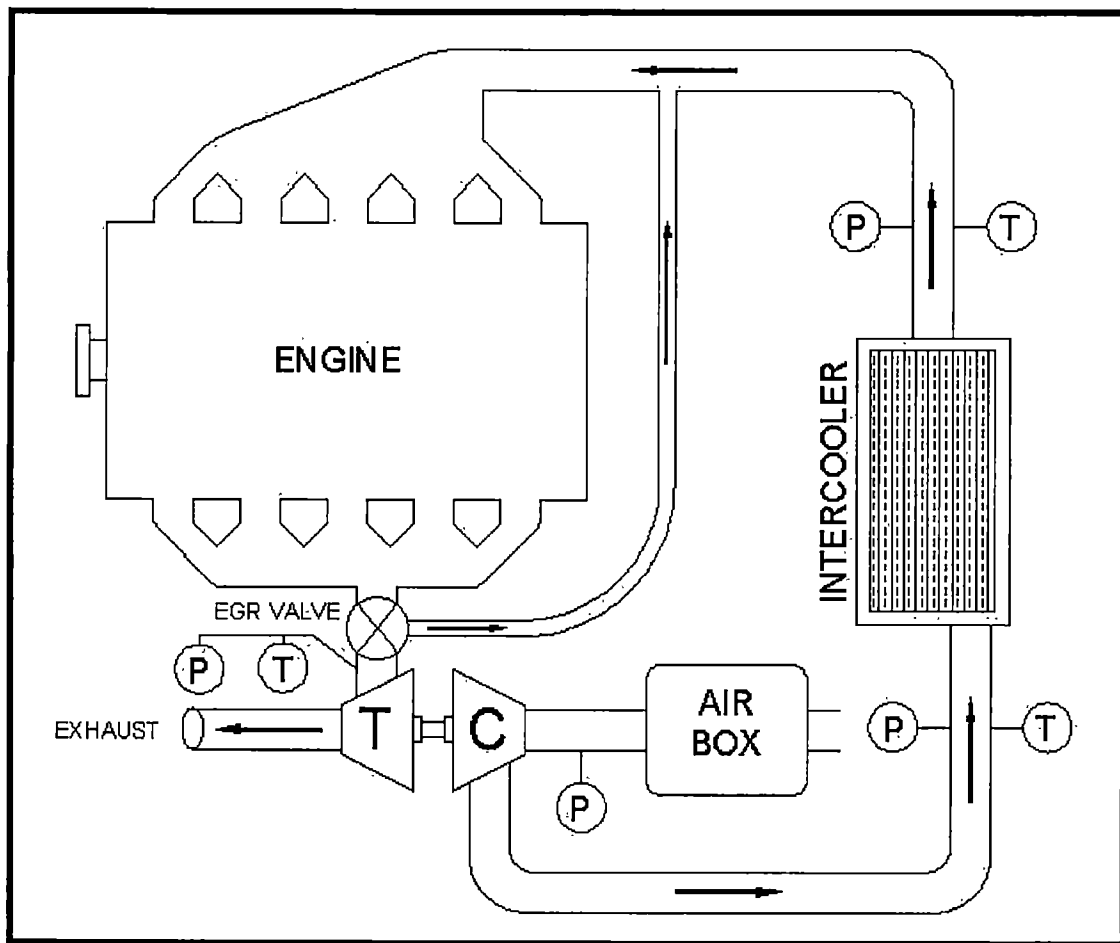


Figure 3.1 – Experimental setup for pressure and temperature measurements.

blades and foul intercooler fins. Nonetheless, pressures and temperatures were measured at these sites. Data was taken at a range of engine speeds at 0, 25, 50, 75, and 100% loads. The results of the pressure tests and the pressure differentials with respect to the exhaust pressures are listed in Table 3.1.

The pressure differential produced by the turbocharger was deemed sufficient for the flow of the EGR into the intake manifold. It should be noted that the test engine is equipped with a variable-geometry turbocharger, allowing the turbine upstream pressure to be effectively tuned to maintain a positive pressure differential for EGR flow. For this reason, it was decided not to implement the venturi tube. Additionally, as it turned out, the testing showed that the increase in pressure differential was minor at low engine speeds and loads, but significant at high engine speeds and loads, thus not uniform throughout the range of speeds. Because of this situation, there would be a need for a variable geometry venturi tube that could be utilized at these various engine speeds and loads.

Table 3.1 – Pressure data from the intake line.

0% LOAD								
RPM	Torque (ft-lb)	Before Compressor (psig)	ΔP_{BC} ($P_{EX}-P_{BC}$)	After Intercooler (psig)	ΔP_{AI} ($P_{EX}-P_{AI}$)	After Compressor (psig)	ΔP_{AC} ($P_{EX}-P_{AC}$)	Exhaust (psig)
1500	1	-0.16	1.33	0.10	1.07	0.27	0.90	1.17
1750	1	-0.16	2.26	0.51	1.59	0.73	1.37	2.10
2000	1	-0.16	3.01	0.75	2.10	0.95	1.90	2.85
2250	2	-0.18	3.76	1.18	2.40	1.39	2.19	3.58
2500	2	-0.19	6.94	2.42	4.33	2.71	4.04	6.75
2750	3	-0.21	11.82	4.20	7.41	4.60	7.01	11.61
3000	4	-0.28	22.28	7.54	14.46	8.04	13.96	22.00
3300	4	-0.32	28.02	9.51	18.19	10.19	17.51	27.70
3500	5	-0.37	31.97	10.58	21.02	11.33	20.27	31.60
25 % LOAD								
RPM	Torque (ft-lb)	Before Compressor (psig)	ΔP_{BC} ($P_{EX}-P_{BC}$)	After Intercooler (psig)	ΔP_{AI} ($P_{EX}-P_{AI}$)	After Compressor (psig)	ΔP_{AC} ($P_{EX}-P_{AC}$)	Exhaust (psig)
1500	42	-0.15	2.77	0.95	1.67	1.16	1.46	2.62
1750	48	-0.16	4.52	1.94	2.42	2.14	2.22	4.36
2000	55	-0.16	7.06	3.45	3.45	3.63	3.27	6.90
2250	52	-0.20	9.33	4.59	4.54	4.81	4.32	9.13
2500	51	-0.18	11.02	5.62	5.22	5.85	4.99	10.84
2750	50	-0.19	14.37	7.45	6.73	7.62	6.56	14.18
3000	49	-0.24	33.14	13.38	19.52	13.67	19.23	32.90
50 % LOAD								
RPM	Torque (ft-lb)	Before Compressor (psig)	ΔP_{BC} ($P_{EX}-P_{BC}$)	After Intercooler (psig)	ΔP_{AI} ($P_{EX}-P_{AI}$)	After Compressor (psig)	ΔP_{AC} ($P_{EX}-P_{AC}$)	Exhaust (psig)
1500	89	0.00	6.06	3.36	2.70	3.49	2.57	6.06
1750	103	-0.02	9.59	5.61	3.96	5.72	3.85	9.57
2000	95	-0.11	23.71	11.75	11.85	12.02	11.58	23.60
2250	103	-0.12	26.32	13.15	13.05	13.45	12.75	26.20
2500	102	-0.14	27.74	13.87	13.73	14.21	13.39	27.60
2750	102	-0.11	30.01	14.21	15.69	14.98	14.92	29.90
3000	94	-0.22	35.02	16.05	18.75	16.41	18.39	34.80
75% LOAD								
RPM	Torque (ft-lb)	Before Compressor (psig)	ΔP_{BC} ($P_{EX}-P_{BC}$)	After Intercooler (psig)	ΔP_{AI} ($P_{EX}-P_{AI}$)	After Compressor (psig)	ΔP_{AC} ($P_{EX}-P_{AC}$)	Exhaust (psig)
2250	165	-0.14	27.94	14.64	13.16	14.92	12.88	27.80
2500	158	-0.15	26.25	15.58	10.52	14.58	11.52	26.10
2750	155	-0.21	26.81	15.92	10.68	15.92	10.68	26.60
3000	154	-0.24	25.94	15.02	10.68	15.57	10.13	25.70
3250	148	-0.27	26.37	14.97	11.13	15.58	10.52	26.10
100% LOAD								
RPM	Torque (ft-lb)	Before Compressor (psig)	ΔP_{BC} ($P_{EX}-P_{BC}$)	After Intercooler (psig)	ΔP_{AI} ($P_{EX}-P_{AI}$)	After Compressor (psig)	ΔP_{AC} ($P_{EX}-P_{AC}$)	Exhaust (psig)
2250	219	-0.18	24.18	16.80	7.20	16.83	7.17	24.00
2500	215	-0.17	18.96	14.99	3.80	15.00	3.79	18.79
2750	212	-0.13	21.03	15.74	5.16	15.80	5.10	20.90
3000	207	-0.05	22.15	15.71	6.39	15.87	6.23	22.10
3250	186	-0.04	22.04	14.74	7.26	14.99	7.01	22.00

EGR Variation Tests

Initial Setup

EGR rate is defined by Heywood [6] as the ratio of the exhaust gas recirculated into the intake and the mass of the intake air plus fuel added.

This relationship is defined below [6].

$$EGR(\%) = \frac{m_{EGR}}{(m_a + m_f)} * 100$$

For the purposes of this study, CO₂ concentration of the intake and exhaust was used to determine the EGR ratio. This ratio is defined in the equation below.

$$EGR(\%) = \frac{CO_{2INTAKE}}{CO_{2EXHAUST}} * 100$$

For this ratio to be determined, CO₂ had to be measured in the intake and the exhaust of the engine. For the exhaust, this was a simple case. A sample of the exhaust was extracted from the exhaust pipe. For the intake, however, modifications to the experimental setup had to be undertaken. A simple way to obtain a sample from the intake is to drill a hole in the intake manifold and install a sample tap. However, that would involve the dismantling of the intake manifold from the engine block. This endeavor would require several other items to be removed from the engine. It could also lead to possible damage to the intake manifold and other parts such as gaskets. Rather than commit to this method, an alternative was selected. A ¼" stainless steel sampling tube

was inserted into the intake manifold where the air enters. This tube was connected to a vacuum pump that collected the sample from the intake manifold and sent to the Horiba CO₂ analyzer. Figure 3.2 and Figure 3.3 show the modified sample tube and the tube oriented into the experimental setup.

Smoke measurements also needed similar alterations. The sample taps in the exhaust line were parallel to the exhaust flow itself. This situation would not allow enough exhaust into the sample line for the analyzer used for the measurement of smoke. To improve the sampling distribution, stainless steel probes that had been cross-drilled were inserted into the exhaust line sample taps. The cross-drilled pattern in the probes allowed for the collection of the necessary exhaust. Two of these probes were used, one downstream and one upstream of the particulate trap. Figure 3.4 shows the two probes used.

Testing

The different load levels and the varying levels of EGR defined the tests that were performed. All testing was conducted under the following engine operating conditions:

Engine Speed:	2000 $\pm$ 25 rpm
Lubricating Oil:	SAE 15W-40
Coolant Temperature:	180 $\pm$ 10°F

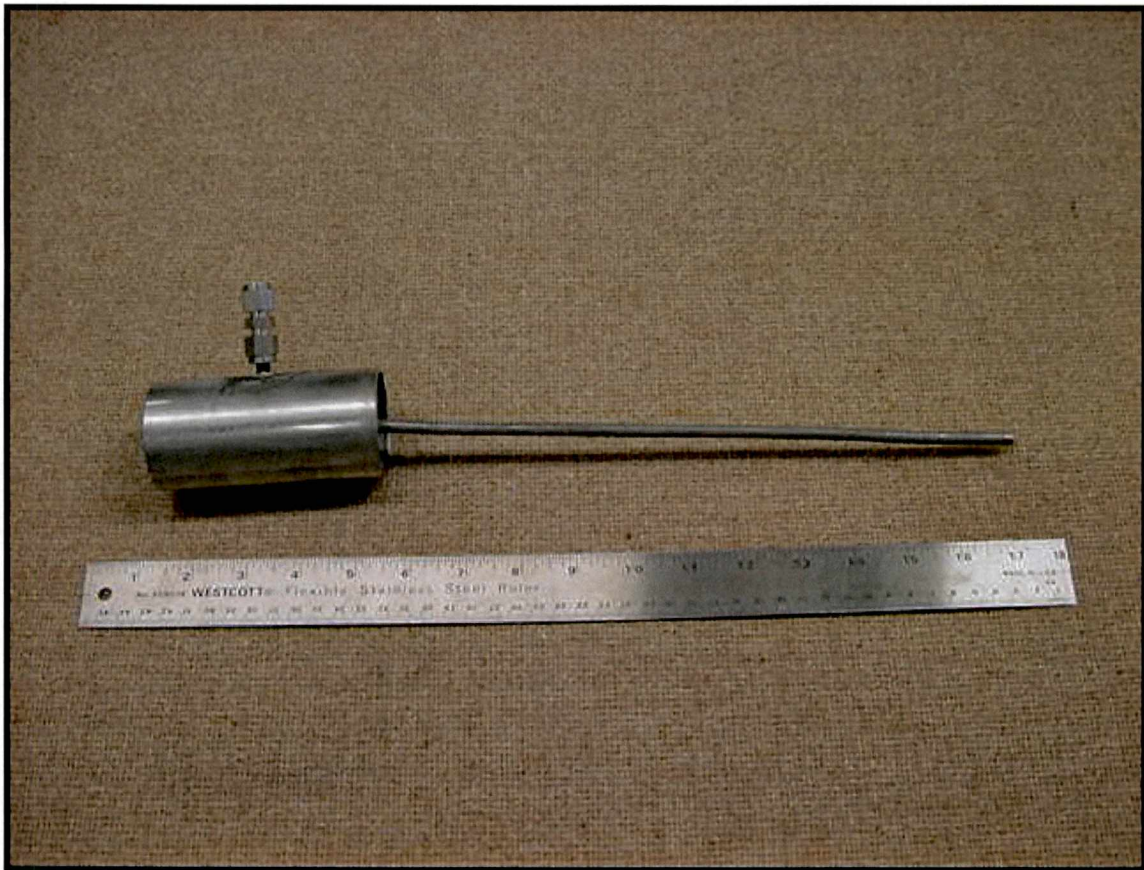


Figure 3.2 – Intake manifold sampling tube.

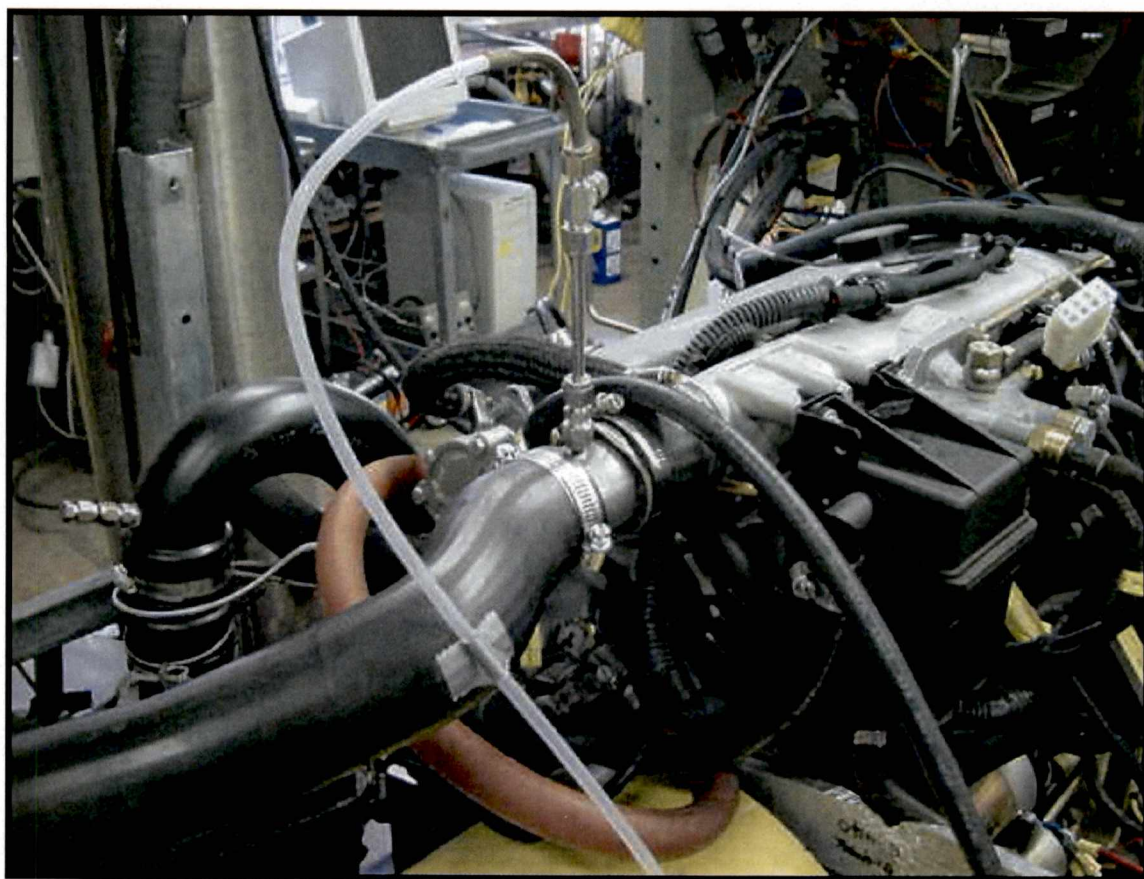


Figure 3.3 – Intake manifold sampling tube orientation in experimental setup.



Figure 3.4 – Sample probes for smoke measurement.

To effectively run the necessary tests, a testing sequence was formulated and implemented. This sequence is listed below. Further discussion on the testing and data reduction is also explained.

Testing Procedure

The following steps illustrate the testing sequence used in this study:

1. Emission analyzers were warmed up, zeroed, and span-checked.
2. Water was turned on for the dynamometer, cooling tower, and intercooler cooling as well as the exhaust fan.
3. The engine was warmed up until the specified coolant temperatures were achieved.
4. Vacuum pumps turned on to allow sample to be drawn in from the exhaust and intake manifold and for the operation of the EGR varying system.
5. The temperature controllers for the heated filter and the aspirating air for the chiller were turned on.
6. The engine was set to the desired speed of 2000 rpm while the dynamometer was set to the desired load setting.
7. The EGR valve started in the closed position and manually allowed to open with the addition of vacuum from the EGR varying system.
8. For each manual addition of vacuum to the EGR valve, readings of intake CO₂, exhaust CO₂, and NO_x concentrations were recorded

along with the smoke measurements before and after the smoke meter.

9. The engine was the set up for the next load setting.

Testing Discussion

As outlined in the testing sequence, the tests were performed at 2000 rpm and load settings of 0, 25, 50, and 75% of the rated torque of the engine. For each of the load settings, the vacuum level to the EGR valve was manually adjusted from no vacuum until the engine showed signs of combustion instability. At this point, it became very difficult to maintain the specified speed and the test was ceased. Also, at each load setting, various quantities were measured and recorded. To calculate the EGR rate, the CO₂ concentrations in the intake and the exhaust were recorded in % by volume. To evaluate the effect of EGR on other emissions, NO_x was recorded in ppm and smoke levels before and after the particulate trap were recorded in both opacity (%) and mass concentration (mg/m³). This procedure was completed for two runs for each engine load. The particulate trap was regenerated at the Industrial Ceramic Solutions laboratory after each test run. The experimental setup is illustrated in Figure 3.5 with the actual setup shown in Figure 3.6.

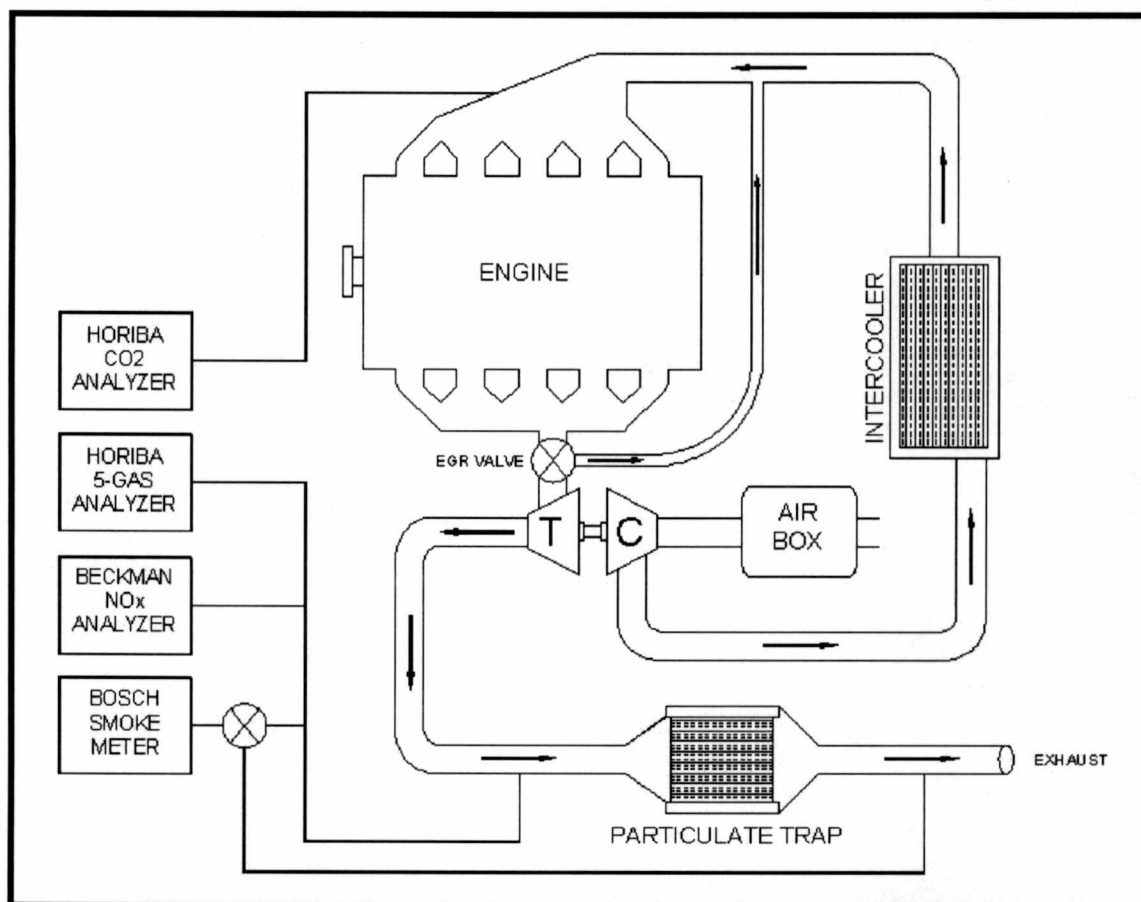


Figure 3.5 – Illustration of experimental setup.

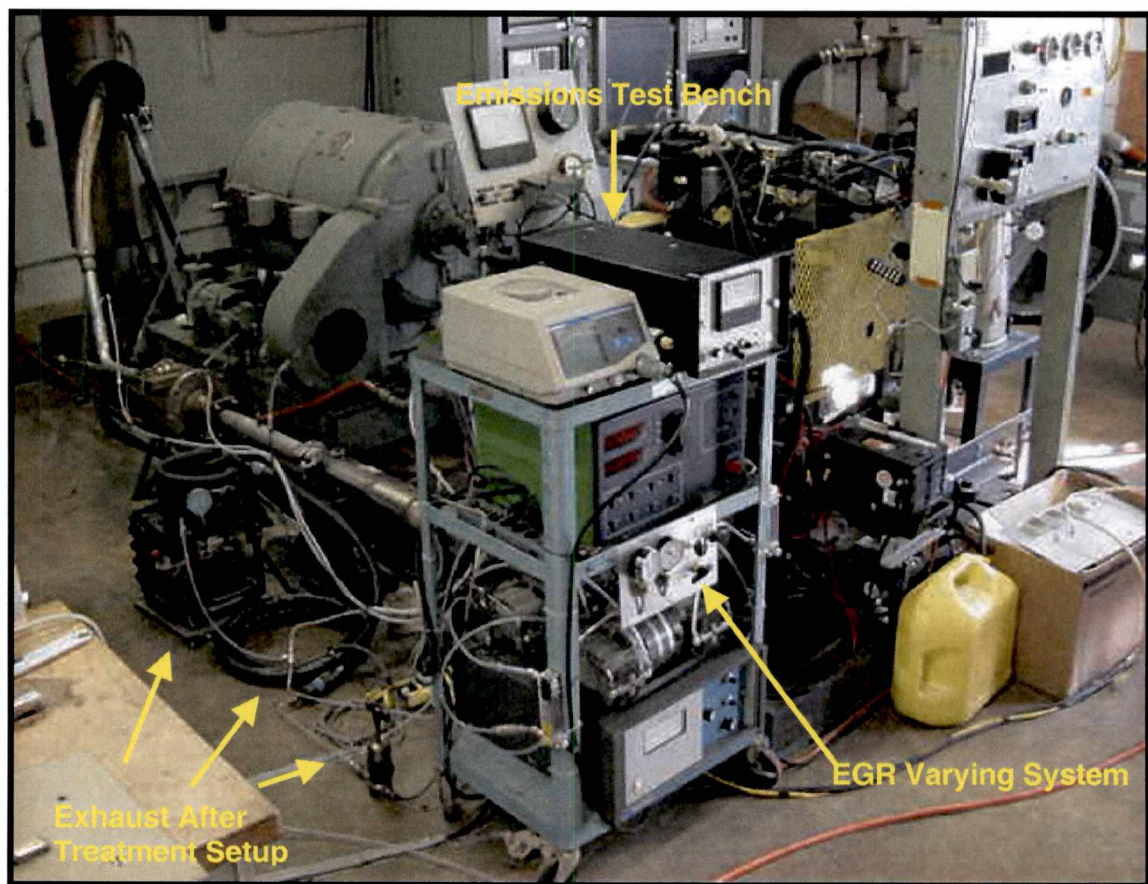


Figure 3.6 – Actual experimental setup.

Data Recording

The data obtained from the testing was entered into an Excel worksheet. This enabled the data to be manipulated into plots of various relationships. These relationships include EGR versus NO_x and smoke levels for each load setting and NO_x versus smoke for 50 and 75% loads and EGR. These relationships are discussed further in Chapters 4 and 5.

CHAPTER 4

RESULTS AND DISCUSSION

Emissions data from the test runs were analyzed in this chapter.

Exhaust quantities recorded for this study are CO₂ concentrations (intake and exhaust) in volumetric concentration, NO_x concentrations in ppm, and smoke levels (pre-filter and post-filter) in opacity and mass concentration. Table 4.1 shows the results of these tests for 0% and 25% engine loads, while Table 4.2 shows the results for 50% and 75% loads. The experimental results from this study are presented in this chapter as a series of plots, which include the effects of EGR on NO_x and particulate emissions in both units of opacity and mass concentration for all engine loads, and relationships of NO_x and smoke for 50%, 75%, and all loads collectively.

The dependence of NO_x on EGR is shown in Figures 4.1 through 4.4. These figures are shown with data points from both test runs. In these figures, it can be seen that NO_x decreases in an almost linear manner against EGR rate. The reduction of NO_x by EGR is better realized at higher engine loads than lower loads. For instance, for 0% engine load, NO_x is lowered by 90 ppm, and for 75% engine load, NO_x is lowered 430 ppm over the respective EGR ranges of approximately 0% to 27% and 0% to 10%. This reduction in NO_x is most likely attributed to the fact that most EGR constituents do not participate in the combustion process. This leads to the reduction of peak

Table 4.1 – Recorded data from two test runs for 0% and 25% engine loads.
Engine operated at 2000 rpm.

	CO ₂ in (% vol)	CO ₂ ex (% vol)	EGR %	NO _x (%) (ppm)	Smoke Pre (opacity %)	Smoke Post (opacity %)	Smoke Pre (mg/m ³)	Smoke Post (mg/m ³)
0% Load Test Run 1	1.00	3.70	27.03	40	1.2	0.7	13	8
	0.88	3.61	24.38	50	1.2	0.8	15	8
	0.80	3.42	23.39	55	1.2	0.8	15	9
	0.64	3.36	19.05	60	1.2	0.8	15	8
	0.52	2.94	17.69	65	1.0	0.7	13	7
	0.36	2.60	13.85	80	1.0	0.6	11	7
	0.28	2.50	11.20	90	1.0	0.6	11	8
	0.20	2.16	9.26	100	1.0	0.6	10	8
	0.12	2.07	5.80	110	1.0	0.7	10	8
	0.00	2.02	0.00	120	0.8	0.6	10	6
0% Load Test Run 2	0.85	3.45	24.64	40	1.2	0.8	15	9
	0.68	3.16	21.52	50	1.2	0.8	15	8
	0.56	2.98	18.79	70	1.2	0.8	14	8
	0.48	2.68	17.91	80	1.1	0.7	12	7
	0.36	2.50	14.40	85	1.0	0.7	11	7
	0.28	2.32	12.07	90	1.0	0.7	11	7
	0.20	2.00	10.00	100	1.0	0.6	11	8
	0.12	1.92	6.25	105	1.0	0.6	10	8
	0.06	1.96	3.06	110	0.8	0.5	10	7
	0.00	1.92	0.00	130	0.8	0.5	9	5
25% Load Test Run 1	1.08	3.96	27.27	80	6.9	2.0	101	28
	0.96	3.84	25.00	90	4.7	1.6	65	18
	0.84	3.62	23.20	100	3.1	1.2	44	15
	0.64	3.40	18.82	130	1.8	0.8	21	8
	0.52	3.24	16.05	150	1.4	0.8	16	8
	0.40	3.04	13.16	180	1.0	0.8	12	8
	0.32	2.94	10.88	190	1.0	0.8	11	8
	0.20	2.90	6.90	240	1.0	0.7	11	7
	0.08	2.85	2.81	270	1.0	0.6	9	7
	0.01	2.80	0.18	320	0.8	0.4	7	5
25% Load Test Run 2	1.05	3.95	26.58	80	5.5	1.8	95	22
	0.92	3.85	23.90	100	4.5	1.6	60	17
	0.78	3.69	21.14	110	2.6	1.3	33	14
	0.68	3.57	19.05	120	1.9	0.9	25	10
	0.55	3.32	16.57	140	1.5	0.8	18	8
	0.52	3.29	15.81	150	1.4	0.8	16	8
	0.40	3.18	12.58	180	1.1	0.8	12	7
	0.28	2.90	9.66	210	1.0	0.9	11	7
	0.12	2.81	4.27	250	1.0	0.6	10	7
	0.00	3.00	0.00	340	0.8	0.4	8	6

Table 4.2 – Recorded data from two test runs for 50% and 75% engine loads.
Engine operated at 2000 rpm.

	CO ₂ in (% vol)	CO ₂ ex (% vol)	EGR %	NO _x (%) (ppm)	Smoke Pre (opacity %)	Smoke Post (opacity %)	Smoke Pre (mg/m ³)	Smoke Post (mg/m ³)
50% Load Test Run 1	0.95	5.45	17.34	120	10.3	3.1	120	30
	0.81	4.92	16.46	210	5.7	2.1	78	25
	0.72	4.82	14.94	240	4.3	1.8	63	20
	0.59	4.54	12.89	300	3.1	1.2	32	16
	0.41	4.40	9.20	330	2.5	1.0	25	11
	0.32	4.36	7.22	400	1.8	1.0	19	11
	0.20	4.32	4.63	450	1.8	1.0	21	12
	0.12	4.26	2.82	480	1.6	0.8	16	8
50% Load Test Run 2	0.01	4.21	0.12	510	1.4	0.8	15	8
	0.92	5.25	17.57	120	10.9	3.3	131	32
	0.86	5.11	16.73	200	6.0	2.3	81	27
	0.72	4.87	14.78	240	4.7	2.0	67	22
	0.50	4.49	11.02	310	2.9	1.2	35	16
	0.41	4.41	9.18	330	2.4	1.1	24	11
	0.36	4.39	8.20	410	1.8	1.0	19	11
	0.24	4.33	5.54	440	1.8	1.0	17	10
75% Load Test Run 1	0.08	4.15	1.93	490	1.6	0.8	17	9
	0.00	4.09	0.00	520	1.3	0.8	13	8
	1.04	9.78	10.63	500	12.2	3.4	188	50
	0.78	9.20	8.48	630	3.6	1.4	50	15
	0.66	9.00	7.33	710	2.5	1.0	32	11
	0.50	8.94	5.54	740	2.2	1.1	25	11
	0.40	8.92	4.48	770	1.8	1.2	22	12
	0.25	8.56	2.92	800	1.6	1.0	20	12
75% Load Test Run 2	0.20	8.48	2.36	840	1.3	0.6	15	8
	0.09	8.22	1.09	870	1.2	0.6	13	7
	0.01	7.74	0.06	910	1.2	0.6	12	7
	0.98	9.50	10.26	520	12.0	3.1	176	44
	0.84	9.40	8.94	600	4.3	1.6	60	19
	0.72	9.12	7.89	700	2.8	1.3	36	13
	0.55	9.00	6.11	720	2.5	1.1	30	11
	0.35	8.77	3.99	780	1.9	1.2	24	11
	0.20	8.44	2.37	840	1.3	0.8	17	10
	0.15	8.37	1.79	880	1.3	0.7	15	9
	0.04	8.16	0.49	900	1.2	0.6	13	8
	0.00	7.80	0.00	930	1.2	0.6	11	7

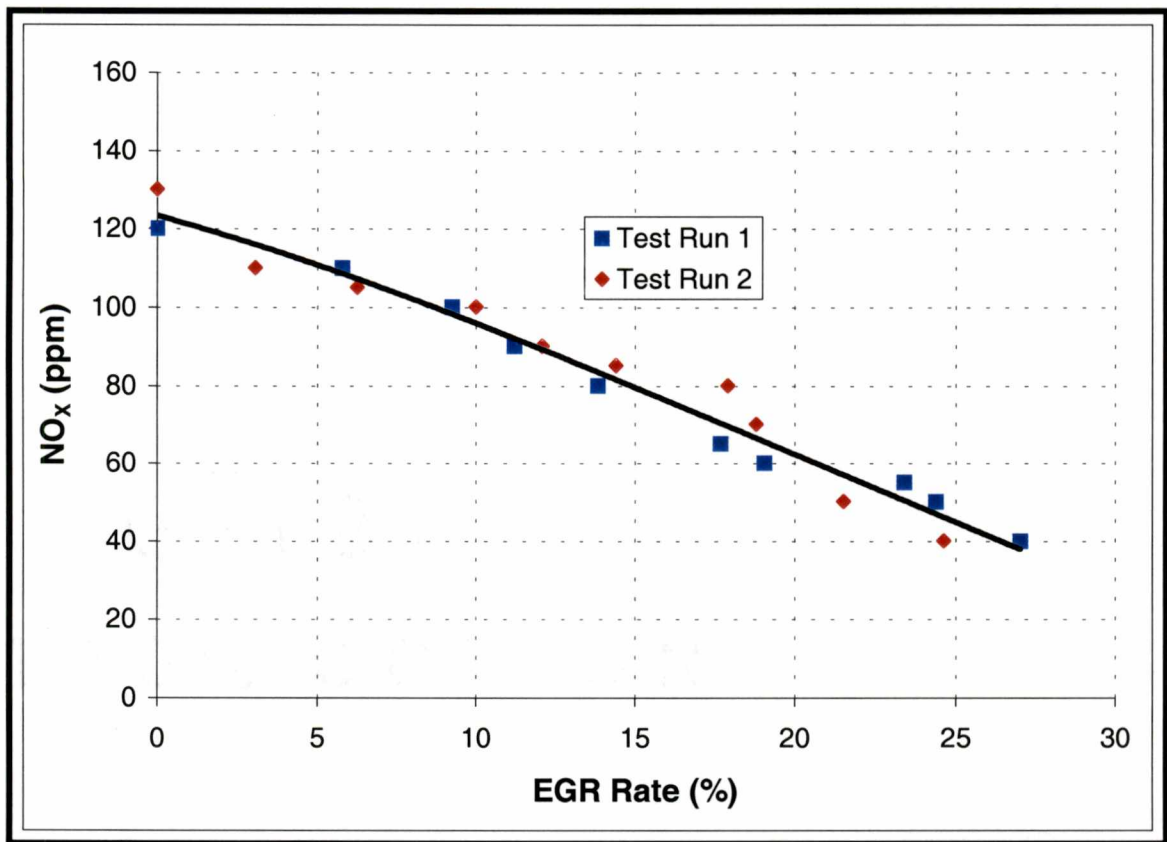


Figure 4.1 – NO_x versus EGR for 0% Load. Engine operated at 2000 rpm.

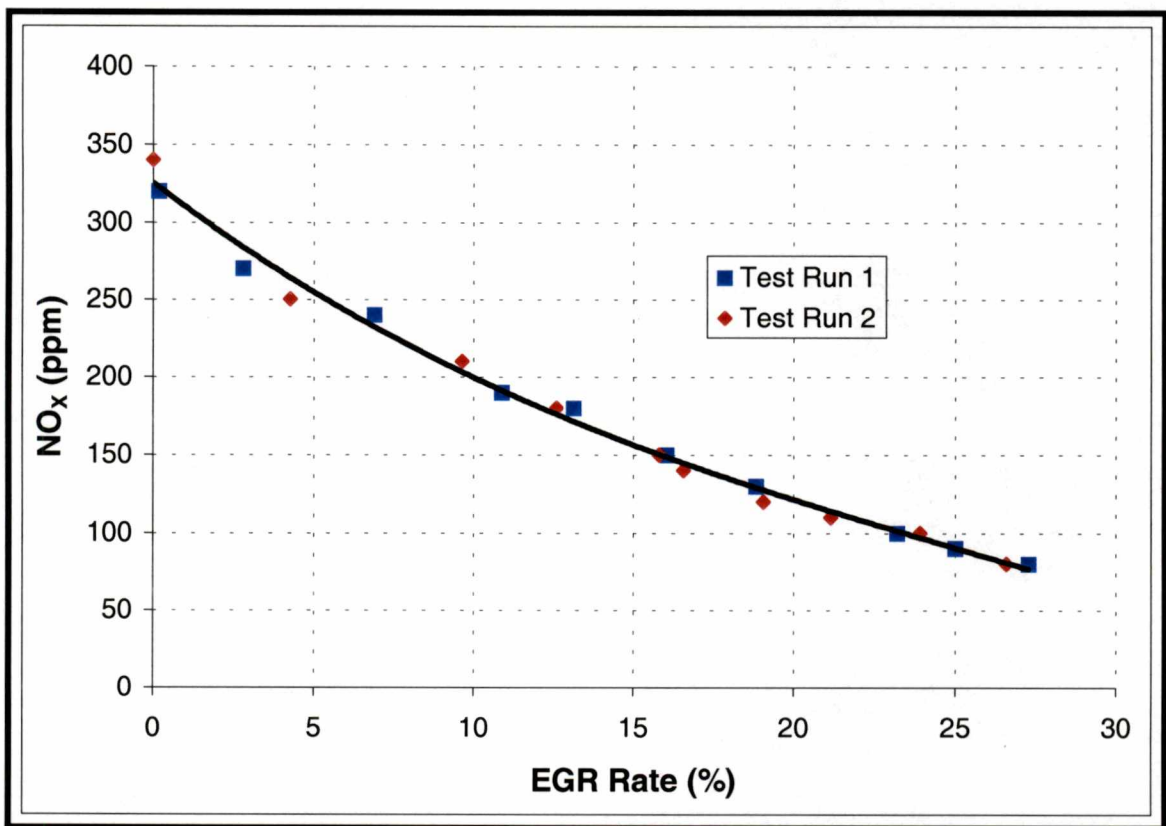


Figure 4.2 – NO_x versus EGR for 25% Load. Engine operated at 2000 rpm.

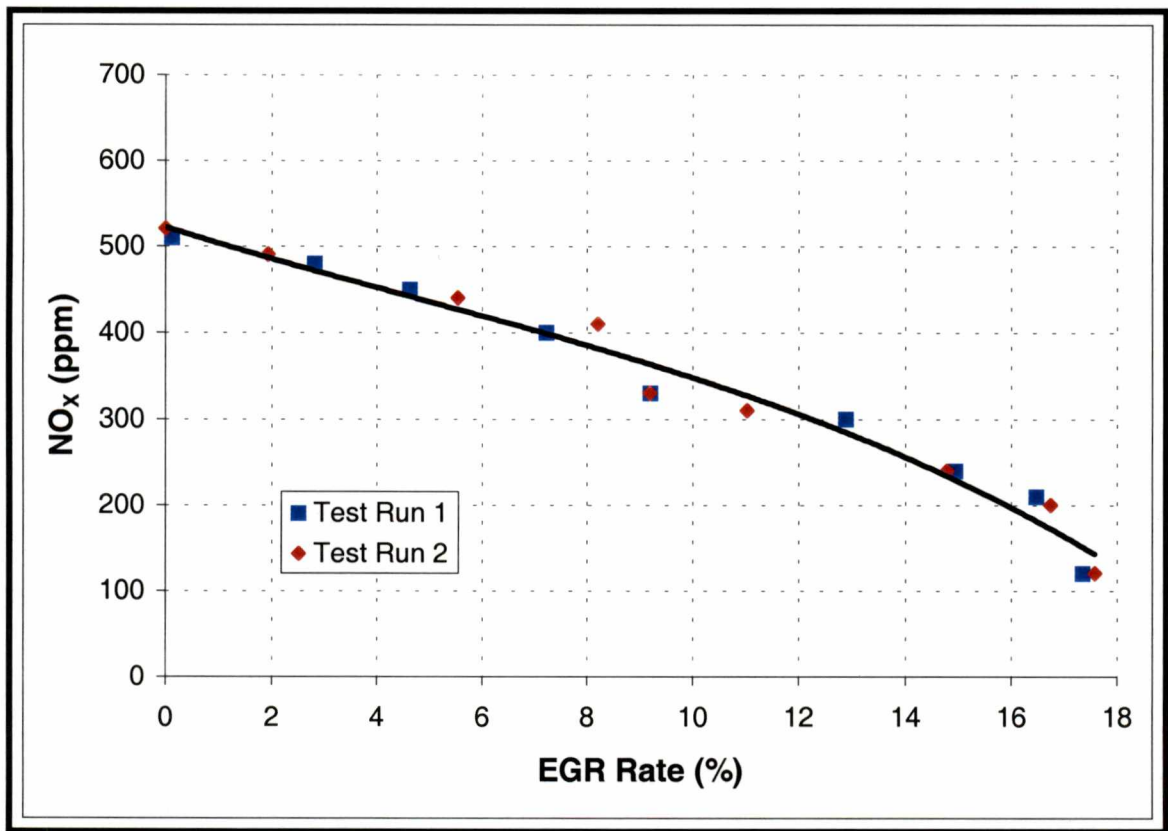


Figure 4.3 – NO_x versus EGR for 50% Load. Engine operated at 2000 rpm.

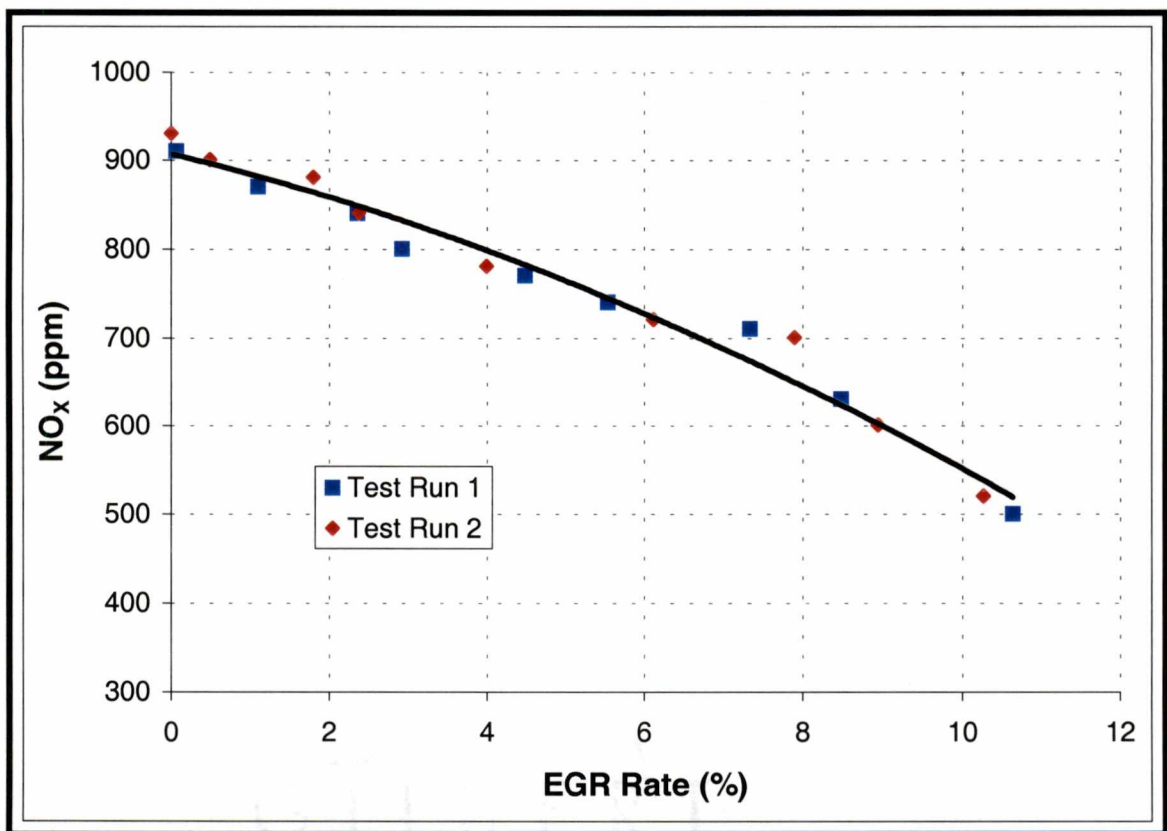


Figure 4.4 – NO_x versus EGR for 75% Load. Engine operated at 2000 rpm.

temperatures in the cylinder as non-combustible EGR constituents absorb some of the energy generated.

This study also investigated the dependence of particulate emissions on EGR. The particulate emission data was plotted in relationship with EGR in Figure 4.5 through Figure 4.12. The emission data was plotted in both units of opacity percentage and mass concentration. In the figures, it is shown that particulate emissions increase with increasing EGR rates. For 0% engine load, the increase in particulate emissions is not as significant as for the higher engine loads. At this engine load, there seems to be an almost linear relationship between opacity and mass concentration values and EGR rate for both pre-filter and post-filter emissions. But as engine loads increase, there appears to be a point at which the pre-filter particulate emissions start to spike. For 25% engine load, as seen in Figures 4.7 and 4.8, particulate emissions start to increase at approximately 15% EGR. For 50% and 75% engine loads, these “critical” EGR rates occur at around 12% and 7% respectively. These increases in PM emissions at higher loads could be explained by the fact that the amount of emissions is increased at these loads. This increase in the amount emissions leads to an increase in EGR introduction into the intake. As more EGR is introduced, less air is available for the combustion of the fuel. This leads to lower combustion efficiencies and more unburned fuel, which would lead to higher particulate emissions. However, for these higher loads, the post-filter emissions do not increase in the same fashion.

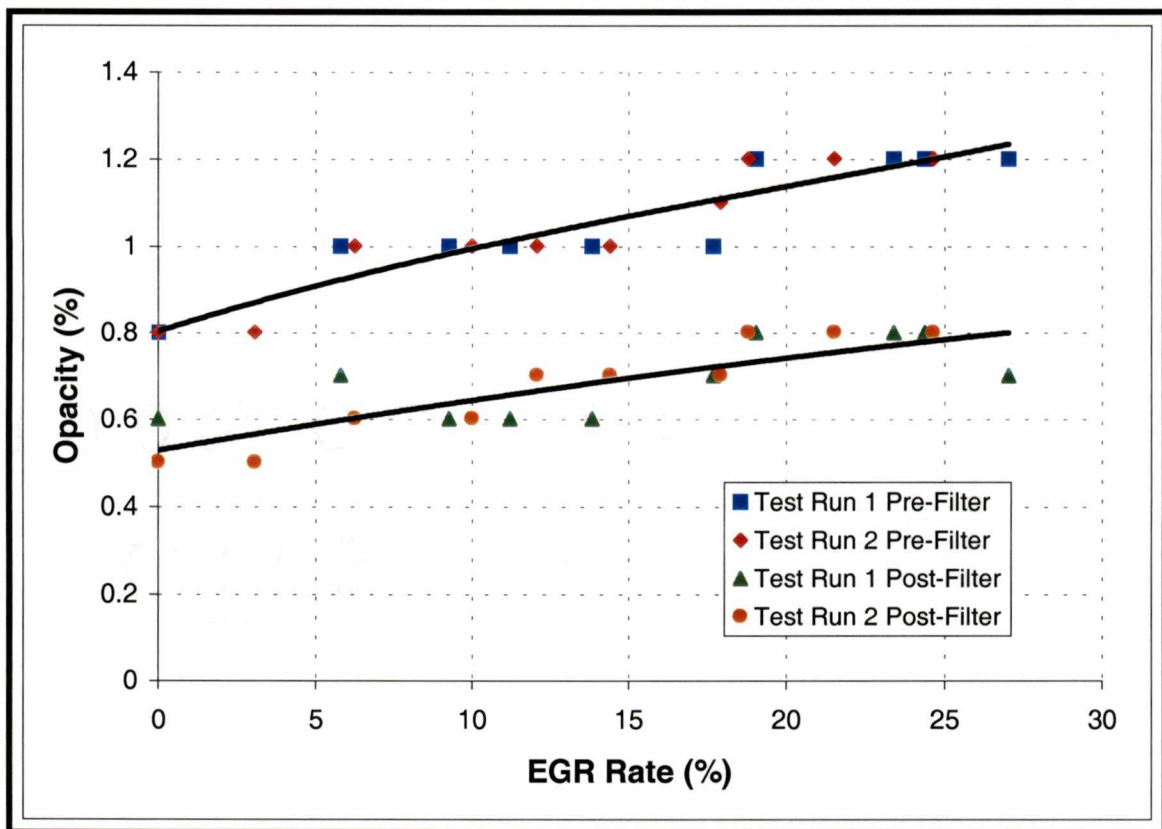


Figure 4.5 – Exhaust opacity versus EGR for 0% Load. Engine operated at 2000 rpm.

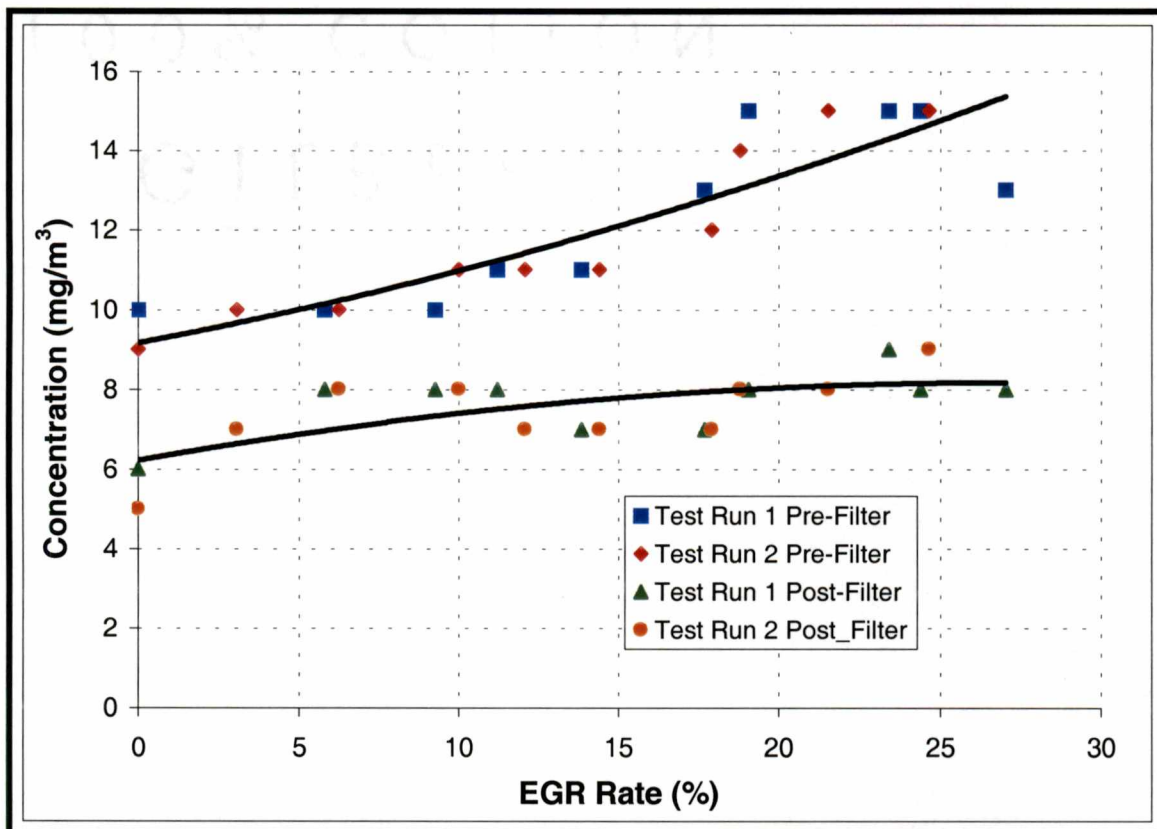


Figure 4.6 – Exhaust particulate concentration versus EGR for 0% Load.
Engine operated at 2000 rpm.

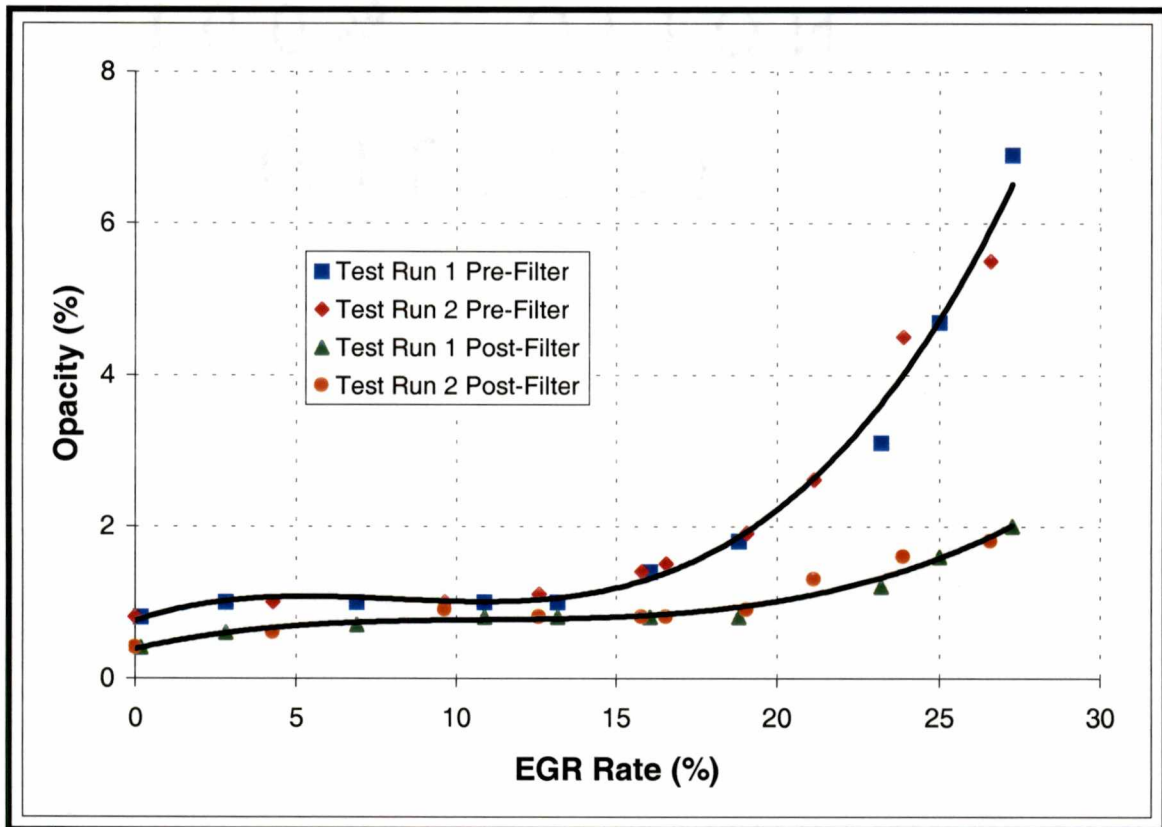


Figure 4.7 – Exhaust opacity versus EGR for 25% Load. Engine operated at 2000 rpm.

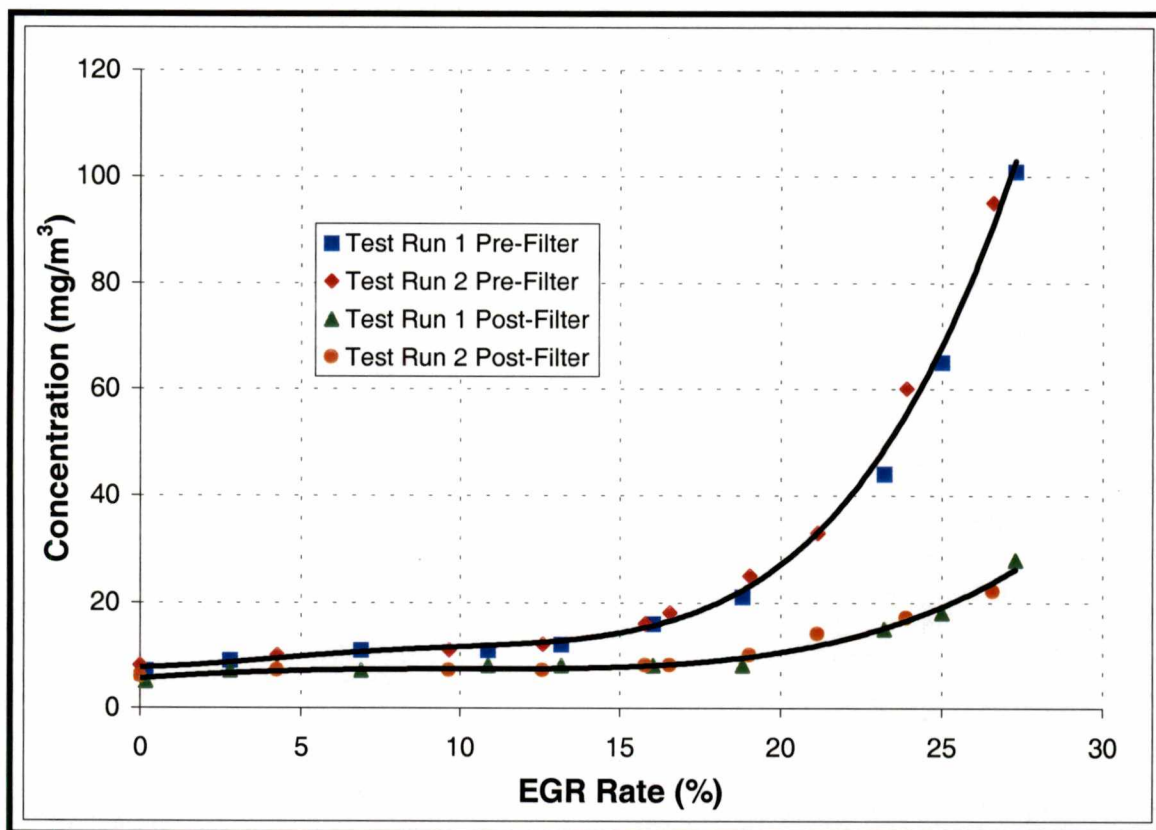


Figure 4.8 – Exhaust particulate concentration versus EGR for 25% Load.
Engine operated at 2000 rpm.

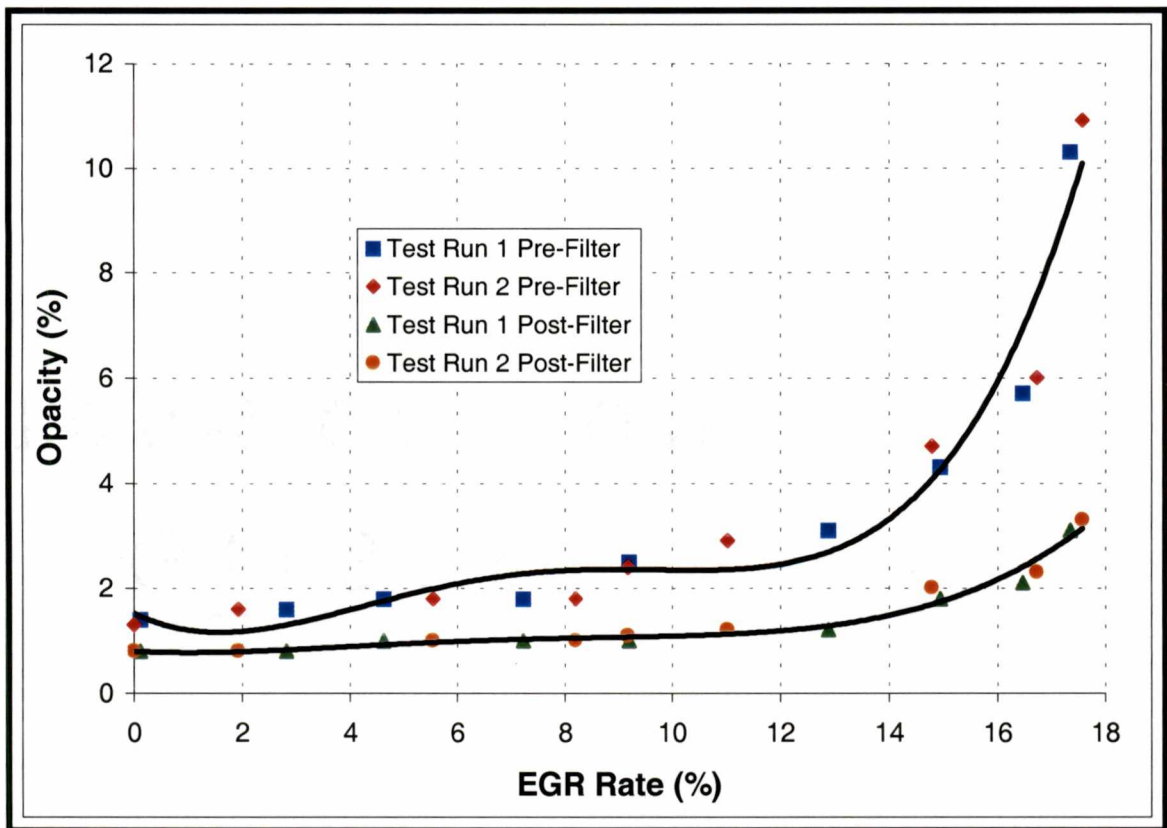


Figure 4.9 – Exhaust opacity versus EGR for 50% Load. Engine operated at 2000 rpm.

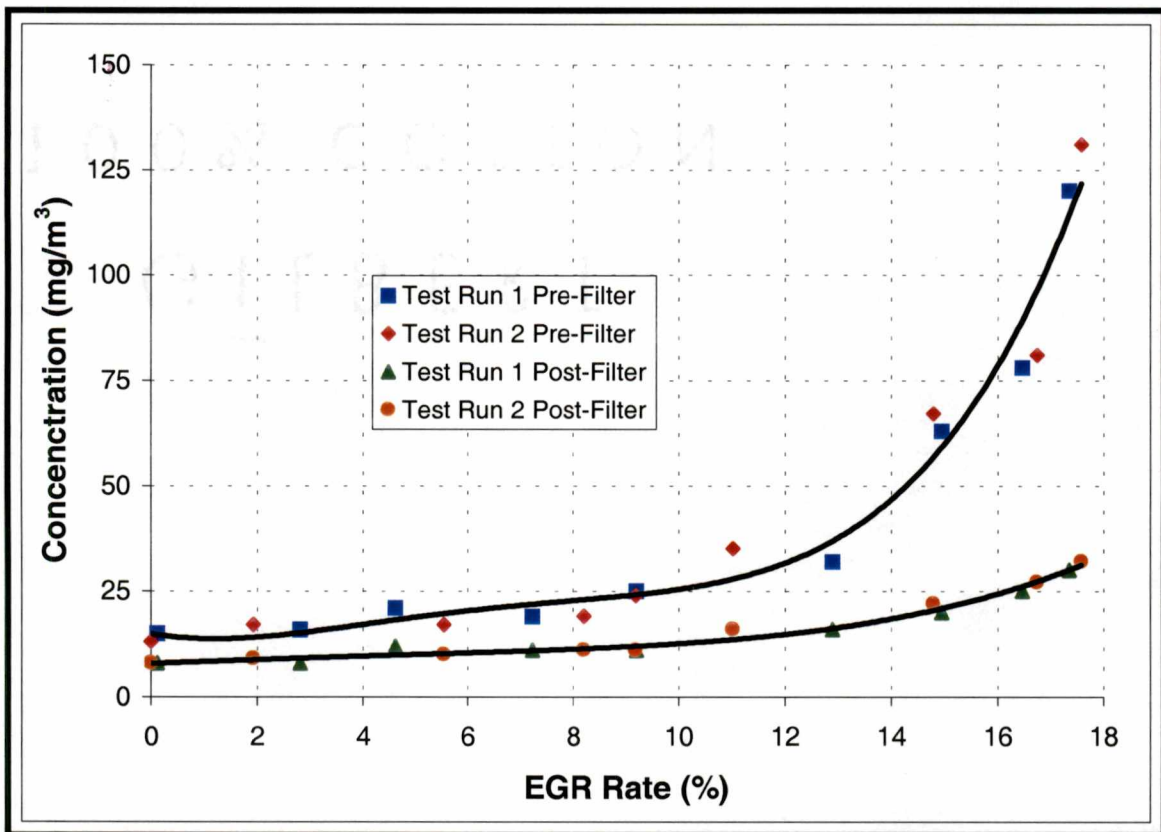


Figure 4.10 – Exhaust particulate concentration versus EGR for 50% Load.
Engine operated at 2000 rpm.

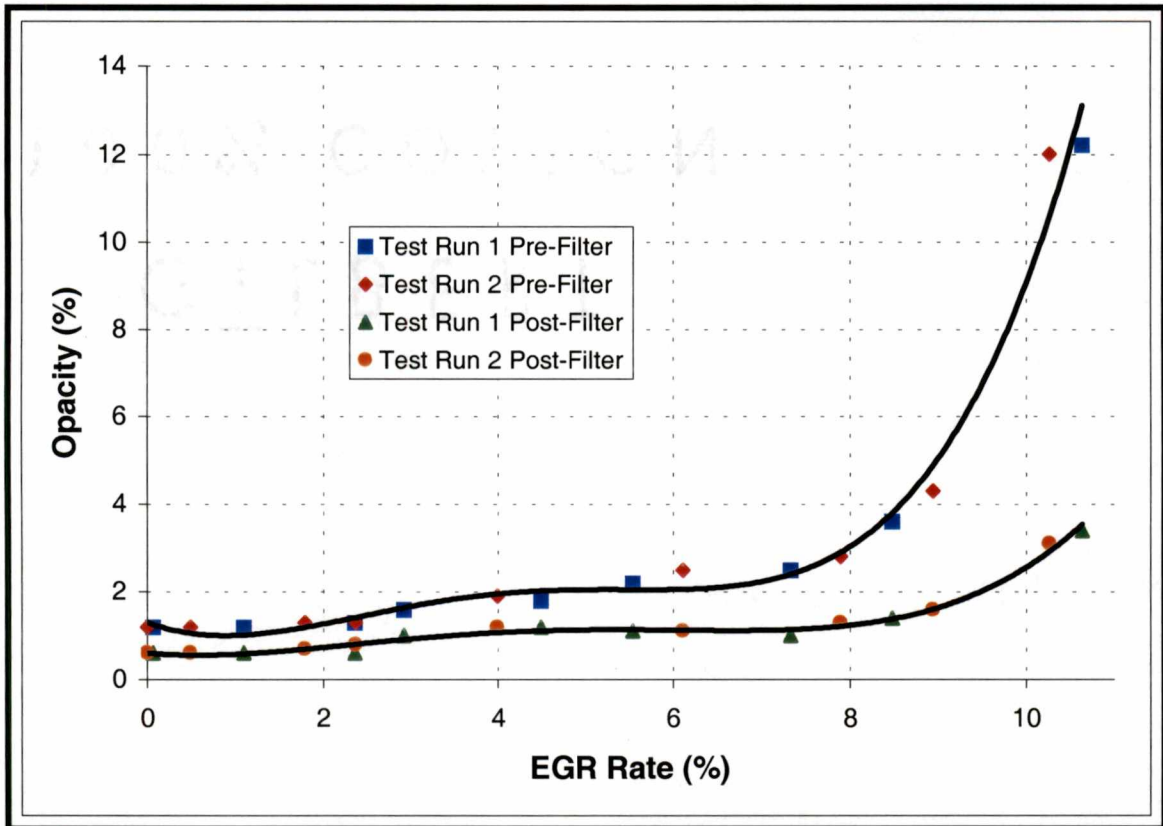


Figure 4.11 – Exhaust opacity versus EGR for 75% Load. Engine operated at 2000 rpm.

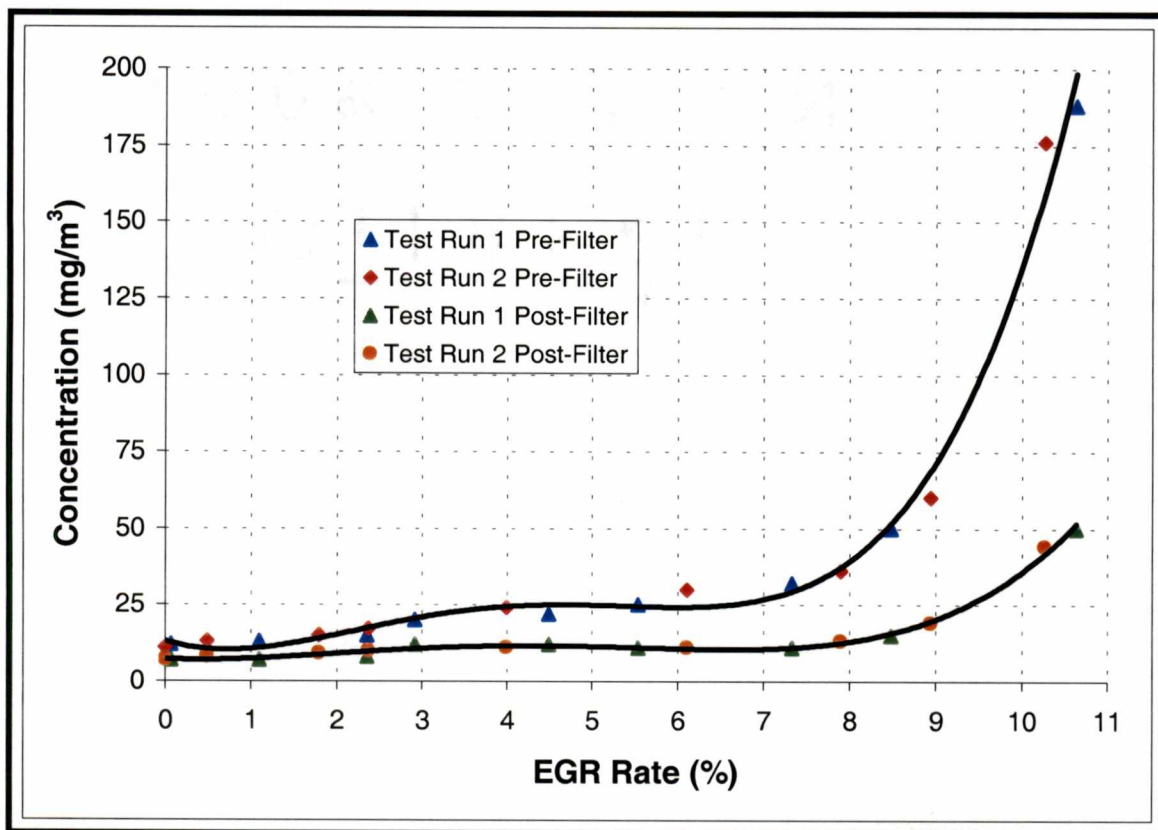


Figure 4.12 – Exhaust particulate concentration versus EGR for 75% Load. Engine operated at 2000 rpm.

Also, it can be seen in Figures 4.7 through 4.12 that the particulate filter was more efficient at higher engine loads and EGR rates. For 0% engine load, the filter efficiency ranges from 37.5% at 0% EGR to 41.2% at approximately 27% EGR for opacity units and similar trends for mass concentration units. For this engine load, the efficiency of the filter seems to be almost constant throughout the EGR range. But at the higher engine loads, the efficiency greatly increases at the higher EGR rates. This higher efficiency is most likely is due to the fact that particulates have larger diameters at higher engine loads, thus making it possible for the filter to more effectively trap the particles. For instance, at 75% engine load, the effectiveness of the filter varies from 50% at 0% EGR to 74.2% at approximately 10% EGR. For the 25%, 50%, and 75% engine loads, the efficiency of the filter noticeably increases beyond the "critical" EGR rates mentioned above.

The last correlation of the data to be presented in this chapter is of the two main exhaust emissions investigated in this study, NO_x and particulate emissions. NO_x was plotted against particulate opacity and mass concentration. Figures 4.13 through 4.16 show NO_x versus particulate opacity and mass concentration for 50% and 75% engine loads. The figures show tradeoffs both pre-filter and post-filter particulate emissions plotted against NO_x with contours added to show various levels of EGR rates. Identical relationships are depicted in Figures 4.17 through 4.20 for all engine loads

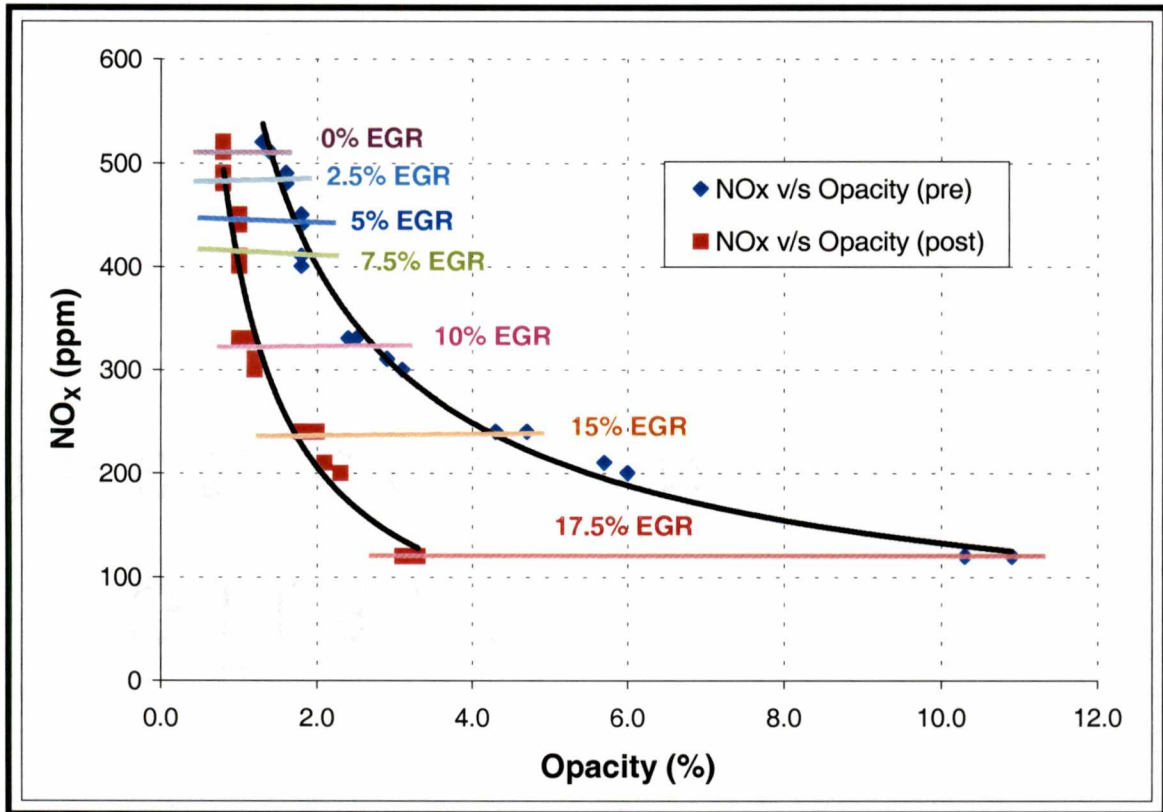


Figure 4.13 – NO_x versus exhaust opacity for 50% Load and both test runs.
Engine operated at 2000 rpm.

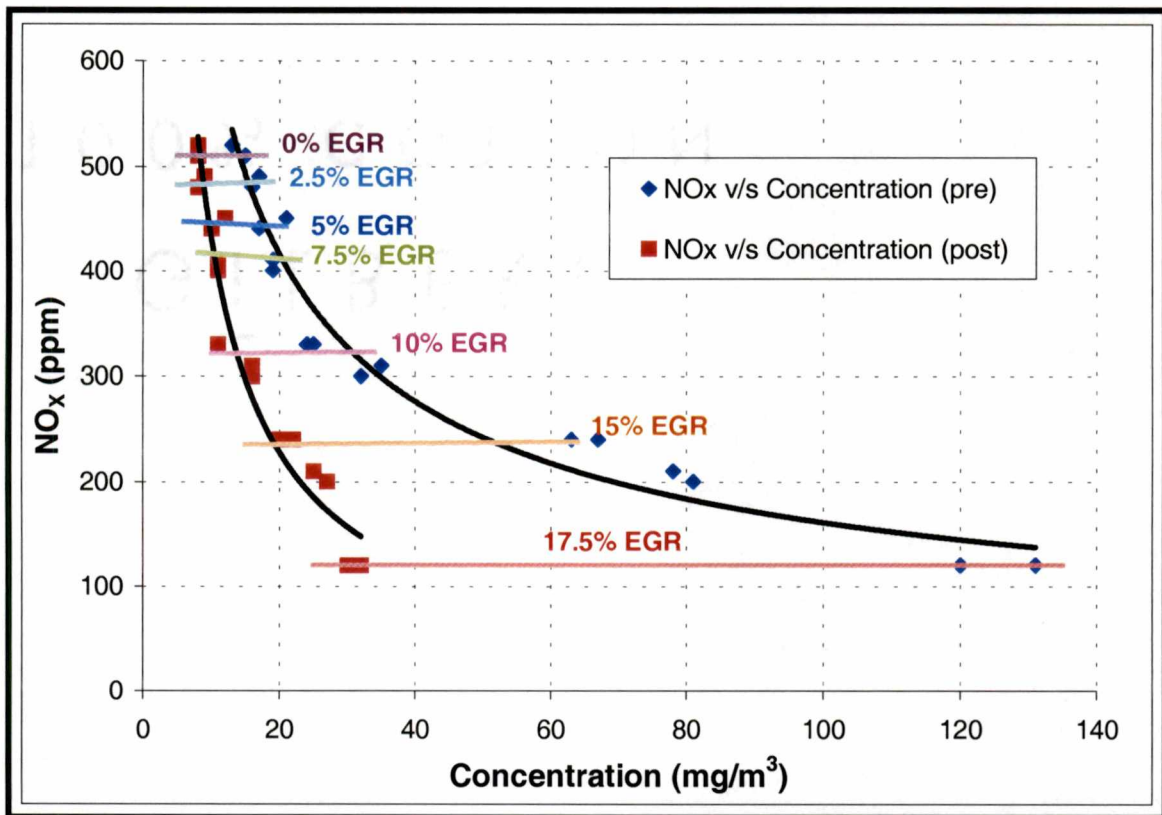


Figure 4.14 – NO_x versus exhaust particulate concentration for 50% Load and both test runs. Engine operated at 2000 rpm.

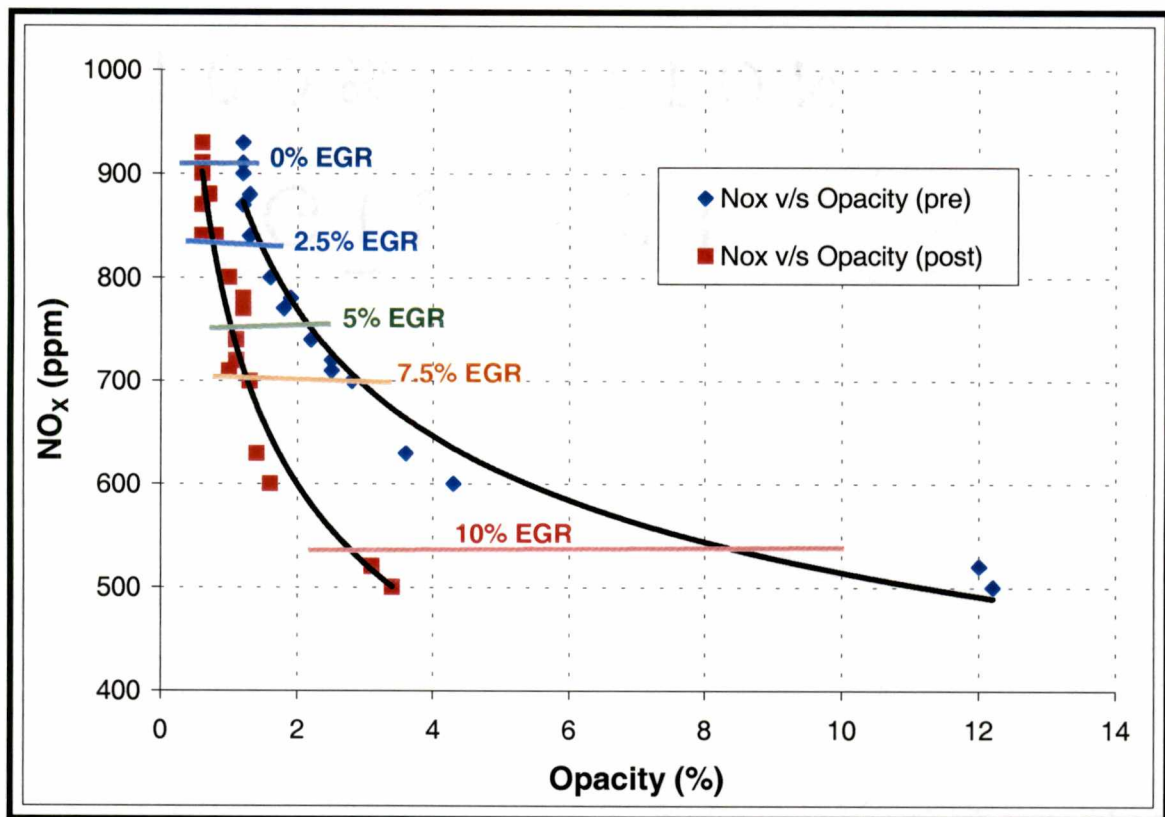


Figure 4.15 – NO_x versus exhaust opacity for 75% load. Engine operated at 2000 rpm.

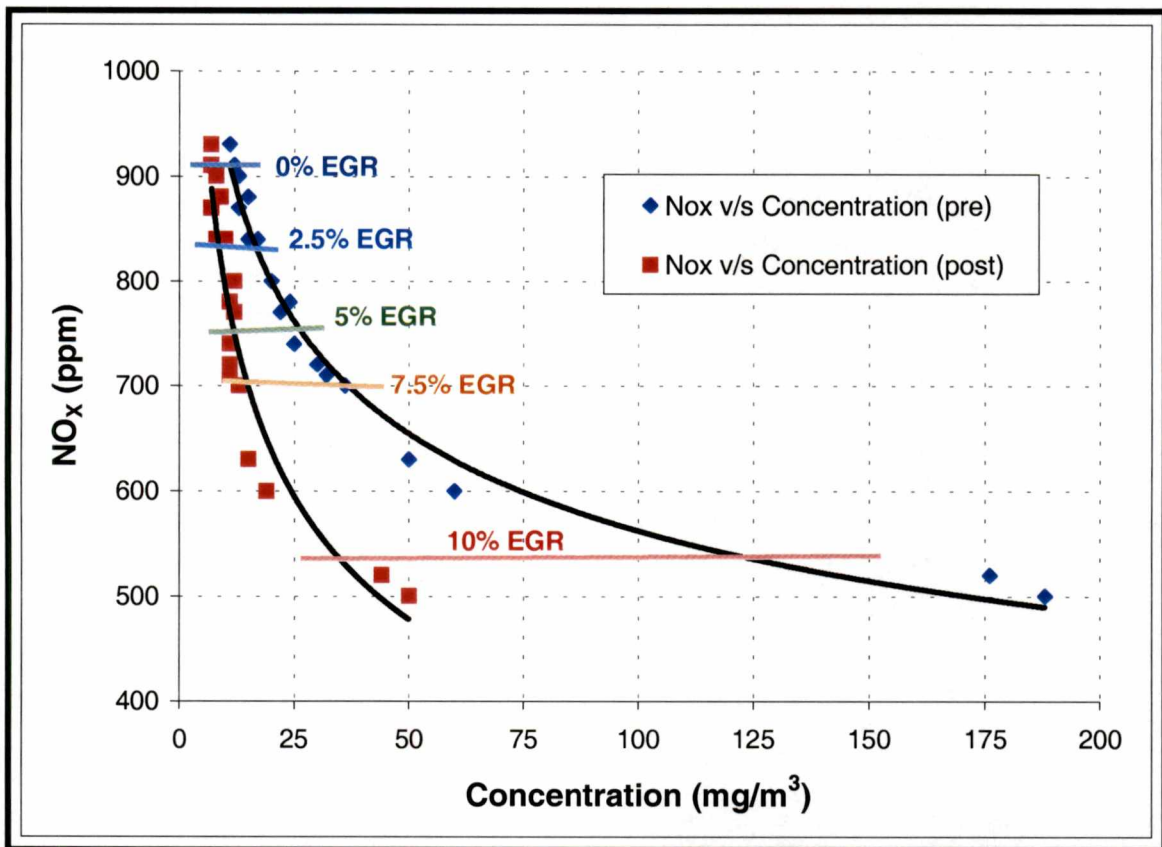


Figure 4.16 – NO_x versus exhaust particulate concentration for 75% load. Engine operated at 2000 rpm.

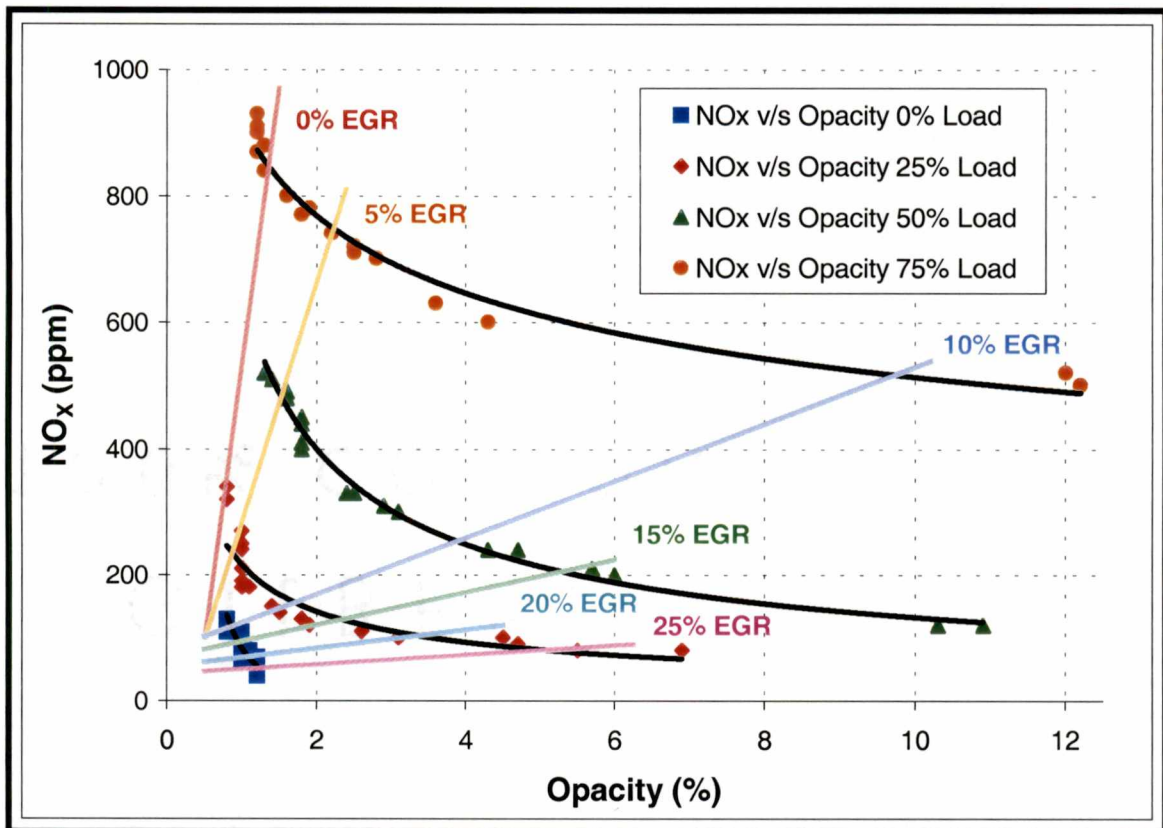


Figure 4.17 – NO_x versus Pre-Filter exhaust opacity for all loads and both test runs. Engine operated at 2000 rpm. Smoke units in opacity (%).

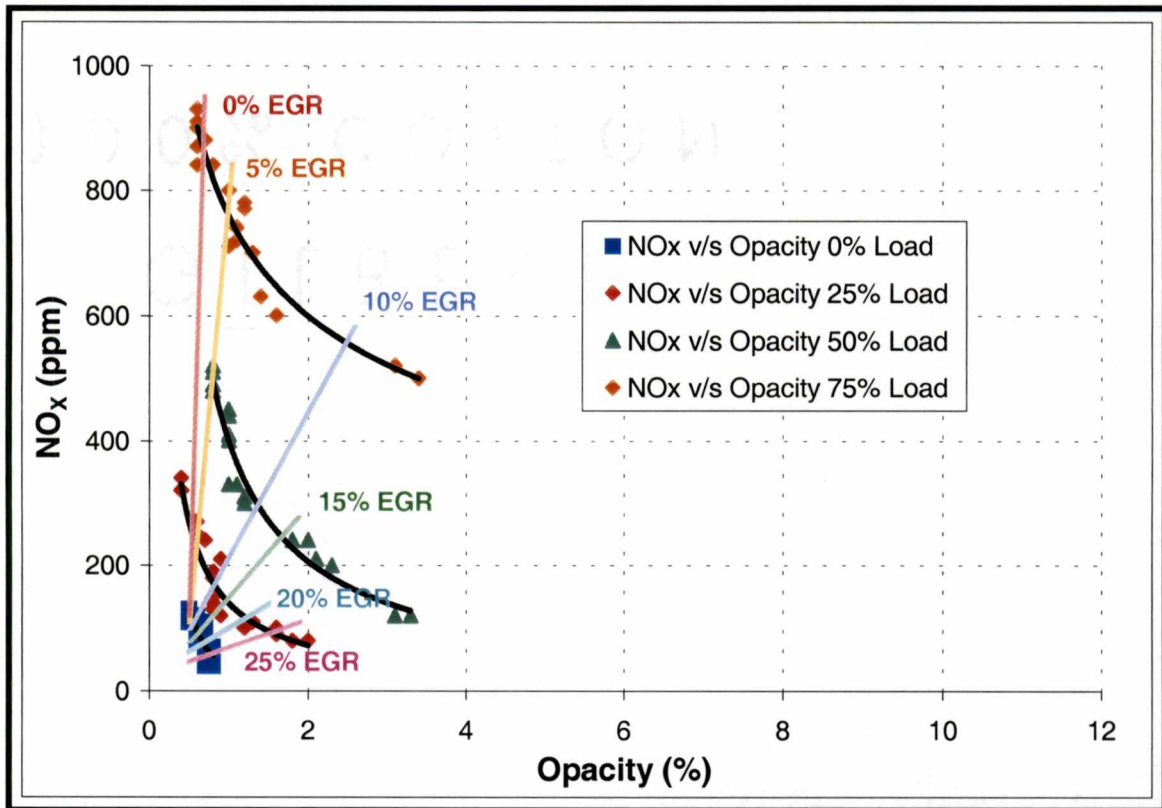


Figure 4.18 – NO_x versus Post-Filter exhaust opacity for all loads and both test runs. Engine operated at 2000 rpm. Smoke units in opacity (%).

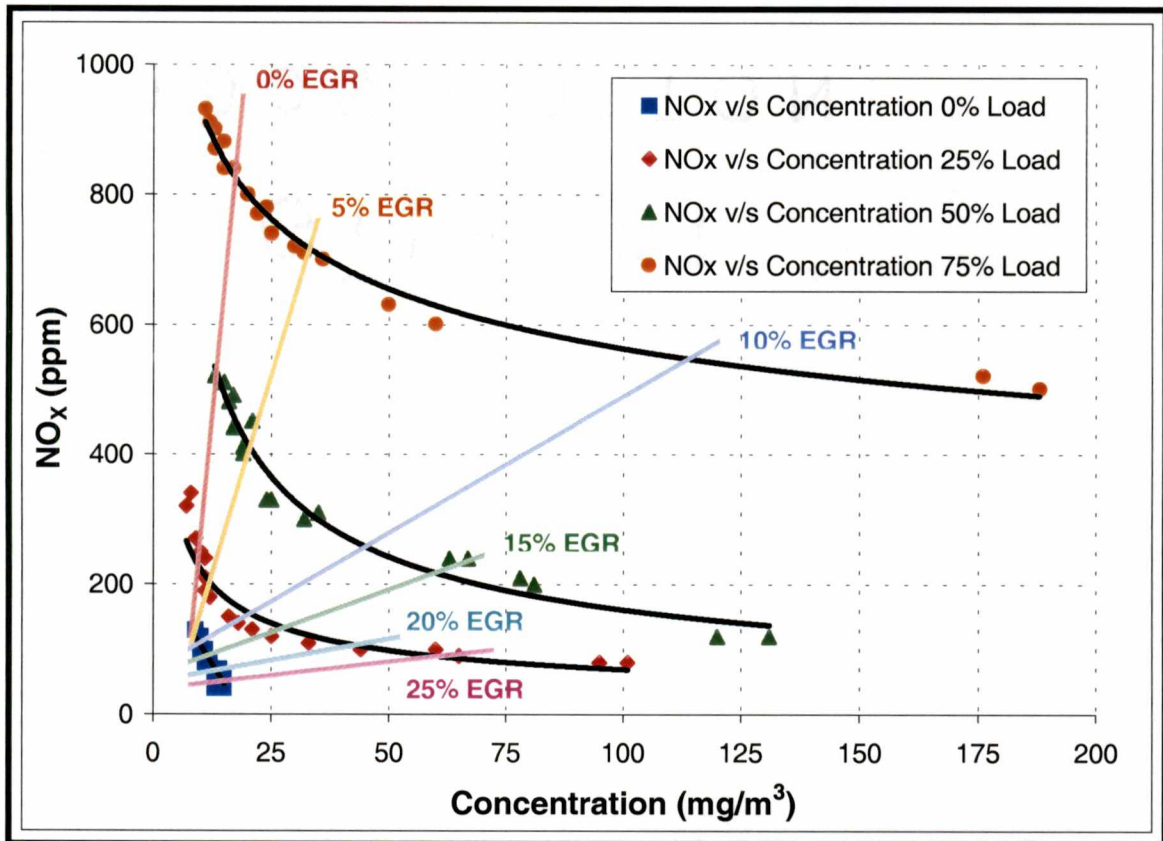


Figure 4.19 – NO_x versus Pre-Filter exhaust particulate concentration for all loads and both test runs. Engine operated at 2000 rpm. Smoke units in concentration (mg/m³)

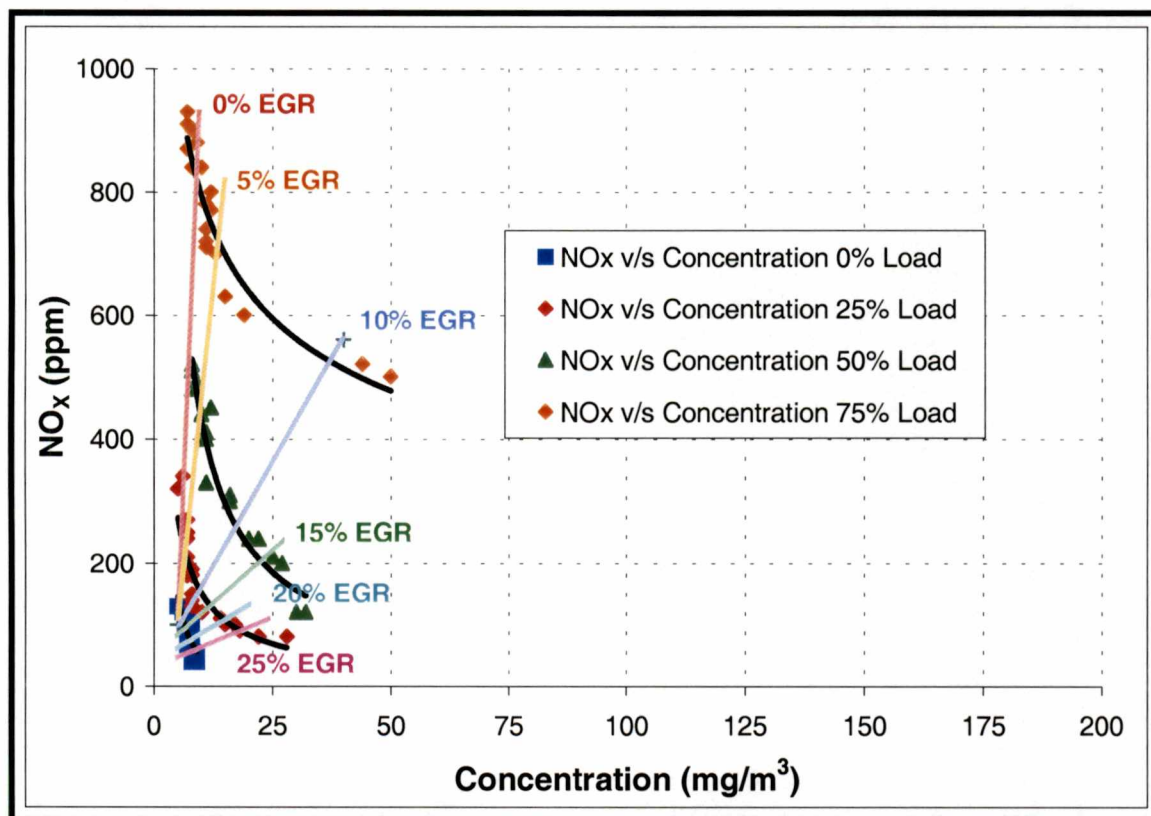


Figure 4.20 – NO_x versus Post-Filter exhaust particulate concentration for all loads and both test runs. Engine operated at 2000 rpm. Smoke units in concentration (mg/m³)

collectively for both pre-filter and post-filter particulate emissions in opacity and mass concentration plotted against NO_x . Contours are also plotted to show EGR rates. As seen from the figures, there is an inverse association between particulate emissions and NO_x . This inverse relationship is more defined in the pre-filter data than the post-filter data and is better illustrated in Figures 4.11a and 4.12a, showing the emissions relationships for all the loads. These figures are plotted with the same axis values to better illustrate the difference among pre-filter and post-filter data. It could be said that if the particulate filter were more effective, the trend lines in Figures 4.18 and 4.20 would be more compressed towards the y-axis.

Several past studies have been conducted that substantiate the validity of the data obtained in this study. Herzog *et al* [23] performed research and development to determine the NO_x reduction potential of several engine parameters including EGR for a single cylinder TCI diesel research engine. Their results, as seen in Figure 4.21, show increases in particulate emissions and decreases of NO_x with increasing EGR rate. Engine conditions in this study were 2000 rpm and 2.8 bar BMEP (brake mean effective pressure). Another similar study by Lapuerta *et al* [24] shows related trends in the effect of EGR on NO_x and particulate emissions. This study, conducted on a single cylinder supercharged diesel engine, also showed decreases in NO_x and increases in particulate matter for increasing EGR. Figure 4.22 represents these results.

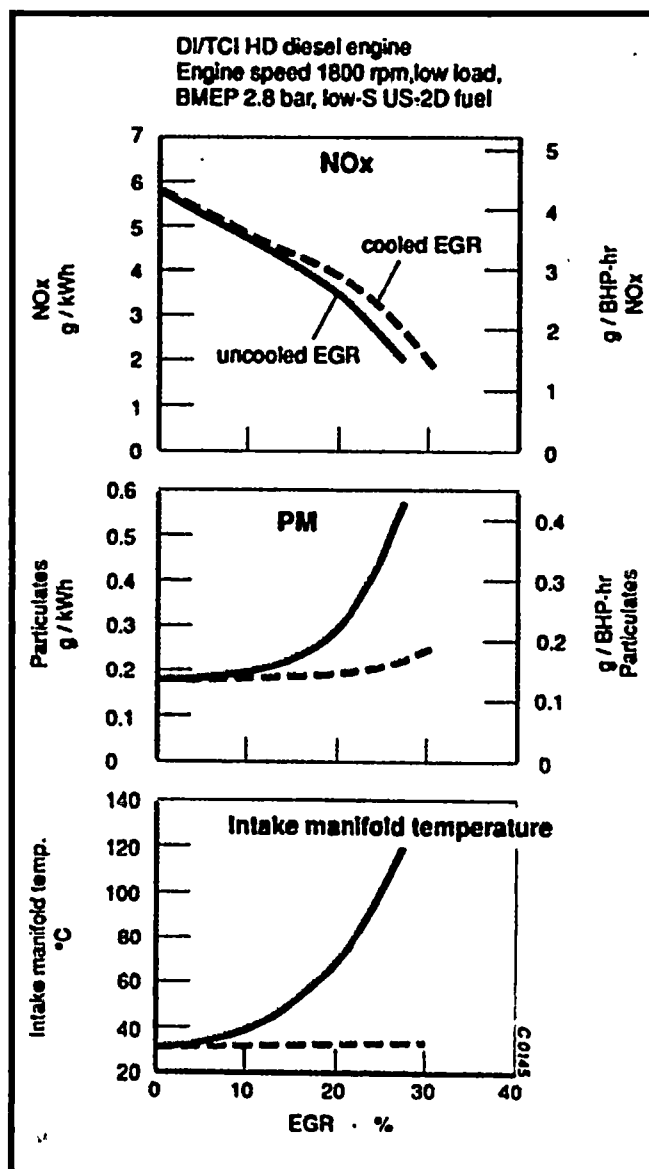


Figure 4.21 – Effect of EGR and EGR cooling on NO_x and Particulates [23].

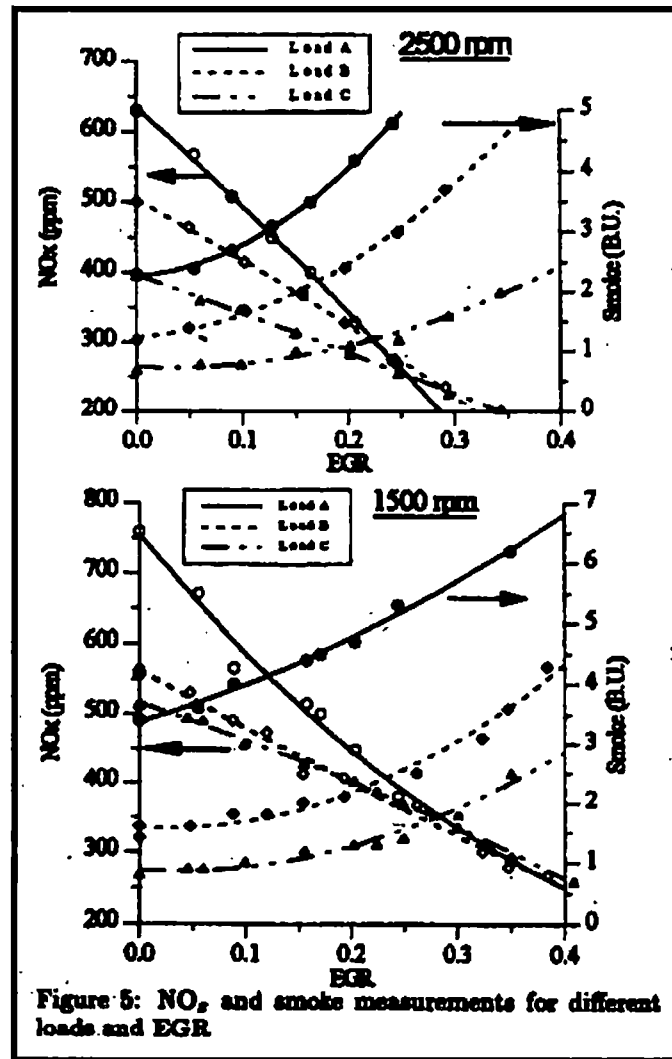


Figure 4.22 – NO_x and smoke measurements for different loads and EGR [24].

Engine conditions for this study were two engine speeds of 1500 rpm and 2500 rpm with three different engine loads.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

An emissions study was conducted to examine the effect of EGR on NO_x and particulate emissions in the Alfa Romeo diesel engine. Testing was conducted at a range of engine loads, EGR was varied using a control system, and the experimental setup was augmented with the use of a ceramic particulate trap. EGR versus NO_x and particulate emission curves were generated. NO_x versus particulate emission curves were also created to provide additional insight into the effects of EGR.

The results of this study have led to the following conclusions:

1. EGR significantly reduced NO_x . This effect was more prominent at higher engine loads.
2. Particulate emissions increase as EGR rises. This relationship was more pronounced at high engine loads with escalated EGR rates.
3. The effectiveness of the particulate filter was shown to be stronger at higher EGR levels and higher engine loads. As pre-filter particulate emissions started to peak for 25%, 50%, and 75% engine loads, the post-filter emissions stayed more stabilized, thus increasing the effectiveness of the filter.
4. For the objectives of this study, the effects of EGR on NO_x and particulate emissions, the emissions analyzers used were adequate.

For the evaluation of EGR ratio, which entailed the measurement of CO_2 in the intake and exhaust, the CO_2 analyzers employed also performed their tasks sufficiently.

5. The experimental setup proved capable to demonstrate the above experimental observations.

The reduction of NO_x is due to the reduction of in-cylinder peak temperatures by the introduction of EGR. It should be noted that situations such as high engine loads would not conventionally incorporate EGR. The application of EGR at higher load levels would decrease combustion and thermal efficiencies and engine power. The effects of EGR incur the opposite response in particulate emissions than that of NO_x . Since this predicament exists, a compromise in EGR would need to be endorsed to achieve adequate NO_x reductions while retaining minimal particulate emissions.

Based on this study, it can be seen that the use of EGR can greatly reduce NO_x emissions, but also increase particulate emissions. But to fully realize the extents of this study, several modifications could be introduced.

The following recommendations are proposed:

1. A motoring dynamometer could be implemented to maintain engine speed so higher amounts of EGR can be introduced at higher engine loads.

2. For the microwave regenerative particulate filter used in the study, the use of a microwave source would be useful to demonstrate the full capabilities of the filter.
3. The application of a more efficient particulate filter at lower engine loads and EGR levels could better complement this study.
4. The use of a purpose dedicated emissions test bench, one that would be better suited to diesel emission testing, would greatly improve the validity of the emission data. This type of emissions testing equipment could include a dilution tunnel, constant volume sampler, total hydrocarbon analyzer, CO and CO₂ analyzers, and instruments that could measure particulate particle size, such as Scanning Mobility Particle Sizer (SMPS). Data gathered from devices such as these could further define the effects of EGR on particulate particle size distributions and other exhaust constituents.

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APPENDIX

Engine Specifications

Alfa Romeo Diesel Engine

Type	Diesel, 4 stroke
Cooling System	Water cooled
Intake System	Turbocharged, intercooled
Main Fuel System	Bosch Radialjet Common Rail Fuel Injection
Secondary Fuel System	Walbro 10-psi Fuel Pump
Cylinder Configuration	Five cylinder, inline
Displacement	2.387 liters
Bore	82.0 mm
Stroke	90.4 mm
Valve Train	2 valves/cylinder, pushrod
Firing Order	1-2-4-5-3
Idle Speed	800 $\pm$ 20 rpm
Maximum Speed	5000 $\pm$ 20 rpm
Maximum Power	100.0 kW @ 4200 rpm (134 hp)
Maximum Torque	304.2 N-m @ 2000 rpm (227 ft-lb)

VITA

Palak Kirendra Patel was born in Piscataway, New Jersey on March 7, 1977. He and his family moved to Tennessee in 1985 before spending a year in South Carolina. He attended Jefferson Elementary and Middle Schools before moving on to Jefferson County High School. He graduated high school in May 1995 and entered the Mechanical Engineering curriculum at Tennessee Technological University in Cookeville, Tennessee the following fall. As an undergraduate, he took an active role in the American Society of Mechanical Engineers and had a concentration in thermal sciences. Palak received his Bachelor of Science Degree in Mechanical Engineering from TTU in May 1999. In August 1999, he entered the University of Tennessee, Knoxville to begin work toward a Master of Science Degree in Mechanical Engineering. In that month, he also accepted a GATE (Graduate Automotive Technology Education) fellowship and began full time work toward his degree. At the University of Tennessee, Palak became involved in hybrid-electric vehicle projects (FutureTruck 2000/2001) and was active in the Society of Automotive Engineers.

Palak received his Master of Science Degree in Mechanical Engineering from the University of Tennessee, Knoxville in December 2001.