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Empirical and Modeling Preparation Research for Diesel Low Temperature Combustion

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Empirical and Modeling Preparation Research for Diesel Low Temperature Combustion

by

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ABSTRACT

The main objective of the thesis work was to propose and produce an advanced engine test platform for diesel Low Temperature Combustion (LTC) research by reconfiguring a high performance modern European diesel engine. Innovative LTC combustion strategies were then tested on this newly created platform, which demonstrated that the modified engine system is fully flexible in the independent control of intake boost, exhaust backpressure, exhaust gas recirculation (EGR), and injection scheduling.

In the first part of the thesis, the implementation of independent control of the modified Ford Puma has been documented in detail. LTC tests conducted on the engine test platform are recorded, and preliminary experimental results are discussed.

In the second part of the thesis, parametric analysis of variable valve timing (VVT) effects on the combustion phasing of diesel homogenous charge compression ignition (HCCI) is studied through the GT-power simulation work, and the results are discussed.

DEDICATION

To My Beloved Parents,
Jianguo Han
Yueying Zhang

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At last, so many thanks to my beloved parents. Without their spiritual support, encouragement and understanding, I could not finish my masters' degree. Here I express my most deeply love to my parents.

Xiaoye Han

Windsor, Ontario

Canada

May 6 2008

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NOMENCLATURE

AC	Alternating Current	
AHRR	Apparent Heat Release Rate	
AI	Analog Input	
ATDC	After Top Dead Center	
abs	Absolute	
BTDC	Before Top Dead Center	
CA50	Crank Angle of 50% Heat Released	
Comb.	Combustion	
Comp.	Compression	
CR	Common Rail	
cRIO	Compact Reconfigurable Input / Output Module	
d	Cylinder Diameter	
DAQ	Data Acquisition	
D	Duty Cycle	[%]
DC	Direct Current	
DCP	Diesel Common-rail Pump	
$(dp/d\theta)_{max}$	Maximum Rate-of-pressure Rise	[bar/°CA]
e	Error	
E	Internal Energy	
ECU	Engine Control Unit	
EGR	Exhaust Gas Recirculation	
EMF	Electro-Magnetic Force	
EOC	End of Combustion	
EVP	Exhaust Valve Position Sensor	
FPGA	Field Programmable Gate Array	
GND	Ground	
HCCI	Homogenous Charge Compression Ignition	
HP	High-pressure	
HPP	High-pressure Pump	

HTC	High Temperature Combustion	
Hz	Frequency in Hertz	
IMEP	Indicated Mean Effective Pressure	[bar]
I/O	Input / Output	
K_C	Controller Gain	
T_I	Integral Time, Reset Time	[minutes], [m]
T_D	Derivative Time, Rate Time	[minutes], [m]
KS/s	Kilo Samples per Second	
L	Liter	
LTC	Low Temperature Combustion	
MS/s	Mega Samples per Second	
NI	National Instrument	
NOx	Oxides of Nitrogen	
ns	Nano-second	
OEM	Original Equipment Manufacturer	
PID	Proportional, Integral and Derivative	
PM	Particulate Matter	
p_{int}	Intake Pressure	[bar]
p_{max}	Maximum Cylinder Pressure	[bar]
PCV	Pressure-control Valve	
PID	Proportional-Integral-Derivative	
PV	Process Variable	
PWM	Pulse Width Modulation	
Q	Cumulative Heat Release	
r_c	Compression Ratio	
Re	Reynolds Number	
RPM	Revolutions per Minute	
RT	Real-time	
SAES	Synthetic Atmosphere Engine Simulation	
SOC	Start of Combustion	
SOI	Start of Injection	
SP	Set-point	

T	Working Fluid Temperature	[K]
T_{PWM}	Duration of the PWM Signal	[second], [s]
TDC	Top Dead Center	
T_{int}	Intake Temperature	[K]
T_{ON}	On-time of the PWM Signal	
TTL	Transistor-transistor Logic	
T_w	Cylinder Wall Temperature	[K]
VCR	Variable Compression Ratio	
VCV	Volume-control Valve	
VGT	Variable Geometry Turbocharger	
VI	Virtual Instrument	
VVT	Variable Valve Timing	
zero-D	Zero-Dimensional	
ϕ	Equivalence Ratio	
θ, CA	Crank Angle	[°CA]
θ_{pmax}	Crank Angle of Maximum Cylinder Pressure	[°CA]
$\theta_{(dp/d\theta)max}$	Crank Angle of Maximum Rate-of-pressure Rise	[°CA]
μs	Microsecond	
ΔHR	Heat Release Duration, Combustion Duration	[°CA]
η_{ind}	Indicated Thermal Efficiency	[%]

CHAPTER I

1 INTRODUCTION

The main objective of the thesis work is to propose and produce an advanced engine test platform for diesel Low Temperature Combustion (LTC) research by reconfiguring a high performance modern European diesel engine. Further, innovative LTC combustion strategies are tested on this newly created platform, which demonstrates that the modified engine system is fully flexible in independent control of intake boost, exhaust backpressure, exhaust gas recirculation (EGR), and injection scheduling.

1.1 Conventional Diesel Combustion

The combustion processes of conventional diesel engines in direct injection (DI) configurations are illustrated in Figure 1.1. After an amount of fresh air is taken into the engine, the cylinder charge is compressed to a higher temperature prior to an amount of liquid diesel fuel is injected to the combustion chamber at a high pressure and when the piston approaches the top dead center (TDC) of the cylinder. Under the high compression temperature and pressure, the physical and chemical processes proceed before the injected diesel fuel gets auto-ignited as described by Heywood in 1988 [1]. Conventional diesel engines were more fuel-efficient than gasoline engines and produce very little carbon monoxide owing to the nature of air excess burning even at full loads. It was quite common that the quantity of fuel injected per cycle is still about 50% leaner than stoichiometric conditions under high load engine operations [1].

However, such traditional diesel engine were prone to produce black soot, or more specifically diesel particulate matter (PM), that includes of dry carbon and unburned carbon compounds [1]. Furthermore, although the high temperature and pressure combustion is desirable for power production, Nitrogen oxides (NOx) is commonly generated at the high temperature with excess oxygen. In general, the conventional diesel combustion temperature exceeds 1800K [2]; therefore, the conventional diesel combustion can be categorized as the high temperature combustion. The heterogeneous charge in conventional diesel engines results in the uneven distribution of the air/fuel ratio (Φ) over the combustion chamber, which means the local Φ is different from the global Φ

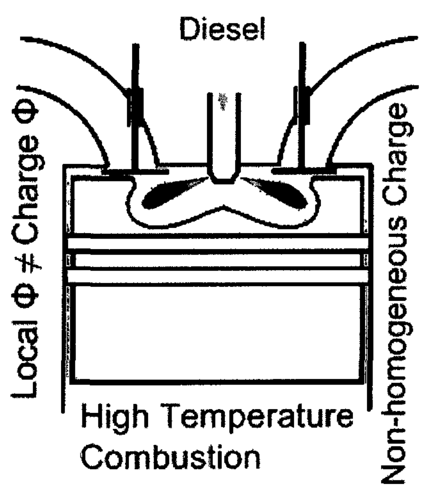


Figure 1.1 Conventional Diesel Combustion

1.2 NOx and Soot Emissions of Diesel Engines

During the past decades, research attention on the diesel engines has been shifted from the higher power and robust operation towards better fuel efficiency and cleaner emissions [www.dieselnet.com/standards], as the emission regulations getting stringent especially on NOx and soot emissions as shown in Figure 1.2. The NOx and soot emissions are regulated into a very narrow range according to the 2007 emission standard of Environmental Protection Agency (EPA) for the heavy duty diesel vehicles. Even so, engine–out NOx in year 2010 is proposed to be reduced from 1.2g/HP·hr to 0.2g/HP·hr. From year 2007 to 2010 the requirement of soot will be kept as 0.01g/HP·hr, which is already at an ultra-low level [3].

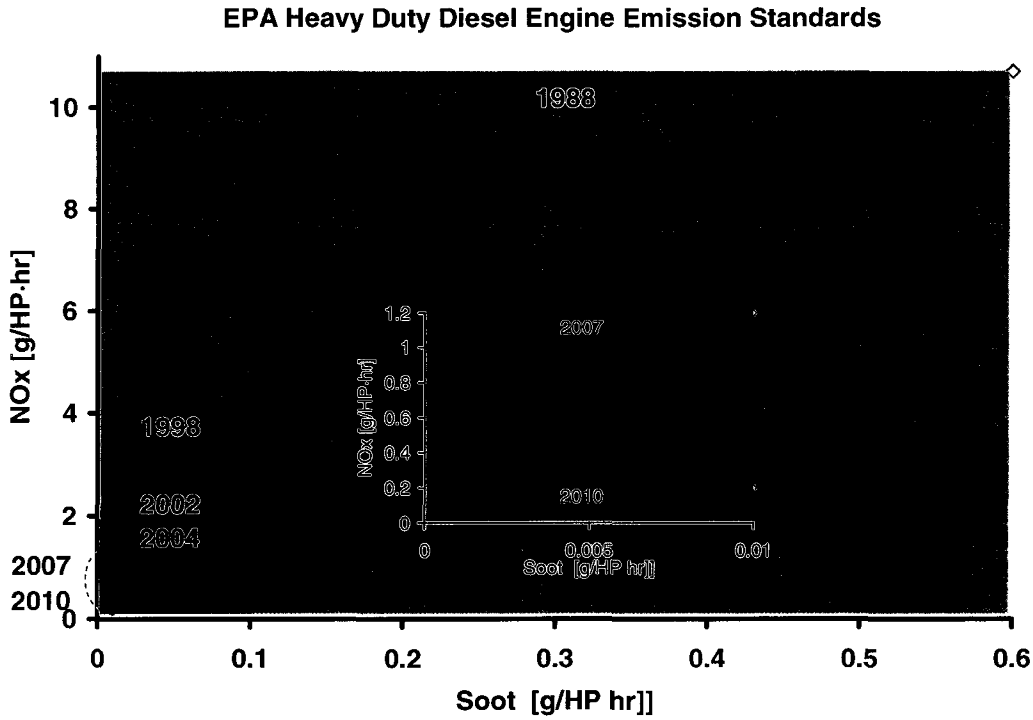


Figure 1.2 Environmental Protection Agency Emission Regulations on NOx and Soot over the Years

The formation of NOx and soot in the conventional diesel combustion can be explained by analyzing the local air excess ratio (or air-to-fuel ratio) of the injected diesel fuel spray and combustion flame.

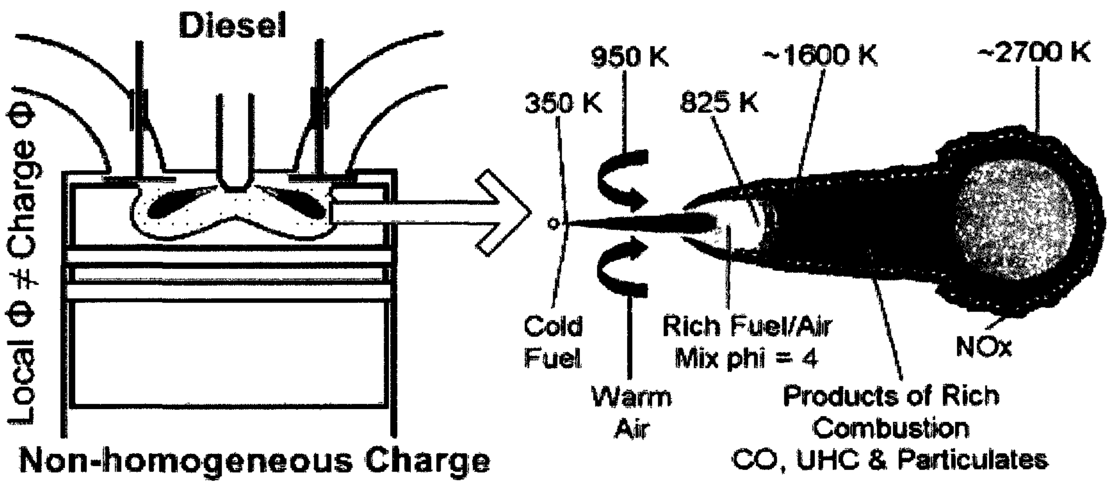


Figure 1.3 Diesel Fuel Spray and Flame (adapted from Flynn et al.) [4]

A conceptual picture of the injected diesel fuel spray and combustion flame is displayed at the right of Figure 1.3. The whole diesel fuel spray can classified into several zones according to the local excess air ratio. The outer layer of the spray has the most chance to access the surrounding oxygen and high temperature, and consequently NOx generates most at this zone. On the other hand, the inner part of the spray is so poorly mixed with air that the core of the spray could be even rich (the amount of fuel is more than the stoichiometric proportion), where the soot formation mostly takes place. This kind of the fuel and air mixture is so-called non-homogeneous charge which has regional rich/lean pockets. When the diesel fuel auto-ignites under the non-homogeneous condition, a large amount of soot and NOx will be generated simultaneously.

1.3 Control Strategies for NOx and Soot Emission Reduction

A number of major in-cylinder combustion control strategies have shown to be effective to reduce NOx or soot emissions (Figure 1.4 and Figure 1.5), as listed in Table1.1. These control strategies could be categorized into four groups: injection scheduling, injection pressure, EGR, and intake boost.

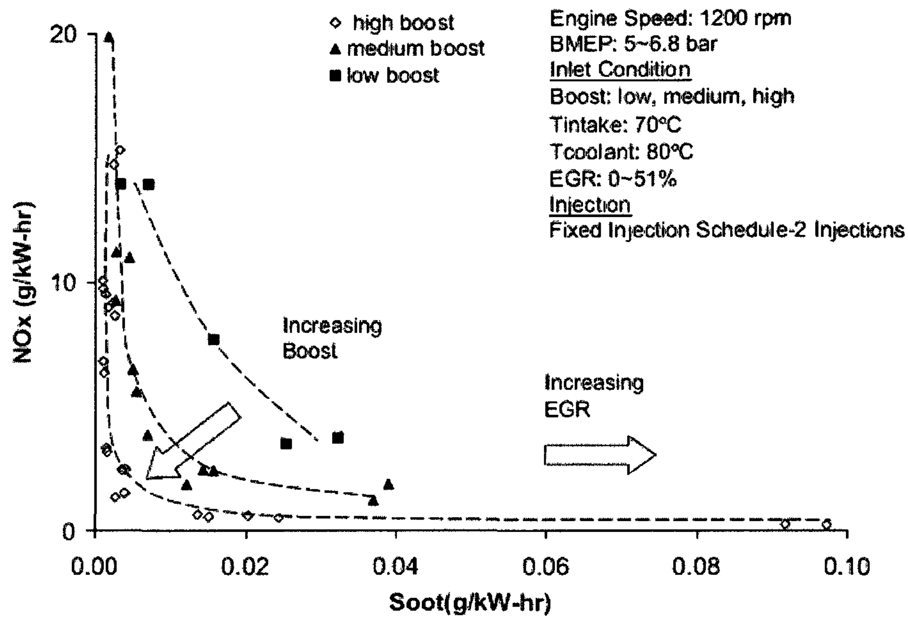


Figure 1.4 Boost and EGR Effect on NOx/Soot Reduction [5]

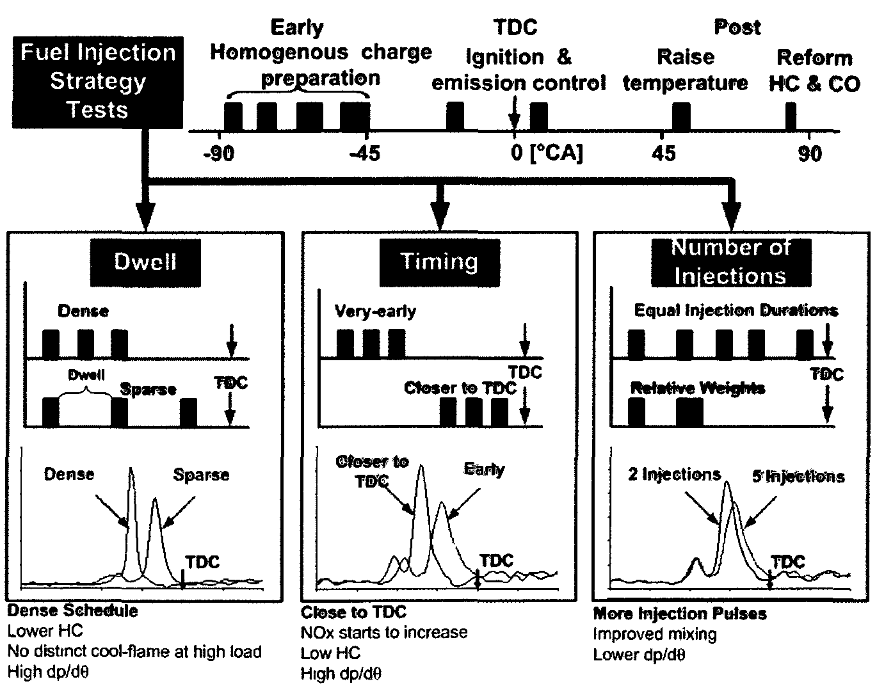


Figure 1.5 Injection Strategies for Diesel Combustion Research

Table1.1 Major In-cylinder Control Strategies on NOx/Soot Reduction for Conventional Diesel Combustion

Strategy	Implementation	Target Emission
Injection Postpone	Control of Injection Timing	NOx
Injection Scheduling Improvement	Improve the Injection Shaping; Pilot Injection; Multi-pulse Injection	NOx
High Injection Pressure	Common Rail System; Electronic Control High Pressure Fuel Pump	Soot
EGR	EGR, EGR Coupled with Intercooler	NOx
Boost	Boost; Boost Coupled with Intercooler; Variable Geometry Turbocharger	Soot

Nevertheless, each one of these strategies alone does not target at the reduction of NOx and soot at the same time, as illustrated in Table1.1. It is noted that under the conventional diesel high temperature combustion mode, it is difficult to achieve simultaneous NOx and soot reduction because of the classical NOx and soot trade-off (Figure 1.6) [6].

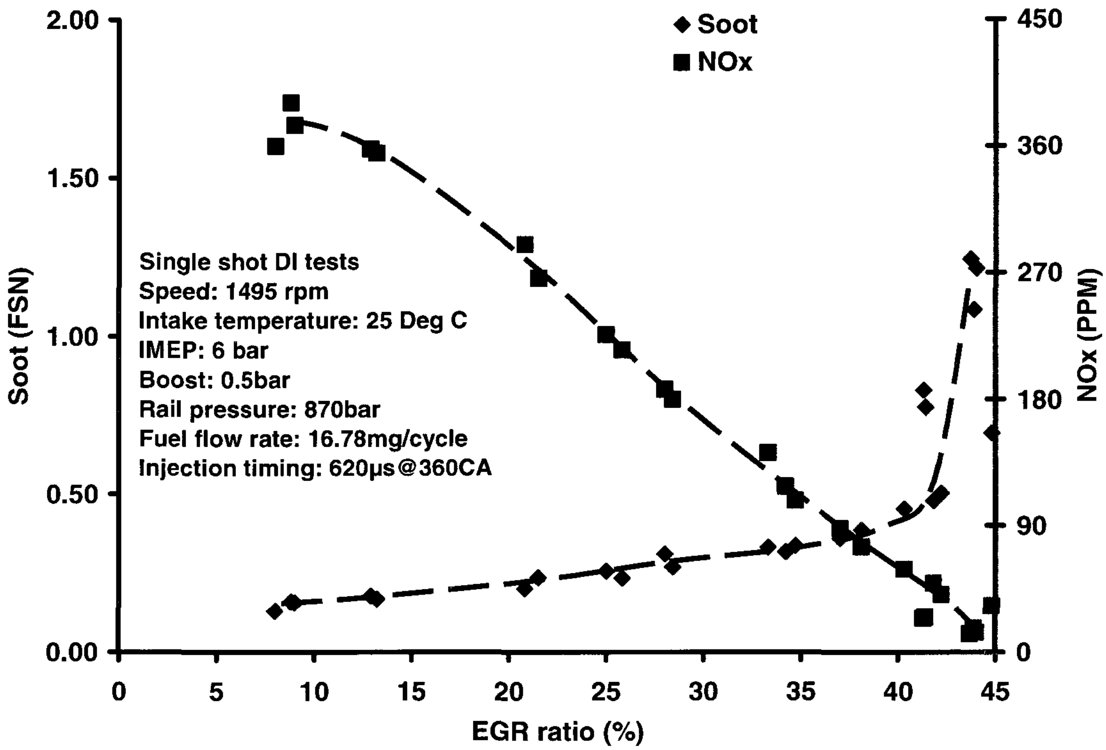


Figure 1.6 Classical NOx and Soot Trade-off

1.4 Diesel Low Temperature Combustion Research

1.4.1 Diesel LTC

Low temperature combustion (LTC) in diesel engines is capable of reducing nitrogen oxides (NOx) and soot simultaneously, which can be implemented by the heavy use of EGR or the homogeneous charge compression ignition (HCCI) type of combustion. Recent empirical and analytical research in the Clean Diesel Laboratory also indicates that the low temperature combustion can reduce the reliance on NOx and soot after-treatment for compliance with the stringent diesel emission standards [7,8]. Previous experimental and modeling studies have provided insights of the effect of in-cylinder temperature and air-fuel ratio on the formation of NOx and soot, which has been traditionally shown on Φ -T or 1/Φ-T diagram as indicated in Figure 1.7, where Φ is the air excess ratio, and T is the combustion temperature.

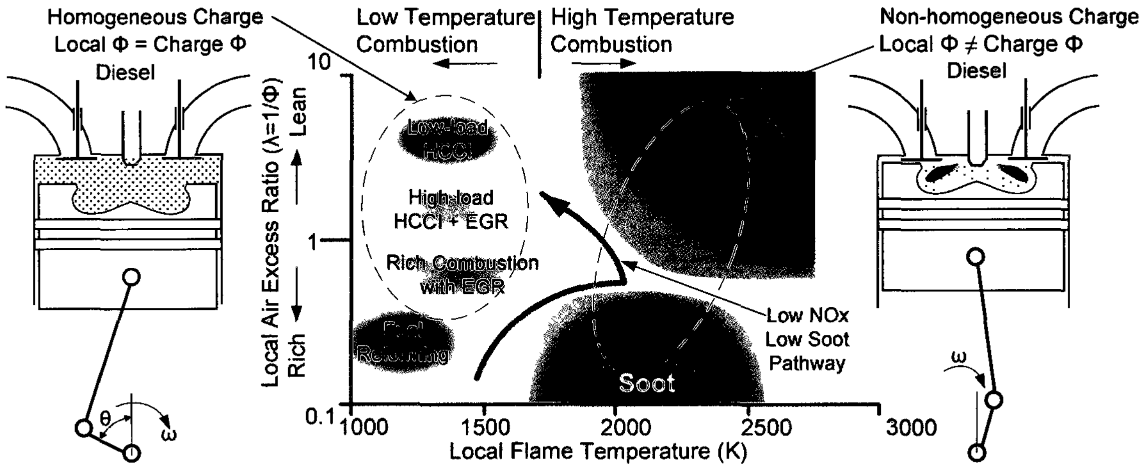


Figure 1.7 Conventional Diesel Combustion and Low Temperature Combustion (Zheng et al. 2007e)

Figure 1.7 [7] classifies the diesel LTC and HTC, and it also illustrates two types of diesel fuel mixing, as well as the NOx and soot formation in diesel combustion according to the combustion temperature and air excess ratio (Φ). The map also displays two narrow pathways of very low NOx and soot. Compared with the non-homogeneous charge, the term of "Homogeneous Charge" represents that the injected diesel fuel, commonly injected earlier during the compression stroke, has sufficient time to mix with the intake air towards thorough homogeneity in the combustion chamber before the mixture auto-ignites under the compression temperature and pressure. The global air excess ratio equals to the local air excess ratio. This pattern of mixing strategy offers a better air fuel mixing that is in favor of soot reduction. Diesel engines operating in Homogeneous Charge Compression Ignition (HCCI) mode tend to produce very low levels of NOx and soot. However, this pattern of combustion mode could only be applied at low load, since the auto-ignition of the homogenous charged diesel can be extremely rough if the engine is not running at very lean condition. The burning of a diesel fuel in an excessively lean homogeneous cylinder charge tends to release less heat than under stoichiometric burning and thus LTC prevails, the representative case of which is the low-load lean HCCI (λ>2) combustion mode. In the high load case, the heavy use of EGR should be implemented together with the HCCI type of combustion in order to reduce the combustion temperature and engine noise [6]. Rich combustion with EGR and fuel reforming are another two patterns of the diesel LTC, which intend to build up higher exhaust temperature for diesel emission after-treatment and to enhance the in-cylinder combustion through the after-treatment method respectively. It is noted that the proposed platform is primarily designed to perform advanced diesel LTC research including HCCI at low load and HCCI plus EGR at high load. For each case, it also provides the capability to carry out the after-treatment tests with necessary instrumentation.

1.4.2 Research on Diesel LTC

Researchers are motivated to focus on diesel LTC owing to the benefits of simultaneous NOx and soot reduction. Figure 1.8 is plotted based on a review of SAE papers from 1996 to 2008 (key words “diesel LTC” or “diesel HCCI”). As shown, the number of engine-based experimental research increased during the past 8 years. Most of the experiments have been performed on the single cylinder engines. The requirement for the advanced diesel LTC test platform is very tight as the pathway for low NOx and low soot emissions is fairly narrow as shown in Figure 1.7. This narrow range of combustion control demands a set of sophisticated control system.

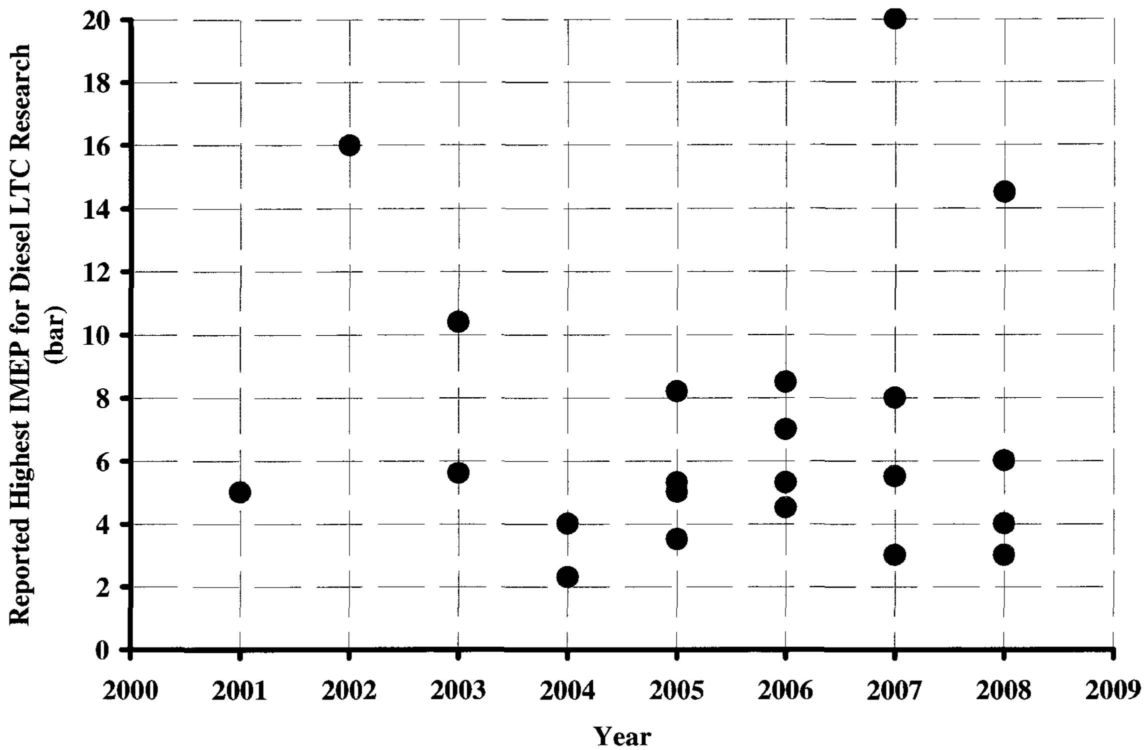


Figure 1.8 Reviewed Peers' Diesel LTC Research over Years [9~37]

Additionally, as represented statistically in Figure 1.9, the majority of the researchers have been investigating at the low to medium load range, whereas few experiments were carried out at high loads. Few higher IMEP cases (marked as black triangles in Figure 1.9) were performed on the engines instrumented with variable valve timing or variable compression ratio system. These two systems can reduce the compression ratio to expand the load range of diesel LTC. The VVT system will be studied through the simulation work in Chapter V.

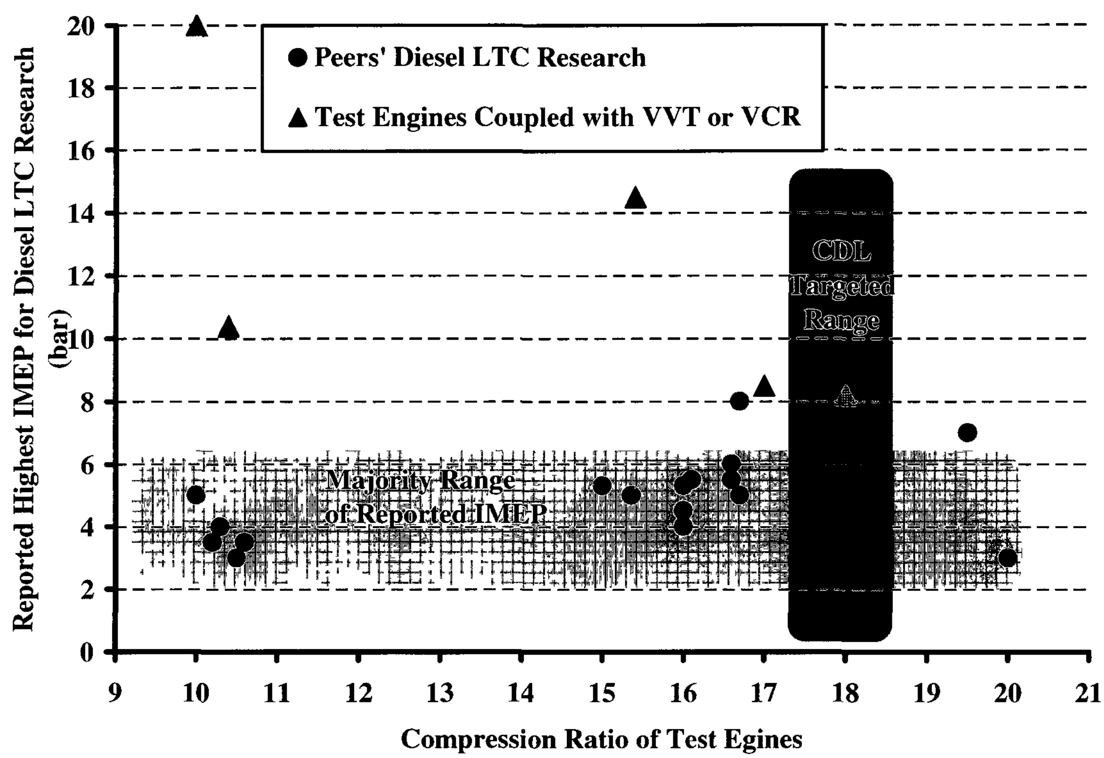


Figure 1.9 Load Range of Reviewed Peers' Diesel LTC Research according to Different Compression Raito [9~37]

Unfortunately, the low load experimental results could not predict and validate the high load condition because almost every combustion characteristics changes during the transition from low load to high load.

1.5 Research Objectives

The proposed test platform in the thesis is for setting up and enabling the capabilities of studying the major control parameters in diesel LTC. From low to relative high loads as highlighted in blue from Figure 1.9 and listed in Table1.2.

Table1.2 Control Ability of the Proposed Test Platform for Diesel LTC

Major Control Parameters	Control Variables	Target Emission
Injection Timing	Injection Duration; Start of Injection	NOx and /or soot
Multiple-shot and Single-shot Injection	Improve the Injection Shaping; Pilot Injection; Multi-pulse Injection	NOx and /or soot
High Injection Pressure	Pressure Control up to the Common Rail System Limit	Soot
EGR	Any allowable amount of EGR (Engine Safety Issue); EGR Cooling	NOx and /or soot
Boost	Independent Intake Pressure and Temperature Control	Soot

It is a valuable practice for Clean Diesel Laboratory to set up such an advanced research platform, therefore completing a detailed documentation of the platform setup is also an objective of the thesis.

1.6 Thesis Outline

According to the objectives of the work, this thesis is divided into 2 parts. The major part in Chapters II - IV is the empirical work and the detailed documentation of the new research platform setup. The second part of the thesis focuses on the variable valve timing (VVT) simulation work in Chapter V. The conclusive remarks are in Chapter VI.

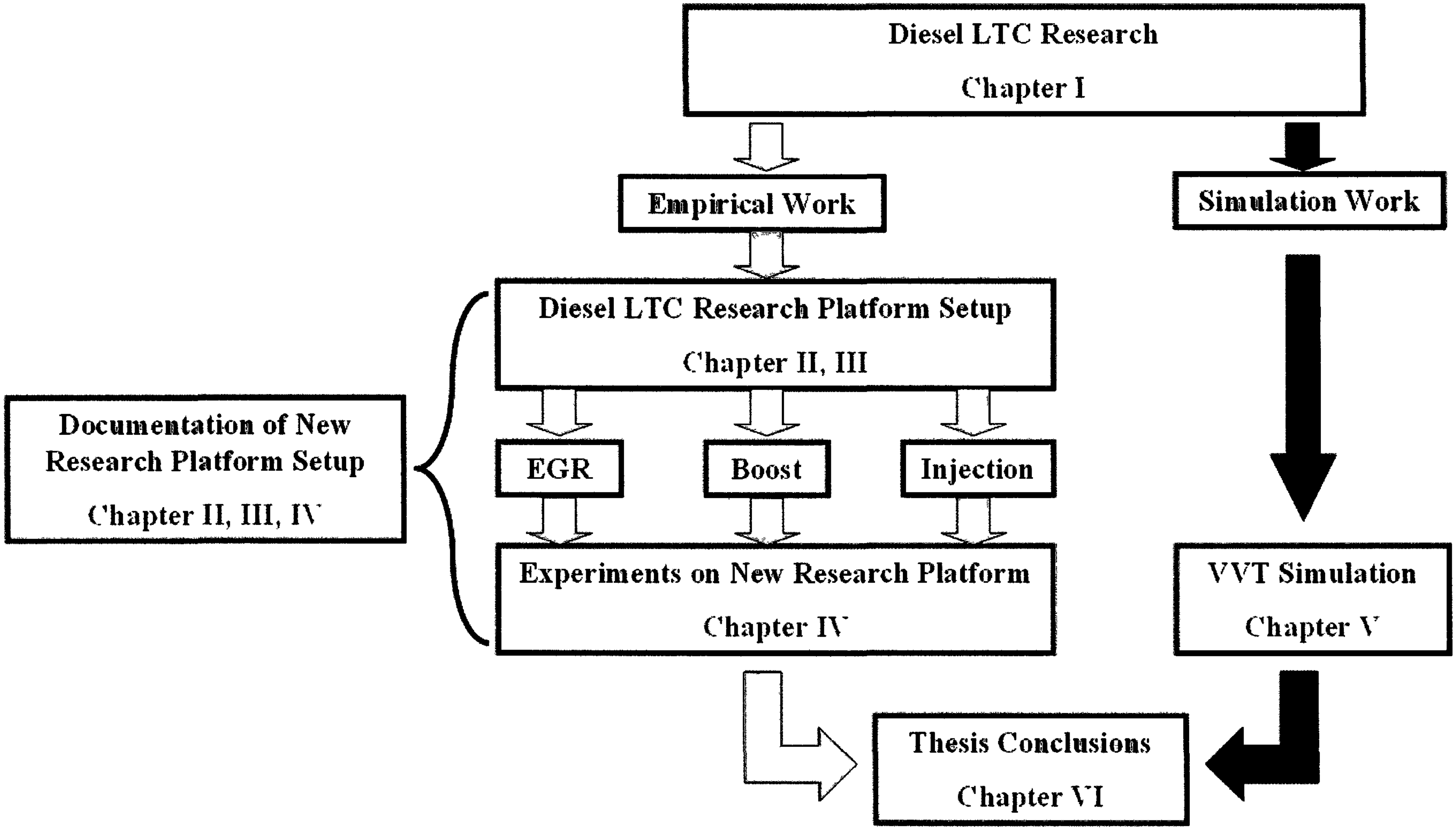


Figure 1.10 Thesis Outline

CHAPTER II

2 BACKGROUND STUDIES

The research group in clean diesel laboratory (CDL) has been working on clean diesel combustion control technologies for 4 years at the University of Windsor. The valuable expertises in engine testing system setup and state-of-the-art facilities have been established for various engine researches. Therefore, the existing engine test platform and available resources in the CDL is reviewed and analyzed. The Ford common-rail Puma engine was identified as the key component of the research platform for this thesis work.

2.1 Existing Engine Test System in the CDL

In the CDL, the experimental setup of a single cylinder research engine is illustrated in Figure 2.1. The testing cell includes both compressed air and natural aspirated intake systems that are dedicated to the intake supply for the operating single cylinder engine. The pressure regulator (ConservAIR™) controls the intake boost. The intake flow rate is measured by the ROOTS™ flow meter. Before the air enters the intake manifold, an intake surge tank dumps the pressure fluctuations that are caused by the intake valve opening and closing. On the exhaust side, the exhaust surge tank stabilizes the exhaust gas pressure. The exhaust exit is partially blocked to build up the exhaust backpressure, and a pneumatic pressure regulator controls the level of the exhaust backpressure. The EGR loop connects the intake and exhaust through an EGR valve and EGR cooler. The EGR amount is dependent on the intake boost, exhaust backpressure, and EGR valve position. The same dependency and correlation will be applied to the proposed test platform setup.

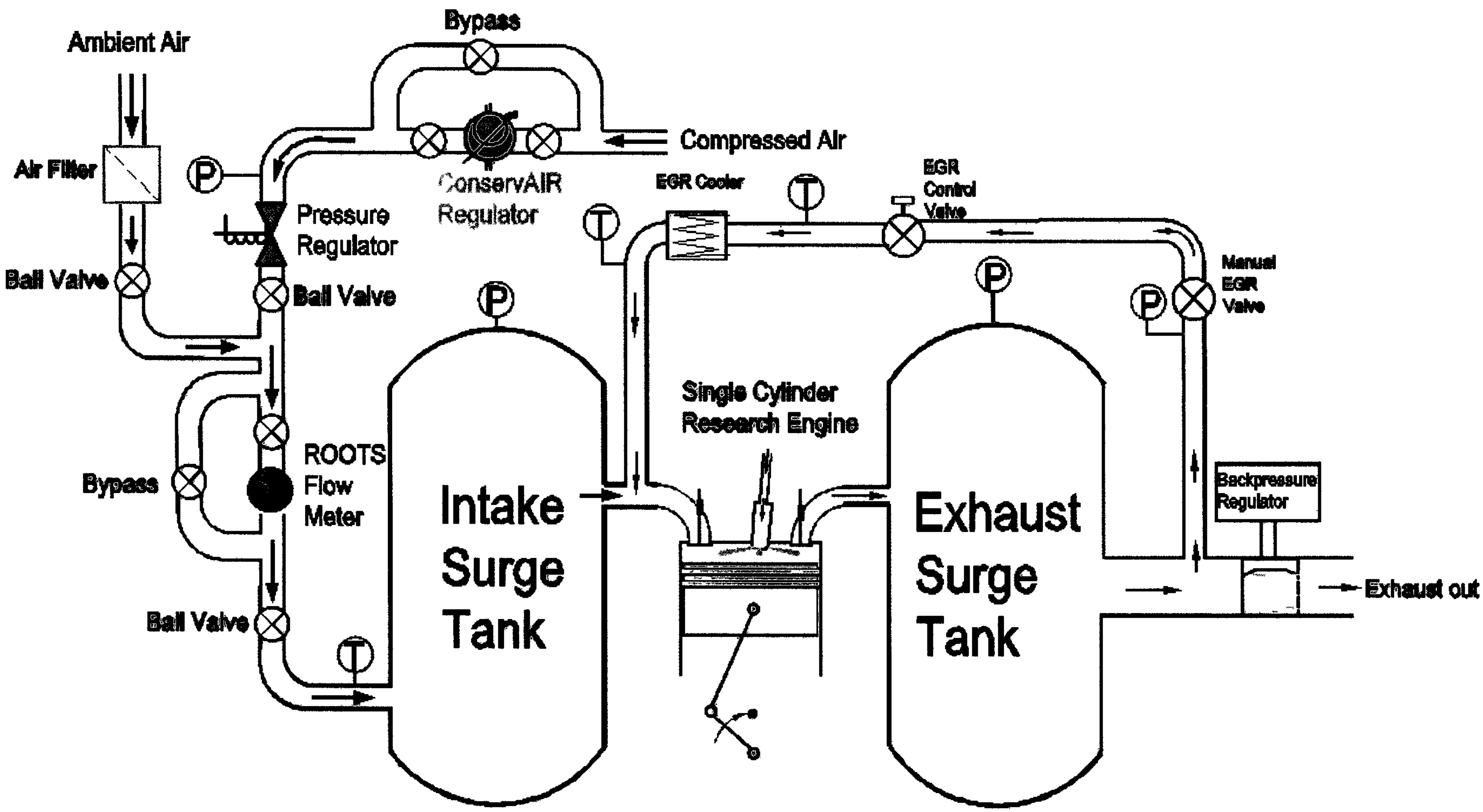


Figure 2.1 Intake and Exhaust Systems of Single Cylinder Research Engine in the CDL

2.2 Clean Diesel Laboratory Resources

In this section, the facilities and resources in the CDL necessary to run the clean diesel LTC tests associated to the proposed platform are discussed in detail.

2.2.1 Gas Sampling Analyzer Benches

To evaluate the emission levels for both intake and exhaust, the gases should be sampled, monitored and recorded throughout the engine tests. Dr. Ming Zheng and the senior graduate students in the CDL have built the gas sampling benches (Figure 2.2) connecting to a dual-bank gas analyzer system. The analyzers include California Analytical Instruments O_2, CO_2, NOx, CO, HC gas analyzers to measure the exhaust emissions and to monitor the intake gas concentrations.

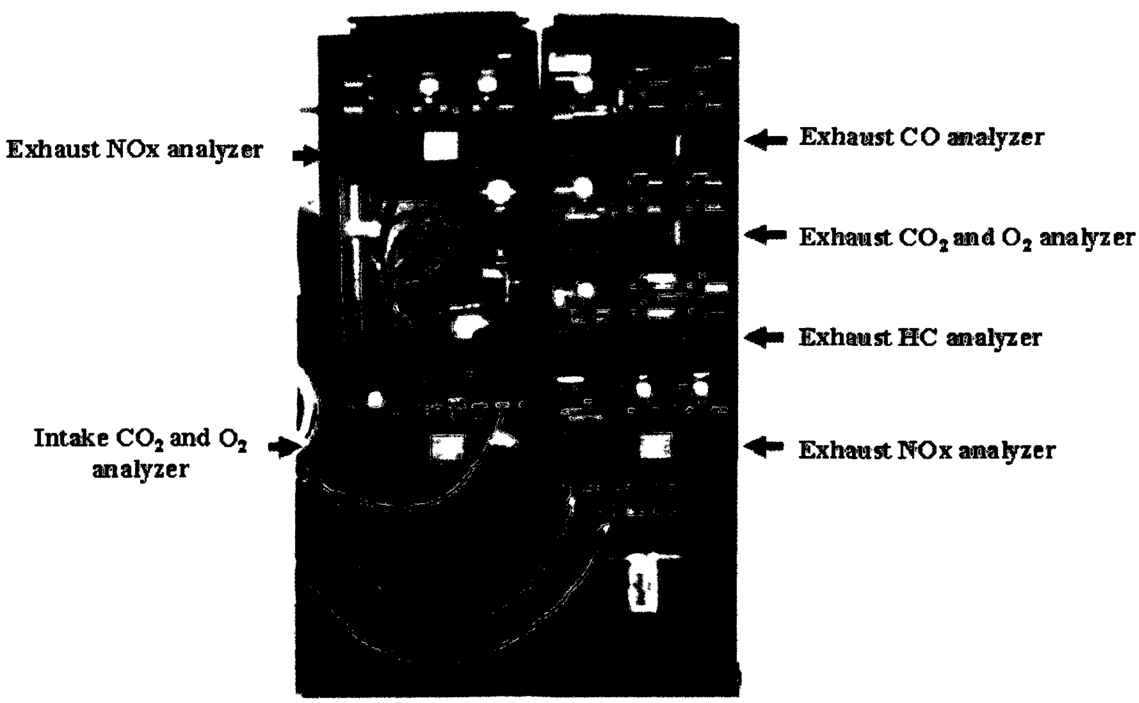


Figure 2.2 Gas Sampling Analyzer Benches

In addition, the soot emission is measured by the AVL smoke meter (Figure 2.3)), which samples the engine-out soot and calculates the filtered smoke number (FSN).

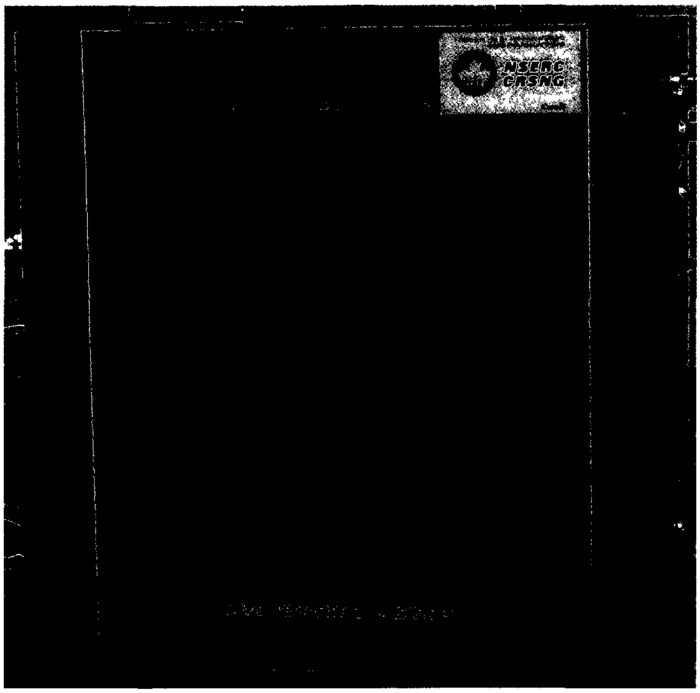


Figure 2.3 AVL Smoke Meter

The emission data from the smoke meter and analyzers are displayed and recorded on several computers through data acquisition (DAQ) cards in each computer via TCP-IP network protocol. The recorded gas sampling data is then stored via data socket to a central reporting computer for on-line analyses. Several mission critical monitoring and control program are developed in-house and are being used in the engine research. The temperature program is for monitoring the coolant and oil temperature/pressure conditioned by FEV LubCon and CoolCon. The fuel pump and oil pump performance are also monitored using this program. The Emission program displays on-line accumulative emission data such as oxygen (O_2), carbon dioxide (CO_2), nitrogen oxides (NO/NO_2), carbon monoxide (CO), and hydrocarbon (HC). The EGR level, and backpressure and

NOx, IMEP are also displayed. An overall monitor and reporting program display all data with targeted power output, and combustion and emission analyses.

2.2.2 IPOD Electronic Valve Power Drivers

IPOD electronic valve power drivers (Figure 2.4) are capable of controlling the operations of solenoid injector valves by regulating both the duration and timing of the injector valve opening. Therefore, the fuel scheduling control could be managed through the IPOD driver for each cylinder. There are 4 IPOD EV drivers from EFS Company used on the Ford 4-cylinder engine. The IPOD configuration is through RS232 communication and the control command is communicated through digital channels on the IPOD. The injection control program, EGR valve control and Boost pressure control program are the three main control programs. The injection control program interactively carries out injection strategies through the IPODs to the injectors. An on-line heat release program is to monitor the cylinder pressure at real-time and to display heat release characteristics used for adaptive combustion control in LTC tests.

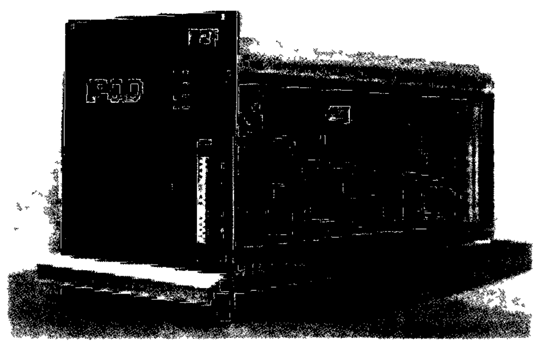


Figure 2.4 IPOD Solenoid Injector Valve Driver

2.2.3 Fuel Supply and Return System

The initial fuel supply and return system is illustrated in Figure 2.5 (adapted from Mr. Usman Asad). This fuel system was designed for all the three engines in the CDL. The low pressure pump generates the driving force and delivers the fuel to the engine assemblies. In the fuel supply and return loop, several filters are instrumented to clean the extraneous substances. The fuel flow rate is measured by a flow meter, and the readings are recorded on the computers via a data acquisition card. A fuel and air flow-monitor program is for displaying the measured fuel and air flow rate as well as calculated rates that are based on carbon balance and calibrations. The fuel supply and return system can be coupled with the new test platform. However, it is necessary to re-route the fuel system to the new test platform.

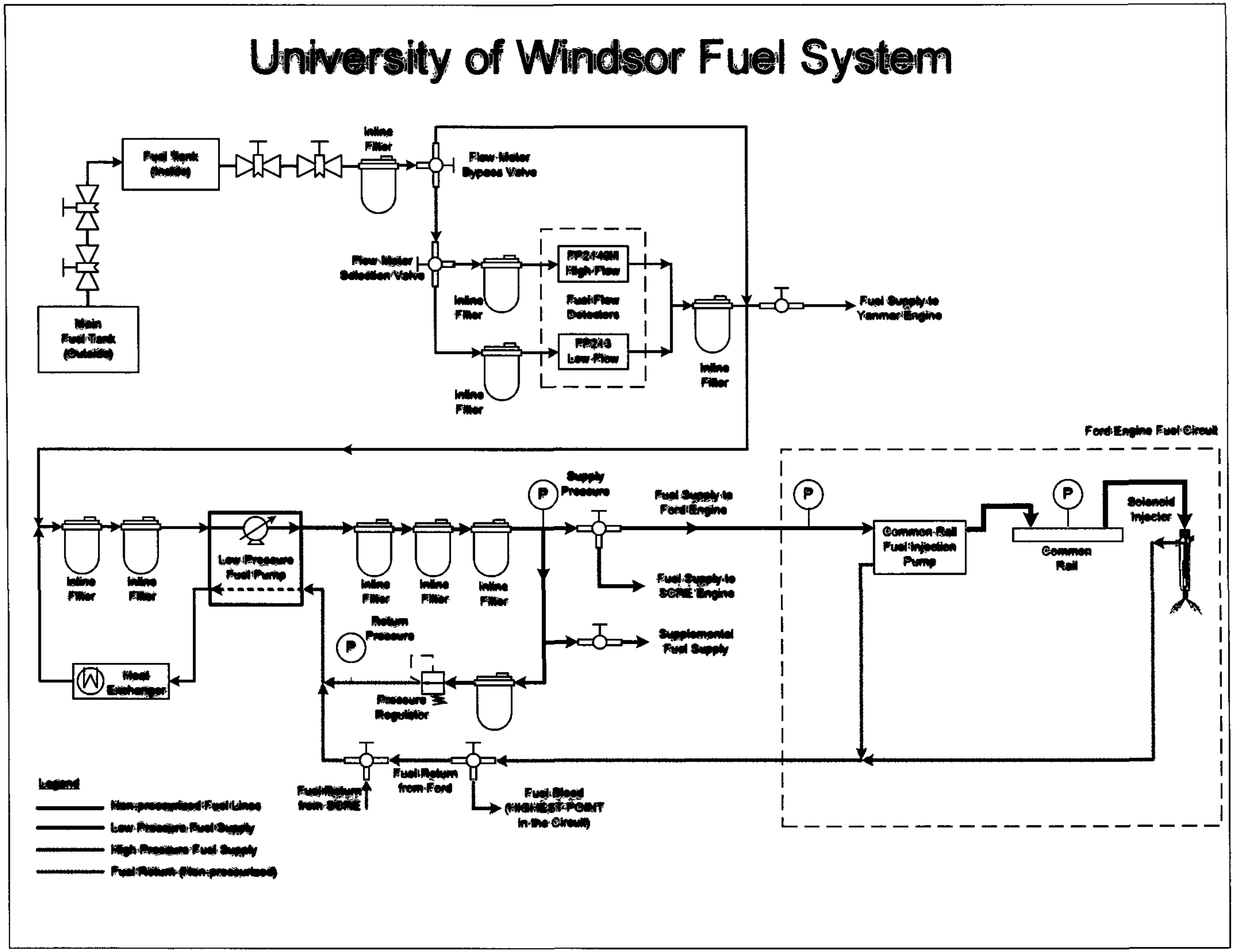


Figure 2.5 Original Fuel Supply and Return System

2.3 Engine Component of Newly Produced Platform

The engine is the most significant part of the whole platform setup. The majority of empirical diesel LTC research (Figure 1.9) reported is at the low to medium loads [9~37]. The capability of performing higher load tests is usually limited by the testing platforms. The limitation is illustrated with the following reasons.

The diesel LTC research is typically performed on the single cylinder research engines. Most of engines are not capable of handling very high cylinder peak pressure. Normally higher load leads to higher cylinder peak pressure [5]. Some of these single cylinder engines, for instance, the Yanmar engine in the CDL, can not take a cylinder pressure of more than 120 bar. However, the maximum cylinder pressure of high load diesel LTC may exceed 180 bar. The limitations on high cylinder maximum pressure confine the LTC research in load ranges.

Moreover, the engine control unit (ECU) manages and often restricts the engine performance with fault-detection and failure-protection modes. The ECU will shut down the engine whenever it detects that certain operating parameter goes beyond the programmed limits. For example, the ECU turns off the engine if it identifies the injection that occurs too early in the combustion cycle. The ECU control tactics is to avoid the unstable running conditions. As a result, the ECU actually restrains the combustion from reaching diesel LTC. For this very reason, the commercially designed engines nowadays are not suitable for the diesel LTC research in spite of their high peak pressure bearing capability.

In fact, some of test platforms are not able to control the independent EGR and boost at the same time. To run high load diesel LTC, a heavy use of EGR is needed to suppress the high combustion temperature and to lower the engine noise. A suitable level of intake boost should be applied accordingly to maintain the air-to-fuel ratio in the lean combustion mode. However, the levels of EGR and boost are mostly adjusted by the turbocharger in those researches of Figure 1.9. An important limitation is that the EGR and the boost systems are coupled and can not realize the high-EGR and high-boost simultaneously. Therefore, the LTC research could not be achieved at high loads.

Last, but not the least, the cost varies from 100 thousands to a million dollars to build a sophisticated single cylinder engine for diesel LTC research [40]. Most laboratories at universities can not afford such an expensive engine setup.

In order to overcome the maximum pressure limitation, the available Ford Puma engine is selected as the research platform. It can take cylinder pressures up to approximately 200 bar. Since the Ford Puma is also an advanced production engine, certain modifications are necessary to solve the issues mentioned above.

2.3.1 Ford Puma Modern Common Rail Diesel Engine

The Ford Puma engine is a four-cylinder common-rail diesel engine that has a high compression ratio of 18.2:1 (Table2.1). The Ford Puma engine was designed for the Euro IV emission standard. The hardware design, such as the combustion chamber, has been optimized to meet the emission regulation. Therefore, the Ford engine offers a high-quality start for the new platform.

Table2.1 Ford Puma Engine Configurations

Engine type	4 Cylinder, 4 Stroke Diesel
Displacement	1.998 Litre
Bore x Stroke	86mm x 86mm
Compression Ratio	18.2 : 1
Combustion System	Direct Injection
Injection System	Delphi Common Rail Maximum Rail Pressure ~1600 bar

The Ford engine was coupled with a cooling system and an eddy current dynamometer (Figure 2.6). The engine cooling system will be utilized on the new platform. Nevertheless, the coupled eddy current dynamometer is capable of measuring the engine torque output but it cannot motor the engine. Moreover, the diesel LTC is an exploratory research in nature and the low temperature combustion potentially might be extremely rough and unstable in certain regimes. Thus, it is inappropriate to push all four cylinders into LTC mode. For these reasons, in order to target LTC research, it was decided to separate one cylinder from the other 3 cylinders. The other 3 cylinders are suitably fuelled to run conventional diesel combustion, stabilizing the engine speed.

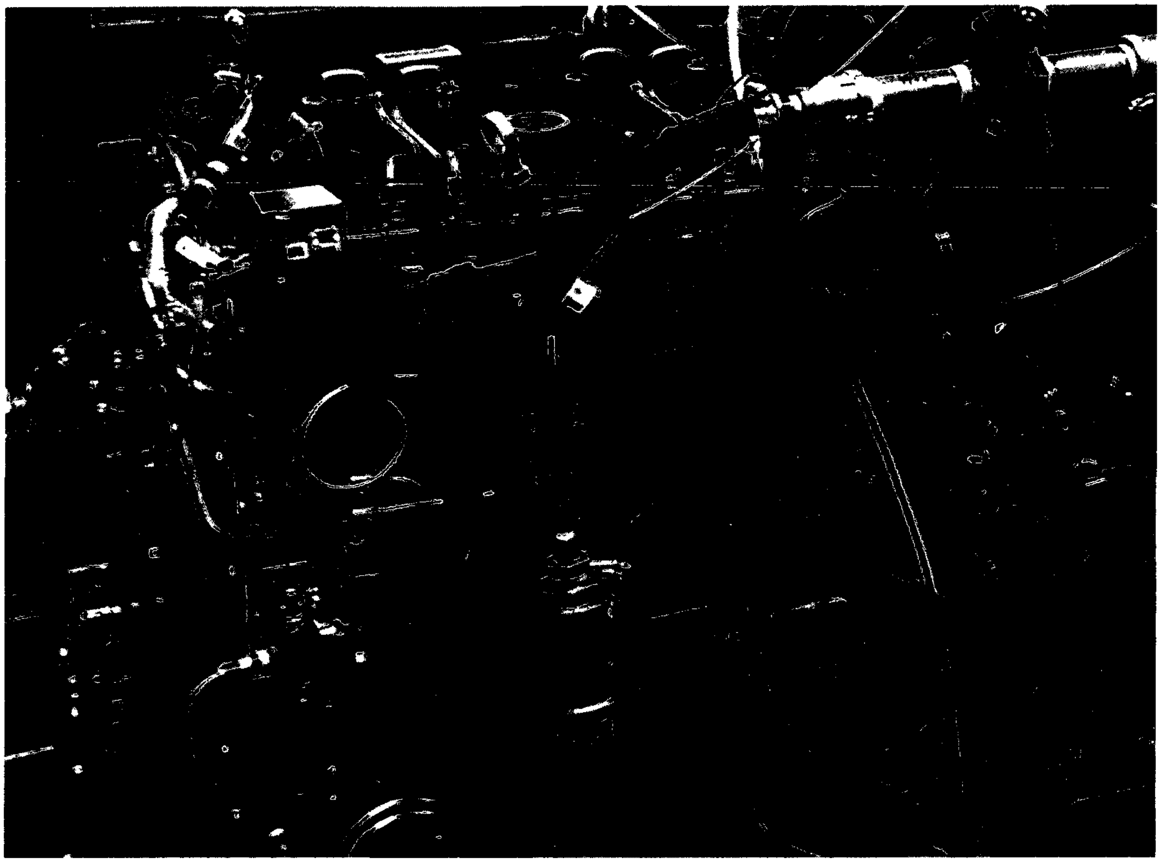


Figure 2.6 Original Ford Puma Engine

The schematic configuration of Ford Puma engine is illustrated in Figure 2.7. Variable geometry turbocharger (VGT) is coupled to generate the boost. The same turbocharging challenge mentioned above will occur to the original Ford engine, therefore, the independent boost and EGR control should be set up to perform the LTC research.

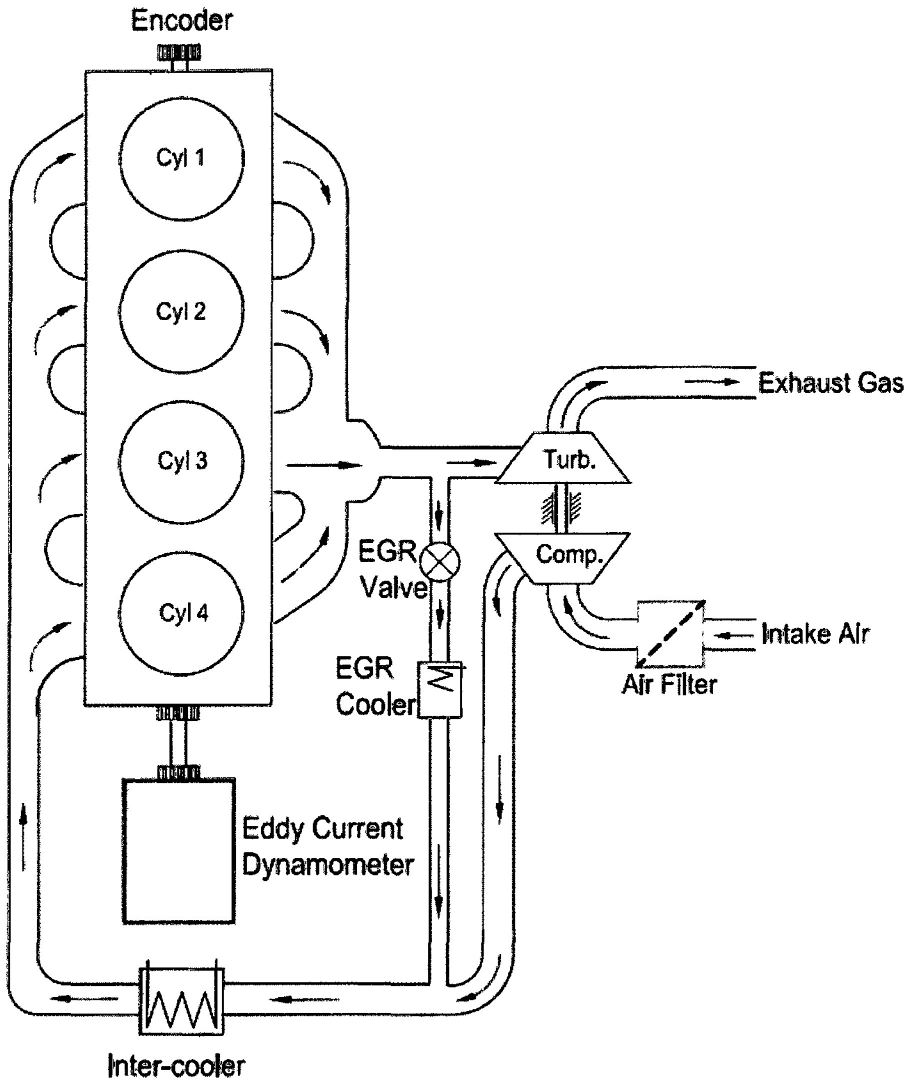


Figure 2.7 Schematic Chart of Ford Puma Original Configuration

Additionally, the Ford ECU manages the safe and reliable engine performance in the original state. In another sense, the ECU restrains the ranges of the operating parameters of the engine, such as the EGR amount, boost level, injection events and injection pressure. To carry out the diesel LTC on the Ford engine, it is essential to transcend the ECU allowed limits and extend the control capability in exploring any new combustion mechanism (Figure 2.8).

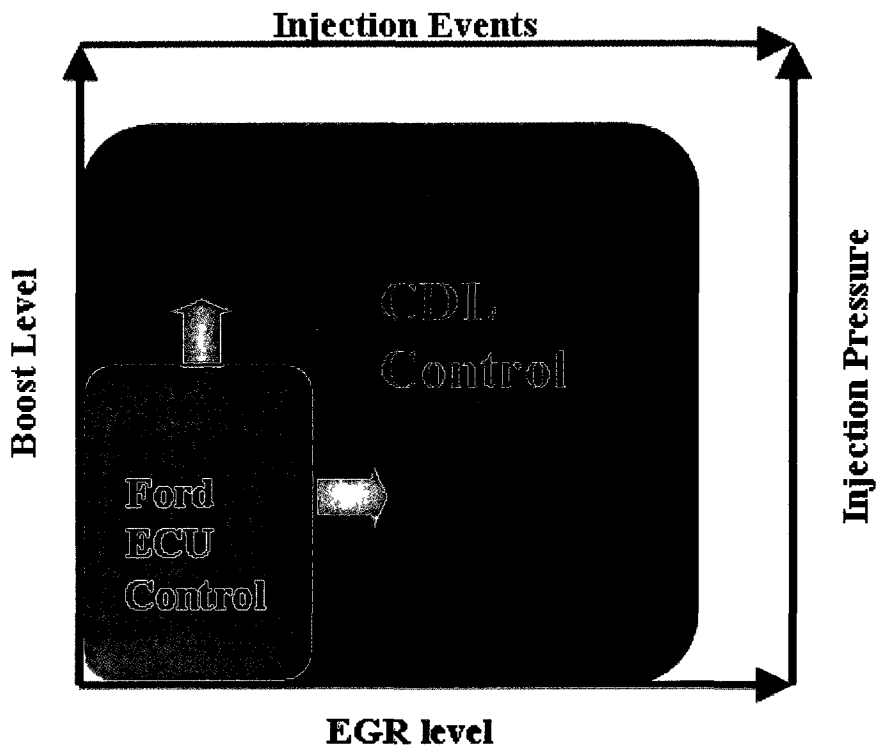


Figure 2.8 CDL Control vs. Ford ECU

2.4 Chapter Summary

In this chapter, the existing experimental setup of a single cylinder research engine in the CDL has been reviewed. The previous work and resources in the CDL are studied to provide a solid base for the proposed test platform. The primary focus of the Ford Puma engine setup is identified as following:

1. The intake and exhaust separations of the single cylinder from other 3 cylinders;
2. The new EGR loop setup for Ford Puma engine;
3. The independent control of injection systems.

In addition to those, other work such as fuel supply and return system needs to be done to fulfill the overall independent control of the single research cylinder on the Ford Puma.

According to the discussions in this chapter, the implementations of each independent control part are deliberated in the following chapter.

CHAPTER III

3 IMPLEMENTATION OF NEW PLATFORM FOR LTC RESEARCH

3.1 Intake and Exhaust Systems

The implementation plan is to modify one cylinder of the 4-cylinder Ford Puma engine to be able to run in single-cylinder mode for the independent EGR, boost and injection control while the remaining 3 cylinders are kept in original mode. The intake and exhaust manifolds are modified first. The intake and exhaust loops are then routed and connected to the existing intake and exhaust systems in the CDL.

3.1.1 Intake Manifold Modification

The original intake manifold on the present Ford Puma engine, as mentioned in Chapter 2, is shown in Figure 3.1. The intake air flows in through the main intake port (represented by the arrow), and then the air is distributed into all four cylinders. It is impossible to realize the independent control of the single cylinder intake unless modifications are done to the original intake manifold.

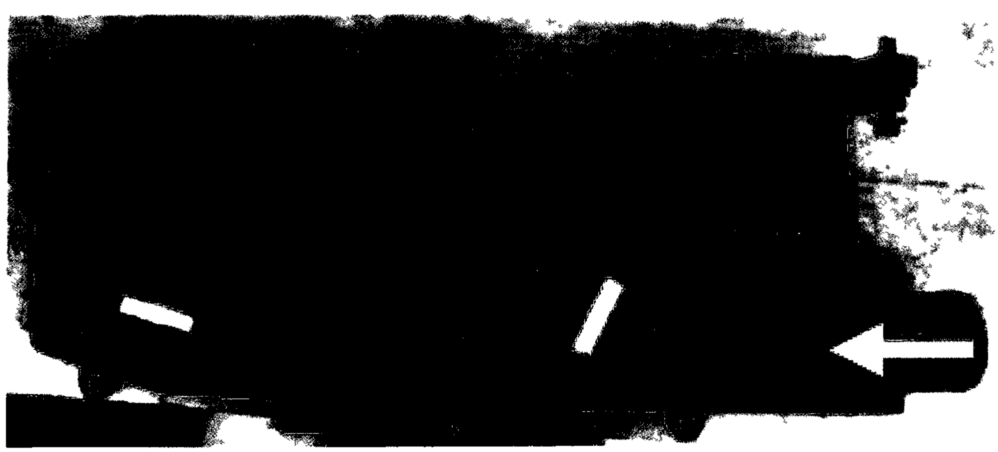


Figure 3.1 Original Intake Manifold of The Ford Puma Engine

To isolate the intake to one particular cylinder, a new intake manifold was designed. Based on the Ford engine orientation, the intake passage has space limitations. The manifold needs to be designed convertible between "1+3" configuration and 4-cylinder mode. The intake passage of Cylinder 1 has to be physically separated from other cylinders to guarantee that there would be no interference from other 3 cylinders. The materials and thickness of the manifold need be designed so that the manifold system can withhold high pressure and also easy to fabricate and weld together. The manifold fabrication was done in the Mechanic Shop with the help from the technologists. A series of performance tests and configurations were conducted for the newly-made manifold.

Figure 3.2 displays the new intake manifold. The tests include a leakage test for the accurate flow measurement and a high pressure test for the boost and safety issue. Since the air-to-fuel ratio is a very important factor in the diesel combustion, the accurate measurement of the intake air flow rate is very critical. Any leakage in the newly machined manifold will cause measurement errors. Moreover, high levels of boost will be applied to the diesel LTC experiments, and the modified manifold should withstand such high intake pressure. Therefore, up to 4 bar pressure was applied in the tests to ensure the manifold sturdiness. The intake air and boost of Cylinder 1 was confirmed to be physically separated from other 3 cylinders to guarantee the independent intake control.

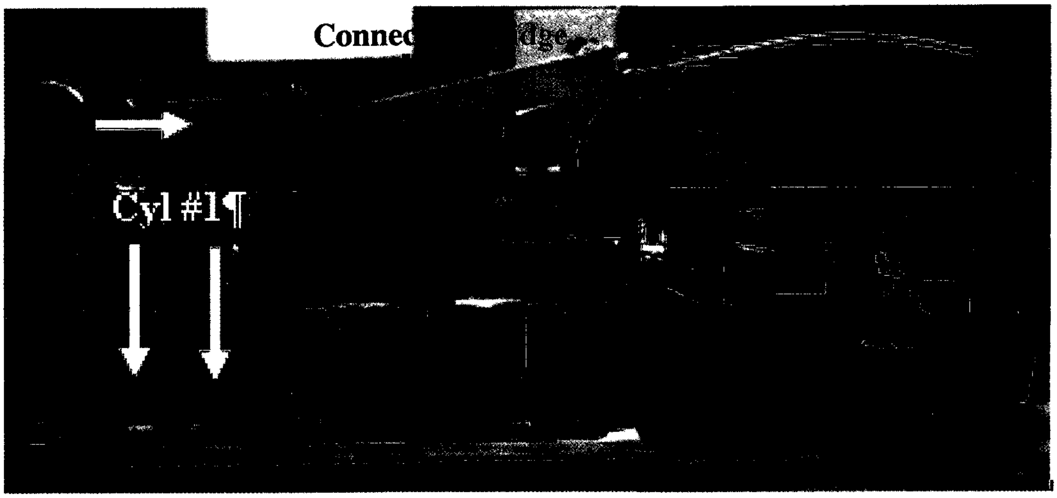


Figure 3.2 New Intake Manifold of The Ford Puma Engine

Figure 3.2 shows the setup for the 4-cylinder mode. The connecting bridge can be disassembled and the opening ports can be blocked by blind flanges (Figure 3.3). Then the single cylinder is separated from the other 3 cylinders to achieve the one-cylinder mode for the independent control on Cylinder 1.

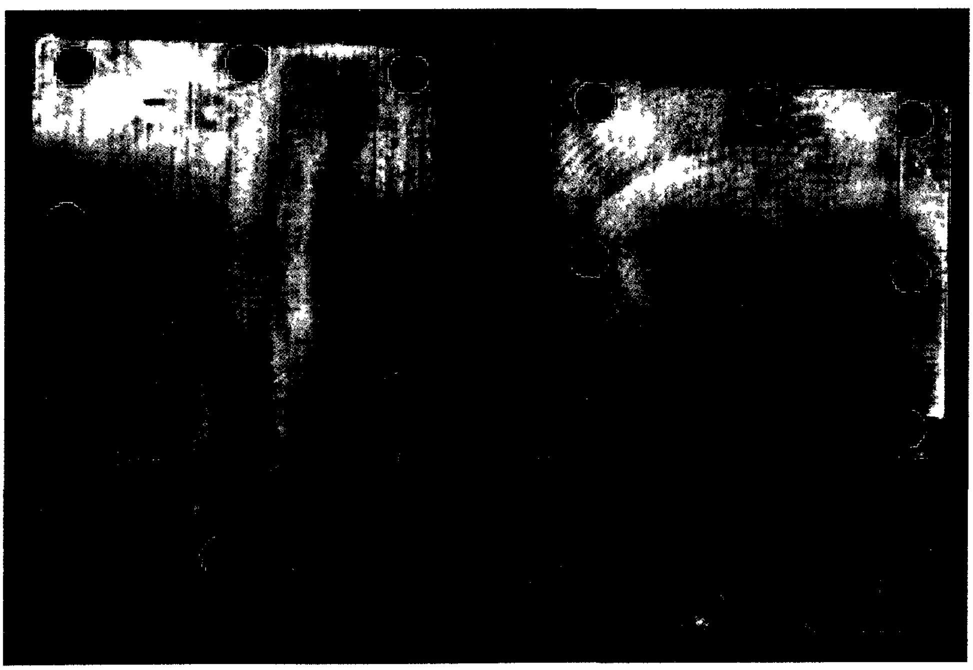


Figure 3.3 Blocking Flanges

3.1.2 Exhaust Manifold Modification

Figure 3.4 shows the exhaust manifold separation from other 3 cylinders of the Ford Puma engine. The original manifold was split and separated Cylinder 1 from other 3 cylinders. An adaptor with a pipe and two side-flanges was designed and fabricated to connect to Cylinder 1 and 3-cylinders. One blind flange was welded and blocked on the 3-cylinder side. On the single cylinder side, the flange was connected to the corresponding exhaust port, shown in the circled area in Figure 3.4.

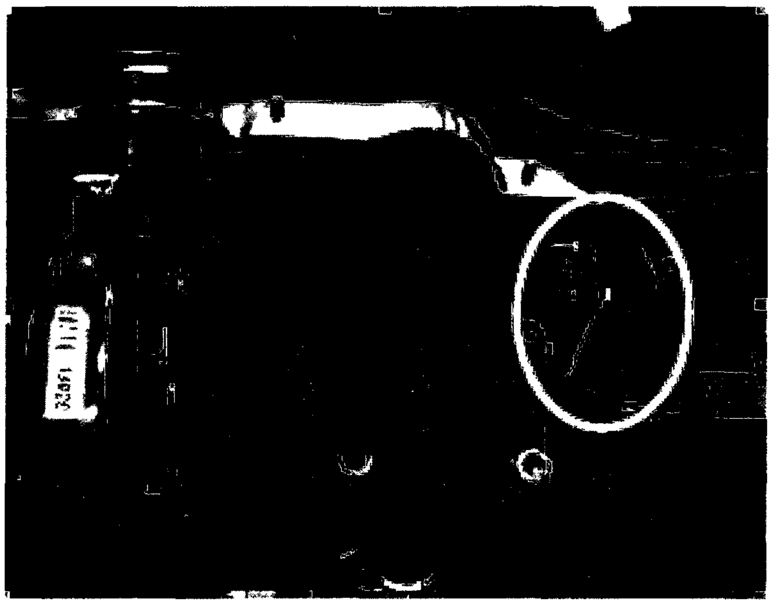


Figure 3.4 Exhaust Manifold Separation of the Ford Puma Engine

3.1.3 Intake and Exhaust Loop Connections

With the resources available in the CDL, the single research cylinder of The Ford Puma Engine should be coupled into the present intake and exhaust systems, shown in Figure 3.5. Therefore, these systems are shared for both the Ford Puma engine and another single cylinder research engine (SCRE) in the CDL.

On the intake side, the separation between these two engines is achieved by two ball valves. On the exhaust side, each engine has its own connection to the exhaust surge tank; therefore, only the running engine is connected to the exhaust system.

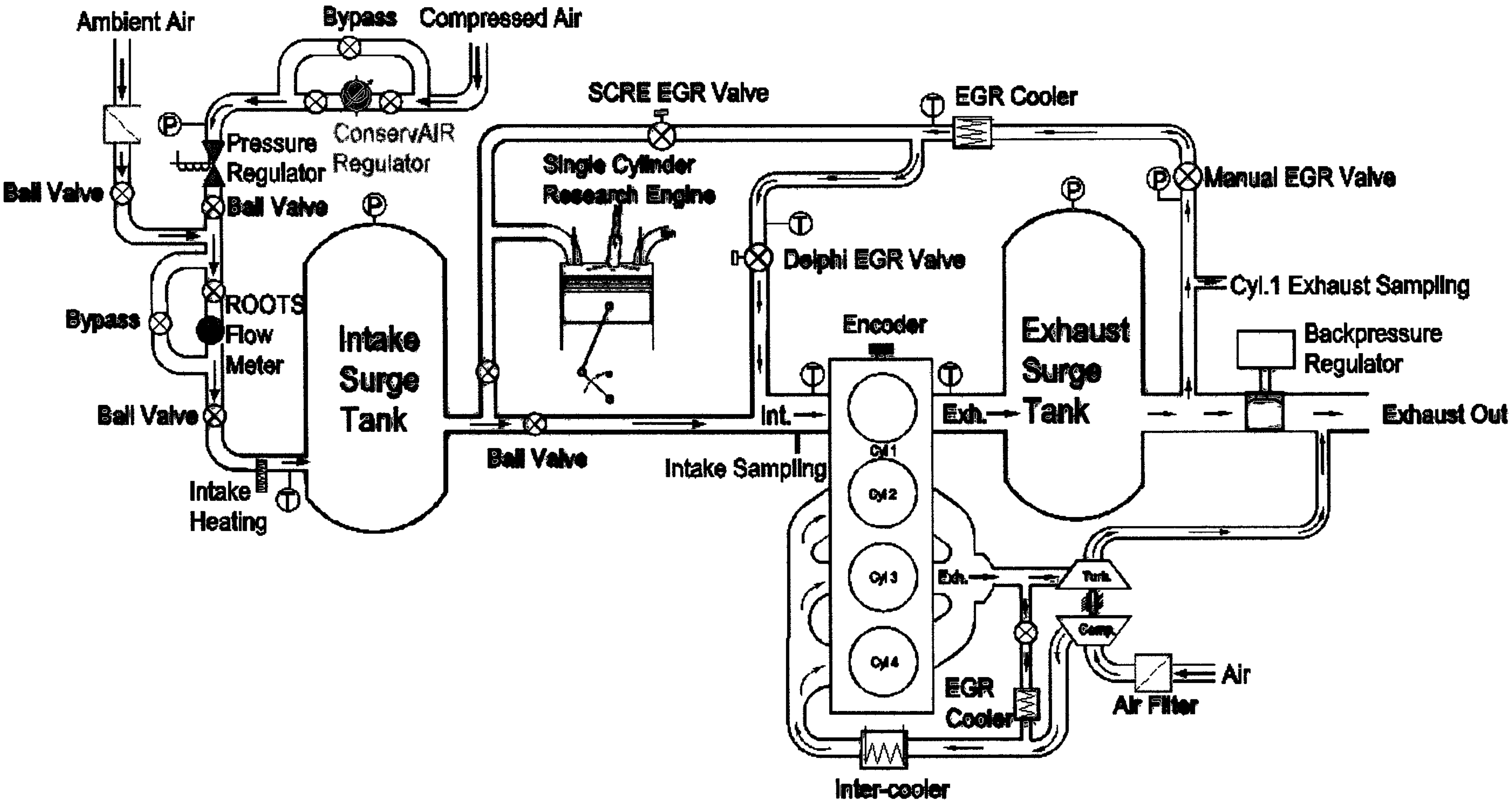


Figure 3.5 The Ford Puma Intake and Exhaust Systems

3.2 Exhaust Gas Recirculation

A new EGR loop has been set up for the new research platform, including the EGR cooler and the EGR valve.

3.2.1 EGR Cooler

The EGR cooler for SCRE can also be shared with the Ford Puma after re-routing the exhaust and intake pipe connections (Figure 3.6). One ball valve performs the EGR separation between the two engines.

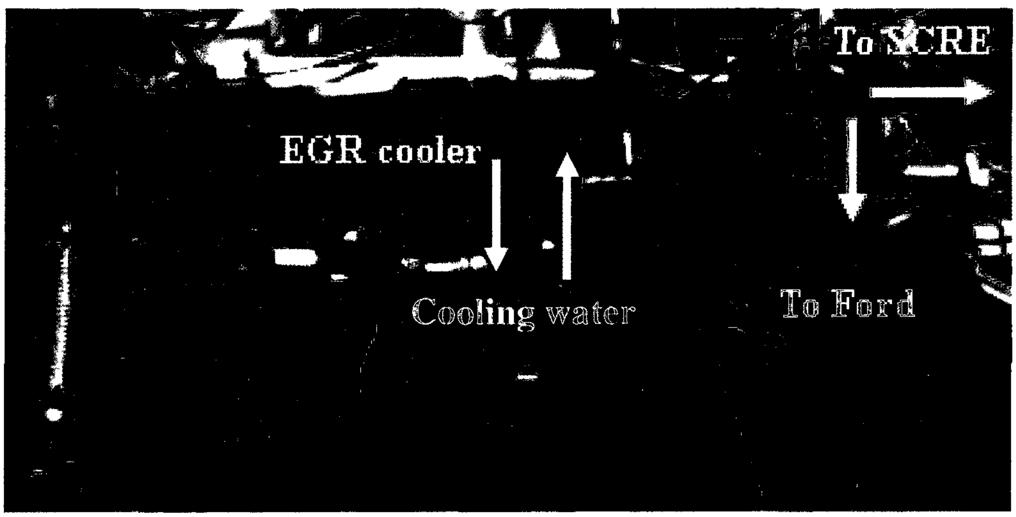


Figure 3.6 EGR Cooler for Ford Puma and SCRE

3.2.2 EGR Valve

A Delphi EGR valve has been mounted into the intake loop of Cylinder 1 on The Ford Puma engine (Figure 3.7). The valve opening position determines the EGR flow area, which can regulate the EGR levels with the exhaust backpressure control. The control algorism of the EGR valve is programmed by Yuyu Tan.

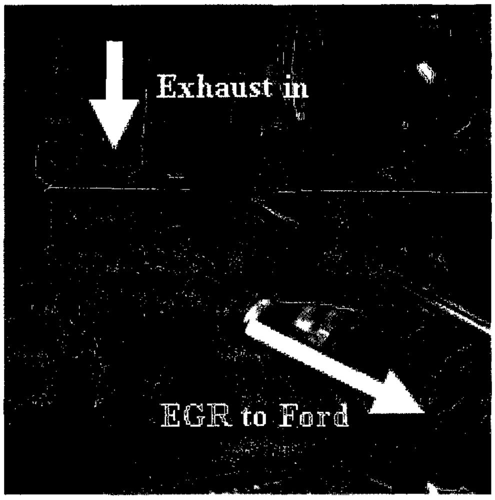


Figure 3.7 Delphi EGR Valve

3.3 Injection Scheduling Control

The injection control is managed through controlling the IPOD injector drivers. The IPOD drivers are able to regulate the opening and closing of the injector valves. Therefore, the injection scheduling is under the control.

3.3.1 Injection Scheduling Control Strategies

The controlling of injection through the IPOD drivers is illustrated in Figure 3.8. The commanding signals are programmed (by Dr. Zheng and Yuyu Tan) on a Real-Time controller (National Instruments). To initialize the IPOD injection power drivers, communication between IPODs and computers in the control room of CDL needs to be built up. When the IPODs are working, it is necessary to set up the monitoring ranges of IPOD working current, voltage, and effective injection signals in order to make sure that the IPODs function properly. In case of the functional failure, an ON/OFF switch is set up in the control room to shut off the power supply to IPODs. The connection wiring chart of the IPOD setup is summarized in next section.

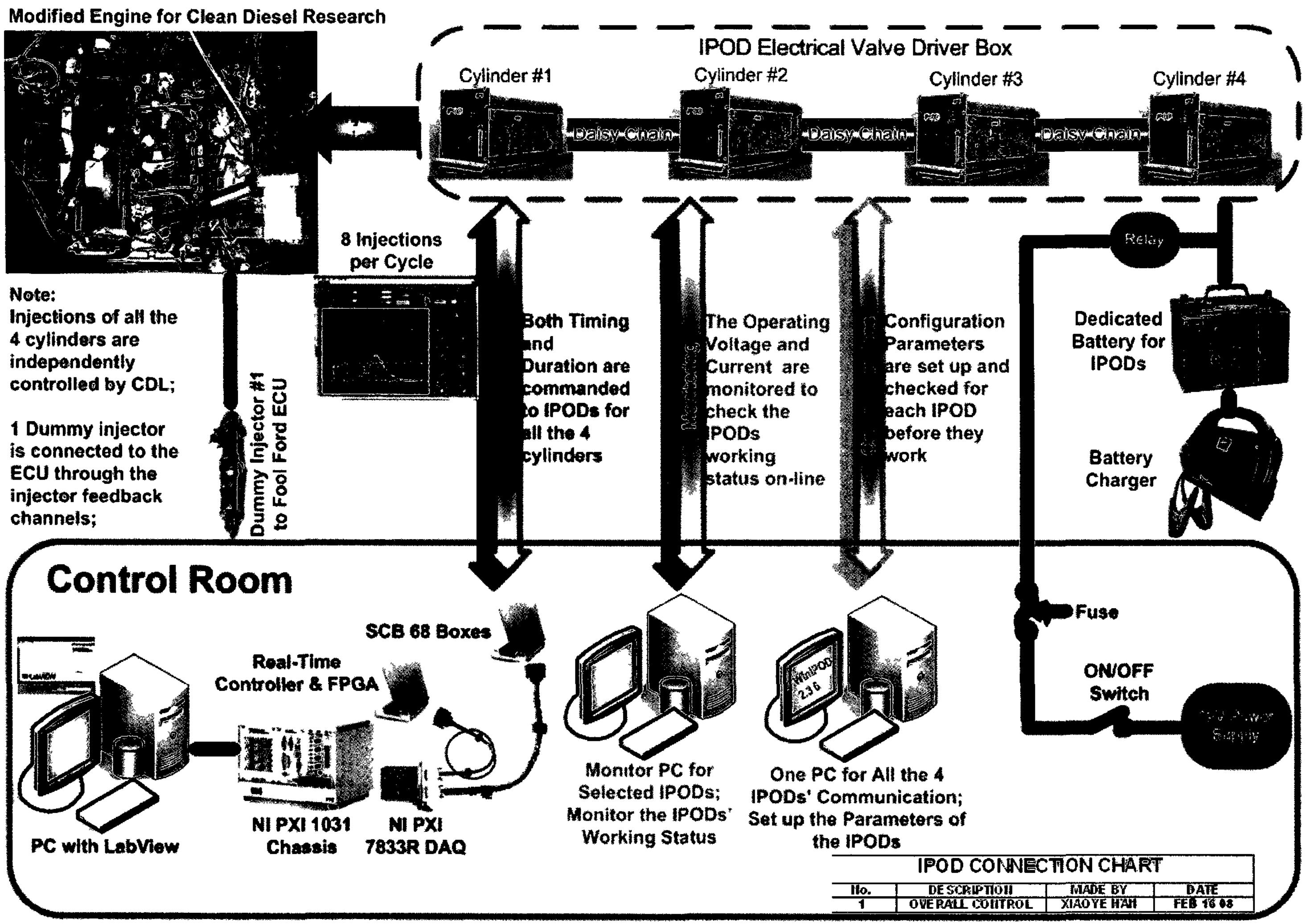


Figure 3.8 Injection Scheduling Control Strategies in the CDL

3.3.2 IPOD Electric Valve Driver Setup

3.3.2.1 Power Supply for IPODs

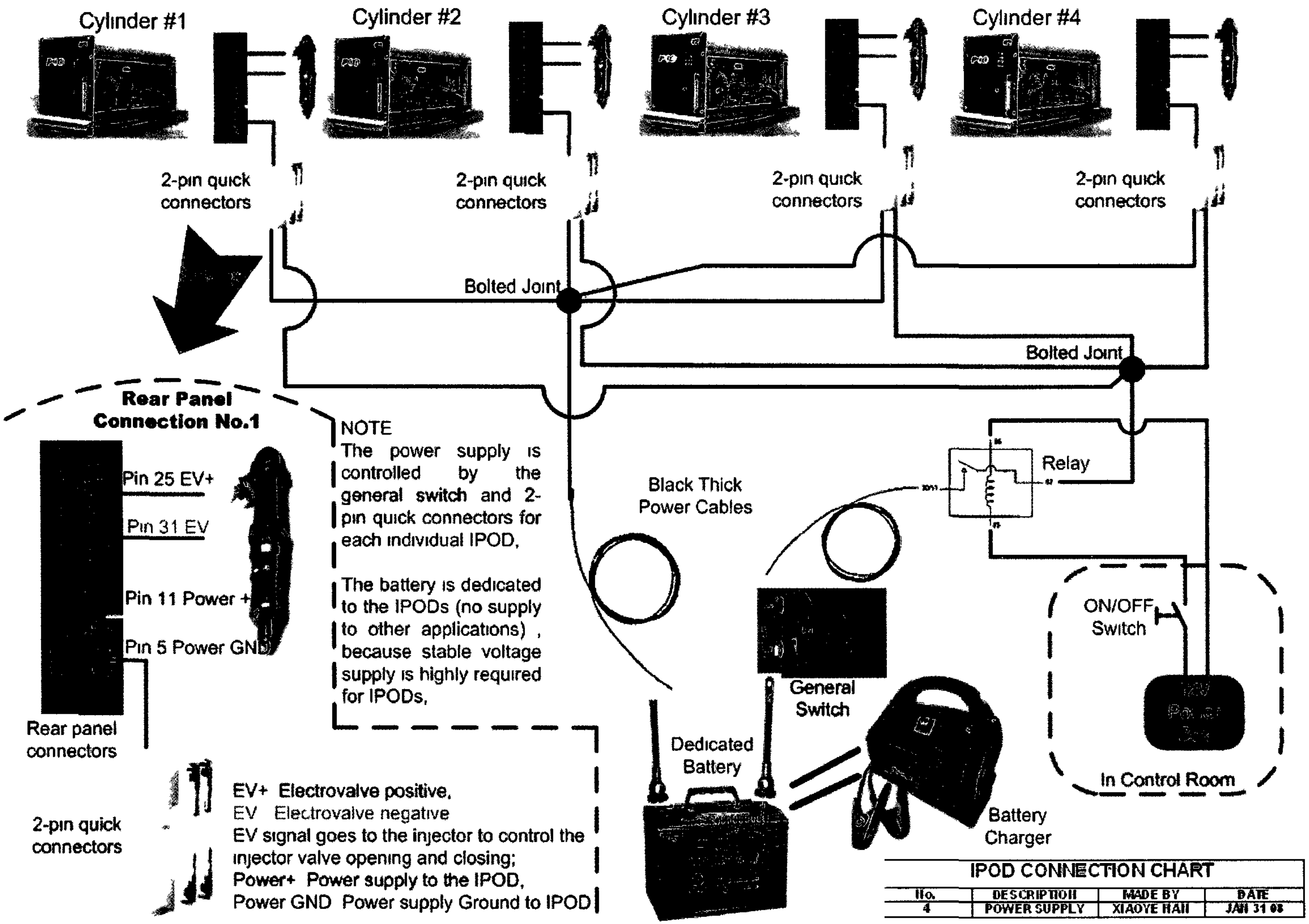
The IPOD drivers are particularly sensitive to power supply voltage fluctuations. The power supply voltage can fluctuate as low as 11V and as high as 35V, but must be regulated during the working periods. Therefore, a dedicated battery is connected to the IPODs and a high quality battery charger is required to maintain the power in the battery. All the detailed wiring connections are depicted in Figure 3.9.

3.3.2.2 Injection and Selection Signals

The injection signal is generated and controlled by a Real-Time controller. When the selection signal is kept as 5V for all the IPODs, it indicates that all the IPODs are selected to work. The commanded injections in each cylinder are determined by the injection signals. The wiring of the connections are illustrated in Figure 3.10

3.3.2.3 Communication between IPODs and PC

The RS232 cross-over cables establish the communication between IPODs and the computers in control room. The daisy chain connections among the 4 IPOD drivers save computer resources as they allow all the 4 IPODs to communicate with only one computer.



IPOD CONNECTION CHART			
No.	DESCRIPTION	MADE BY	DATE
4	POWER SUPPLY	XIAOYE HAN	JAN 31 08

Figure 3.9 IPOD Power Supply Connections

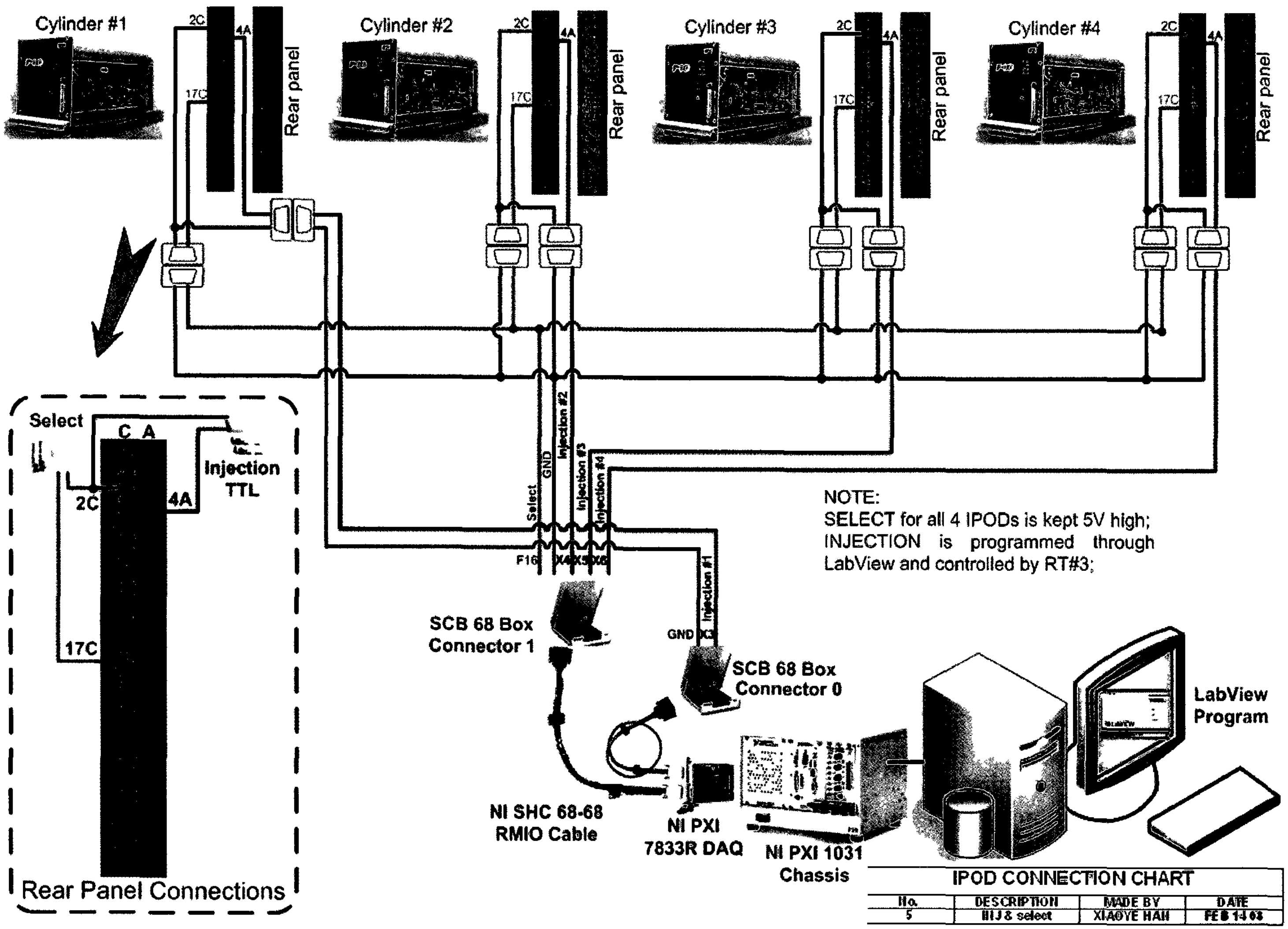


Figure 3.10 IPOD Injection and Selection Signal Connections

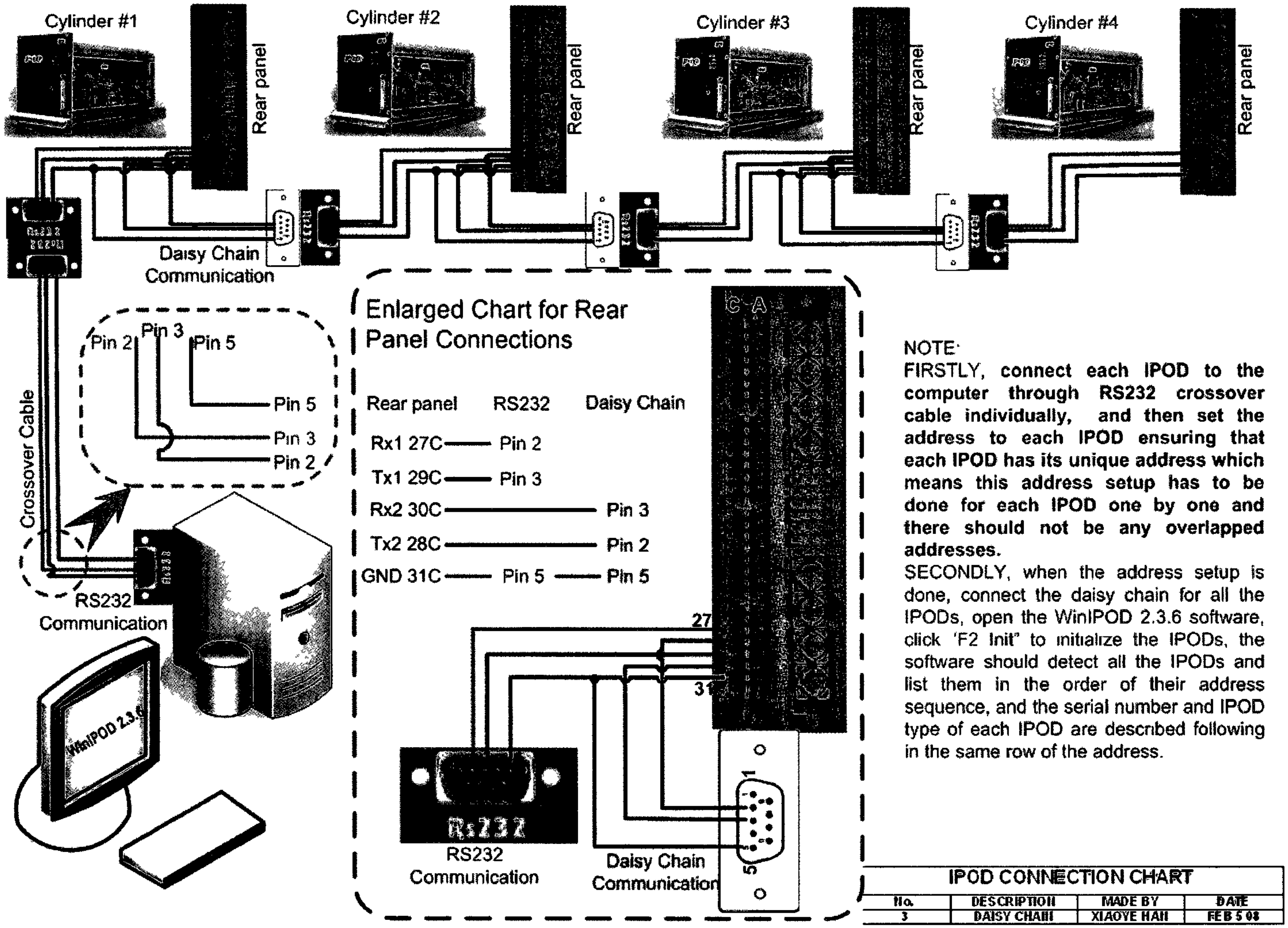


Figure 3.11 Daisy Chain and Communication Cabling of IPOD Drivers

3.3.3 Dummy Injector Fooling Ford ECU

When the engine is running in the "1+3" research mode, the Ford ECU still monitors the performance of all 4 cylinders. The 3 cylinders are operated in the conventional combustion mode that does not exceed the ECU limitations. However, when the independent control signal of the injection scheduling is sent to the Cylinder 1 and reaches certain ECU limits, it will trigger the ECU to shut down the engine as programmed by the built-in algorism. Therefore, a dummy injector is connected to the injection feedback of all the injectors to fool the ECU. The injection signals sent by the ECU to the Cylinder 1, as well as the other 3 cylinders, are routed to the dummy injector. The dummy injector behaves as a regular injector whenever it receives the injection command from ECU and sends the feedback to ECU. Thus, the control of injection events for Cylinder 1 and the other 3 cylinders is totally taken over by the CDL independent control.

3.4 Common Rail Pressure Control

The control of the common rail pressure is taken over by the CDL. The Delphi common rail coupled on the Ford Puma can take the high pressure up to 1600 bar. The common rail pressure is controlled by regulating the pressure control valve (PCV) in the high pressure fuel pump. The PCV control program (by Yuyu Tan) is used to realize the on-the-fly control [41].

3.5 Fuel Supply and Return Systems

To improve the fuel flow measurement for the engine testing, a gravity tank for the fuel supply has been added to the initial fuel system (Figure 3.12). The gravity generated by the height difference not only drives the fuel through the fuel flow meter to the fuel pump on Ford engine but also reduces the fuel flow fluctuations.

The low pressure pump was suspected as one major reason for the fuel flow reading fluctuations. A new fuel system was built up to bypass the low pressure pump. Figure 3.13 shows the current set-up of fuel system in the CDL. The gravity tank is raised to a height of 7 feet 10 inches, while the flow meter is 1 foot high and the high pressure fuel pump on the engine is 3 feet 4 inches above the floor. The height differences between the gravity tank and the flow meter as well as the high pressure fuel pump are supposed to generate a pressure with little fluctuations compared with the previous system since the fuel level in the gravity tank should decrease continuously and steadily

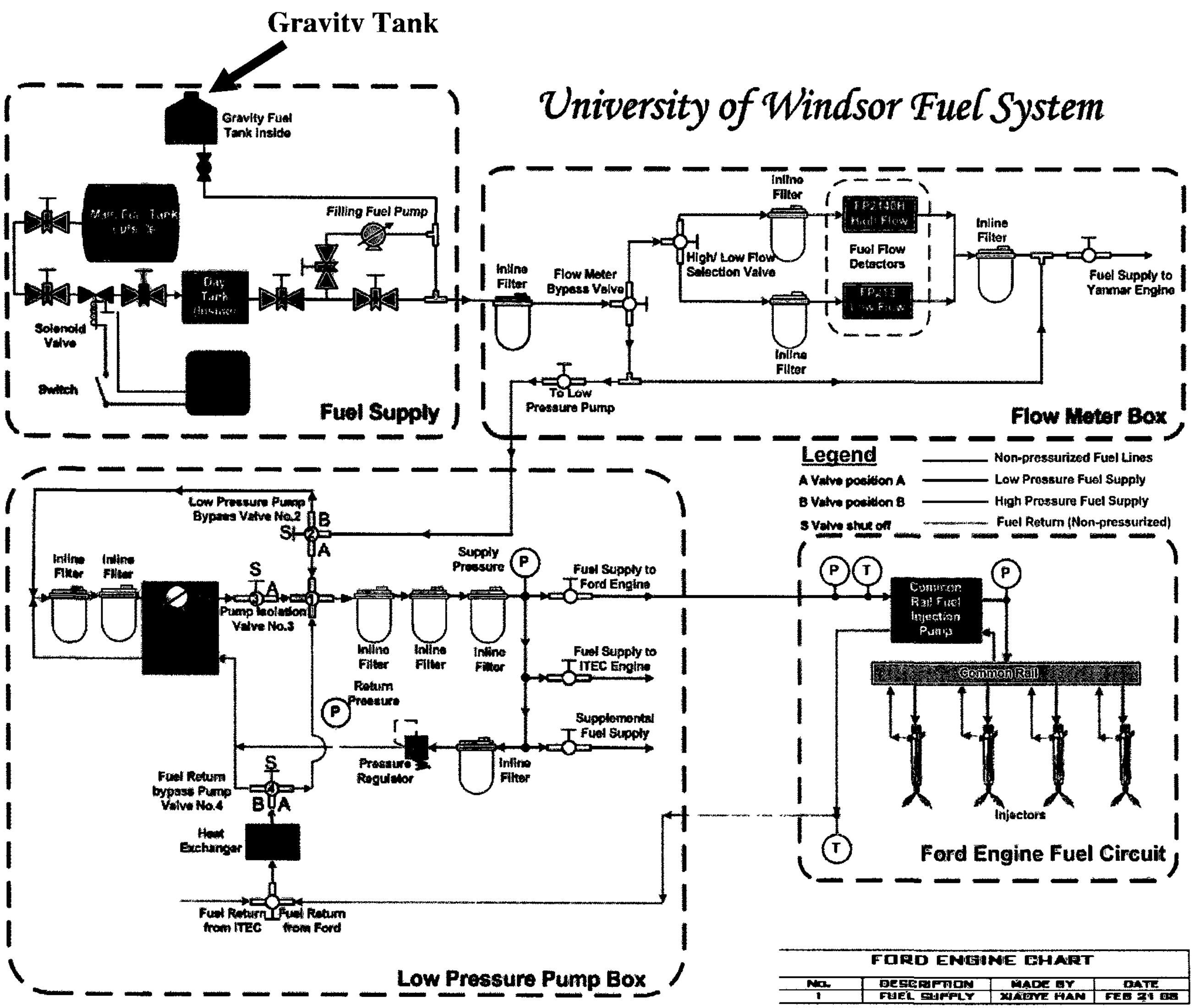


Figure 3.12 New Fuel Supply and Return Systems in the CDL

Figure 3.13 Gravity Tank Setup

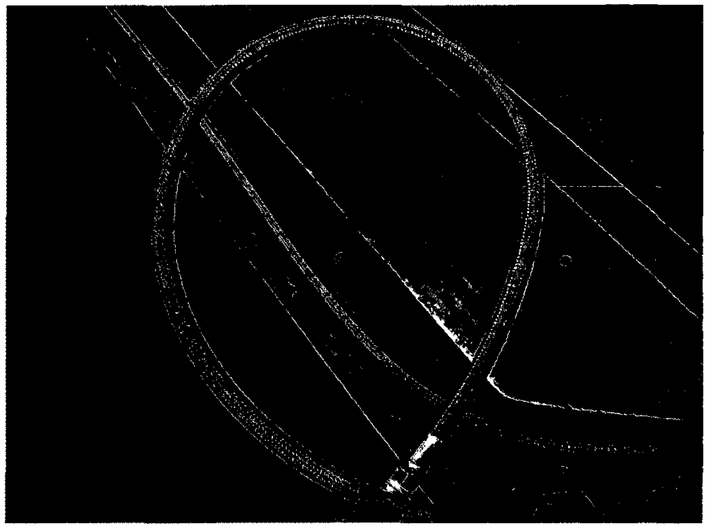


Figure 3.14 Teflon Tubes with Metal Lining

To further reduce the fluctuations of the fuel line, the previous rigid stainless steel tubes are replaced by a flexible Teflon tube with metal lining (show in Figure 3.14). The Teflon tube dumps the pressure waves along the return loop from the engine back to the supply loop.

3.6 Chapter Summary

This chapter consists of a description of each independent control that has been implemented on the Ford Puma engine. Figure 3.15 shows the control capability of the new test platform in single cylinder research mode. The procedures of implementations are documented in detail including the initial engine intake and exhaust conditions, the modifications for independent injection and pressure control. The new test platform is shown in Figure 3.16.

The implementation of the Ford Puma setup is tested and discussed in next chapter.

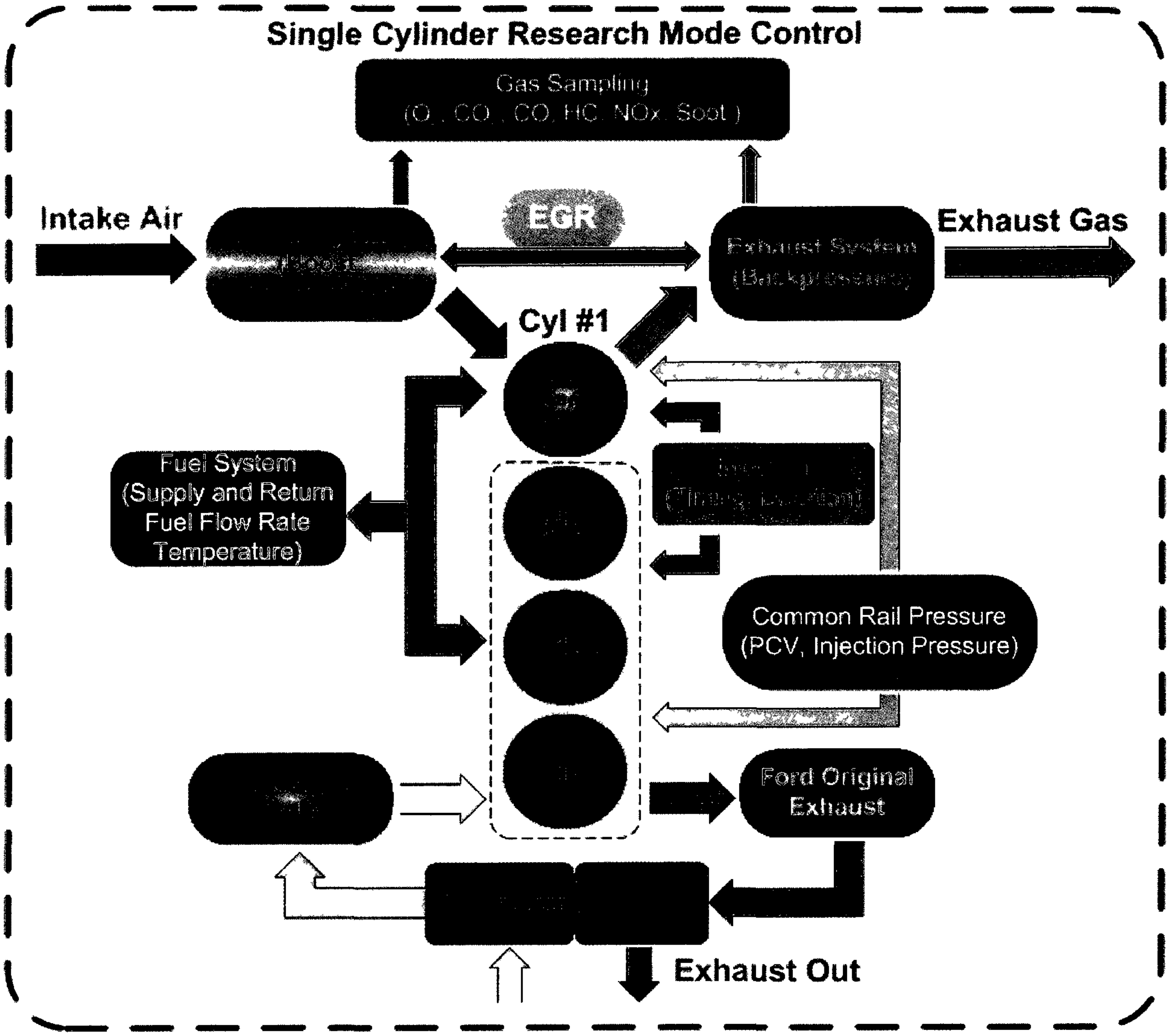


Figure 3.15 Single Cylinder Research Mode Control in the CDL

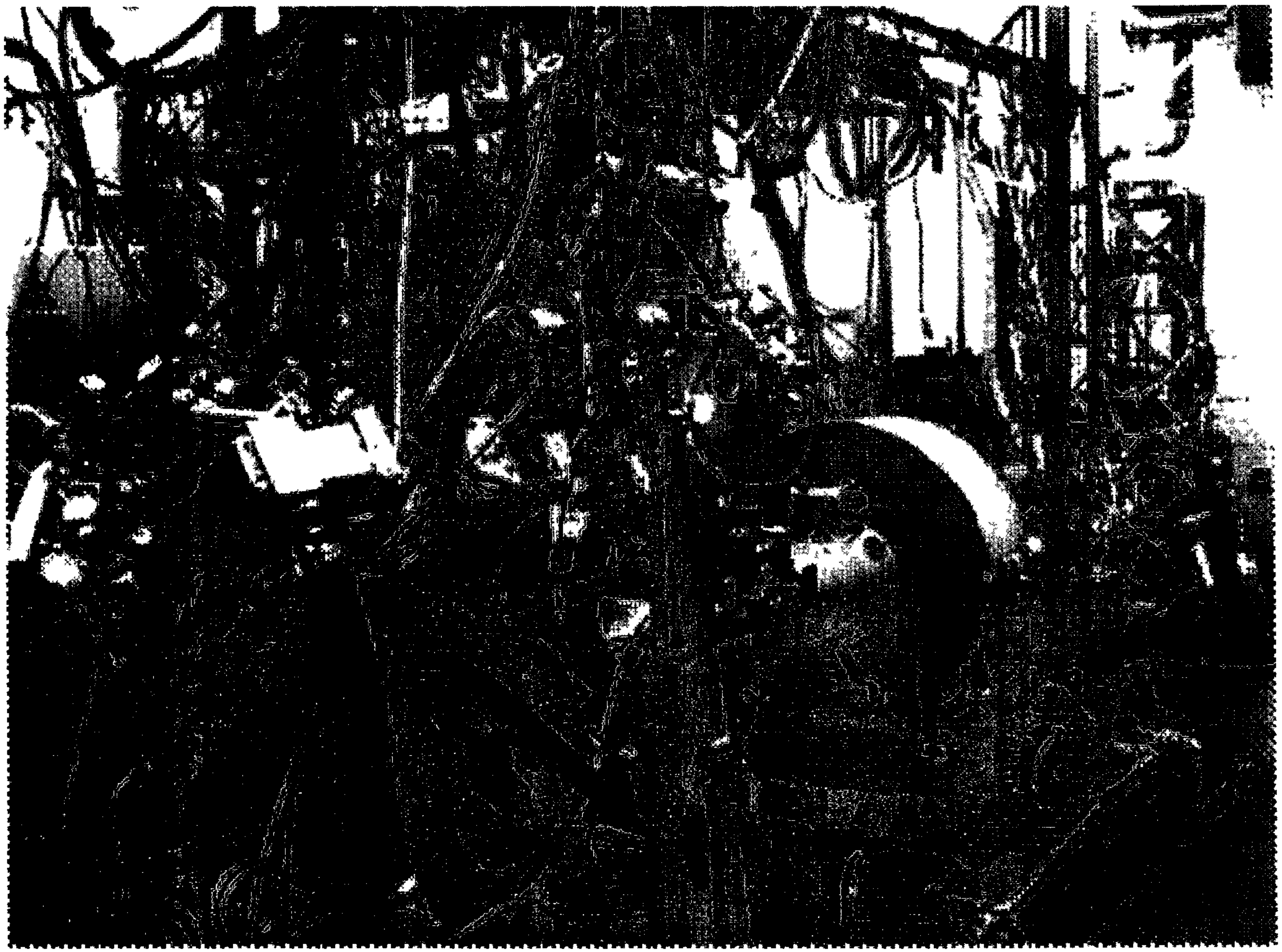


Figure 3.16: Produced Test Platform in the CDL

CHAPTER IV

4 SYSTEM DEMONSTRATION AND EXPERIMENT RESULTS

4.1 Single Cylinder Research Mode Setup Tests

The performance validation tests of the newly produced engine platform are conducted before any research experiments. These tests include interference tests for intake and exhaust contamination, injection scheduling, and injection pressure control tests.

4.1.1 Contamination Tests

The primary goal of this engine setup is to isolate one cylinder from other 3 cylinders, and measure the emission of the single cylinder for diesel LTC research. Hence, any contamination of emissions from the other 3 cylinders would affect the accuracy of the single cylinder emission measurement [8].

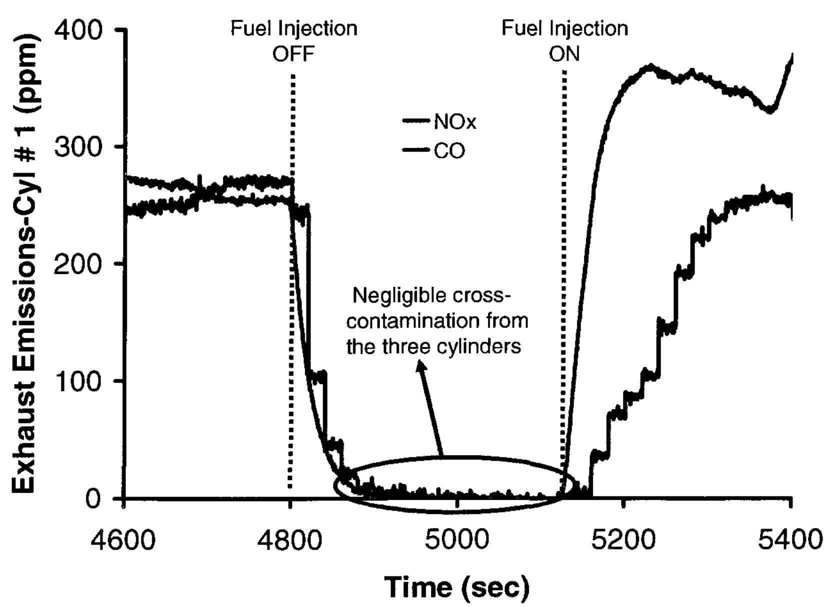


Figure 4.1 Exhaust Contamination Test

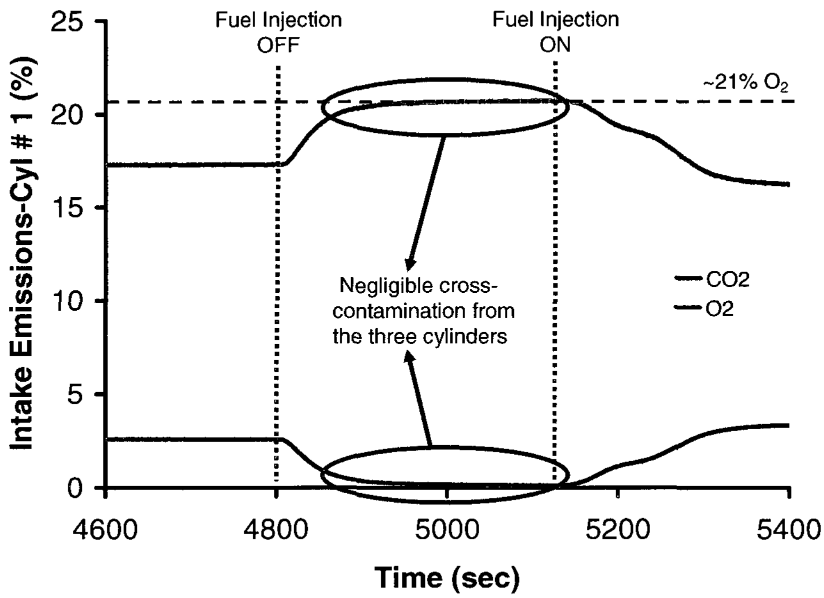


Figure 4.2 Intake Contamination Test

The single cylinder setup was tested for both exhaust and intake streams cross-contamination from the other three cylinders to confirm the accuracy of the emission measurements. The fuelling to Cylinder 1 was switched off while the rest of the three cylinders continued to fire. The results for both the exhaust and intake emissions are shown in Figure 4.1 and Figure 4.2. It can be seen that the cross contamination and background noise in the emission are negligible. The single-cylinder isolation setup for experimental research is validated.

4.1.2 Injection Control Test

To test the injection control system, both single shot and multi-shot injections have been commanded to Cylinder 1 via an in-house injection control program (by Dr. Zheng). In Figure 4.3 and Figure 4.4, the top blue curve is the common rail pressure monitoring, and the white curve is the cylinder pressure monitoring. The red signals are the current pulses of the IPOD injection driver.

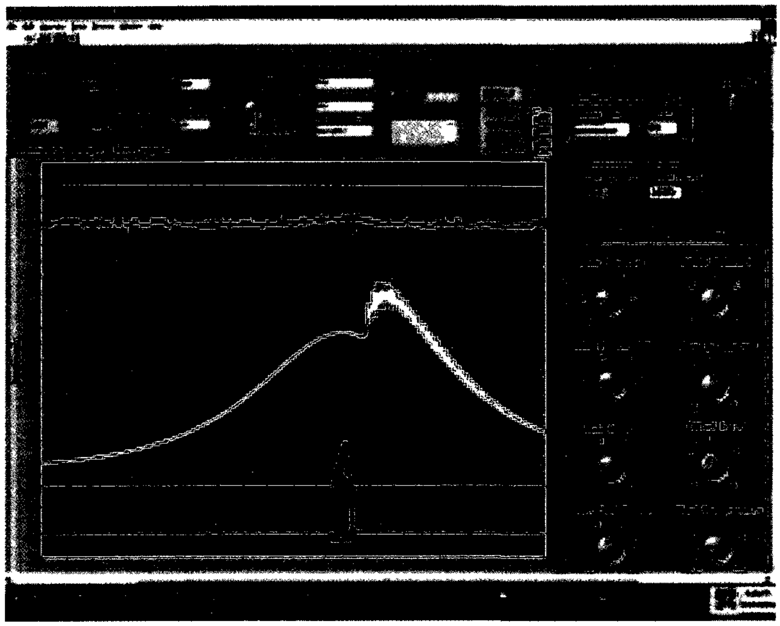


Figure 4.3 Single Shot Injection

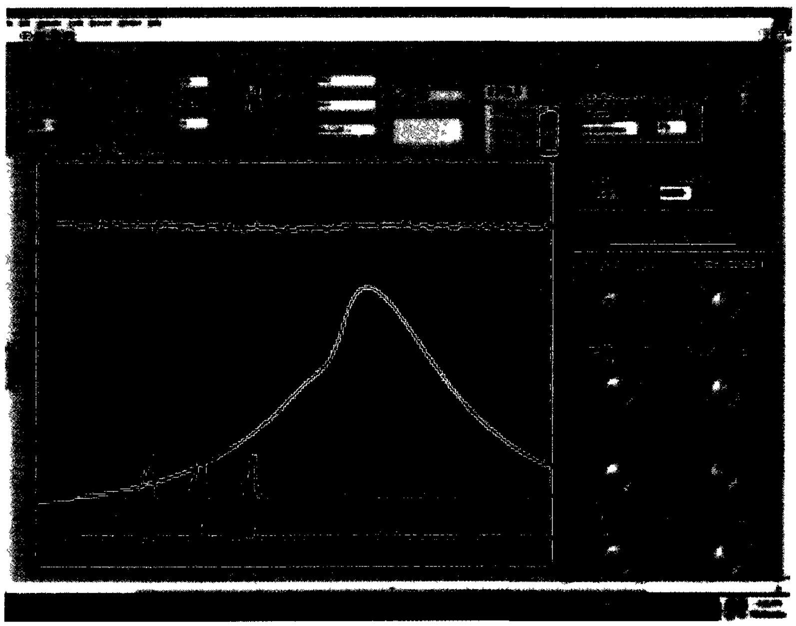


Figure 4.4 Multi-shot Injection (3 shots)

The injection strategies were successfully executed through the communication set-up between the IPOD and Cylinder 1.

4.1.3 Intake Boost and Exhaust Backpressure Test

Various levels of the intake boost pressure were used for high pressure tests of the modified intake system. Up to 3 bar of boost pressure has been applied by using the in-house Boost and Exhaust Backpressure Control program (by Usman Asad) shown in Figure 4.5. The intake manifold has withstood high boost pressure in many engine tests.

With the extended use of boost and EGR for Cylinder 1, simultaneous reduction of NOx and soot has been achieved in LTC tests.

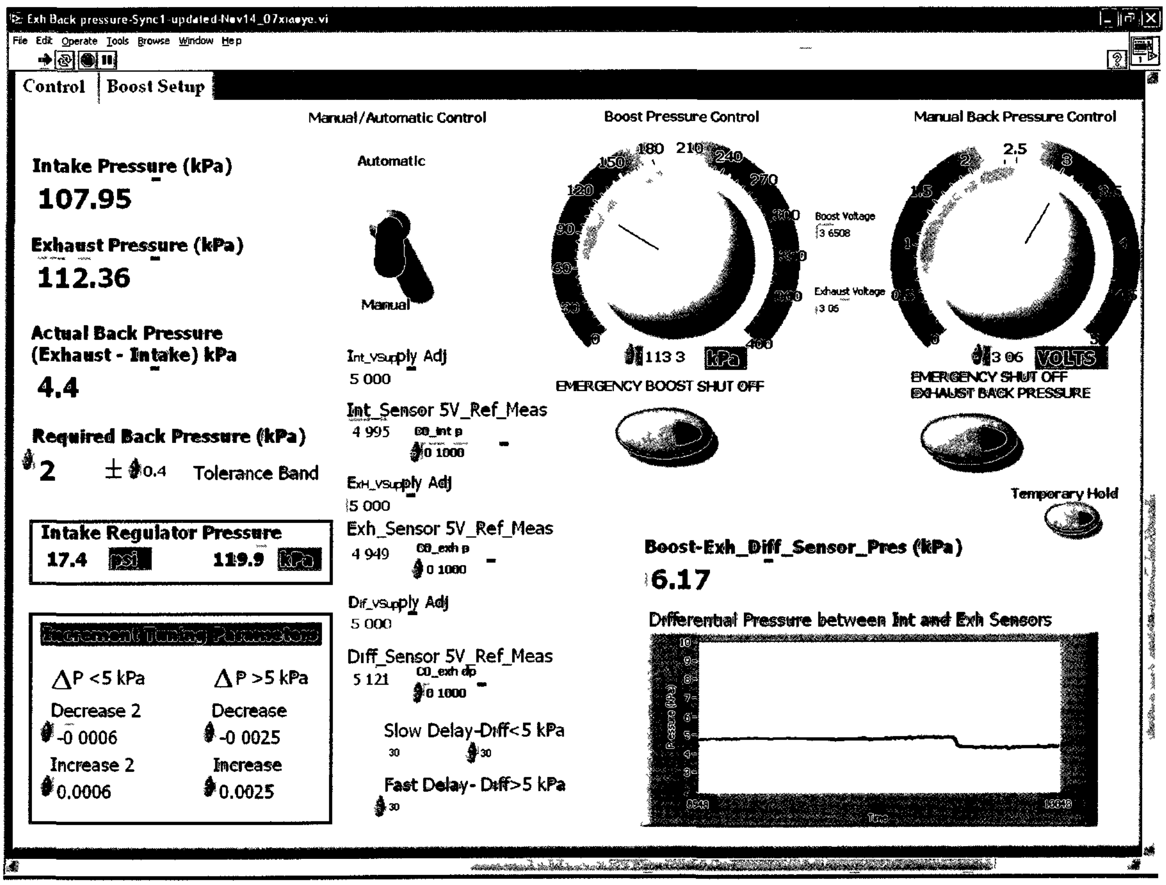


Figure 4.5 Boost and Exhaust Backpressure Control Program

4.2 Diesel LTC Research Experiments

4.2.1 Fuel Flow Rate Calculation for Single Research Cylinder

The fuel from the supply flows to the common rail where it is pressurized and then injected into all 4 cylinders. It is nearly impossible to take direct fuel flow measurements of the single research cylinder. For this reason, a conditioning mode test has to be carried out before any experiment. In the conditioning test, after setting a targeted common rail pressure, the injection durations of all 4 cylinders are controlled to be the same for each engine cycle. In other words, the fuel flow rate of each cylinder should be equal to each other. This would be a good approximation for the real experimental cases. During the LTC research experiment, only the fuel scheduling of the single cylinder is adjusted according to the test plan while the fuel injections of the other 3 cylinders are kept the same as those in the conditioning test.

4.2.2 EGR and Injection Timing Effect on Diesel LTC

The simultaneous reduction of NOx and soot has been investigated using EGR and injection timings from 350 to 362°CA. The EGR ratio was defined as the value of the intake CO_2 concentration divided by exhaust CO_2 concentration. A single fuel injection of a fixed quantity was maintained throughout the tests. The emission results are shown in Figure 4.6 and Figure 4.7. As the EGR was progressively increased, the traditional NOx-Soot trade-off for conventional diesel engines was initially observed. However, as the EGR levels went higher, the combustion processes resulted in simultaneous reduction of NOx and soot emission where the combustion essentially entered the LTC regime. The testing results indicate that the fuel injection scheduling can significantly affect the soot emission and the fuel efficiency as for the SOI of 356°CA [8].

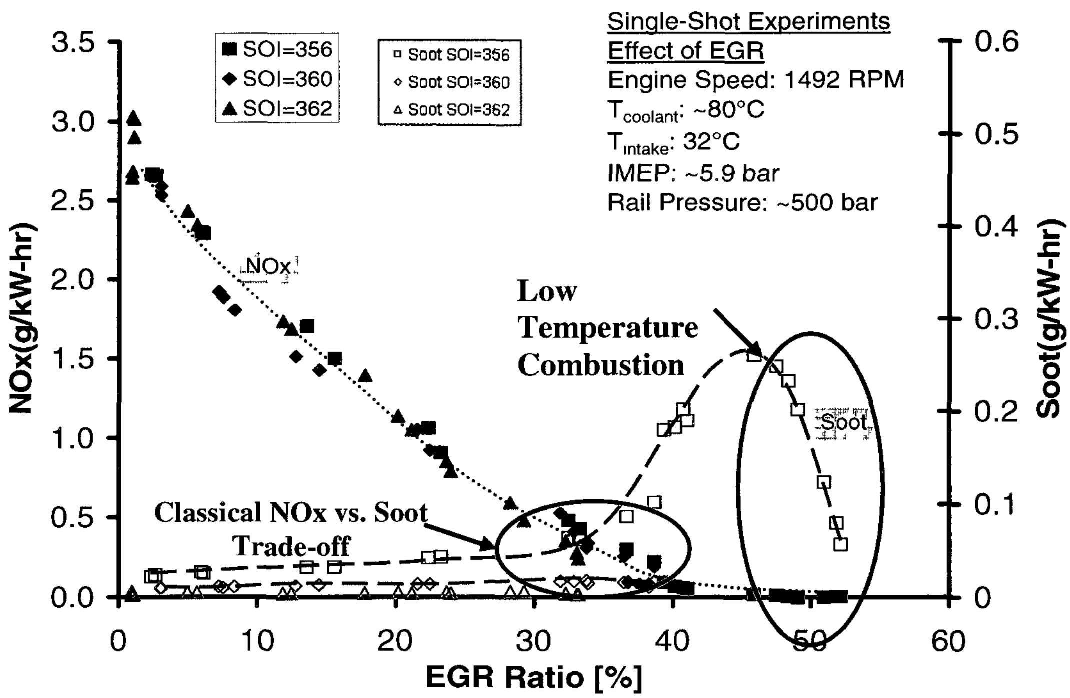


Figure 4.6 Effect of Increasing EGR on Soot and NOx

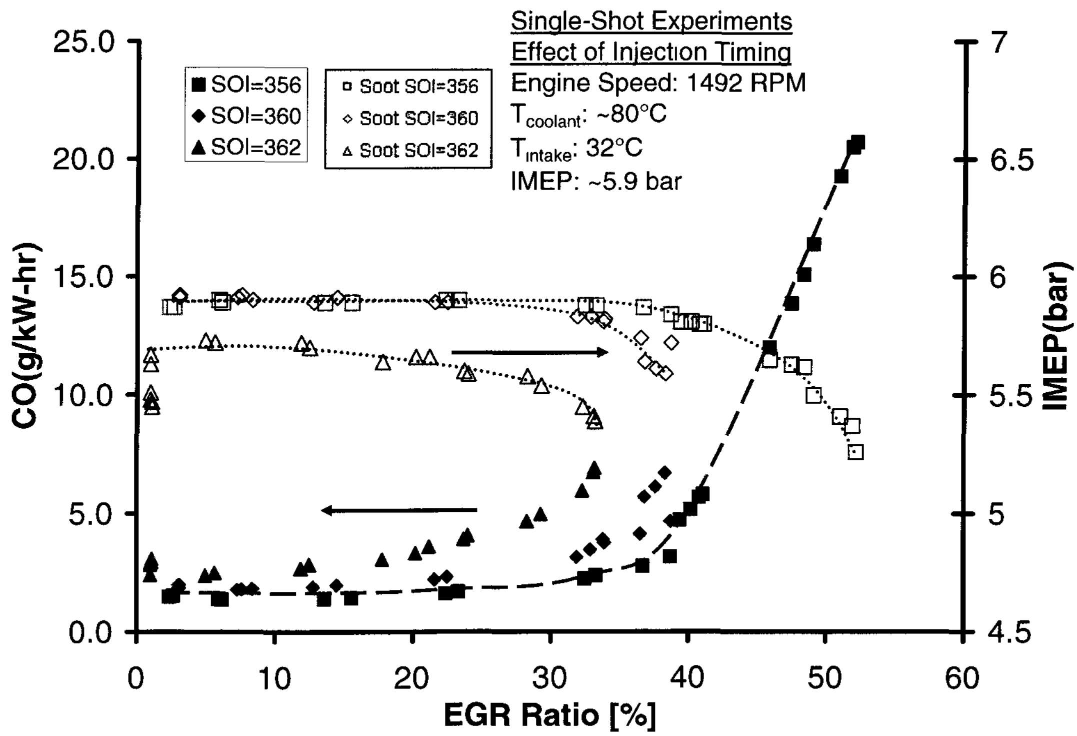


Figure 4.7 Effect of Increasing EGR on CO Emissions and IMEP

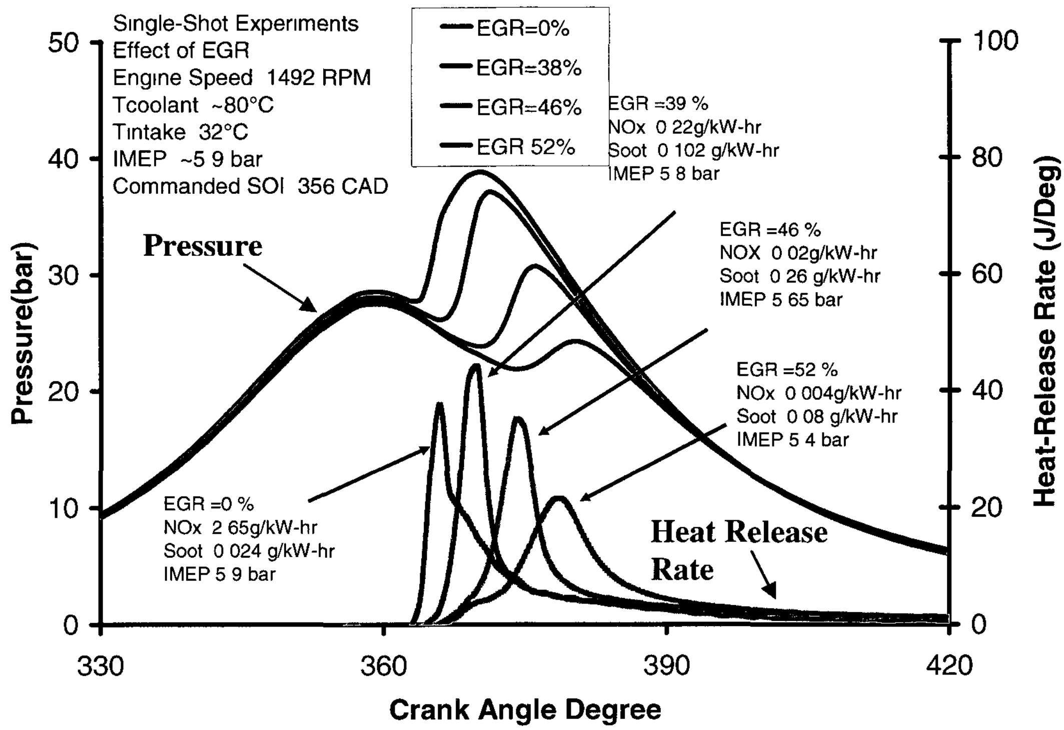


Figure 4.8 Effect of Increasing EGR on Heat Release Rate

The cylinder pressure and heat release rate are plotted in Figure 4.8. With increasing EGR, the increased ignition delay period provides more time for the mixture to reach near-homogeneity. For the fixed start of injection (SOI), the CA 50% of heat released retards as the combustion is delayed significantly. The effect of EGR on the ignition delay was investigated to identify the transition of conventional diesel combustion into the LTC regime. It was observed that once the ignition delay was prolonged by more than 50%, the simultaneous reduction of NOx and soot was achieved [8].

4.3 Biodiesel Tests on Newly Setup Platform

Biodiesel was also tested on the new platform. The effects of EGR, injection timing, and boost level on biodiesel were studied.

4.3.1 EGR and Injection Timing Effect on Biodiesel

Figure 4.9 and Figure 4.10 show the effect of EGR on the NOx and soot emissions of biodiesel and diesel fuels at 8bar IMEP and a fixed commanded SOI of 354°CA. The NOx emission was monotonically decreasing with the increased EGR, while the soot remained almost constant at low EGR level but accelerated with further EGR increases. This mode of combustion responds for the HTC. As the EGR ratio was increased further, the soot emission rapidly dropped from the peak soot value, and simultaneous ultra-low levels of NOx and soot were achieved when the EGR value of more than 70% was applied. This mode of combustion responds for the LTC [7].

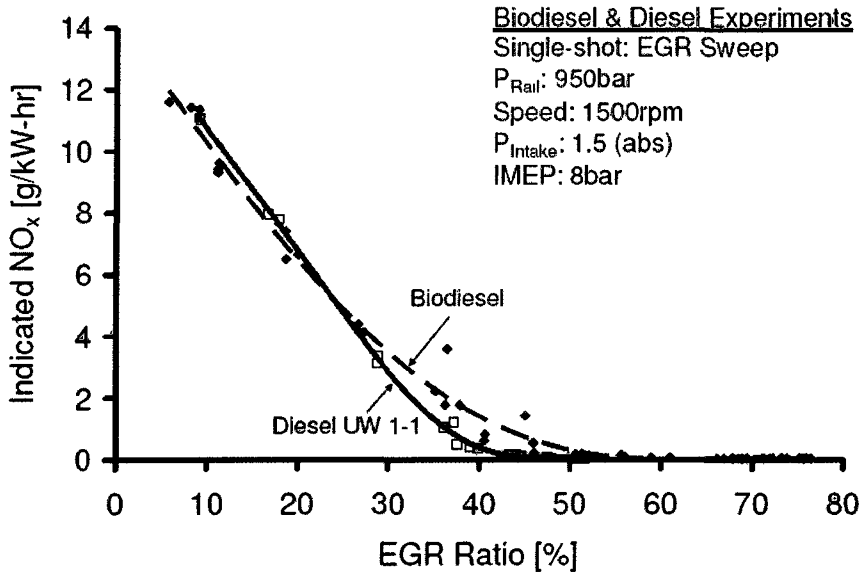


Figure 4.9 Comparison of the EGR Effect on NOx Emissions between Diesel and Biodiesel Fuels

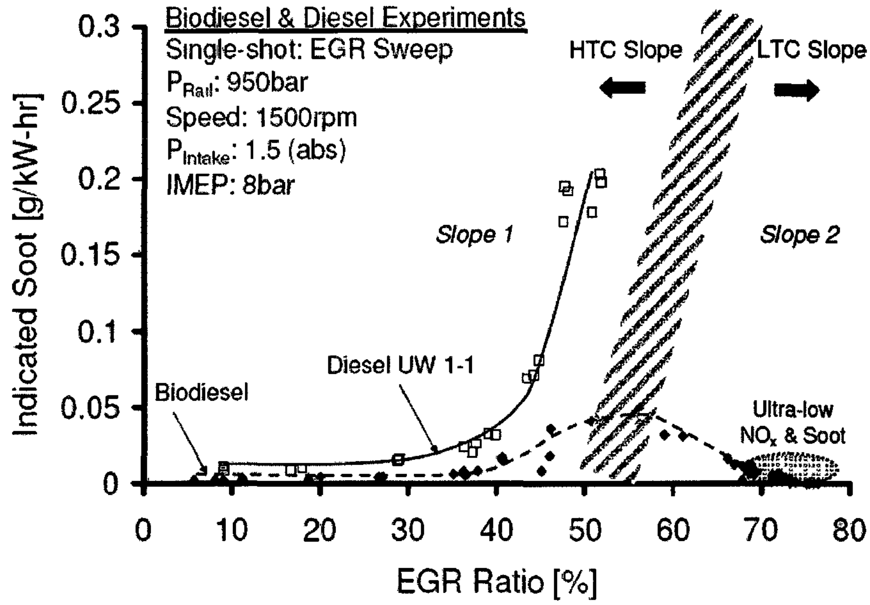


Figure 4.10 Comparison of the EGR Effect on Soot Emissions between Diesel and Biodiesel Fuels

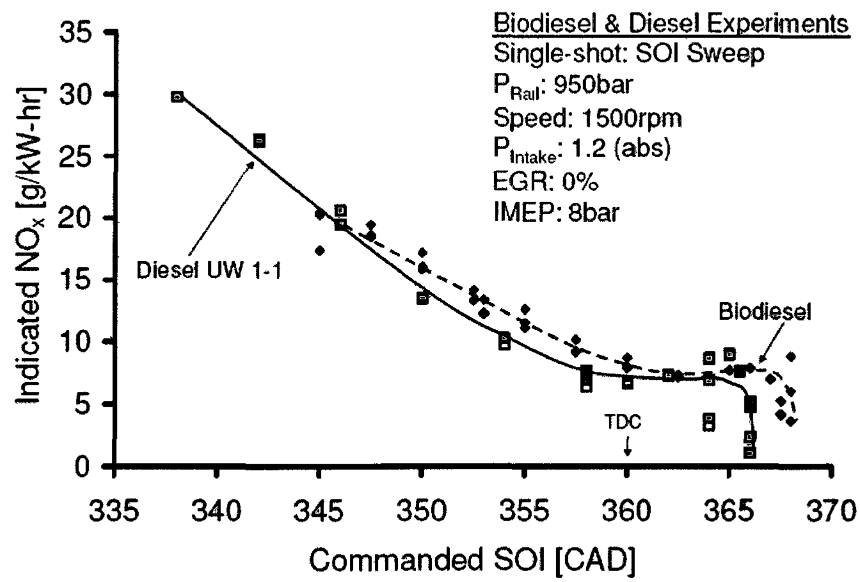


Figure 4.11 Comparison of the Injection Timing Effect on NOx Emissions between Diesel and Biodiesel Fuels

Figure 4.11 and Figure 4.12 show the injection timing effect on NOx and soot emissions for diesel and biodiesel fuels. With the retarding Start Of Injection (SOI), the NOx emission decreased monotonically, and a sharp drop occurred at SOI equal to 365°CA for diesel fuel, whereas the same pattern of NOx drop happened at SOI equal to 367°CA for biodiesel.

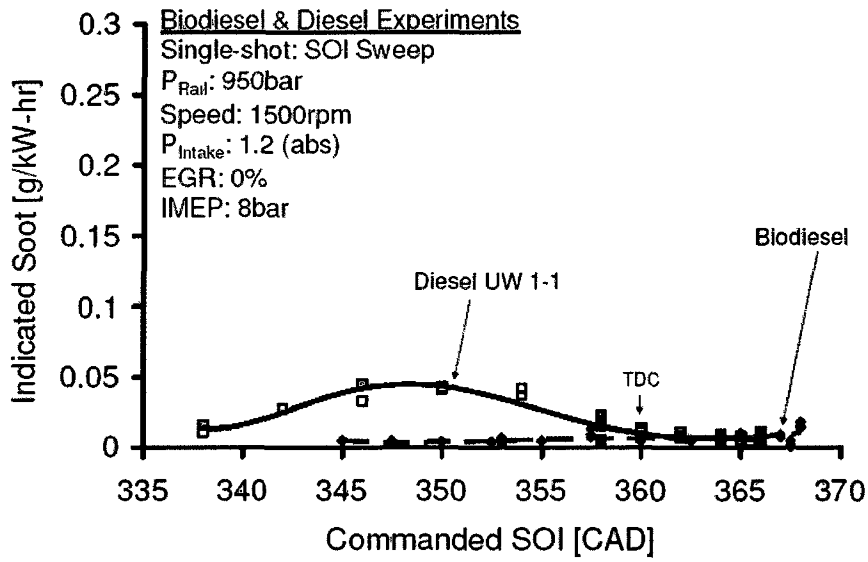


Figure 4.12 Comparison of the Injection Timing Effect on Soot Emissions between Diesel and Biodiesel Fuels

Regarding the soot emission, the influence of injection timing is not as sensitive for biodiesel as for diesel fuel. In the tested conditions, the soot level was almost constant and in a low range for biodiesel (Figure 4.12).

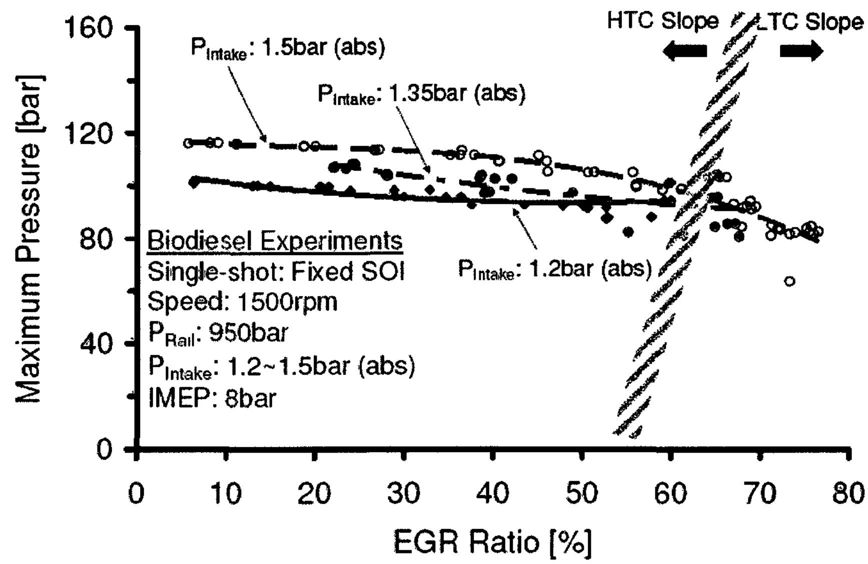


Figure 4.13 Pmax with EGR under Different Boost for Biodiesel

4.3.2 Boost Effect on Maximum Cylinder Pressure for Biodiesel

Effect of different boost levels on cylinder peak pressure was studied according to the increasing EGR (Figure 4.13). Generally, the peak pressure decreased with the increasing use of EGR; the higher boost (other conditions were the same) would result in the higher maximum cylinder pressure.

4.4 Preliminary Conclusions of Platform Setup

Innovative LTC combustion strategies were tested on the newly created platform, which demonstrated that the modified engine system is fully flexible in independent control of intake boost, exhaust backpressure, EGR, and injection scheduling.

In the experiments, the combustion of the single research cylinder was pushed into LTC regimes. The effect of EGR, injection timing, and boost was investigated on the new test platform. Moreover, the biodiesel fuel has also been successfully tested for LTC research.

These experiments prove that the modified engine test system is capable of performing diesel LTC research.

CHAPTER V

5 PRELIMINARY SIMULATION WORK

Diesel engines have major advantages such as a higher compression ratio compared to gasoline engines. However, as the intake boost is normally applied to expand the EGR range in diesel LTC, the elevated intake pressure, with the high compression ratio, commonly leads to a very high cylinder peak pressure. This is also one of the reasons why most diesel LTC research is limited in the low load range (Figure 1.8 and Figure 1.9).

Variable Valve Timing (VVT) is a new technology that is capable of changing the intake and exhaust valve timing so that the equivalent compression ratio can be reduced to a desirable value. Additionally, the intake charge temperature should be lowered if the intake valve closing is retarded, since the compression stroke is reduced physically. On the other hand, the expansion stroke is kept the same if there is not any change of exhaust valve timing. Therefore, the VVT system is able to take the advantage of a short compression stroke (negative work) as well as a longer expansion stroke (positive work). The VVT should potentially improve the engine efficiency. Furthermore, the lowered intake charge is also helpful for the combustion phasing of diesel LTC.

A set of VVT system will be available in the CDL in the near future. Before the system is set up, the parametric analysis by GT-power is carried out to study how the VVT would help the combustion phasing in HCCI mode.

5.1 Parametric Analysis through GT-power Simulations

The GT-Power simulation model is illustrated in Figure 5.1. All the necessary parameters of the engine type, cylinder geometry, intake and exhaust systems, and an injector can be input to each co-responding component of the model.

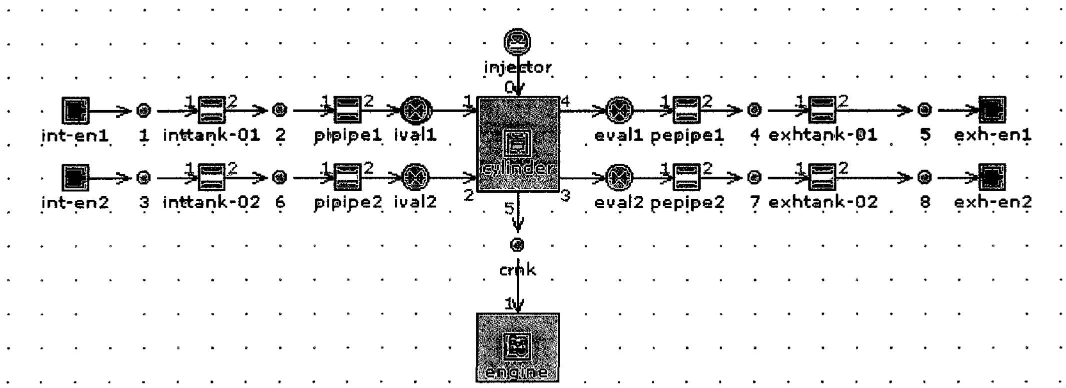


Figure 5.1 GT-power Simulation Model

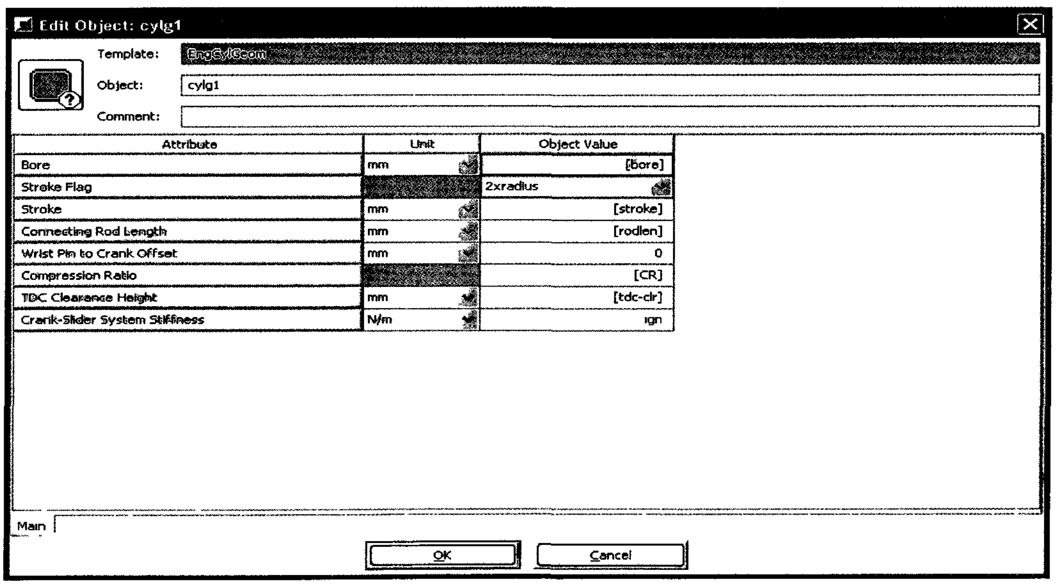
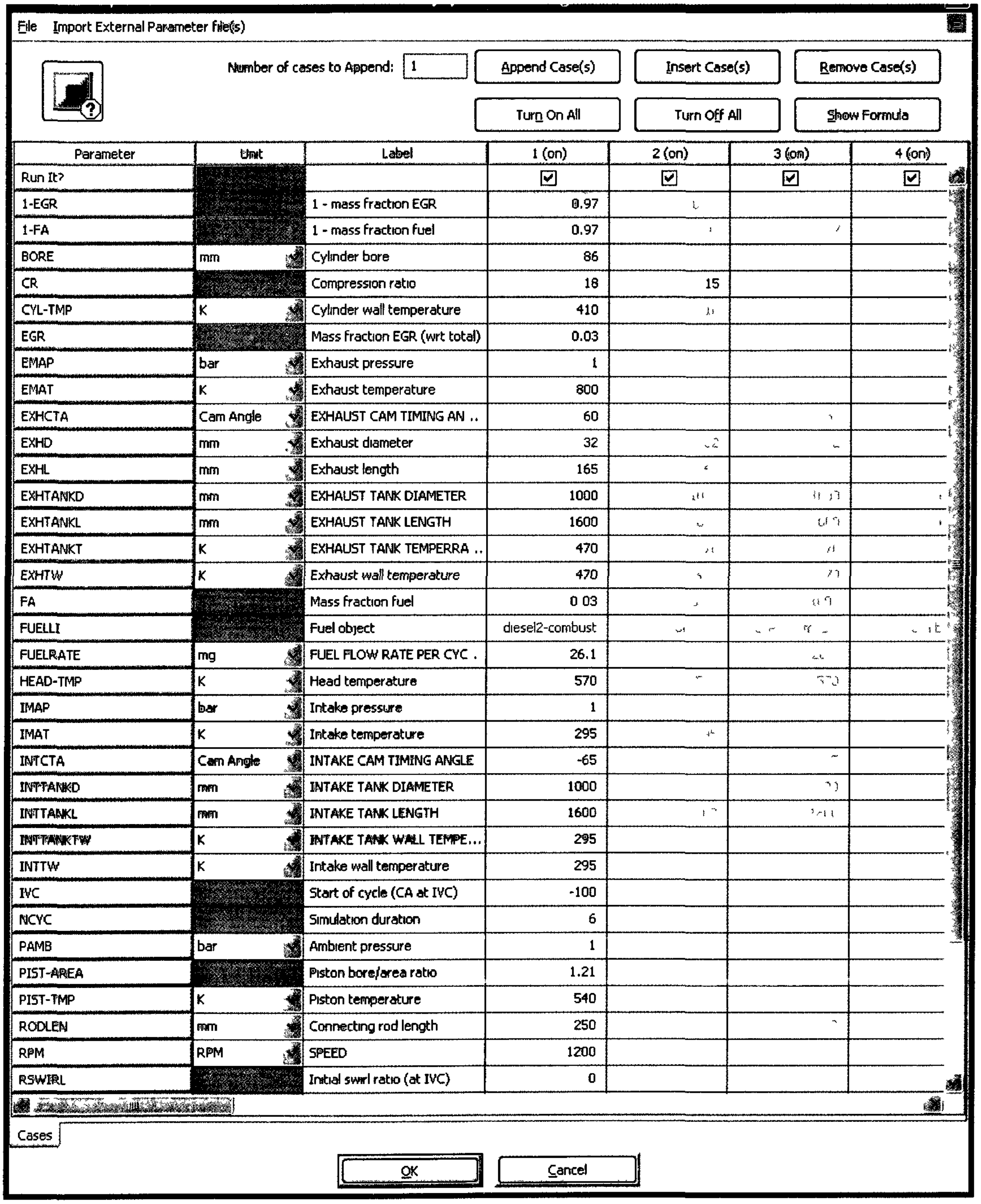


Figure 5.2 Cylinder Geometry Definition in GT-power

For example, the definition of the cylinder geometry is demonstrated in Figure 5.2. The parameters can be defined as input variables and assigned in the simulation RUN set-up (Figure 5.3).



Parameter	Unit	Label	1 (on)	2 (on)	3 (on)	4 (on)
Run It?			☑	☑	☑	☑
1-EGR		1 - mass fraction EGR	0.97			
1-FA		1 - mass fraction fuel	0.97			
BORE	mm	Cylinder bore	86			
CR		Compression ratio	18	15		
CYL-TMP	K	Cylinder wall temperature	410			
EGR		Mass fraction EGR (wrt total)	0.03			
EMAP	bar	Exhaust pressure	1			
EMAT	K	Exhaust temperature	800			
EXHCTA	Cam Angle	EXHAUST CAM TIMING AN ..	60			
EXHD	mm	Exhaust diameter	32			
EXHL	mm	Exhaust length	165			
EXHTANKD	mm	EXHAUST TANK DIAMETER	1000			
EXHTANKL	mm	EXHAUST TANK LENGTH	1600			
EXHTANKT	K	EXHAUST TANK TEMPERRA ..	470			
EXHTW	K	Exhaust wall temperature	470			
FA		Mass fraction fuel	0 03			
FUELLI		Fuel object	diesel2-combust			
FUELRATE	mg	FUEL FLOW RATE PER CYC .	26.1			
HEAD-TMP	K	Head temperature	570			
IMAP	bar	Intake pressure	1			
IMAT	K	Intake temperature	295			
INTCTA	Cam Angle	INTAKE CAM TIMING ANGLE	-65			
INTTANKD	mm	INTAKE TANK DIAMETER	1000			
INTTANKL	mm	INTAKE TANK LENGTH	1600			
INTTANKTW	K	INTAKE TANK WALL TEMPE...	295			
INTTW	K	Intake wall temperature	295			
IVC		Start of cycle (CA at IVC)	-100			
NCYC		Simulation duration	6			
PAMB	bar	Ambient pressure	1			
PIST-AREA		Piston bore/area ratio	1.21			
PIST-TMP	K	Piston temperature	540			
RODLEN	mm	Connecting rod length	250			
RPM	RPM	SPEED	1200			
RSWIRL		Initial swirl ratio (at IVC)	0			

Figure 5.3 Assignment of Simulation Variables

5.2 Simulation Results and Discussions

Typical simulation results shown in Figure 5.4 and Figure 5.5 have been demonstrated in this section. The results indicate that the withheld intake temperature is obvious when the intake valve closing is retarded. In Figure 5.4, the temperature difference at TDC between VVT and the original valve timing is 150°C. More importantly, to reach the same charge temperature, the VVT system postpones the phasing by about 25° crank angle (CA). The significance is that the early-pilot injected fuel in HCCI mode potentially will have a sufficiently long period to get well-mixed with the air owing to the retarded combustion phasing. However, the cylinder pressure at TDC drops significantly with the retarded intake valve closing.

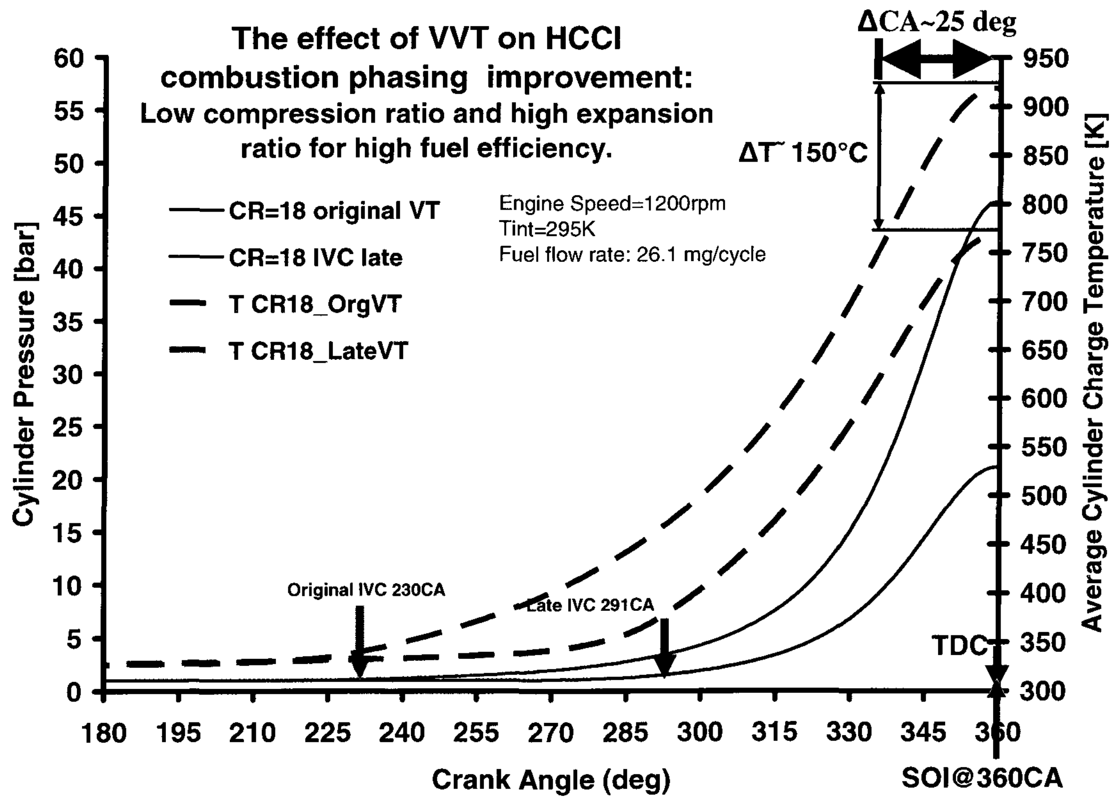


Figure 5.4 Pressure/Temperature Comparison between VVT and Original Valve Timing Case

In order to maintain cylinder pressure, appropriate boost should be applied to the intake charge. In Figure 5.5, the intake boost is selected as 2.18 bar absolute. The simulation results indicate that the desirable phasing effect could be reserved and high cylinder pressure at TDC could be reached as well with the application of appropriate boost level. Furthermore, it is observed that the maximum cylinder pressure before the combustion taking place is highly related to the intake boost level. Thereby the cylinder peak pressure (with combustion) can be partially controlled by the level of boost application.

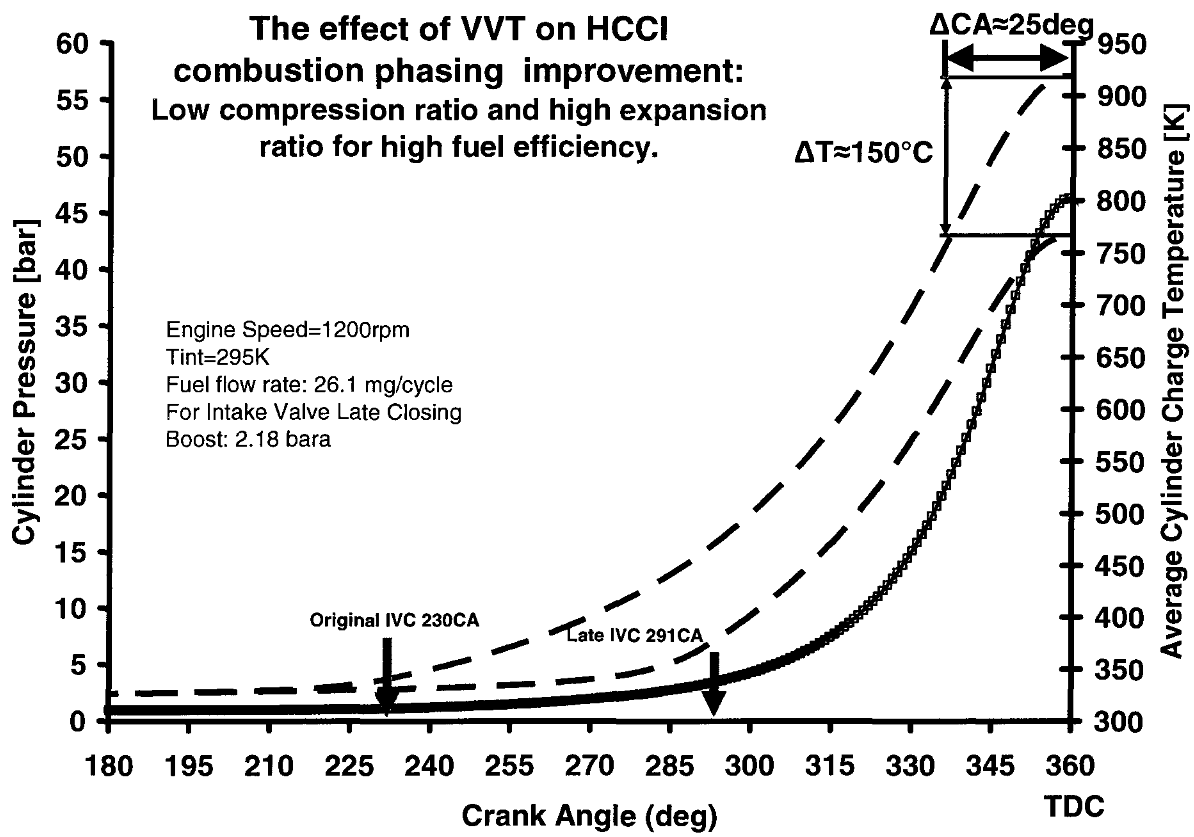


Figure 5.5 Pressure/Temperature Comparison between Boosted VVT and Original Valve Timing Case

5.3 Simulation Work Summary

GT-power has been studied to perform the parametric analysis of the VVT effect.

The delayed closure of the intake valve is indicated to help the HCCI combustion phasing. The cylinder charge temperature history may be modulated to better the mixing preparation. In this way, it helps to hold a homogenous charge during low temperature combustion cycles at higher loads.

The boost effect has also been investigated via the simulation work. It is shown that boost levels nearly have no effect on the favorable combustion phasing mentioned above. Moreover, the cylinder peak pressure without the combustion events is highly related to the boost levels. Thereby the maximum combustion pressure can be partially regulated by the intake boost. This will lighten the burden of cylinder peak pressure limitations on most research engines.

CHAPTER VI

6 SUMMARY OF THE THESIS WORK

6.1 Conclusions of Thesis Work

The investigation of unstable combustion regimes with a single-cylinder engine requires a motoring dynamometer to be coupled to the engine. In this work, a novel setup to transform a 4-cylinder engine into an independently controlled single-cylinder configuration for use with a non-motoring dynamometer has been carried out. The research work can be summarized as follows:

1. An advanced research platform for conducting advanced in-cylinder combustion research on a single cylinder of a 4 cylinder modern diesel engine has been setup. The key issues addressed during the conversion process are as follows:

    a) A new exploration strategy with a 3 cylinders-to-1 cylinder configuration was successfully implemented by isolating the operation of cylinder # 1 from the rest of the cylinders.

    b) This new strategy enabled investigation of unstable combustion regimes with a non-motoring dynamometer. The 3 cylinders were operated in the conventional high temperature combustion mode at low load for stable engine operation while as Cylinder # 1 is being monitored. The combustion in Cylinder 1 was then independently controlled by boost, EGR, and injection events to be in the low temperature combustion cycles.

c) The intake and exhaust flow streams for Cylinder # 1 were isolated from the rest of the cylinders and coupled to an automated independent exhaust gas recirculation, boost and exhaust backpressure control system. This allowed the boost pressure and the exhaust gas recirculation to be increased to higher levels that were otherwise not achievable with the stock turbocharger.

d) The original Ford engine control unit was dispensed and an independent system for controlling the fuel injection quantity and scheduling was setup. This system allows the injection timing to be commanded on a crank angle basis and the injection quantity to be specified on a time basis, thereby providing a high degree of flexibility in the fuel control system.

2. The isolation of the intake and exhaust systems for the cylinder # 1 from the rest of the three cylinders was experimentally confirmed. The measurement of the intake and exhaust emissions between fired and motoring engine conditions for cylinder # 1 verified that the modified intake and exhaust manifolds provided adequate isolation and therefore, confirmed the reliability of the empirical results.

3. A number of experimental tests were performed to investigate the effects of changing the injection timing and EGR on the NOx and soot emissions for both conventional high temperature combustion and low temperature combustion modes of operation with a single fuel injection.

a) For the high temperature combustion cycles, the injection timing sweep results indicated that the injection timing has a direct correlation with the phasing of combustion. Increasing the EGR levels for a given injection timing significantly reduces the NOx emissions and retards the combustion phasing, as for the soot emission tends to increase, following the classic NOx and soot trade-off.

b) The large amount of EGR application pushed the combustion into the LTC cycles, resulting in ultra low emissions of NOx and soot. However, the excessively retarded combustion phasing results in unstable engine operation.

4. The detailed documentation of the advanced research platform has been completed.

5. The concept of variable valve timing was investigated with GT-Power simulations. The preliminary results indicate that delaying the closure of the intake valve allows the effective cylinder compression ratio and in-cylinder compression temperature peak to be reduced, thereby retarding the mixing preparation phasing in HCCI mode. In this way, the cylinder charge temperature history may be modulated to more favorable windows for the preparation and holding of a homogenous charge during low temperature combustion cycles at higher loads.

6.2 Future Work

1. To identify the effects of EGR, boost, and injection patterns on the diesel LTC emissions, numbers of empirical tests have been performed on the new research platform. The experimental results need to be analyzed further and summarized systematically, so that a deeper understanding of the diesel LTC can be obtained and the platform configuration will be improved.

2. The highest IMEP of the diesel low temperature combustion that has been run on the research platform was 8 bar. The VVT system helps to expand the load range of the

diesel LTC research [24,33]. Therefore, a VVT system should be coupled to the research platform to improve the research capability of handling the engine load range.

3. More simulation cases should be conducted to provide certain boundary conditions for the engine test design. When the VVT system is instrumented and tested on the engine test platform, simulated results should be compared with the empirical data. Therefore, the simulation will be improved and validated.

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APPENDICES

A. Variable Valve Timing (VVT)

Variable valve timing (VVT) and the variable length intake manifold (VLIM) are designed to broaden the torque band of the engine.

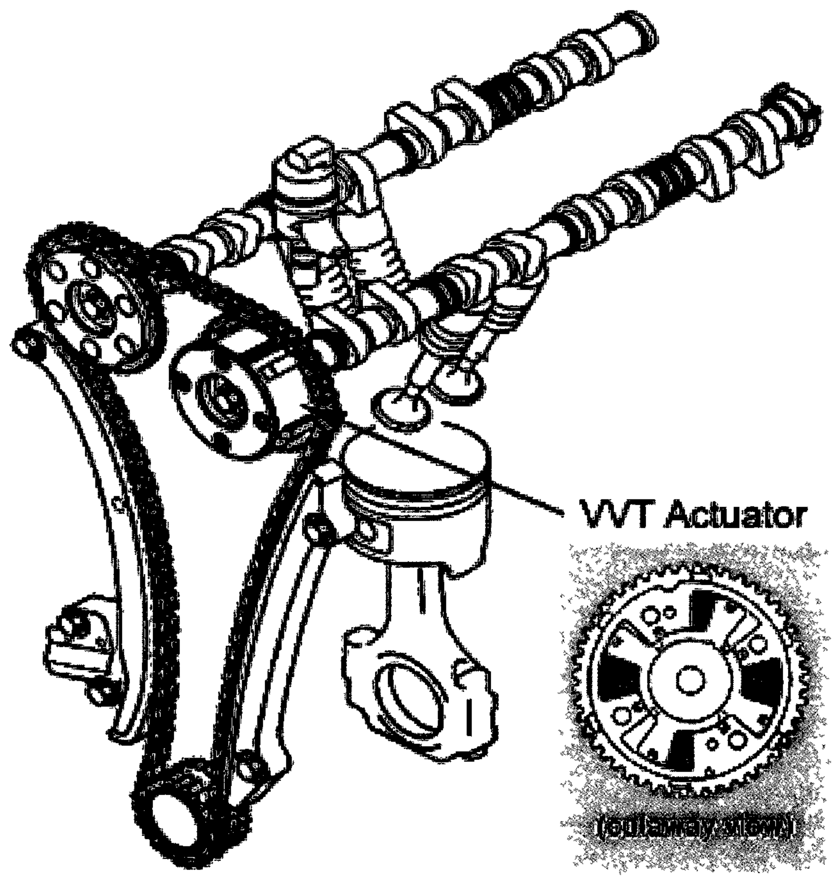

Figure A 1 VVT Actuator [38]

B. Variable Geometry Turbocharger (VGT)

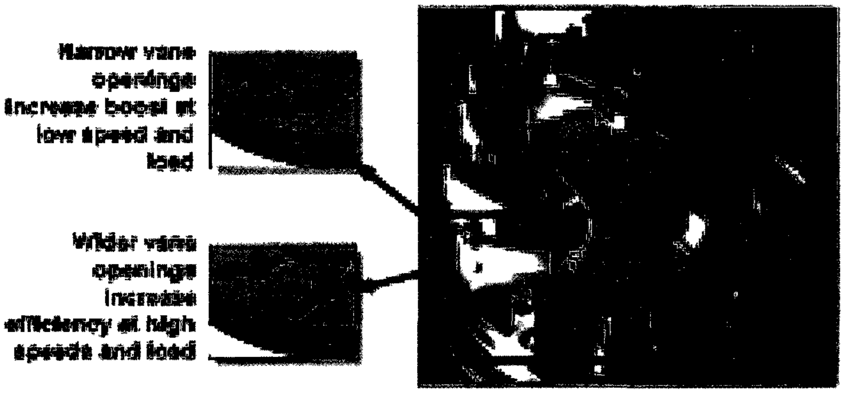

Figure A 2 VGT vanes in exhaust flow [39]

The Variable Geometry Turbocharger (VGT) is used for better economy and load response. The "variable" part of the turbo provides performance by electronically positioning exhaust airflow vanes. The vanes are in the exhaust flow. The external actuator has a mechanical linkage to move the vanes to the appropriate position. The opening or closing of the vanes changes the outlet volume and airflow speed against the turbocharger impeller. More specifically, narrow vane openings increase boost at low speed and load while wider vane openings increase efficiency at high speed and load [39].

The ability to keep the airflow going at the optimum point provides more consistent engine boost pressure and the ability to respond to load quickly. Boost pressure in the intake manifold is controlled at its optimum point to provide economy and performance regardless of engine speed or load. Overall, the applying of the VGT results in the increase in the low-speed torque and the peak torque and the improvement in the fuel economy and engine performance at high altitudes. In addition, VGT also allows quicker response to engine load [39].

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