2022

AN EXPERIMENTAL STUDY OF FUEL SELECTION FOR A GASOLINE MULTI-MODE, SPARK IGNITED – COMPRESSION IGNITION ENGINE

Zachary J. Stanchina
Michigan Technological University, zjstanch@mtu.edu

AN EXPERIMENTAL STUDY OF FUEL SELECTION FOR A GASOLINE MULTI-MODE, SPARK IGNITED – COMPRESSION IGNITION ENGINE

By:

Zachary J. Stanchina

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Mechanical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2022

This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering.

Department of Mechanical Engineering-Engineering Mechanics

Thesis Advisor:	*Dr. Jeffrey D. Naber*
Committee Member:	*Dr. Jeremy Worm*
Committee Member:	*Dr. Scott Miers*
Department Chair:	*Dr. Jason Blough*

Table of Contents

List of Figures

List of Tables

Acknowledgments

Several people and organizations have been instrumental in me being able to complete these studies and write this thesis.

First, I would like to thank my defense committee, Dr. Jeffrey Naber my advisor as well as Dr. Jeremy Worm and Dr. Scott Miers. Each of these people has been my instructor in the courses which provided me with the knowledge to complete this research. I am very thankful for the weekly feedback on progress and input provided by Dr. Jeffrey Naber and Dr. Jeremy Worm to keep me moving forward and understanding the data collected. I would also like to thank the APS Labs Staff: Paul Dice, William Hansley, Tucker Alsup, Joel Duncan, and Alex Normand for helping me acquire the components I needed as well as in the test cell and with the experimental efforts. Tucker and Joel were extremely helpful when constructing the testbed Paul and William helped continuously throughout the project with testbed setup and installation as well as troubleshooting hardware issues. My fellow students who have helped me along the way are Tyler Miller, Tyler White, and Nic Tuma. They were always around working on their projects and would lend a hand when needed.

I would also like to thank the people who I worked with that introduced me to the APS labs and the engine research field. Conor Berndt was a graduate student whom I was an undergraduate assistant for and taught me a significant amount about testing. Dr. Jeffrey Naber and Dr. John Johnson for hiring me to be his assistant in the Heavy-Duty Diesel Lab and learn about after-treatment systems and emissions instrumentation. As well as Dr. Niranjan Miganakallu for the time, I spent working on the Hydra with him as well as his knowledge about combustion knock.

Nick Fantin, Mark Shirley, Phillip Zoldak, Shengrong Zhu, and Jeffrey Hollowell were extremely helpful from HATCI. They provided the information required as well as all of the OEM hardware for the engine.

Audrius Brazauskas at WMI for the help setting up the controller as well as the combustion feedback system and modifying the system to fit our needs in our test cells here at the APS.

This work was financially supported by the U.S. Department of Energy, Office of Science, Office of Energy Efficiency and Renewable Energy Award Number DE-EE-0008478.

List of Abbreviations

GCI – Gasoline Compression Ignition

GDCI – Gasoline Direct Compression Ignition

SI – Spark Ignited

SCRE – Single Cylinder Research Engine

CR – Compression Ratio

LTC – Low-Temperature Combustion

RPM – Revolutions per Minute

CAD – Crank Angle Degrees

aTDC – After Top Dead Center

TDC – Top Dead Center

IAT – Intake Air Temperature

$IMEP_g$ – Indicated mean effective pressure, gross

$IMEP_n$ – Indicated mean effective pressure, net

BMEP – Brake mean effective pressure

CA10 - Location of 10% of the burned fuel mass

CA50 – Location of 50% of the burned fuel mass

CA90 – Location of 90% of the burned fuel mass

BD10-90 – Burn Duration, time in crank angle from CA10 – CA90

COV – Coefficient of variation

AFR – Air-Fuel Ratio

EGR – Exhaust Gas Recirculation

EGT – Exhaust Gas Temperature

FRP – Fuel Rail Pressure

AHR – Apparent Heat Release

MFB – Mass Fraction Burned

MPRR – Maximum Pressure Rise Rate

ITE – Indicated Thermal Efficiency

BTE – Brake Thermal Efficiency

BSFC – Brake Specific Fuel Consumption

LFE – Laminar Flow Element

DOE – Department of Energy

MTU – Michigan Technological University

WMI – WM International Engineering

P66 – Phillips 66

EPA – Environmental Protection Agency

CARB – California Air Resource Board

CAFE – Corporate Average Fuel Economy

HATCI – Hyundai America Technical Center Inc.

NI – National Instruments

PID – Proportional Integral Derivative

OEM – Original Equipment Manufacturer

LD – Light-Duty

CRDI – Common Rail Direct Injection

CVVD – Continuously Variable Valve Duration

SOI – Start of Injection

IMOP – Intake Maximum Open Position, centered around TDC Gas Exchange

EMOP - Exhaust Maximum Open Position, centered around TDC Gas Exchange

GE – Gas Exchange

RON – Research Octane Number

MON – Motored Octane Number

AKI – Anti-Knock Index, (R+M)/2

E10 – 10% Ethanol, by volume

IB51 gas – 51.2% Iso-butanol + 48.8% Phillips 66 RON 60, by volume

Eth36 gas – 36.6% Ethanol + 63.4% Phillips 66 RON 60, by volume

P66 IB25 gas – 25% Iso-butanol + 75% Phillips 66 RON 60, by volume

Halterman IB25 gas – 25% Iso-Butanol + 75% Phillips 66 RON60, by volume

THC – Total Hydrocarbons

UHC – Unburned Hydrocarbons

NO, NO_2, NO_x – Nitric Oxide, Nitrogen Dioxide, (NO + NO_2)

CO_2 – Carbon Dioxide

ATS – After Treatment System

FID – Flame Ionization detector

ECHO – Engine Controller High-Speed Oversight

CAS – Combustion Analysis System

°C – Degrees Celsius

Abstract

In this study of fuels of different reactivities and their performance in a low-temperature combustion (LTC) engine. The engine was a 2.2L CRDI engine code D4HB provided by industry partner Hyundai America Technical Center inc. (HATCI). The engine was instrumented with in-cylinder pressure sensors allowing for monitoring of the combustion process.

First, the engine was operated with standard US pump grade gasoline, Research Octane number (RON) 91 E10, to find initial operation conditions as well as control points of stable operation for daily checks on system conditions.

Tested were 8 different fuel blends, the four base blends were provided by Phillips 66 (P66) with a RON value ranging from 60 to 91, and three other variations of these fuels were formulated by splash blending alcohols, iso-butanol, and ethanol, with the RON60 fuel and the final blend, was US RON91 E10 pump gasoline. Using these 8 fuels, the low load performance was analyzed allowing a selection of one of the fuels to be made to proceed with experimentation.

To study the low load performance of each fuel, the load was decreased until combustion became too unstable to continue. This was done at 1500 rpm with all of the fuels. At 1200 rpm, the same methodology was applied, though all of the fuels were not tested, only the fuels which showed promise at 1500 rpm. Meaning that the lowest targeted load was achieved without any aid to the combustion process other than advancing combustion, increasing intake air temperature (IAT) for example was not done to maintain consistency across all fuels. The same methodology was applied at 800 rpm based upon the 1200 rpm results to see the ability of the engine to idle with the given fuel.

It was found that fuel with a RON of 80 showed good low load performance while allowing for high load performance to be maintained. A blend of 25% Iso-Butanol and 75% RON 60 equated to a RON of 80 and showed good low load performance and showed peak indicated thermal efficiency (ITE) numbers of 46% at 17 bar indicated mean effective pressure (IMEP) and 2200 rpm.

1 Introduction

This chapter's purpose is to give background information on what is being studied and to explain the goals and objectives of this research, where the research fits into the world of internal combustion engines, and how it could specifically provide a pathway forward for internal combustion engines. For the past few decades, the Environment Protection Agency (EPA) and California Air Resources Board (CARB) have developed new regulations regarding emissions from internal combustion engines. EPA CO_2 regulations are a decrease of 28.3% fleet-wide for model years 2023-2026, [1]. The new corporate average fuel economy (CAFE) standards required fleet fuel efficiency increases of 8% per year for model years 2024-2025 with 2026 having a 10% increase, [2]. The need to fulfill or exceed these requirements is the motivation for this research and the continued development of advanced combustion methods.

1.1 Background

Funding for this research was provided by the US Department of Energy (DOE). The program is part of the Co-Optima initiative, which focused on the co-optimization of fuels and engines. Modern light-duty engines are becoming limited by fuels. Focusing on developing fuels along with the engine can unlock potential for improvement in efficiency [3].

1.2 Goals and Objectives

Co-Optima findings showed that Multi-Mode approaches to engine operation can lead to an additional 9-14% fuel economy gains [4]. Goals specific to our portion of the project were to first choose a fuel that allowed for operating in compression ignition over the widest range and for good low load SI operation in a high compression ratio engine. The challenge was that properties favorable to one combustion mode are not to the other. Choosing a fuel with a high RON can limit the low load ability of the engine in a compression ignition mode while a fuel with a high RON will allow the engine to operate in SI mode at a higher load without having large amounts of combustion knock.

Figure 1.1 has a targeted speed load map displaying the operating mode at a speed load point as well as the challenges which will be encountered. Our studies focused on the lower speed and load region where mode switching is required. This is the region that will be heavily influenced by the fuel properties.

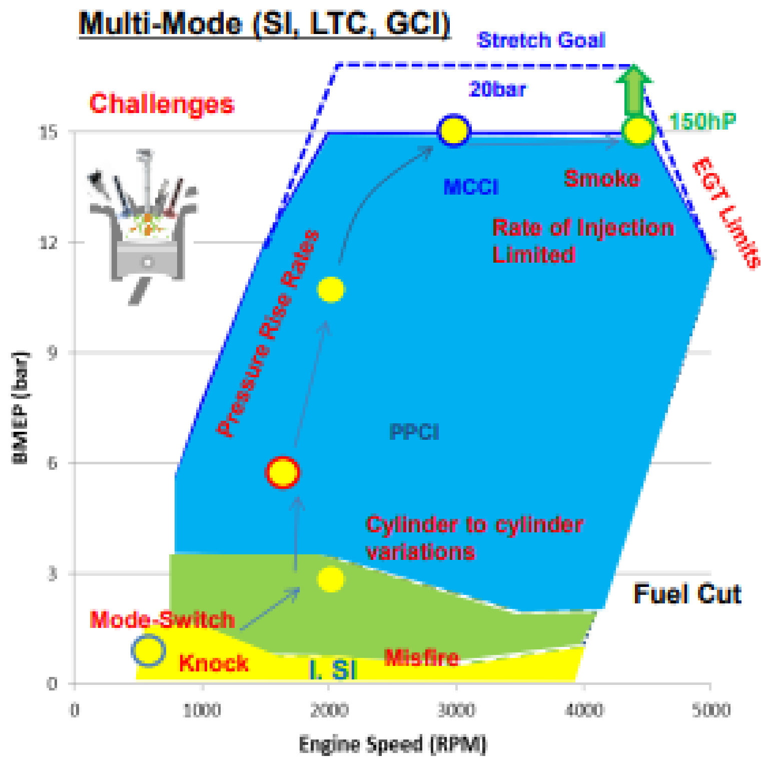

Figure 1.1. Speed Load map for targeted multi-mode operating [5]

To meet the goal of fuels selection for this portion of the project the following objectives were developed

1. Map out the low load operation of the provided fuels in GCI mode: Operate the 2.2L engine at low speed, low load where GCI operation is limited by fuel reactivity.
2. Choose a fuel that allows for successful low load operation without the assistance of elevated inlet air temperatures greater than the baseline 55°C.
3. Experimentally verify the fuel selection was successful in choosing a fuel that did not limit the operation at higher loads while enabling operation at low loads.

1.3 Thesis Overview

This thesis discusses the experimental study which was conducted to explore the low load operation of a GCI engine with fuels of different reactivities. Chapter 2 contains the literature review of materials relevant to this thesis. Procedures for the experiments as well as the engine setup and instrumentation are discussed in Chapter 3. Chapter 4 contains the results of the experiments Chapter 5 is the summary and conclusions which were drawn as well as suggestions for future work. Appendices contain descriptions of instrumentation and supporting systems and information on the engine operation and experimentation which was conducted for this thesis.

2 Literature Review

When operating an engine in compression ignition mode there are some distinct advantages regardless of the fuel the engine is being operated with. One of them is the increase in efficiency shown by the following Otto cycle ideal cycle relationship.

$$\eta = 1 - \left(\frac{1}{r_c^{\gamma-1}}\right)$$

An increase in compression ratio (r_c) will yield an increase in efficiency (η). There is also a beneficial effect from increasing the ratio of specific heats of the working fluid (γ) due to excess air being present as well as late injection of the fuel meaning that only air is being compressed during the first part of the compression stroke along with residuals. Each of these parameters will be affected positively when working with a compression ignition engine. They tend to operate at higher compression ratios as well as lean of stoichiometric. The lean operation will yield a higher ratio of specific heats due to the increase in the air which has a higher ratio of specific heats than fuel and combustion products. From an engine out emissions perspective, the lean operation would be desirable if combustion remains stable, Figure 2.1 [6]. As the figure shows, the leaner the operation the lower the engine out NOx will be. This is due to the decreased combustion temperatures when operating lean of stoichiometric causing the decrease in NO. An issue faced at light loads where CI engines operate lean is an excess of unburned hydrocarbons, (UNHC). This is due to the very lean conditions as well as flames being quenched due to low temperatures especially at the periphery, causing incomplete combustion. This is described by Heywood when describing diesel combustion and the formation of UNHC emissions. He also describes that at light loads, homogenous charge compression ignition (HCCI) engines and other lean-burn engines, can have very lean combustion that results in incomplete burns and misfires as well, leading to high engine-out CO and UNHC emissions. As discussed by in Heywood, chapter 10.7.2 where advanced combustion concepts are discusses, [6].

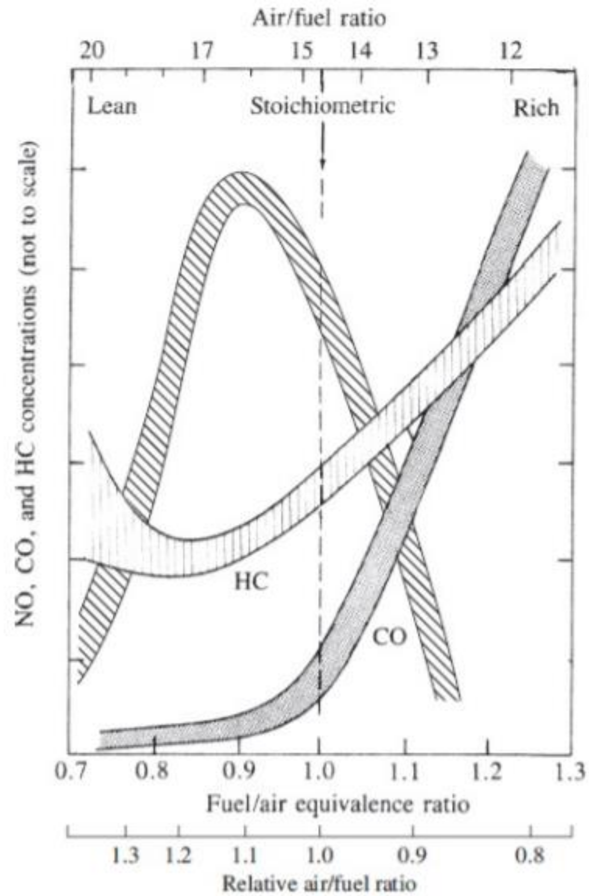

Figure 2.1. Emissions trends with equivalence ratio [6]

The effect of in-cylinder temperature on the formation of emissions such as NOx and soot can be seen in Figure 2.2. The operation of engines lean of stoichiometric locally and globally, $\phi < 1$ benefits from decreases in particulate matter (PM). Using gasoline, a fuel with relatively high resistance to auto-ignition when compared to diesel benefits from the local mixture being able to mix thoroughly, allowing the charge to be slightly less stratified. Meaning that there is a lesser change of locally rich zones producing high amounts of PM as well as UHC.

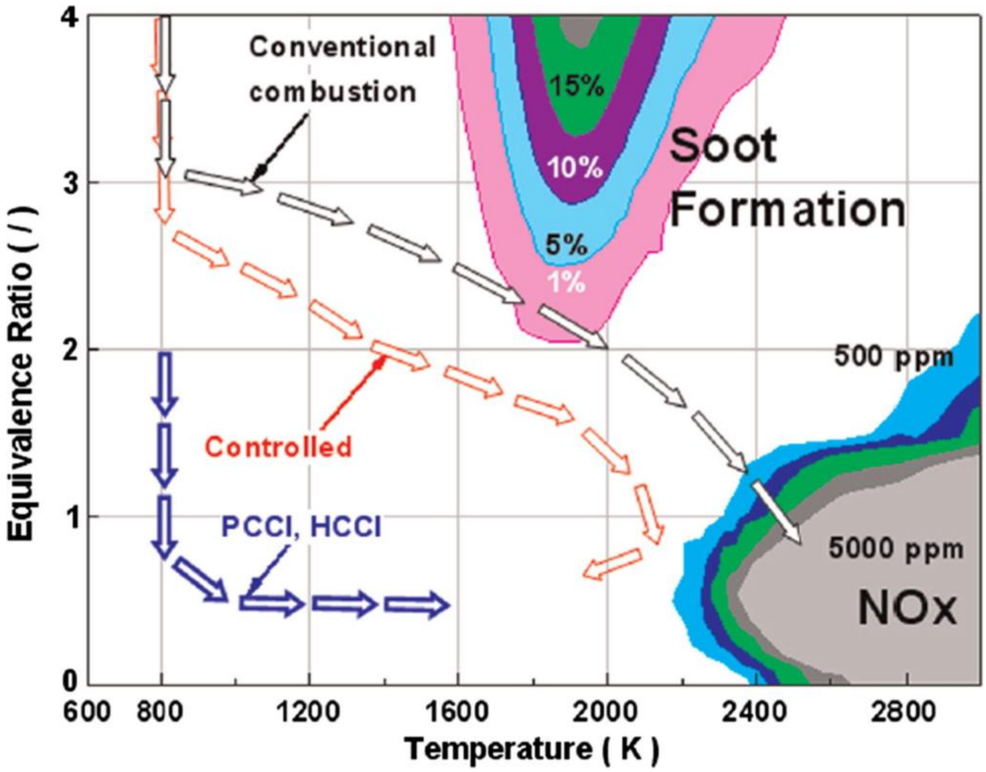

Figure 2.2. Phi - T Diagram of soot and NOx formation [7] , note y-axis label should be ϕ for equivalence ratio

2.1 Advantages of GCI

Utilizing gasoline in a compression ignition (GCI) application requires some hurdles to be overcome though not without benefit. When operating an engine in GCI mode a fuel of lower RON is desirable because of the increased tendency to auto-ignite. When making fuels with lower RON, the refining process can be simplified by removing the isomerization and catalytic reforming units. There is not only an increase in BTE at the engine point in the life cycle of the fuel but also a benefit from an energy perspective at the refining level [8].

When operating an engine with gasoline in a compression ignition mode there is a longer ignition delay due to the increased resistance to auto-ignition over diesel fuel. This increase in ignition delay leads to more premixed combustion resulting in decreased emissions of PM and decreased combustion temperatures resulting in decreased production of NOx. With the use of high quantities of exhaust gas recirculation (EGR), the ignition delay can be increased even further which can also cause a decrease in NOx and PM emissions at given operating conditions. EGR can control these aspects as well as lead to a decrease in indicated specific fuel consumption (ISFC) as shown by Hanson, Splitter, and Reitz in their studies of GCI in a 2.44-liter single-cylinder engine [9]. The reduction in PM emissions is quite critical to analyze. PM emissions tend to be the

Achilles heel of a conventional diesel engine. There is a significant benefit when using gasoline as a fuel to combat this issue due to the increased ignition delay [10]. Extensive studies have been done by many parties on this topic and it has proven to be one worth pursuing due to the benefits associated with it, though there are inherent cost and control complexity increases.

Another opportunity for improvement is through the use of a multi-injection strategy, which increases control complexity and cost but opens another door for potential benefits. It would allow for potential decreases in indicated CO_2 emissions when compared to the same engine operating on diesel. The decrease in specific CO_2 emissions is also accompanied by an increase in thermal efficiency and a decrease in specific fuel consumption [11].

Engineers at Delphi Technologies developed a fully functioning GCI engine model over years of research and development. Results from the studies conducted at Delphi, funded by the US Department of Energy, demonstrate significant improvements in brake specific fuel consumption (BSFC) over competitive SI engines as well as matching and in some cases surpassing those of production CI engines [12].

2.2 GCI Technologies

The idea of using gasoline in a diesel engine is not a new one but one which has only recently been attainable due to the complexity of the controls systems required as well as the desire to improve engine efficiency. This has happened through the development of fuel injection systems such as those carried out at Delphi Technologies. Delphi has developed multiple generations of its GCI engine concept which they call GDCI (gasoline direct compression ignition). The series of progression can be noted from the beginning of the single-cylinder development [11, 13, 14].

Following the development done with the single-cylinder research engine (SCRE), a 1.8 l four-cylinder engine was designed based on the results of the SCRE experiments. A compression ratio of 15:1 was used along with an advanced boost system [15]. The boost system was a large step in the development of the GCI engine. Being that they operate in a low-temperature combustion regime, which allows operation lean of stoichiometric, there is a low exhaust enthalpy when compared to a stoichiometric SI engine. The exhaust enthalpy is what drives the turbocharger and without the turbocharger, there is no way to achieve the boost levels required to achieve the desired in-cylinder conditions to have GCI combustion at low load. There were extensive simulations performed with both turbochargers and superchargers along with combinations of each. Due to the low exhaust enthalpy, a system comprised of both a supercharger and a turbocharger was chosen. This allows for the difference in exhaust enthalpy to be accounted for in crankshaft work associated with driving the supercharger [12, 15].

Further development by Delphi Technologies showed improved performance from a tailpipe emissions perspective. The Generation 3 engine outfitted with a custom active

after-treatment system (ATS) showed that it was possible to operate a catalyst with the low exhaust temperatures exhibited with low-temperature combustion [16]. The use of exhaust gas rebreathing was a large contributor to being able to meet catalyst light-off temperatures at low loads [16, 17, 18]. Rebreathing is a process in which the exhaust valve is opened in the intake stroke allowing hot exhaust gases to be scavenged into the cylinder. This technique aids in increasing gas temperatures in a situation where the gas temperatures need to be increased but there is no need for increased fuel consumption. The same increase in exhaust temperature could be achieved by increased fueling and retarding combustion. When combustion is retarded, to an increasing extent, more of the fuel energy leaves through the exhaust instead of being changed work by the pistons acting on the crankshaft, via the crank-slider mechanism, causing a decrease in thermal efficiency. Utilizing the waste heat in the exhaust by rebreathing the exhaust gases into the engine during the intake stroke allows the high-efficiency lean-burn tactics to be employed allowing combustion phasing to remain optimal while maintaining proper exhaust gas temperatures for an effective after-treatment operation [19].

2.3 Pathway Forward

The current GCI technology still faces some issues, even with all the upsides. One issue is the highly complicated boosting system required at low loads when operating with conventional gasoline-like fuel; this issue stems from the lack of exhaust enthalpy to drive the turbocharger. The lack of enthalpy means that something else would have to be done to increase the temperature at TDC such as intake air heating. To combat this, some interesting paths are being explored within this programs' development; one is operating the engine in multiple combustion modes throughout the speed load map as well as investigating multiple fuels with increased reactivates. This will allow issues like low exhaust enthalpy to be combated by operating in an SI mode closer to stoichiometric allowing for catalyst light-off as well as cold-start ability to be maintained. At other light to medium loads, there would also possibly be benefits in using other modes such as HCCI and at part loads using PPCI. This would lead to many benefits aside from thermal efficiency, the ability to control downstream exhaust gas temperature to maintain catalyst conversion efficiency would allow for tailpipe emissions to be minimized.

Interesting simulations were carried out by Delphi Technologies following the development of their GCI engine. A diffusion burn combustion strategy was used at high loads which allowed a load of 25 bar BMEP to be reached while maintaining low BSFC numbers of less than 210g/kWh (40% BTE) throughout most of the speed load range [17]. This shows that there is potential for advancement in the technology with the addition of a transient mode-switching capable controller as well as a capable calibration.

The initiative of which this research is a part of is the US Department of Energy Co-Optima program [3]. The goals of the co-optima program are to simultaneously optimize fuels and engines to improve fuel economy and performance. The coordinated approach to developing fuels and engines together allows for another degree of freedom when

developing the combustion system and the fuel. When the combustion system is developed, the fuel is usually a constraint, but with the co-optima program, multiple fuels are being developed and tested. The fuels are being formulated to display the distinct characteristics needed to achieve stable engine operation in these advanced combustion modes. If stable, transient combustion is achieved it may prove to be a way forward in meeting future ultra-low emissions targets.

Co-Optima findings show that a 10% gain in fuel economy can be found in current light-duty (LD), turbocharged SI engines by utilizing current advanced engine technology along with sustainable fuels produced from domestic, renewable, non-petroleum resources. Current advanced LD engine performance is reaching fuel constraints and Co-Optima has found opportunity for a 10% increase in fuel economy with an additional 14% attributed to the utilization of multi-mode engine technologies [4].

Current state of the art LD engines and their BTE's are shown in Table 2.1, showing where the HATCI GCI-01 stands in terms of performance. GCI-01 is at the top in terms of BTE, being essentially a retrofitted production Diesel engine, additions of advanced technologies such as Continuously Variable Valve Duration (CVVD) and specialized fuel system will drive peak BMEP as well as BTE of the second generation of HATCI GCI engines.

Table 2.1. Current state of the art light-duty engines

Engine:	**BMEP (bar)**	**BTE (%)**	**Induction**	**Reference**
Mazda e Skyactiv-X	14.1	40-42%	Supercharged	Estimated
Delphi Gen3x	25.0	43%	Turbocharged	**[17]**
Toyota Dynamic Force	11.3	41%	Naturally Aspirated	**[20]**
HATCI GCI-01	20.0	42%	Turbocharged	

3 Experimental Setup and Procedures

Contained in the following chapter is a detailed description of the experimental setup and procedures used to collect and analyze the data which is presented in Chapter four of this document.

3.1 Experimental Setup

For the studies performed in both GCI mode and lean-burn spark-ignited mode, a modified Hyundai 2.2L Diesel engine was used. The engine was outfitted with a common rail direct injection system with a high-pressure Bosch CP4 pump capable of injection pressures > 1000 bar with gasoline. The injectors were able to operate at a minimum of 270 bar injection pressure, Bosch 2.2 The cylinder head was modified to include spark plugs that were inserted between the intake valves. There was an adapter machined to allow the use of port fuel injection as well which was placed between the intake manifold and the cylinder head. Cylinder head design modifications were performed by HATCI.

Table 3.1. Engine Characteristics table

Bore (mm)	84.5
Stroke (mm)	96
Connecting Rod Length (mm)	145
Compression ratio (-)	16.0
Displacement (l)	2.2

3.1.1 Engine Controller and Combustion Feedback system

To control the engine a PI Innovo M670 was used in conjunction with an Engine Controller Highspeed Oversight unit (ECHO). The M670 was programmed by WM International Engineering[1], and support was continued throughout the project. In conjunction with this program, the ECHO was developed by WMI to provide real-time combustion feedback, next cycle control modifications to the start of injection (SOI) and injection quantity were able to be done on a cylinder-to-cylinder basis. These controls allowed the controller to maintain a constant CA50 across all cylinders as well as balance IMEP if necessary.

3.2 Test Bed Layout

For our testbed at MTU's APS LABS, the Light Duty Engine test cell was used. This cell is equipped with an 8000 rpm, 460 HP AC dynamometer, allowing for motoring of the engine as well as constant speed control. For the testing performed, speed control was used.

[1] Engine Controls specialists [25]

The test cell is isolated from the control desk with closed-circuit cameras allowing for observation of engine operation. The engines are fitted on rolling carts with bulkhead connections for electrical components as well as plumbing of liquids, Figure 3.1. This allows engines to be moved in and out of the test cell when not in operation and work to be performed in build bays. With this, time can be used more efficiently because the test cell is not occupied by an idle engine as well as any work being done to the project-specific cart can be carried out in a well-lit, and tool-equipped area.

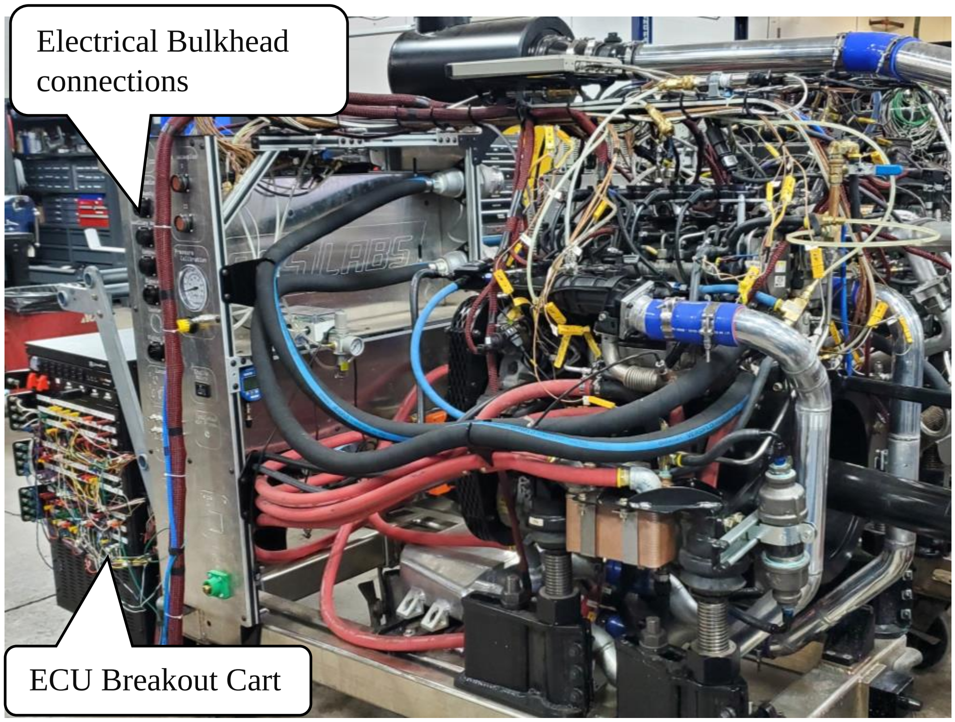

Figure 3.1. Engine Cart, showing the extensive amount of plumbing, wiring, and fixturing required to operate and monitor the systems of this engine

3.3 Data Acquisition Systems

The testbed employed four different systems to acquire data on the operation of the engine as listed in Table 3.2 with their corresponding functions.

Table 3.2. Data acquisition systems and purpose

Data Acquisition System	Data Type	Trigger Type, Sample Rate
NI PXI Chassis, NI Veristand	Test cell monitors, thermocouples, pressure transducers, temperature control	Time-based, 10 Hz
AND CAS	Cylinder pressure, MAP, exhaust pressure, injection, and coil trigger traces	0.1° crank angle via an optical encoder and AND SODEP interpolation
PI Snoop	ECU parameters	Time-based, 10 Hz
Horiba	5 gas emissions data	Time-based, 1 Hz

3.4 Instrumentation

The engine, as well as the test cell, were instrumented for the measurement of temperatures and pressures throughout the system to monitor the engine operation. These signals were monitored in real-time on the control screen by an NI PXI chassis, Veristand developed user interface which allows for user control of the system by switching digital signals on and off and varying analog outputs through the use of a proportional integral and derivative (PID) control loop with feedback from one of the temperatures or pressure in the system.

3.4.1 Combustion Analysis

Real-time combustion analysis was performed using AND Redline CASII, Appendix 7A.3. Table 3.3 lists the signals which were being inputted to the CAS chassis as well as the sensor model and the sample rate of the signal.

Table 3.3. CAS Input Instruments and model description

Signal	Sensor Model	Sample Rate	Signal	Accuracy
Cylinder 1-4 Pressure	AVL GP15DK	0.1°CA	Analog	≤ ± 0.3%
MAP	OMEGA: MMA100V10P5D1T3A3	0.1°CA	Analog	0.08%
Exhaust Pressure	OMEGA: MMA100V10P5D1T4A3	0.1°CA	Analog	0.08%
DI Injection Trace	Fluke: 80I-110S	0.1°CA	Analog	-
PFI Injection Trace	Fluke: 80I-110S	0.1°CA	Analog	-
Ignition coil trigger signal	Signal tap	0.1°CA	Digital	-
Fuel Mass Flowrate	Micromotion: CFMS010M323N2BAECZZ	0.1°CA	Analog	0.1%
Crank Angle	BEI:	1.0°CA	Digital	-

3.4.2 Test Cell Instrumentation

Temperatures were monitored via K-type thermocouples instrumented throughout the engine system. Air mass flow rate was measured with a laminar flow element (LFE) and compensated for humidity changes in the ambient air. Instrument descriptions and models are listed in Table 3.4.

Table 3.4. Test cell instrumentation

Signal	Instrument	Model
Air Mass flowrate	Laminar Flow Element	Z50MC2-4
Temperature	Thermocouple	K-type
Fuel Mass Flowrate	MicroMotion Coriolis Meter	CFMS010M323N2BAECZZ

3.4.3 Intake Temperature Management

Gasoline Compression Ignition is highly dependent on the temperature at IVC. To control this, the temperature of the air charge needs to be closely controlled. To regulate this temperature, a system consisting of two liquid to air heat exchangers in parallel was used as shown in Figure 3.2. One of them contains a metered flow of building water through the heat exchanger for cooling and the other heat exchanger was filled with hot coolant at a controlled temperature from the system described in the charge air heater portion of Appendix 7G.2. The engine controller utilized the temperature sensor portion of the MAP sensor as feedback to meter the airflow through the two heat exchangers.

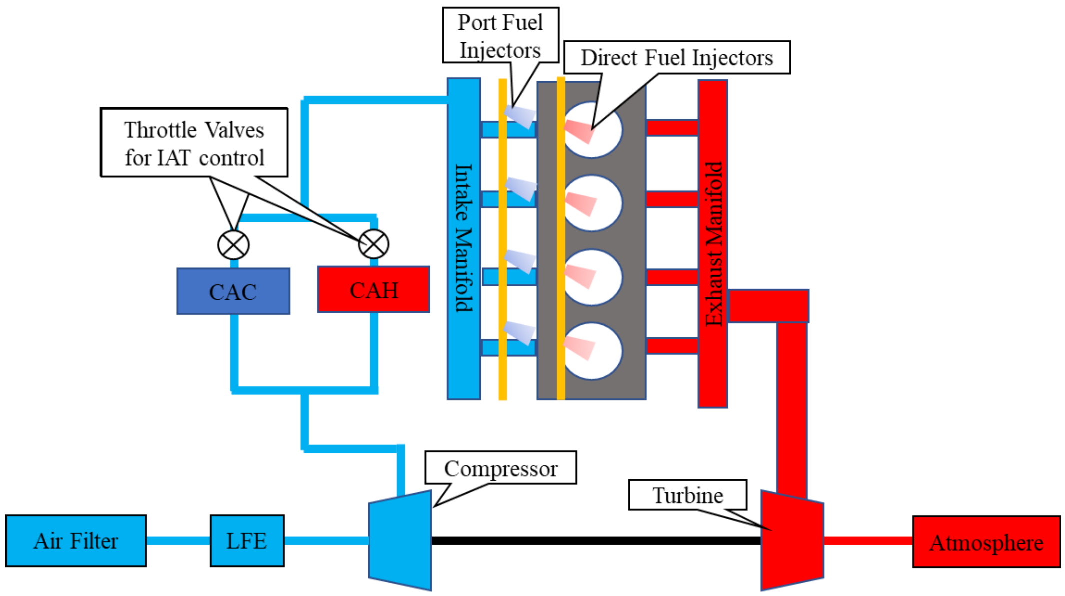

Figure 3.2. Intake Temperature Management System

3.4.4 Emissions Measurement

Emissions were measured with a Horiba 5 gas analyzer described in Appendix 7B.1. Emissions samples were drawn through a heated filter and a heated sample line from the turbine outlet of the engine. To sample the exhaust, steady-state operation was achieved. Following this, there was a sample drawn from the exhaust. Before recording the data, it was ensured that each of the exhaust constituents being analyzed was at steady state ensuring that the data accurately reflected the current operating condition.

3.5 Test Conditions

Part of the experiments were conducted to see the low load operation ability of the engine, to achieve this, the tests at 800, 1200, and 1500 rpm were conducted by starting at a medium load and decreasing load incrementally. Defining the low load limit was done by finding the minimum load which the COV of IMEPg was less than 3% for loads greater than 2 bar IMEPg, for loads below 2 bar IMEPg, the standard deviation of IMEPg needed to be less than 15 kPa to be deemed a stable operating point. Other experiments were also conducted in spark-ignited (SI) mode to find the upper load limit of SI. To do this with a high compression ratio and high reactivity fuels, a lean burn technique was used where the AFR was kept at the lean limit. The metric of coefficient of variation COV was used to determine the lean limit with a threshold of 3%. Upper load limit of SI was found to exceed the range needed for investigation. 4.6 bar BMEP was easily achieved with SI. This was chosen as the highest load for SI because GCI operation was stable well below this load and was more efficient 45% for GCI compared to 38% for SI with the same RON91 E10 fuel and the same load of 80 Nm and IAT of 55°C. Mode switching could happen between 2.0 and 2.3 bar BMEP.

Following the low load experiments, higher load experiments were conducted to find the peak efficiency of the engine with the selected fuel. They were conducted based on results obtained from [21]. These results were obtained on a sister engine at Hyundai America Technical Center Inc (HATCI). Results from the baseline GCI tests were compared to the results with iso-butanol 25% and 75% RON 60, (IB25 gas).

3.5.1 Fuel Specifications

Neat fuels were tested as received from P66. RON91 E10 was purchased already mixed from the pump. Other alcohol blends were splash blended by weighing the amount of each fuel added to the tank and calculating the volume of the fuel based on the densities in Table 3.5 to reach the desired mixture ratio by volume. Once the selection of the IB25 gas was done, additional RON 60 was ordered from Halterman to continue testing. Quantities of the P66 fuels were low so they were consumed by the initial low load testing leaving none for medium-high load mapping operations. Each fuel was dosed with 200 PPM of fuel lubricant from BG Products, XX-6RX for lubrication of the diesel fuel system.

Research from Co-Optima found blend stocks that would reduce the lifecycle carbon emissions when combining them with base gasolines up to 30%, [4]. From these blend stocks, ethanol and iso-butanol were chosen and blended with the base RON 60 to achieve a RON of 94. After testing was completed with the IB51 and E36 gas, it was decided to try a lower iso-butanol concentration, making the IB25 gas.

Table 3.5. The fuel specification table for the 8 different fuels tested, 2 batches of the IB25 gas from different suppliers

Fuel	**RON**	**Cetane (#)**	**Alcohol**	**Alcohol (%Vol.)**	**Supplier**	**LHV (Mj/kg)**	**Density (kg/m^3) @ 25°C**
RON 60	58.1	29.8	-	0	P66	44.4	694.9
RON 70	69.3	24.9	-	0	P66	44.2	706.7
RON 80	78.8	22.1	-	0	P66	44.5	680.0
RON 91	89.4	18.8	-	0	P66	43.9	712.9
RON 91 E10	91.0	-	Ethanol	10	Shell	42.4	716.4
IB51 gas	94.0	20.6	Iso-Butanol	51.2	P66	37.7	747.7
Eth 36 gas	93.4	20.5	Ethanol	36.6	P66	37.9	728.2
IB25 gas	77.8	-	Iso-Butanol	25	P66	40.9	720.7
IB25 gas	77.8	-	Iso-Butanol	25	Halterman	41.45	736.3

3.5.2 Compression Ignition

Experiments were conducted at multiple conditions to see the effect of fuel reactivity on combustion in GCI mode. For all the tests in GCI mode where operation was possible,

the IAT was held at a constant 55°C. Operation was tested at five engine speeds, 800, 1200, 1500, 2000, and 2200 rpm. At each one of these speeds, there were load sweeps done.

GCI was studied along with different fuels and their abilities to aid in GCI operation over a wider speed-load regime. The focus of this study was the low load range and the ability of the fuel's reactivity to lower the low load operation range.

3.5.2.1 Fuel Reactivity

For the studies regarding the reactivity of the fuel, there was a common technique employed for each of the fuels. Due to the small quantity of fuel, a coordinated approach to the experiments was needed to minimize test time allowing for the most points to be run, filling in the speed load map.

A common point of 1500 rpm, 80Nm, 4.6 bar BMEP with an IAT of 55°C and a CA50 of 10° after top dead center, (aTDC) was chosen. This allowed for a comparison of metrics across each fuel showing the effects on combustion at a common, stable point. At 80 Nm a sweep of combustion phasing was done as well from a CA50 of 12°aTDC to 7°aTDC to demonstrate the effect of combustion phasing on performance.

The effect of the reactivity of the fuel on the low load operation range was found by finding the minimum load at which the engine could stably operate. This was done at three speeds, 800, 1200, and 1500 rpm. The load was swept down until combustion became unstable or a low load limit was reached, 15 Nm or 0.9 bar BMEP.

3.5.2.2 Medium-High load efficiency

Testing points where the highest efficiency was expected to occur was done with the fuels selected based upon fuel reactivity testing for the low load performance of GCI. These tests were conducted at 2000 and 2200 rpm based upon the results in [21] where the entire speed load map was tested allowing our test matrix to only encompass the targeted region. This was beneficial due to the relatively small quantity of P66 fuel for the testing.

The testing occurred at 2000 and 2200 rpm with four load points of 10, 12, 14, and 15 bar BMEP which encompassed the region where the peak engine efficiency is expected.

3.5.3 Spark Ignited

Spark ignited combustion was planned to be used at low loads where the operation of the engine in compression ignition is not possible. When operating in a spark-ignited mode, the counteracting effects of the fuels with properties favorable to compression ignition on spark-ignited operation are demonstrated.

3.5.3.1 Fuel Reactivity

When operating in spark-ignited mode, the lean operating limit was found. To allow for mode switching, there needed to be overlap in the operating range of the two modes. To find out the size of this overlap region in terms of load and where it existed, the lean operating limit was found for each fuel at 1500 rpm. The methodology for these experiments was to start near stoichiometric, lambda ~1.1, and record data at increments of 0.05 lambda. Knowing that each fuel operated well below the 4.6 bar BMEP point, it was chosen as the high load needed to be reached to allow for a large enough overlap region to allow for mode switching and hysteresis in the switch.

Fuel injection for the SI mode testing was all done for the through the PFI injectors for the successful points. To choose the injection pressure it was swept from 3.3 bar up to 5 bar at a constant load, speed, IAT, and CA50. Through these experiments, the lean limit was not able to be found with the higher injection pressure near 5 bar. Due to the nature of the intake ports, being a diesel cylinder head with ports designed to induce swirl, higher injection pressures led to increased wall wetting. Wall wetting was believed to cause significantly increased combustion knock due to the fuel not vaporizing and liquid fuel entering the cylinder resulting in locally rich zones prone to knock.

4 GCI Operation Results

4.1 Fuel Reactivity Effects on Combustion

Three test programs with the fuels from Table 3.5 were conducted. The first was conducted to determine the fuel's impact and effects on low load operation and their ability to extend GCI operation loads below 3 bar BMEP. This was conducted at three engine speeds including 800 rpm representing idle and 1200 and 1500 rpm. The second test program was conducted at medium loads from 3 to 7 bar BMEP at 1200 and 1500 rpm. The third test program was conducted at 2000 rpm from 7 to 10 bar BMEP. These explored the upper region of medium loads at a slightly higher speed. The third and final test program explored loads from 10-15 bar BMEP at speeds of 2000 and 2200 rpm. Discussion of the results of these three test programs is in the next three subsections.

The apparent heat release (AHR) traces for each fuel show the results for cylinder 2 of the engine in this chapter. Cylinder 2 was chosen to be analyzed because it was found to be representative of the engine average of all four cylinders. The cylinders all perform nearly the same with the use of the CA50 control. The trigger signal for the injectors is also plotted to show where the pilot and main injections are taking place relative to the AHR. For each test point, the pilot SOI and pilot quantity were held constant unless the pressure-rise rate (PRR). Under conditions where the PRR was above the threshold of 10 bar/°CA, the SOI of the pilot injection was retarded. The impact of the pilot SOI was greater than that of pilot quantity when regulating MPRR.

4.1.1 Low Load

Low load testing was conducted at 800, 1200, and 1500 RPM with GCI operation. The primary constraint for low load GCI operation is combustion stability and for this, the standard deviation of IMEPg was considered with a threshold of 15 kPa for loads below 1 bar BMEP. For loads greater than 1 bar BMEP COV of $IMEP_g$ was used with a threshold of 3% as well as maximum pressure rise rate, (MPRR) with a limit of 10 bar/°CA.

The load ranges tested for each fuel are shown in Figure 4.1. Stable low load operation at 800 rpm for the RON 60, 70, and 80 fuels was achieved; whereas the other fuels with lower reactivities were not tested at the idle condition because they would not operate at such a low load without elevated MAP or IAT. Horizontal black bars in Figure 4.1 highlight the load points which will be examined in this subsection. At 800 rpm, the lowest load operated at is not the load that will be looked at because the RON 80 was not able to operate at that point, 10 Nm or 0.6 bar BMEP. To compare all three fuels at tested at this speed, the second lowest load is examined, 15 Nm or 0.86 bar BMEP.

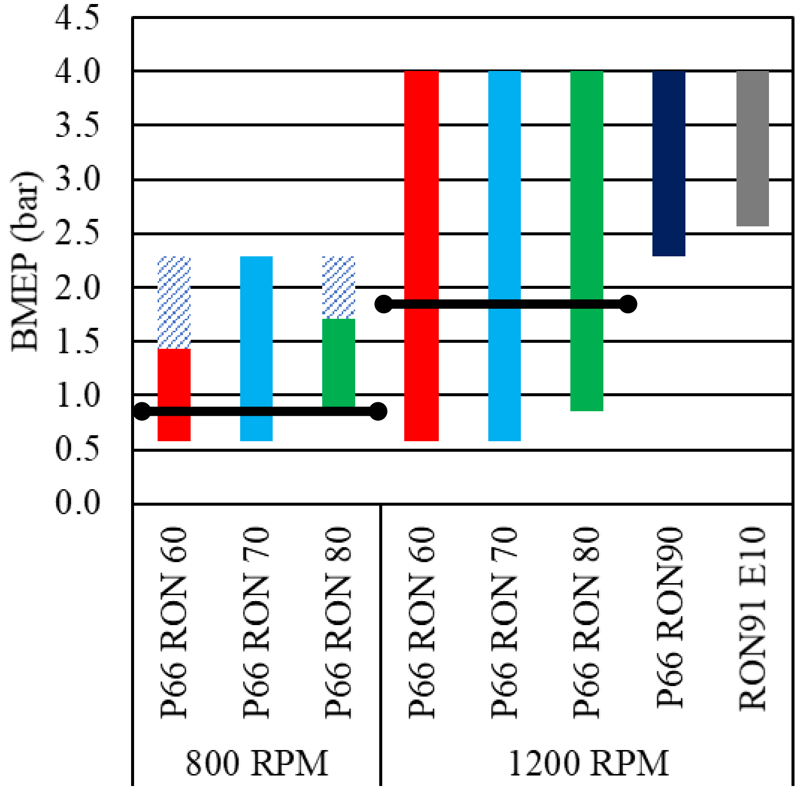

Figure 4.1. Low load operation test points for each fuel. Solid horizontal black lines signify the loads which are looked at in-depth in the following sections. (Solid vertical bars signify tests were carried out at these regions, hashed bars mean operation was assumed but not tested for that load)

With the use of higher reactivity fuels, stable low load operation was able to be achieved at 800 rpm and 15 Nm. From Figure 4.2 the advancement of the first portions of combustion can be observed. As the reactivity of the fuel increases this portion advances because the ignition delay becomes shorter meaning that if fuel is injected at the same time, combustion will begin earlier.

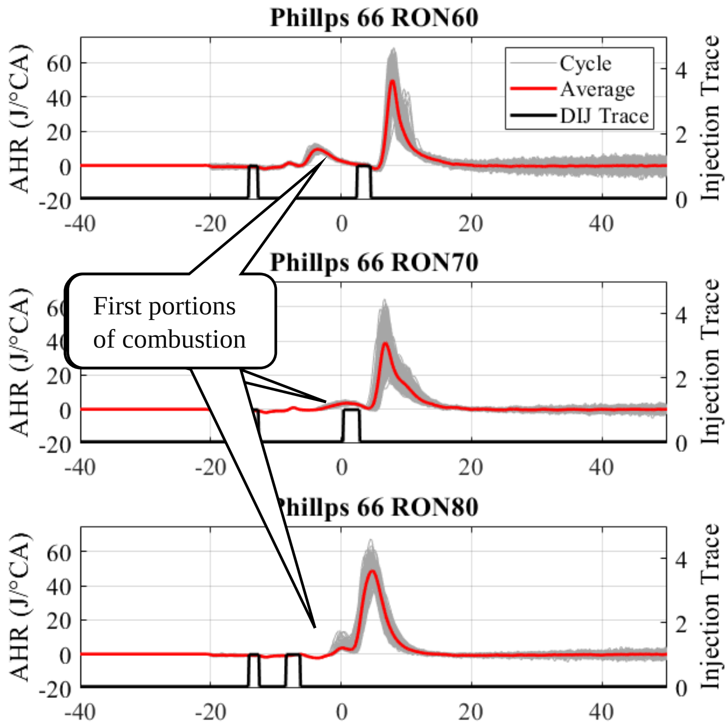

Figure 4.2. GCI operation at the idle condition (800 RPM 15N-m) with the high reactivity fuels

Table 4.1 contains the main controlled parameters for engine operation for this 800 rpm, 0.85 bar BMEP points. IAT was held constant as well as MAP, injection pressure, and pilot SOI. Main injection quantity was used to control load and main SOI was used to maintain a constant CA50 between fuels.

When operating at an idle condition with the pilot amount and SOI held constant, the effect of reactivity of the fuel is evident in the trend of main SOI to maintain constant CA50, Table 4.1. The fuel with the lowest RON, RON 60 has the latest main SOI with nearly constant CA50, Table 4.2. This trend demonstrates the effect of fuel RON on the reactivity of the fuel which is affecting the ignition delay, the time it takes the fuel to combustion after injection.

Table 4.1. Controlled parameters for 800 RPM, 0.85 bar BMEP tests

Parameter	RON80	RON70	RON60
IAT (°C)	55	55	55
MAP (kPa)	104	104	104
Injection Pressure (bar)	260	260	260
Pilot SOI (°aTDC)	-15	-15	-15
Pilot/Main (fraction)	0.38	0.5	0.38
Main SOI (°aTDC)*	-9.1	0.3	1.2
* Main SOI was varied to phase combustion ** Main Quantity was varied to control load			

At idle, keeping the standard deviation of $IMEP_g$ below 15 kPa was able to be achieved. Table 4.2 shows the STD of $IMEP_g$ for the different fuels which were capable of sustaining combustion at idle. RON 80 required an advanced CA50 to sustain operation, even with the advanced CA50 the COV was still greater than 5%. Although this was the case, the gross indicated thermal efficiency, (gross ITE), was still the highest of the fuels.

Table 4.2. Combustion characteristics from 800 RPM 0.85 bar BMEP idle condition

Fuel	IMEPg (bar)	Gross ITE (%)	CA50 (°aTDC)	STD_{IMEP} (kPa)	BD 10-90% (°CA)	MPPR (bar/°CA)
RON60	2.2	30.6	8.3	8	13.6	2.8
RON70	1.9	35.4	8.0	10	7.4	2.4
RON80	2.2	37.3	5.2	8	5.4	3.3

The extended burn duration of the higher reactivity fuels appears to cause a reduction in gross indicated thermal efficiency (ITE), Table 4.4. This is not necessarily the trend one would expect when increasing the reactivity of the fuel. Due to the fueling strategy used, constant pilot quantity, the combustion happened in two stages with the higher reactivity fuels. This was caused by the shorter ignition delay of the fuel meaning that the pilot had enough time to ignite and burn before the main injection occurred Figure 4.3.

Operation at low load causes large differences in the AHR of the fuel depending on the reactivity and its effect on ignition delay as well as mixing. Figure 4.3 shows the differences in AHR as reactivity increases and time allowed for mixing changes, there are two distinct peaks in heat release. This is a portion where changing the pilot timing would have possibly allowed for an efficiency increase. This was not done, for the fuel studies we tried to eliminate all the changes in independent variables possible. This allowed for the effect of the fuels to be isolated and eliminated the possibility that a change in an independent parameter changed the effect of the fuel on combustion.

Table 4.3 displays the controller parameters for tests performed at 1200 rpm and 1.7 bar BMEP. The IAT, MAP, injection pressure, and pilot SOI were held constant. The change

in pilot/main fraction for RON60 was done to maintain load by adjusting the main quantity. The increase in the quantity of fuel to maintain load can be attributed to the early combustion portion which occurred before TDC, Figure 4.3.

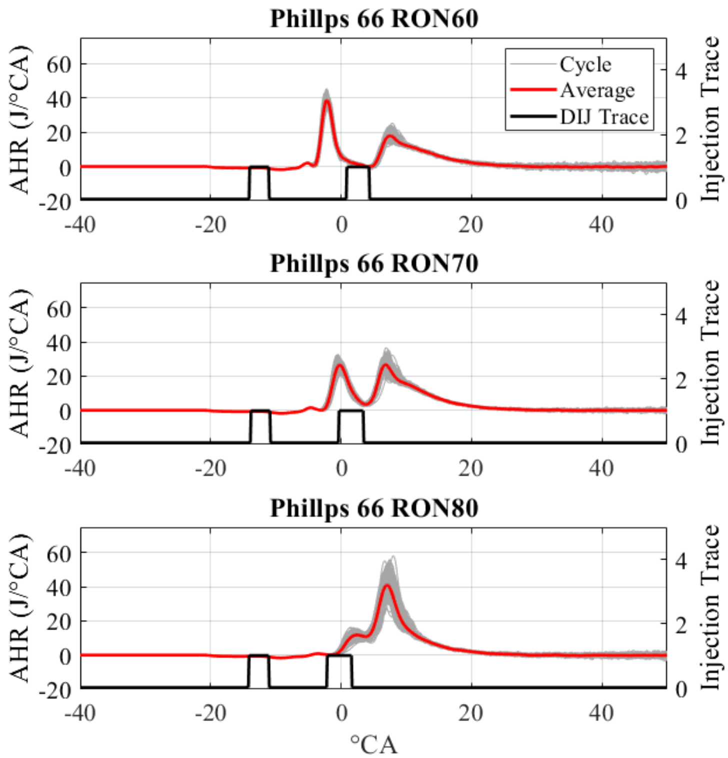

Figure 4.3. 1200 rpm 1.7 bar BMEP low load operation AHR characteristics

Table 4.3. Controlled Parameters for 1200 rpm 1.7 bar BMEP tests

Parameter	**RON80**	**RON70**	**RON60**
IAT (°C)	55	55	55
MAP (kPa)	120	120	120
Injection Pressure (bar)	260	260	260
Pilot SOI (°aTDC)	-15	-15	-15
Pilot/Main (fraction)	0.43	0.43	0.30
Main SOI (°aTDC)	-2.4	-1.1	1.6
* Main SOI was varied to phase combustion ** Main Quantity was varied to control load			

When operating with a lower reactivity fuel the ignition delay is increased. This also leads to a shorter burn duration which is contributed to by the increased in-cylinder mixing. Combustion characteristics listed in Table 4.4 for the 1200 rpm 1.7 bar BMEP points show this effect is that the gross ITE is increased by 2.8%. This could be due to the

decreased in-cylinder surface area because a larger portion of the combustion is happening when the piston is higher in the cylinder. Eliminating some surface area for heat transfer to occur, meaning more of the fuel work is converted to usable work.

Table 4.4. Combustion characteristics for the three high reactivity fuels which allowed for GCI operation at 1.7 bar BMEP and 1200 RPM

Fuel	**IMEPg (bar)**	**Gross ITE (%)**	**CA50 (°aTDC)**	**COV (%)**	**BD 10-90% (°CA)**	**MPPR (bar/°CA)**
RON60	3.4	41.2	8.1	2.4	18.8	4.8
RON70	3.4	43.6	7.6	2.4	14.8	2.5
RON80	3.5	44.0	7.6	2.5	9.6	2.3

To compare each of the fuels at a low load, 3 bar BMEP was chosen to analyze because each of the Phillips 66 fuels as well as the baseline pump gasoline operated with good stability defined by the COV of $IMEP_g$ being below 3%, Table 4.5. The AHR curves shown in Figure 4.4 and Figure 4.5, demonstrate the effect of the different fuels on ignition delay and the rate of heat release. As increasing RON, the peak heat release rate increases as well as the early portion of heat release caused by the pilot injection igniting before the main moves toward the main heat release. When conducting these experiments there were parameters controlled, listed along with their corresponding values for each fuel, in Table 4.5. IAT, MAP, and injection pressure were held constant for each fuel. Pilot SOI was retarded for the RON 91 E10 fuel to decrease combustion noise for that fuel. The pilot/main fraction was held near 0.20 for each fuel and the main SOI was used to maintain a constant CA50 across all fuels.

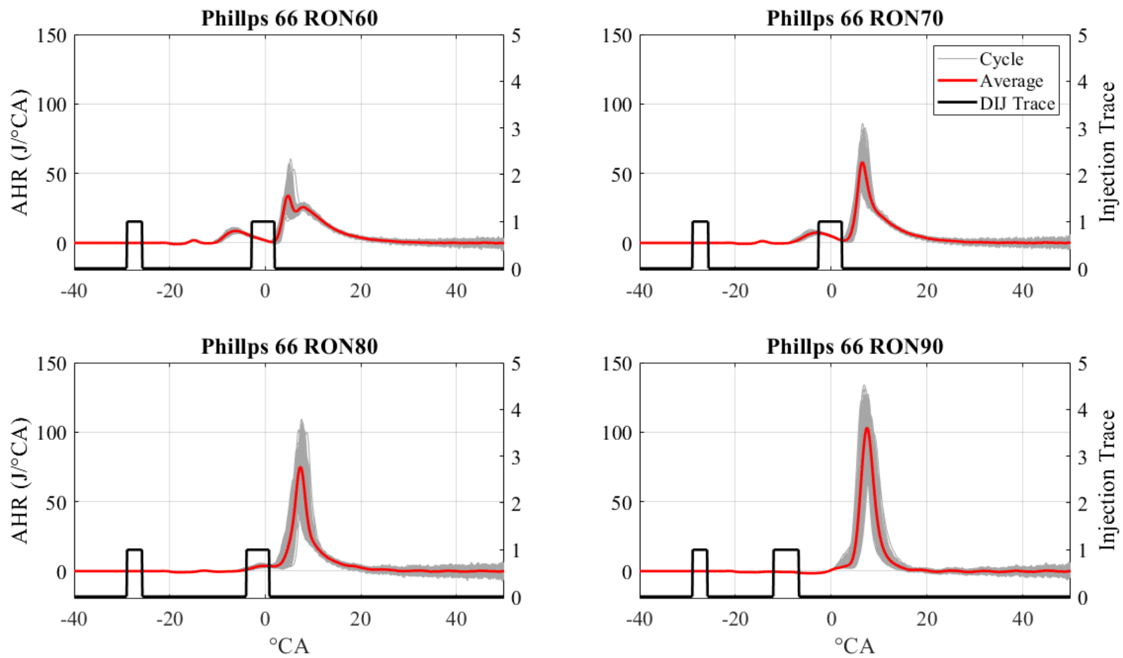

Figure 4.4. AHR comparison for the Phillips 66 fuels tested at 1200 RPM, 3 bar BMEP

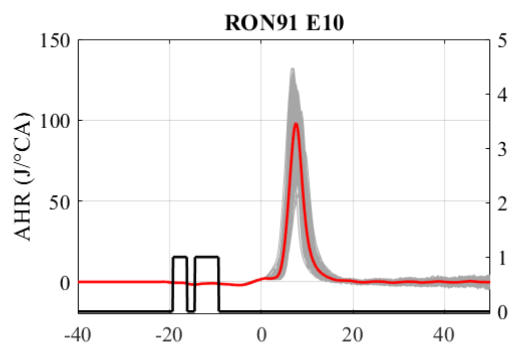

Figure 4.5. RON91 E10 fuel at 1200 rpm, 3 bar BMEP

Table 4.5. Controlled Parameters for 1200 RPM 3 bar BMEP tests

Parameter	**RON91 E10**	**RON91**	**RON80**	**RON70**	**RON60**
IAT (°C)	55	55	55	55	55
MAP (kPa)	125	125	125	125	125
Injection Pressure (bar)	260	260	260	260	260
Pilot SOI (°aTDC)	-20	-30	-30	-30	-30
Pilot/Main (fraction)	0.21	0.18	0.21	0.21	0.21
Main SOI (°aTDC)	-13.7	-11.9	-4.3	-3.3	-3.4
* Main SOI was varied to phase combustion ** Main Quantity was varied to control load					

At 3 bar BMEP and 1200 rpm, five fuels were tested, the effect of the reactivity on the combustion characteristics examined in Table 4.6 shows that each fuel performs well at this load, combustion is stable with a COV of $IMEP_g$ < 3%, and the MPRR is below the 10 bar/°CA limit. Significant differences are shown in the MPRR, where the lower reactivity fuels with short burn durations have the highest pressure rise rates. The effect of fuel reactivity on gross ITE is shown as well. It can be noted that the highest reactivity fuel is 1.8% more efficient than the lowest reactivity fuel. Peak gross ITE occurs at a RON of 80 at 46%. This can be attributed to the heat release happening as one event, without distinct early portions and late portions, as well as the peak rate of heat release not being as high as the lowest reactivity fuels. Lower peak heat release rates point to decreased in-cylinder temperatures which decrease heat transfer.

Table 4.6. Combustion characteristics for 1200 RPM 3 bar BMEP

Fuel	**$IMEP_g$ (bar)**	**Gross ITE (%)**	**CA50 (°aTDC)**	**COV (%)**	**BD 10-90% (°CA)**	**MPRR (bar/°CA)**
RON60	4.6	44.7	7.5	1.7	20.3	2.3
RON70	4.7	45.4	7.5	1.9	14.5	3.4
RON80	4.6	46.0	7.7	1.8	8.4	4.7
RON91	4.7	41.0	7.7	2.0	4.6	6.7
RON91 E10	4.7	42.9	7.8	1.7	4.6	6.3

4.1.2 Medium Load

Medium load testing was conducted at 1200, and 1500 RPM with GCI operation. The primary constraints for medium load GCI operation are combustion stability and MPRR and for this, the COV of IMEPg was considered with a threshold of 3% and the MPRR < 10 bar/°CA.

Each fuel was tested at the medium load points and a load sweep was done from 125 Nm, 7.1 bar BMEP, down, the points which will be examined are around 80 Nm, 4.6 bar BMEP for most of the discussion. The RON 60 from Phillips 66 was not tested at the 100 Nm and 125 Nm points because of the low supply of that blend due to the need to splash blend the biofuel blends. Another condition to be noted is that for the 36.6% Ethanol and the 51.2% Iso-Butanol the IAT had to be raised to 75°C instead of 55°C which is what was used for the rest of the fuels.

Figure 4.6 displays the ranges of medium loads and speeds tested for each fuel. Not all fuels were tested at the lower 1200 RPM speed because of the quantity on hand. The dataset which was gathered at 1500 RPM will be focused on as it is has the most comprehensive dataset for this load range.

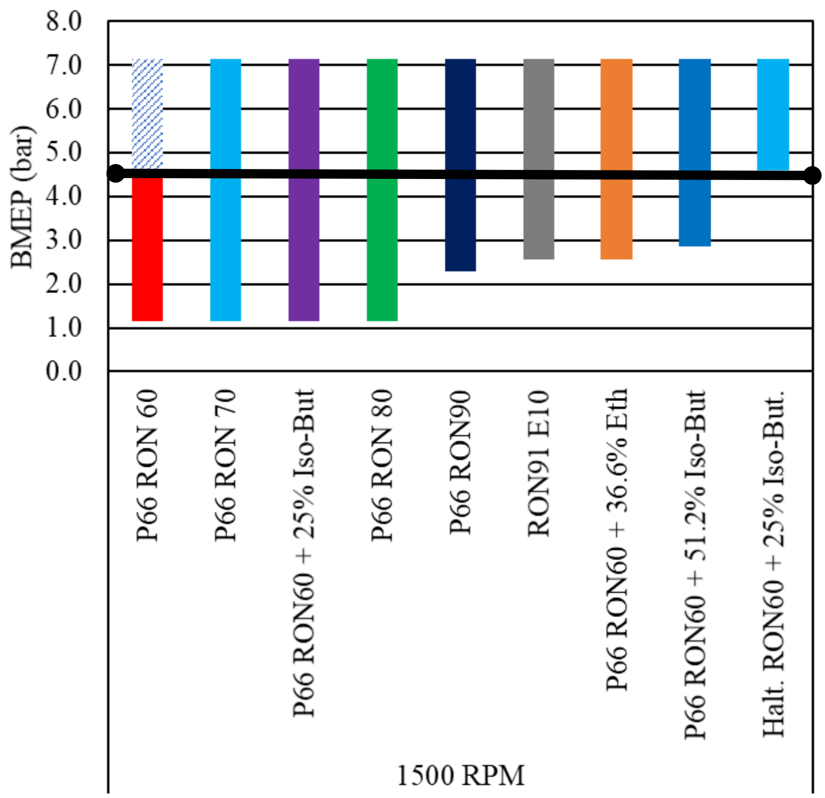

Figure 4.6. Medium load GCI test points. Solid horizontal black lines signify the loads which are looked at in-depth in the following section. (Solid bars signify tests were carried out at these regions, hashed means operation was assumed but not tested for this load)

With the higher RON fuels, the pilot burns simultaneously with the main injection but with the lower RON fuels, the start of the pilot burn is before the main injection has even started. The apparent heat release of the Phillips 66 RON70 and the RON91 E10 baseline are compared in the top row of Figure 4.7. From the overlay of injection trace, it can be

observed that the two fuels have different ignition delays. The differences in apparent heat release can be contributed to the differences in ignition delay, causing variance in the amount of in-cylinder mixing that takes place before combustion begins. The Phillips 66 RON 91 demonstrated similar performance to that of the RON91 E10 baseline at the medium loads, Table 4.7

Figure 4.7 also shows the apparent heat release for the RON80 and RON60 from Phillips 66 in the lower row. A large difference in heat release characteristics can be observed. Ignition delay is decreased drastically with the lower RON. This shorter ignition delay allows for the RON80 and RON60 to operate at lower loads extending the GCI operation regime to lower loads.

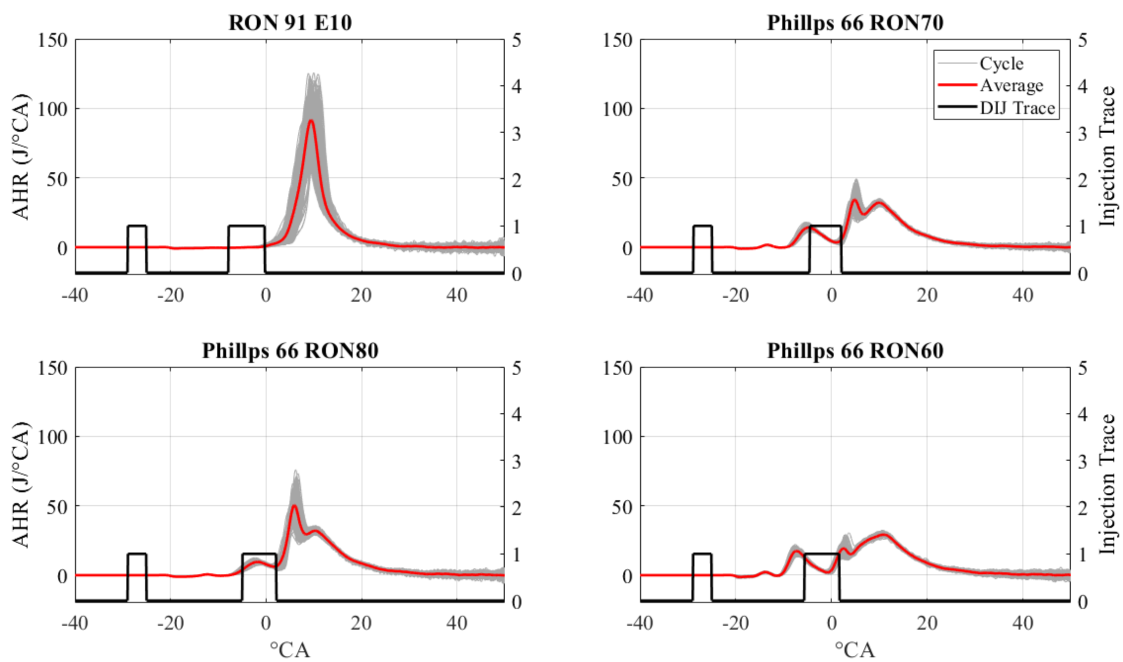

Figure 4.7. AHR Comparison between RON91 E10 Baseline, Phillips 66 RON80, RON70, ad RON60 at 4.6 bar BMEP and 1500 RPM

Table 4.7. Control Parameters for 1500 rpm, 4.6 bar BMEP operation with the following five fuels

Parameter	**RON91 E10**	**RON91**	**RON80**	**RON70**	**RON60**
IAT (°C)	55	55	55	55	55
MAP (kPa)	150	150	150	150	150
Injection Pressure (bar)	300	300	300	300	300
Pilot SOI (°aTDC)	-30	-30	-30	-30	-30
Pilot/Main (fraction)	0.19	0.20	0.21	0.23	0.19
Main SOI (°aTDC)	-8.6	-7.1	-5.5	-5.2	-6.3
* Main SOI was varied to phase combustion ** Main Quantity was varied to control load					

The differences in the combustion characteristics of the fuels in Table 4.8 such as burn duration (10-90%) show that the difference in reactivity influences the combustion significantly. The gross indicated efficiency displays a benefit as the reactivity increases by 2.2% as well. The trend of burn duration increasing as reactivity increases show a strong relationship, increasing from 8.2°CA to 24.1°CA.

Table 4.8. Combustion characteristics for the four fuels at the 1500 RPM 4.6 bar BMEP point

Fuel	**$IMEP_g$ (bar)**	**Gross ITE (%)**	**CA50 (°aTDC)**	**COV (%)**	**BD 10-90% (°CA)**	**MPRR (bar/°CA)**
RON91 E10	6.8	45.4	9.7	1.2	8.2	5.1
RON80	6.8	47.1	9.1	1.3	15.8	2.7
RON70	6.7	47.6	9.0	1.3	20.9	2.8
RON60	6.8	48.1	9.2	1.2	24.1	3.2

A blend of 25% iso-butanol and 75% Phillips 66 RON 60 was also tested which had a RON value of 77.8. The heat release characteristics are similar to that of the RON 80 from Phillips 66 with similar ignition delay and peak heat release rate, Figure 4.8. This blend also allowed for low load extension when compared to the baseline. Similarities between the heat release of the two fuels are evident in Figure 4.8 where the injection traces also display similar main injection SOIs in Table 4.9 of -5.5 and -6.5°aTDC to achieve similar CA50s.

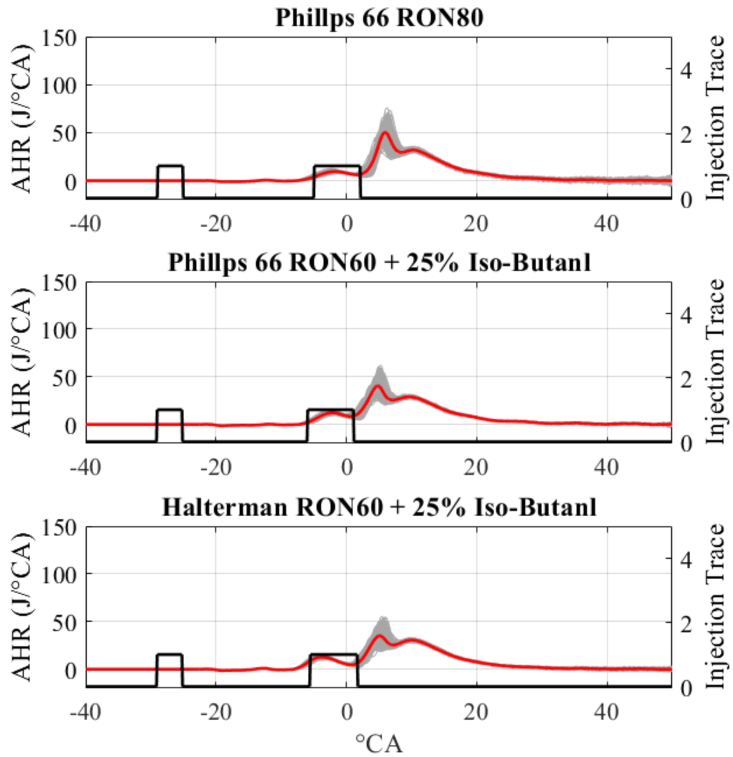

Figure 4.8. Comparison of the AHR characteristics of two fuels with approximately equivalent RONs of 80 at 1500 rpm and 4.6 bar BMEP

When testing the two Iso-Butanol blended fuels, the control parameters all demonstrated similar behaviors at achieve the same operation condition, Table 4.9. There is a discrepancy in the main injection SOI 1°CA, the difference is also apparent in the combustion characteristics of the tests, Table 4.10. The CA50s are +- 1°CA different as well demonstrating the fuels perform similarly.

Table 4.9. Control parameters for two RON80 fuels at 1500 rpm and 4.6 bar BMEP

Parameter	**RON80**	**IB25 Gas P66**	**IB25 Gas Halt.**
IAT (°C)	55	55	55
MAP (kPa)	150	150	150
Injection Pressure (bar)	300	300	300
Pilot SOI (°aTDC)	-30	-30	-30
Pilot/Main (fraction)	0.21	0.21	0.18
Main SOI (°aTDC)	-5.0	-6.0	-5.6
* Main SOI was varied to phase combustion ** Main Quantity was varied to control load			

Combustion of the two fuels with RON values near 80 demonstrated similar combustion characteristics and performance results at the common 80 4.6 bar BMEP 1500 rpm test point. BD10-90% ranges from 18° to 20.7°CA and Gross ITE ranges from 45.5% to 46.0% in Table 4.10.

Table 4.10. Combustion characteristics of the three RON80 fuels tested at a medium load

Fuel	**$IMEP_g$ (bar)**	**Gross ITE (%)**	**CA50 (°aTDC)**	**COV (%)**	**BD 10-90% (°CA)**	**MPRR (bar/°CA)**
RON80	6.4	46.0	9.4	1.1	18.0	3.4
IB25 Gas P66	6.1	45.9	8.6	1.1	19.3	3.0
IB25 gas Halt.	6.2	45.5	9.2	1.1	20.7	2.5

A blend with the Phillips 66 RON60 and 51.2% iso-butanol (IB51) by volume was tested as well as a blend with Phillips 66 RON60 and 36.6% ethanol (ETH36). These blends proved to be difficult to operate with, at the base point of 80Nm with a CA50 of 10°aTDC with an IAT of 55°C operation was not possible. To overcome this, the IAT was increased incrementally until the stable operation was achieved at an IAT of 75°C for these fuels. Note, the results shown for IB51 gas and EH36 gas at 1500 rpm were performed at this elevated IAT of 75°C. With the elevated IATs for the IB51 and ETH36, the results were similar to those of the neat RON 91 from Phillips 66 and the RON 91 E10 baseline fuel.

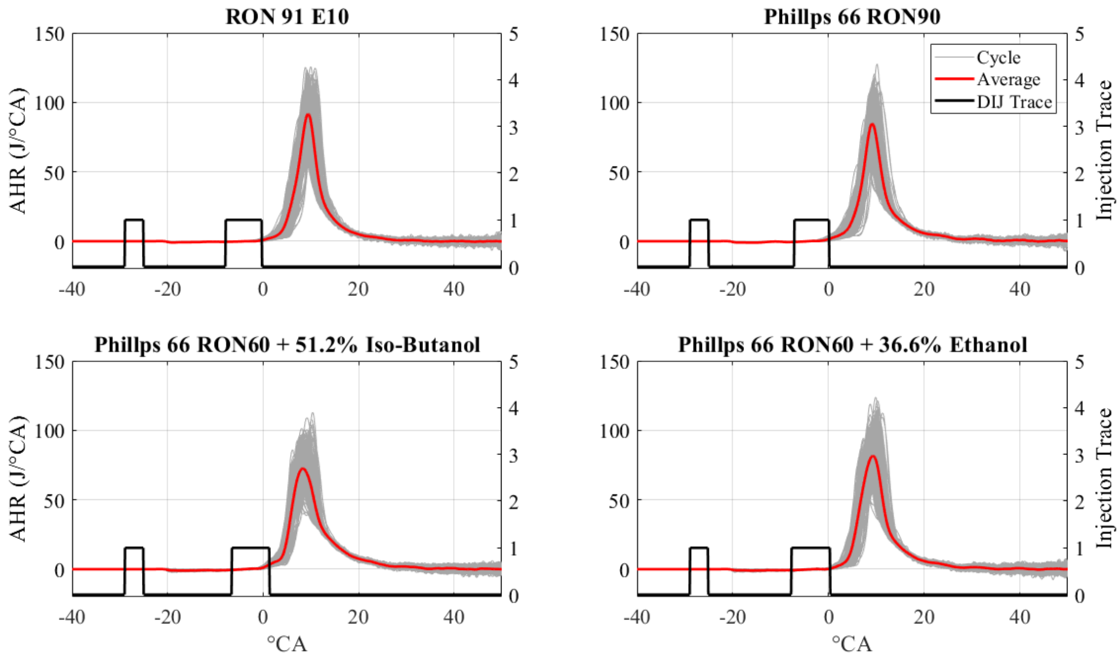

Figure 4.9. Shows the four fuels with RONs 89-94, they all have similar heat release characteristics as well as demonstrated similar low load limits. IAT was raised 20°C for stable operation of the two alcohol blends

The main difference is the elevated IAT for the splash-blended alcohol blends, Table 4.11. The main SOIs are slightly different but the elevated IAT would be expected to decrease ignition delay allowing for SOI to be retarded at a constant combustion phasing.

Table 4.11. Control Parameters for RON 91 fuels at 1500 rpm, 4.6 bar BMEP

Parameter	RON91 E10	RON90	IB51 Gas	ETH 36 gas
IAT (°C)	55	55	75	75
MAP (kPa)	150	150	150	150
Injection Pressure (bar)	300	300	300	300
Pilot SOI (°aTDC)	-30	-30	-30	-30
Pilot/Main (fraction)	0.19	0.2	0.17	0.17
Main SOI (°aTDC)	-8.6	-7.1	-6.1	-6.8
* Main SOI was varied to phase combustion ** Main Quantity was varied to control load				

A comparison of the combustion metrics and ITE is given in Table 4.12. The differences in the combustion characteristics of the four fuels are minimal regarding the burn duration and ignition delay at this speed-load. Results do show a slight gross ITE benefit for the alcohol blends over the neat fuels, neat fuels having an ITE of 44.4% and IB51 gas ITE of 49.0%.

Table 4.12. Combustion Characteristics of the four RON91 fuels at 1500 rpm, 4.6 bar BMEP point

Fuel	$IMEP_g$ (bar)	Gross ITE (%)	CA50 (°aTDC)	COV (%)	BD 10-90% (°CA)	MPRR (bar/°CA)
RON91 E10	6.8	45.4	9.7	1.2	8.2	5.1
RON91	6.7	44.4	9.6	1.3	9.0	4.9
EH37 Gas	6.9	47.7	9.7	2.1	8.1	5.0
IB51 Gas	6.9	49.0	9.6	1.8	10.0	4.3

The medium load testing at 1500 rpm showed that fuel with a RON of 80 allowed for GCI operation to be extended significantly. Furthermore, the two RON 80 fuels that were tested, P66 RON80 and IB25 Gas, both the P66 and Halterman blend, each showed similar results at this speed-load Table 4.10.

4.1.3 High Load

Regarding higher load testing, the loads tested were 10 and 15 bar BMEP. At these loads all the fuels were not tested, the supply was limited and at higher speed and load the consumption of fuel per test point is much higher, so the focus was on the fuels which the most potential was seen in the 1500 rpm, medium load testing.

Experiments were conducted with the RON 70, RON 80, IB25 gas, IB51 gas as well as RON 91 E10 pump fuel for 10 bar BMEP at 2000 rpm and 15 bar, 2200 rpm the IB25 gas with the Halterman fuel was used along with the RON 91 E10. The results of these experiments are discussed in the following section.

Figure 4.10 shows the fuels which were tested at the higher loads, based upon the results from the low and medium load testing, it was determined that fuel with a RON of 70 or greater was going to be the fuel to focus on. This and the lack of supply of fuel determined that we would not perform experiments with the RON 60 at these higher loads.

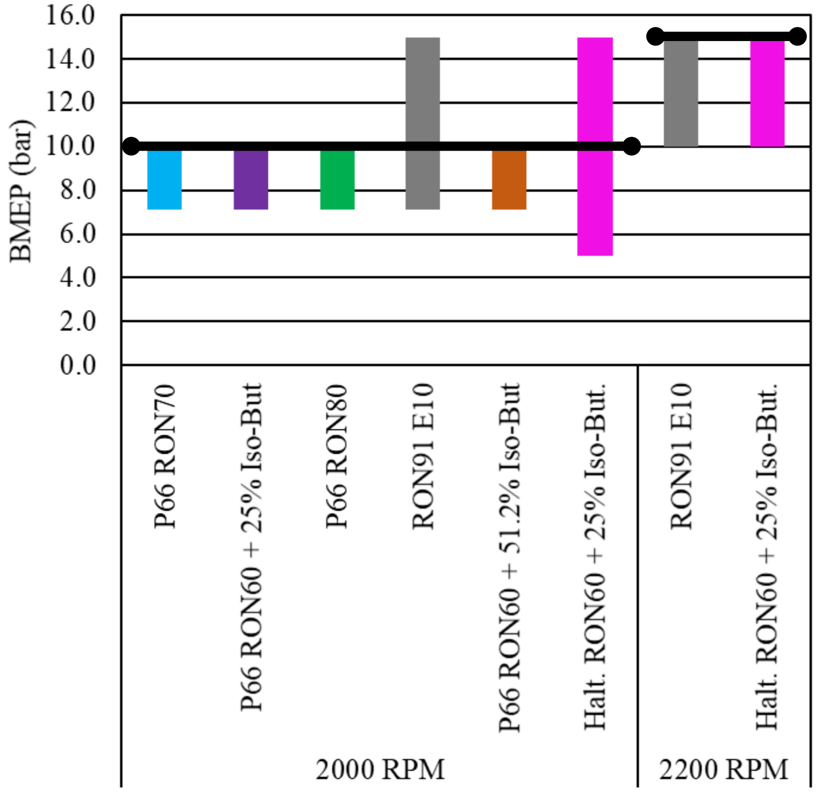

Figure 4.10. Load points tested for the highest load range tested Solid horizontal black lines signify the loads which are examined at in-depth in the following section. (Solid bars signify tests were carried out at these regions, hashed means operation was assumed for this load)

For these experiments, the pilot timing and amount were not able to be held constant because of the effect of the pilot on combustion knock amplitude and pressure rise rates. With the increased amount of fuel overall in the combustion chamber, these parameters could be potentially damaging to the hardware so mitigation with changes to the pilot injection was employed. At the higher load, extended burn duration can be seen in Figure 4.11 for each fuel at the 10 bar 2000 RPM operating point.

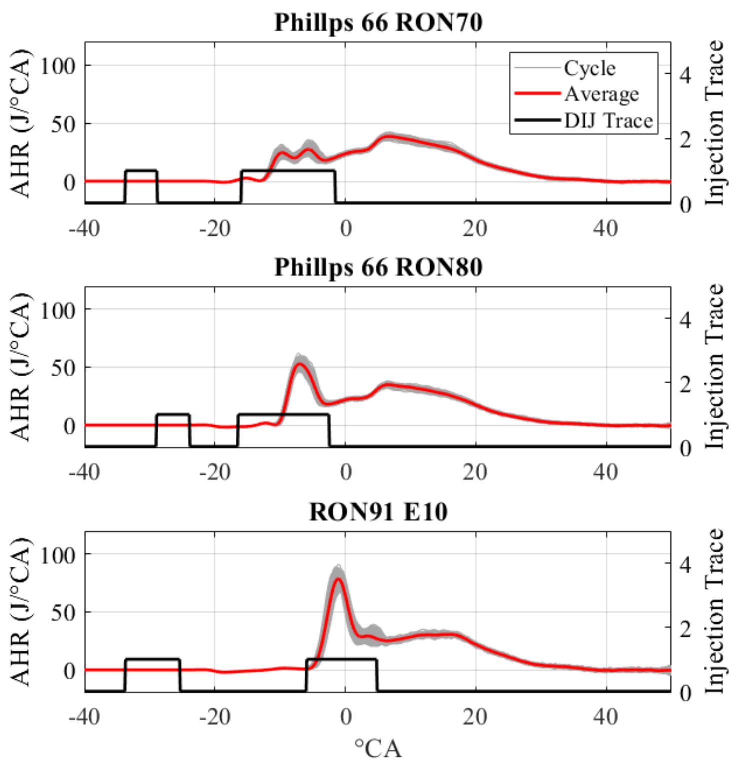

Figure 4.11. 2000 RPM, 10 bar BMEP neat fuels, apparent heat release comparison

During operation with each fuel, although there is a difference in reactivity between them, the trends from the low and medium load testing concerning main SOI are not followed. This is due to the variation in pilot timing and amount, for example in Table 4.13 the fuel which was found to be the lowest reactivity has the latest main SOI as well as the most fuel injected in the pilot, causing the most fuel to be premixed.

Table 4.13. Control parameters for 2000 RPM 10 bar BMEP operation

Parameter	**RON91 E10**	**RON80**	**RON70**
IAT (°C)	55	55	55
MAP (kPa)	220	220	220
Injection Pressure (bar)	350	350	350
Pilot SOI (°aTDC)	-35	-30	-35
Pilot/Main (fraction)	0.38	0.15	0.15
Main SOI (°aTDC)*	-11.6	-17.0	-14.5
* Main SOI was varied to phase combustion ** Main Quantity was varied to control load			

Table 4.14. Combustion characteristics of neat fuels at 10 bar BMEP

Fuel	**$IMEP_g$ (bar)**	**Gross ITE (%)**	**CA50 (°aTDC)**	**COV (%)**	**BD 10-90% (°CA)**	**MPRR (bar/°CA)**
RON70	12.2	46.2	8.4	1.5	32.4	5.2
RON80	12.1	46.0	7.4	1.5	31.4	8.2
RON91 E10	12.0	45.9	8.4	1.4	28.2	7.8

The two iso-butanol blends which were tested at 10 bar BMEP both operated well as expected being at an upper-medium load. With the IB51 gas, there was a higher peak heat release rate and from Figure 4.12 it can be seen that the IB51 main portion of heat release starts later than the other two fuels. The two IB25 gas blends have a distinct early portion and then another peak before tailing off.

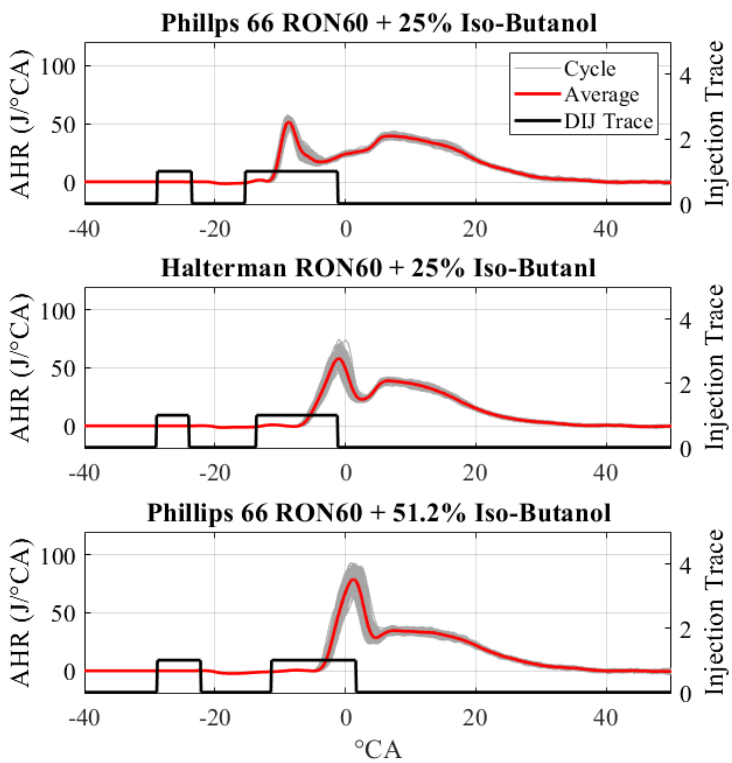

Figure 4.12. 2000 RPM 10 bar BMEP heat release comparison of the three iso-butanol blends tested

See the difference in main injection SOI for the IB51 gas when compared to the IB25 gas in Table 4.15. The effect of the larger amount of fuel in the pilot allowed for a later main injection with similar combustion phasing to the IB25 gas. Note the larger pilot amount allows for more premixing to occur, this resulted in higher heat release rates, Figure 4.12.

Table 4.15. Control Parameters for Iso-Butanol blends at 2000 RPM, 10 bar BMEP

Parameter	IB51 Gas	IB25 Gas P66	IB25 gas Halt.
IAT (°C)	55	55	55
MAP (kPa)	220	220	157
Injection Pressure (bar)	350	350	400
Pilot SOI (°aTDC)	-30	-30	-30
Pilot/Main (fraction)	0.31	0.15	0.2
Main SOI (°aTDC)*	-12.1	-16.0	-14.0
* Main SOI was varied to phase combustion ** Main Quantity was varied to control load			

Table 4.16 shows combustion with the lower reactivity having a shorter duration, following the trend noted in the low and medium load testing. The Halterman fuel and Phillips 66 fuel have differences in burn duration which are caused by AFR differences. The Halterman fuel was tested at a lower AFR than the Phillips 66 fuel at this point, Table 4.15 shows the lower MAP. This was done to minimize pumping losses with that fuel to see if there was a benefit in BTE. The fuels were determined to be similar and able to be used for comparison based on a comparison between the Halterman fuel and Phillips 66 fuel performance was done at the common point of 80 Nm 1500 rpm with the same AFR as well as injection timings and CA50.

Table 4.16. Combustion characteristics from the iso-butanol blends at 2000 RPM 10 bar BMEP

Fuel	$IMEP_g$ (bar)	Gross ITE (%)	CA50 (°aTDC)	COV (%)	BD 10-90% (°CA)	MPRR (bar/°CA)
IB51 Gas	12.3	48.0	8.4	0.8	22.3	8.1
IB25 Gas P66	12.6	46.9	7.5	0.8	28.9	7.9
IB25 Gas Halt.	11.0	46.2	7.5	1.0	22.0	6.9

Continued testing was completed with additional fuel sourced from Halterman which met the RON 60 specifications of the Phillips 66 RON 60 to be blended with Iso-Butanol. This additional fuel allowed for expanded high load testing to be conducted to explore the efficiency of the current system with a fuel that allowed for lower load operations to be carried out.

The highest load tested was 2200 rpm and 15 bar BMEP. At this speed-load point only two of the fuels were tested, the Halterman IB25 gas and the RON 91 E10. Figure 4.13 shows the difference in the AHR traces between the two fuels. Trends of the fuel with the lower reactivity having the higher peak heat release rate continue with these speed-load points. Peak heat release rates are significantly different for the two fuels with the

Halterman RON 60 peaking at 75 J/°CA whereas the RON 91 E10 peaks at 150 J/°CA, Figure 4.13.

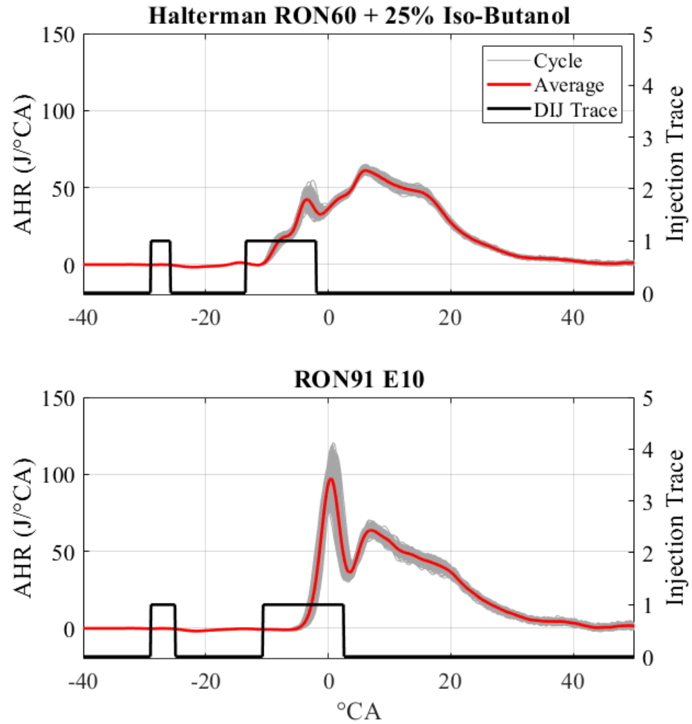

Figure 4.13. 2200 rpm 15 bar BMEP heat release comparison of the Halterman IB25 gas and the RON91 E10 fuel

At these high load points, the injection pressure was found to affect knock and pressure rise rate. To minimize these two parameters the injection pressure was varied between the two fuels, Table 4.17. the control parameters are otherwise similar including the pilot timing and fraction of fuel mass injected.

Table 4.17. Control Parameters for 15 bar BMEP 2200 rpm test points

Parameter	**IB25 Gas**	**RON91 E10**
IAT (°C)	55	55
MAP (kPa)	200.9	203.6
Injection Pressure (bar)	800	650
Pilot SOI (°aTDC)	-30	-30
Pilot/Main (fraction)	0.10	0.15
Main SOI (°aTDC)*		
* Main SOI was varied to phase combustion ** Main Quantity was varied to control load		

When comparing the performance of the two fuels there is a benefit of 0.8% ITE with the IB25 gas over the RON 91 E10 fuel. As well as a benefit of having a MPRR of 6.8 bar/°CA vs the RON 91 E10 fuel having an MPRR exceeding the limit at 10.5 bar/°CA, Table 4.18. Due to the high MPRR, the CA50 could not be advanced to the same point as the IB25 gas coming up 1.9°CA short which could be a contributing factor to the efficiency deficit.

Table 4.18. Combustion characteristics for 15 bar BMEP and 2200 RPM

Fuel	**$IMEP_g$ (bar)**	**Gross ITE (%)**	**CA50 (°aTDC)**	**COV (%)**	**BD 10-90% (°CA)**	**MPRR (bar/°CA)**
IB25 Gas	17.0	45.6	8.8	0.7	25.5	6.8
RON91 E10	16.8	44.8	10.7	0.8	24.7	10.5

4.2 Impacts on Gross Indicated Efficiency

4.2.1 Combustion Phasing

To demonstrate the effect of combustion phasing on performance with each fuel in compression ignition mode, at the 1500 rpm 80 Nm common point, a sweep of combustion phasing was done. When varying combustion phasing, the pilot timing and amount were held constant across all fuels and each test point to eliminate the effects of the pilot from the equation. To vary combustion phasing, the main injection timing was used. The timing was varied by the controller to meet targeted combustion phasing with the closed-loop combustion phasing control on an individual cylinder basis.

Figure 4.14 shows the effect of combustion phasing on the gross indicated thermal efficiency. As the results show, there is little effect on the efficiency when sweeping combustion phasing across this range. Combustion phasing was not optimized for this testing so there is still a possibility of some efficiency gains by advancing combustion. There is as difference between fuels, showing that there is a 3.5% increase depending on fuel selection. This trend shows does not appear to follow any trend with RON or reactivity of the fuel. Errors in fuel flow measurements caused by fuel vaporization in the return system caused variance in the ITE values. The tests with IB25 from Halterman does not have this issue, the system was revise multiple times to minimize fuel vaporization. Though there is an increase in peak cylinder pressure as well as maximum pressure rise rate causing an increase in peak cylinder temperature which leads to higher emissions of NOx, Figure 4.15 when advancing combustion.

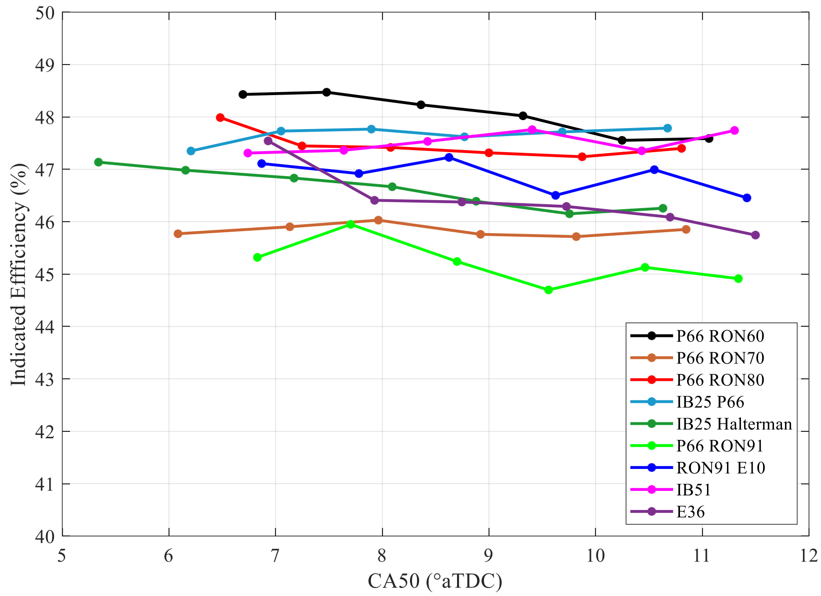

Figure 4.14. The effect of combustion phasing on the gross indicated efficiency at 1500 rpm, 4.6 bar BMEP

Figure 4.15 also shows grouping of the fuels, the fuels with a RON > 90 are higher than the fuels with a RON < 90. This grouping can be attributed to the two-stage heat release that is happening for the fuels with a RON < 90, Figure 4.16.

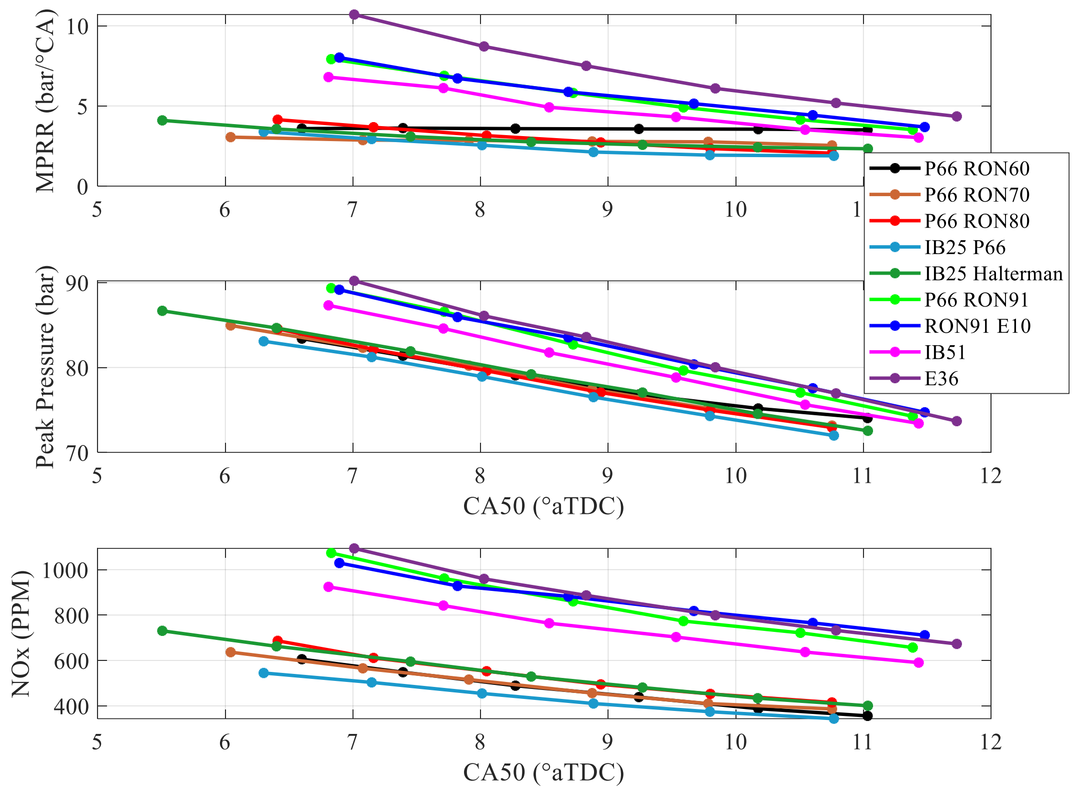

Figure 4.15. Effect on combustion phasing on MPRR and peak cylinder pressure, and NOx concentration at 1500 rpm, 4.6 bar BMEP

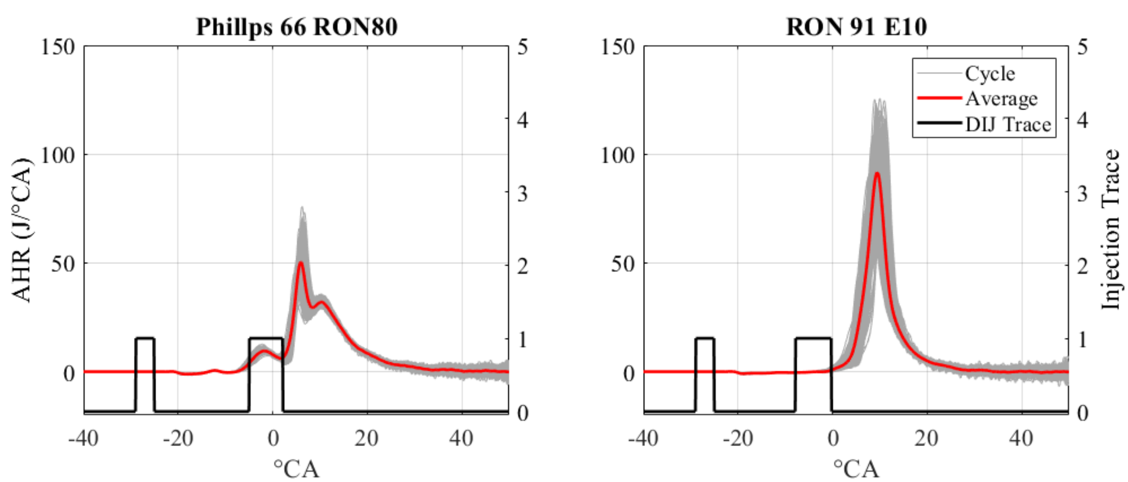

Figure 4.16. Heat release for a fuel with a RON > than 90 and a RON < 90 showing the two-stage heat release with the RON < 90 which is believed to cause the grouping in performance parameters at 1500 rpm, 4.6 bar BMEP

4.2.2 Fuel Rail Pressure

Changes in fuel rail pressure (FRP) yielded little change in the AHR for each of the fuels which were tested, Figure 4.17. The injection pressures tested were different for each fuel because of injection pressure on the maximum pressure rise rate, Table 4.19.

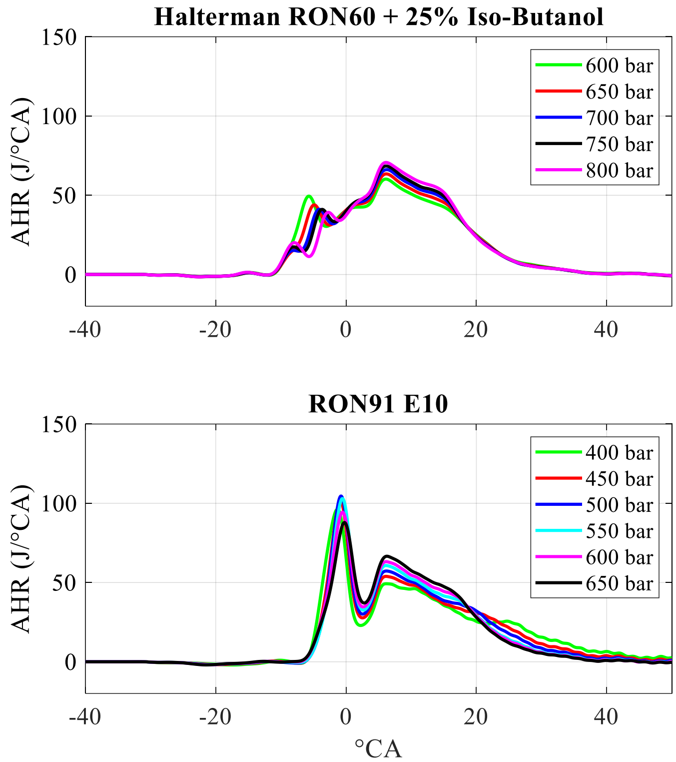

Figure 4.17. AHR Traces for 2000 rpm 15 bar BMEP varying injection pressure

Table 4.19 shows the trend of the maximum pressure rise rate for the IB25 gas showing that the increase in fuel rail pressure causes a decrease in the maximum pressure rise rate. The fuel being injected at a higher pressure decreases the ignition delay causing the charge to have less time to mix. Having less time to mix means that the charge is locally rich where combustion is happening, slowing down the flame kernel because it is propagating as the charge is mixing. For the RON 91 E10 fuel, the trend is not the same, the maximum pressure rise rate remains nearly the same for the range tested. This could be due to the longer ignition delay of the lower reactivity RON 91 E10, this longer ignition delay means that the injection pressure would have to be higher in order to possibly see the benefits. Testing this theory was not possible because of the high MPRR observed with the RON 91 E10. Testing higher pressures was not done to prevent engine damage.

There was a slight benefit in the gross ITE for each of the fuels when increasing fuel rail pressure. Though this benefit was small for the IB25 gas the increase shown was 0.4%. For these tests, the CA50 was held constant when possible. The benefit was more

significant for the RON 91 E10 fuel, showing an increase of 4.3%, the large increase could be attributed to the increase in FRP allowing CA50 to be advanced due to the MPRR decreasing.

The limit encountered was a maximum pressure rise rate of 10 bar/°CA. For the IB25 gas, there was no issue maintaining a combustion phasing of 8°aTDC. The RON 91 E10 fuel did encounter the MPRR limit for all of the experiments. After processing the absolute values of the maximum pressure rise rate were found to exceed the limit of 10 bar/°CA. To prevent damage to the engine combustion was retarded for the first three cases, 400, 450, and 500 bar fuel rail pressure. Realtime monitoring of the maximum pressure rise rate showed to be exceeding the limit even at a slightly retarded CA50. The factors causing this phenomenon are believed to be increased ignition delay allowing for increased mixing and a more homogenous charge rather than the more stratified charge from the increased reactivity fuel. The ignition delay effects are explored in Section 4.4 below.

Table 4.19. Combustion parameters for 2000 RPM 15 bar BMEP

Fuel	**$IMEP_g$ (bar)**	**Gross ITE (%)**	**CA50 (°aTDC)**	**COV (%)**	**BD 10-90% (°CA)**	**FRP (bar)**	**MPRR (bar/°CA)**
IB25 Gas	16.6	45.5	7.5	0.8	25.7	600	7.4
	16.6	45.7	7.8	0.7	24.5	650	6.7
	16.6	45.7	8.0	0.7	23.6	700	6.2
	16.8	45.7	8.0	0.6	23.2	750	6.1
	16.8	45.9	8.3	0.6	22.5	800	5.7
RON91 E10	16.5	42.7	10.1	0.6	32.3	400	11.2
	16.6	44.7	9.4	0.6	29.8	450	11.9
	16.7	45.3	8.8	0.7	25.5	500	12.4
	16.7	47.0	8.3	0.7	23.3	550	12.2
	16.8	47.5	8.3	0.6	22.8	600	11.1
	16.8	47.4	8.4	1.0	22.0	650	10.4

4.3 Emissions

When the RON of the fuel changes, there is a clear trend in how the burn duration is affected which was highlighted in Section 4.1. As the burn duration decreases, this means that there is an increase in peak cylinder pressure, increasing peak cylinder temperature. Heywood shows how the production of NOx gas is directly related to the temperature of the gases in the cylinder and the relative air-fuel ratio [6]. Trends that represent this were found with the testing of the varying reactivity fuels. Although, this trend is opposite of what is preferential for efficiency to an extent as shown in the tables of combustion parameters in 4.1.

As the RON of the fuel increases the fuel has more time to mix in-cylinder before ignition. When the fuel finally ignites, the burn happens at a much higher rate, shown by the burn durations in the combustion parameter tables listed in 4.1.

NOx emissions for these results showed that for a given fuel, as ignition delay increases the NOx emissions decrease. Along with this, peak cylinder pressure, and maximum pressure rise rate decrease, Figure 4.18.

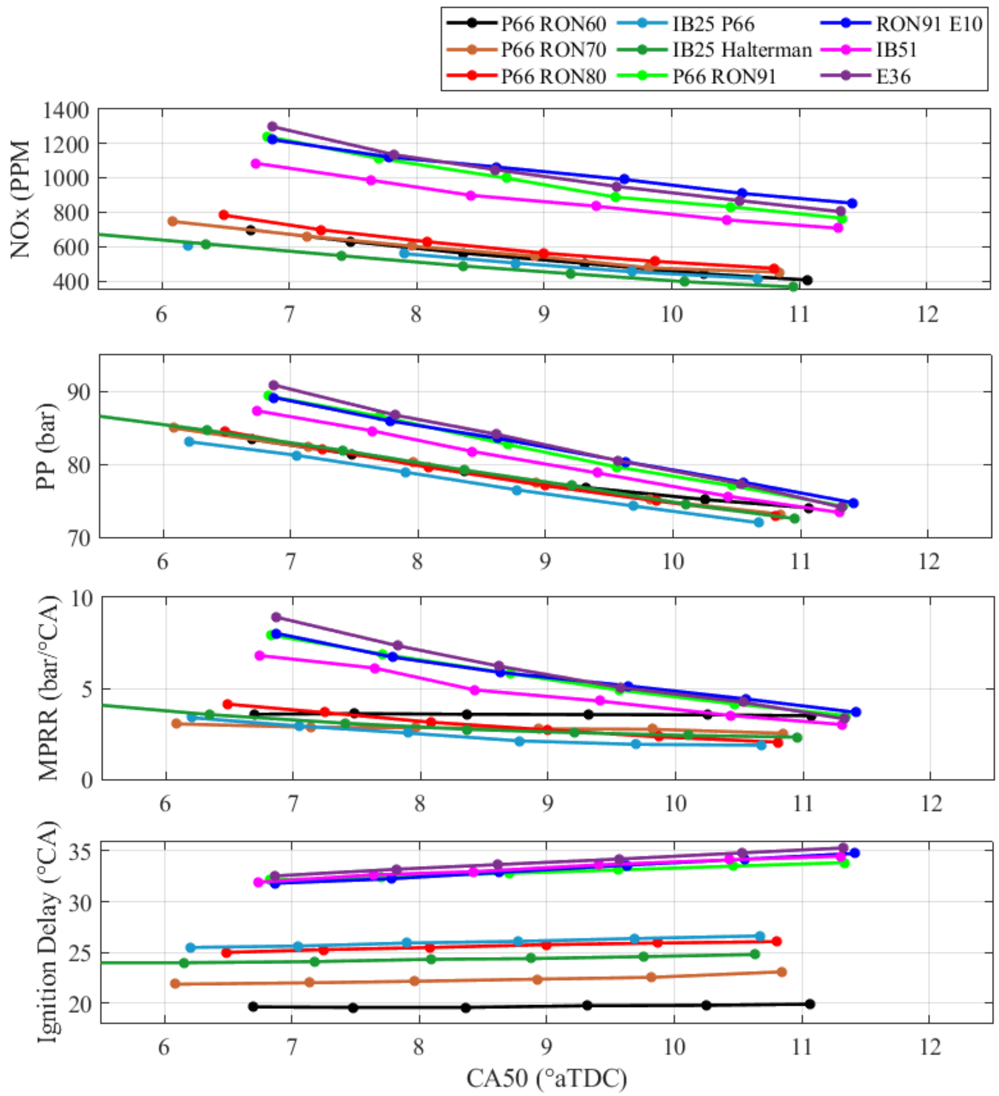

Figure 4.18. NOx emissions at a 4.6 bar BMEP, 1500 rpm over a CA50 sweep

Figure 4.19 shows the NOx emissions vs the RON of the fuels tested. Three different speed load conditions are shown, and it can be noted that as the RON of the fuel increases so does the NOx production for 4.6 and 7.1 bar BMEP. Being that NOx production is highly temperature-dependent, this trend makes sense in that as the peak cylinder

pressure increases, the in-cylinder temperature increases increasing NOx production. Along with that, the higher RON results in a more mixing allowing more combustion to happen around stoich, resulting in higher temperatures. The difference between the 80 RON fuel and the 91 RON fuels is more prominent than the difference in the 60, 70, and 80 RON fuels at each test point. For the 10 bar BMEP test point, the higher RON fuels, RON > 90 show the lowest NOx emissions, this can be attributed to the increased pilot amount resulting in more pre-mixed combustion, Figure 4.11. The AHR shown demonstrates the increased amount of premixed combustion due to a larger pilot injection. The other two loads were more of a diesel like combustion, resulting in the traditional relationship between NOx and cylinder pressure being the main driving factor in NOx production.

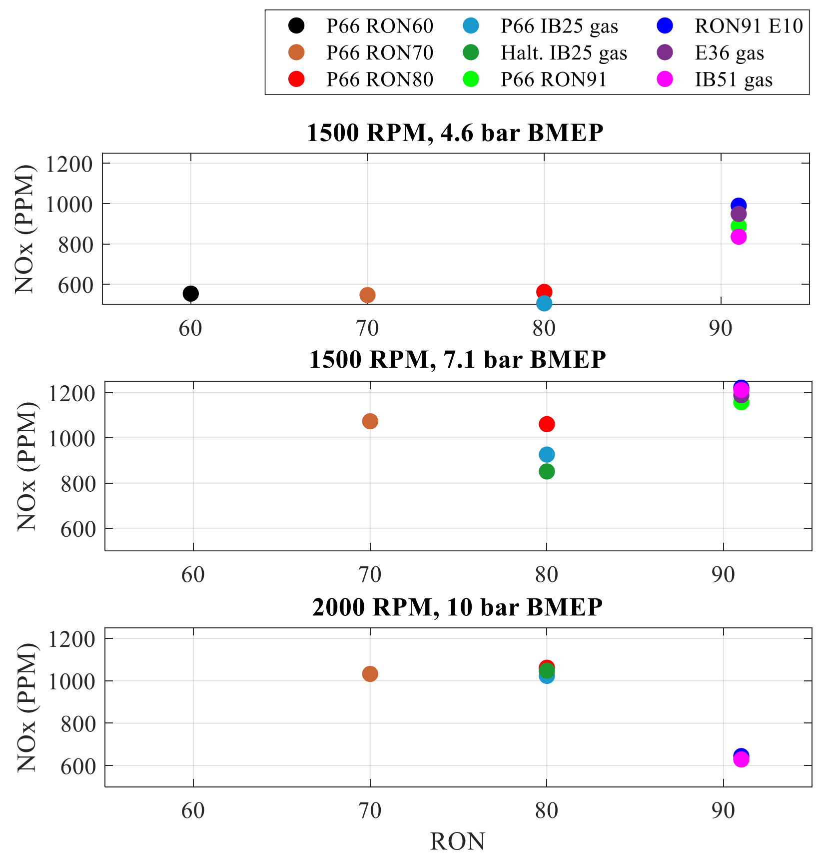

Figure 4.19. NOx concentration at three speed load points for each fuel

Figure 4.20 demonstrates the trends of the carbon monoxide production relative to the RON of the fuel being used in GCI mode at multiple loads. As the RON of the fuel decreases there is an evident trend in decreasing carbon monoxide production. These results show that there is a benefit to operating in compression-ignition mode with a fuel with a lower RON value. This causes the fuel to have less time to mix which prevents

zones of mixtures so lean that combustion becomes incomplete. When the fuel has less time to mix the fuel stays localized to a smaller region of the combustion chamber resulting in a mixture that is locally closer to stoichiometric allowing for more complete combustion. Figure 4.20 also shows the benefit of operation with a low carbon fuel, and alcohol blend. Resulting in lower CO emissions at the same speed-load point.

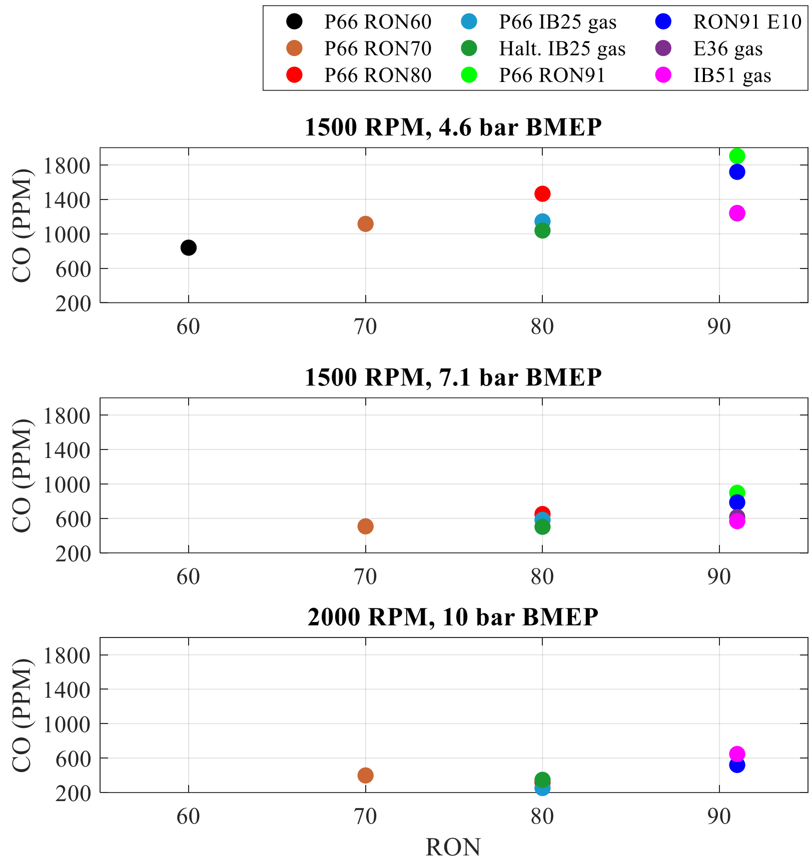

Figure 4.20. Carbon Monoxide concentration at three speed load points for each fuel tested at that point

The third emission that is being targeted to minimize is the total hydrocarbons (THC). Figure 4.21 displays the trend of the THC emissions on a C1 basis. These measurements show the same trend as the CO did in the prior figure, the fuels with a RON greater than about 80 show a significant increase in hydrocarbons as well as a fuel with a RON less than 80 showing a slightly lesser increase. The presence of hydrocarbons is indicative of the same combustion characteristics as CO, poorer than ideal combustion quality. Having a fuel with a slightly higher reactivity will allow the engine out hydrocarbons to be significantly lower.

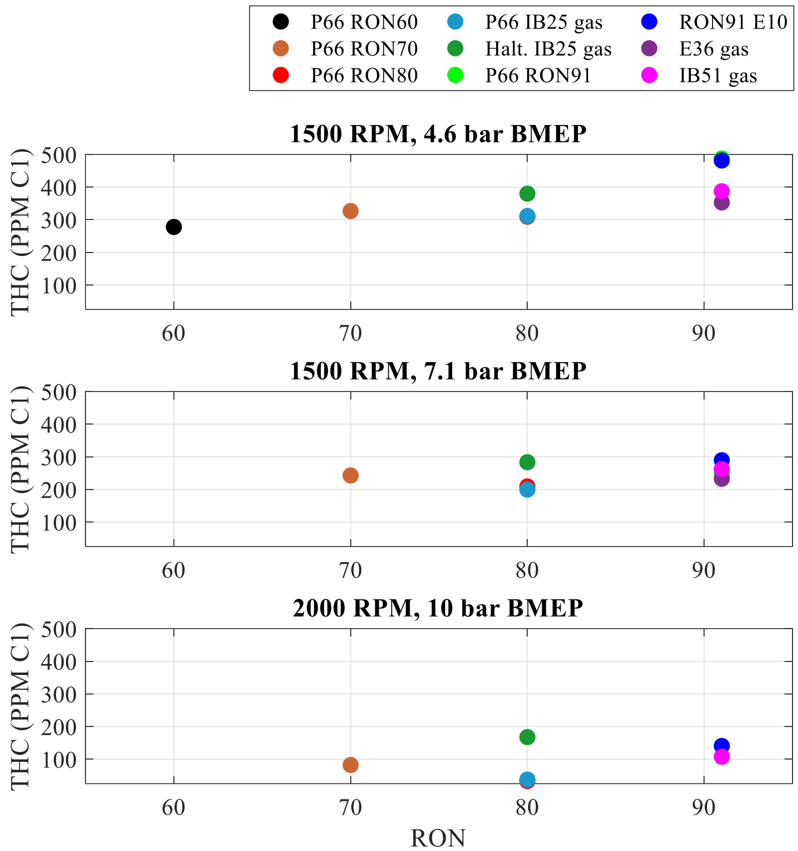

Figure 4.21. Total Hydrocarbons C1 at three speed load points for each fuel

CO_2 emissions benefit slightly as well at the low loads at 80 and 91 RON, Figure 4.22. The addition of more Iso-Butanol in the IB51 gas showed a greater decrease in CO_2 when compared to the IB 25 gas at 80 RON compared to the neat fuel.

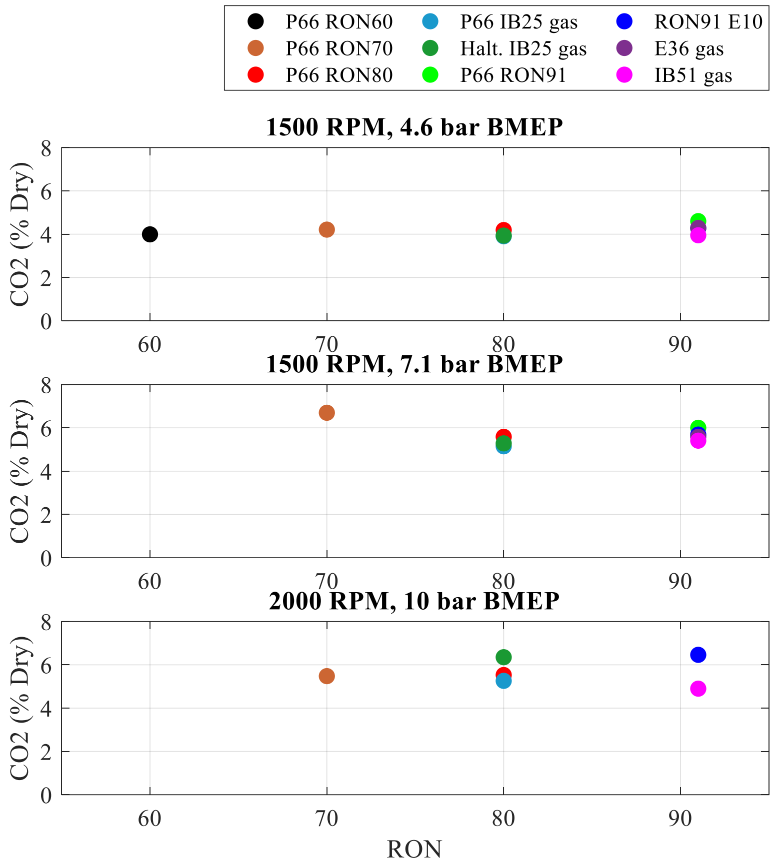

Figure 4.22 CO_2 concentration for each fuel tested at three speed load points

Based upon the results of section 4.1 on fuel reactivity and the effect it has on GCI combustion, fuels with a RON of 80 yield the best performance in GCI. They allow for extended low-load operation without a large deficit in top-end performance by long burn durations causing high exhaust gas temperature (EGT). These results are shown as well in Figure 4.23. There is a clear benefit at the lower loads when it comes to CO emissions when comparing the IB25 gas to the neat RON 80 from Phillips 66.

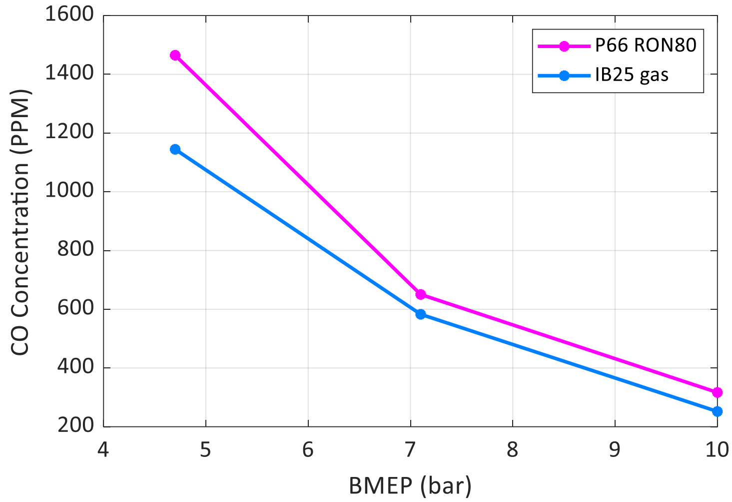

Figure 4.23. RON 80 neat and P66 RON 60 + 25% Iso-Butanol Carbon Monoxide emissions

4.4 Ignition Delay

A major part of this work was influenced by the effects of ignition delay on the charge mixture within the cylinder. Changing the reactivity of the fuel displayed changes in the ignition delay which influenced other combustion metrics to variable degrees. The effect of combustion phasing on ignition delay is small when compared to the effect of fuel reactivity, as shown in Figure 4.24 and. Quantifying the ignition delay was done in two different ways, referencing the CA00 to be at the pilot (SOI), Figure 4.24, and referencing the CA00 to the start of the main injection, Figure 4.25. They both yield a similar trend when comparing the effects of the fuels at the same test point, meaning that with each method the fuel with the longest ignition delay remains the longest as does the shortest. The difference between the methods is displayed in the effect of combustion phasing.

With the CA50s being constant across all fuels for a given test point, as you change what is considered the beginning of combustion and there is a difference in the ignition delay change between fuels. For example, when examining Figure 4.24 it can be noted that as the end of ignition delay changes from CA02 in the top figure to CA10 in the bottom figure the difference between each fuel becomes less. This is an observation that makes the first figure seem like it would be the logical choice because of the difference being the largest. An issue with this is that the error associated with calculating the CA02 vs the error when calculating the CA10 is significantly different. The CA02 measurement is much more susceptible to small variations in combustion or errors in measurement of pressure or the relationship between pressure and crank angle. For this reason, the choice was made to examine all three figures to verify trends, as well as show relative differences between each fuel.

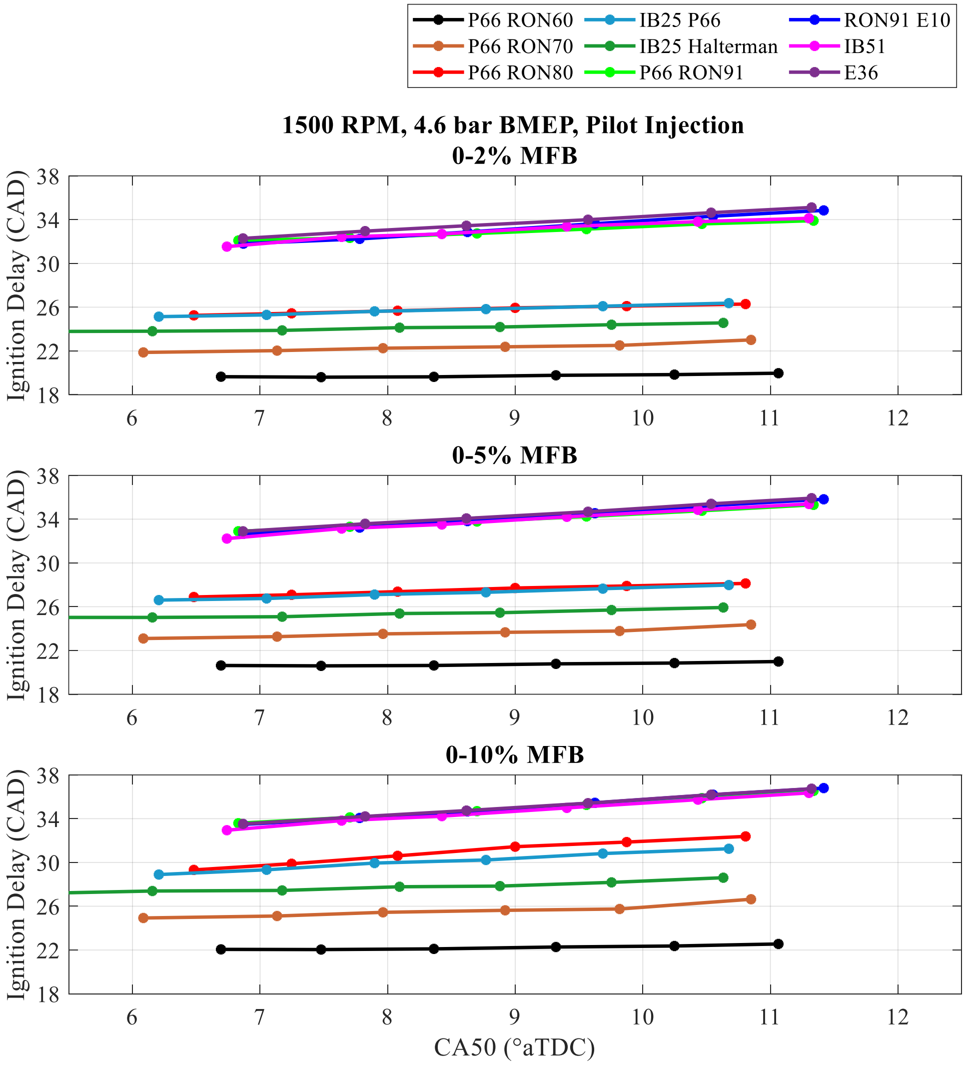

Figure 4.24. Ignition Delay referenced to the start of the Pilot Injection for 80Nm and 1500 RPM for each fuel tested

Figure 4.25 shows ignition delay calculated based on the main injection SOI. The negative values indicated that combustion started before the start of the main injection SOI occurred. This is what would be expected of the higher reactivity fuels based upon the reactivity studies in 4.1 where the higher reactivity fuels were shown to have a two-stage combustion process if the pilot SOI was held constant as well as the CA50. An interesting trend is that as the CA50 increases, the ignition delay decreases. This trend is deceiving because the main injection timing was being used to change CA50. Meaning that if the CA02 point for instance was after the start of the main injection if CA50 is retarded, then the start of the main injection moves towards the CA02 point making the ignition delay appear to be shorter. Due to this relationship, using the main injection

timing yields results that are misleading if the CA50 is changing between test points for a given fuel. This relationship means that Pilot Injection timing is better reference to use in this case given the testing strategy, keeping the pilot constant and adjusting the main quantity and timing to achieve load an CA50.

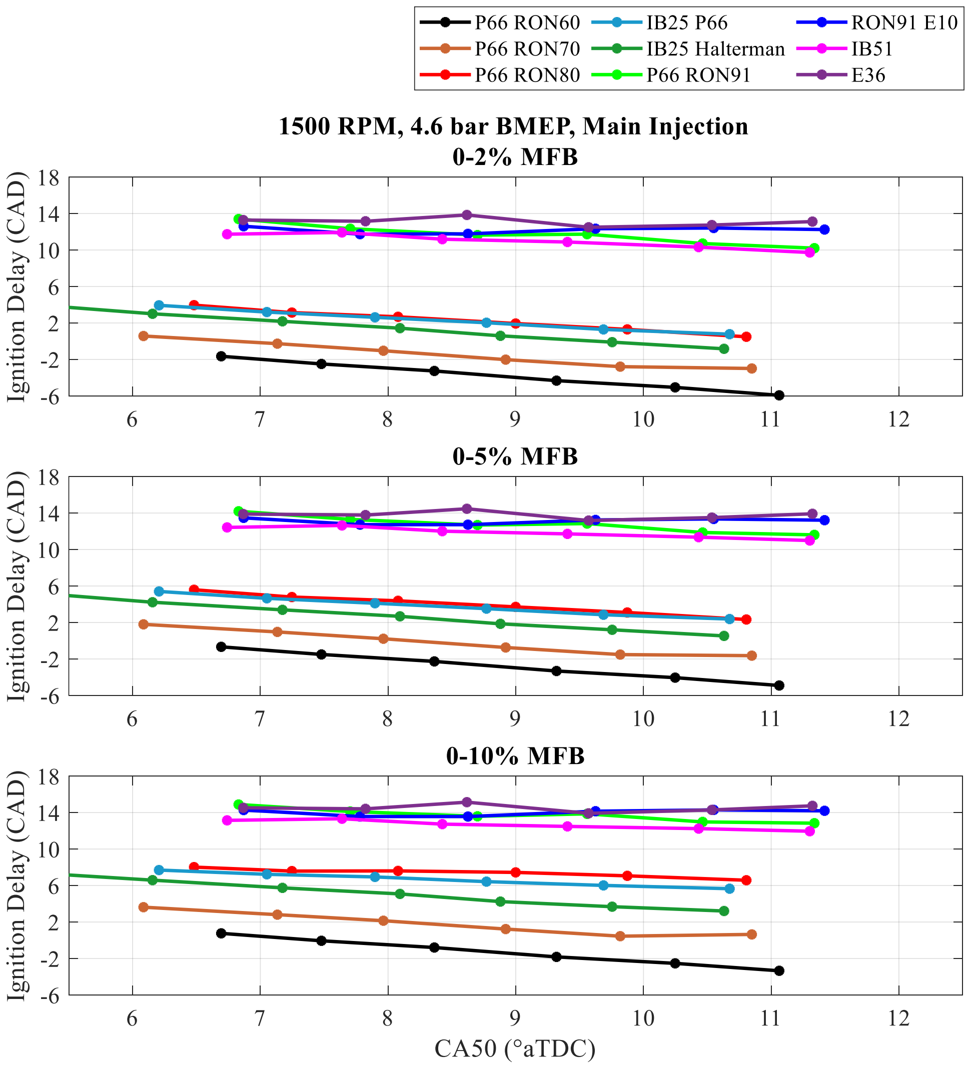

Figure 4.25. Ignition Delay referenced to the start of the Main Injection for 80Nm and 1500 RPM for each fuel tested

As described in the previous paragraphs, Figure 4.26 shows the effect that the main injection has on the CA02 for RON 80 at 1500 rpm and 4.6 bar BMEP. The diamond markers on the mass fraction burned traces represent the CA02 position and the square waves represent injection traces. The colors are consistent for each test, i.e. black traces and diamond is for the CA50 of 12°aTDC case. The main injection does not affect the

CA02 position substantially because the fuel from the pilot injection has already started burning. This would mean that the earliest position, i.e. CA02 vs CA10, will represent the ignition delay the best because it is going to be least influenced by the main injection and should be relatively constant if the pilot injection SOI is held constant while the main injection SOI is varied to change CA50.

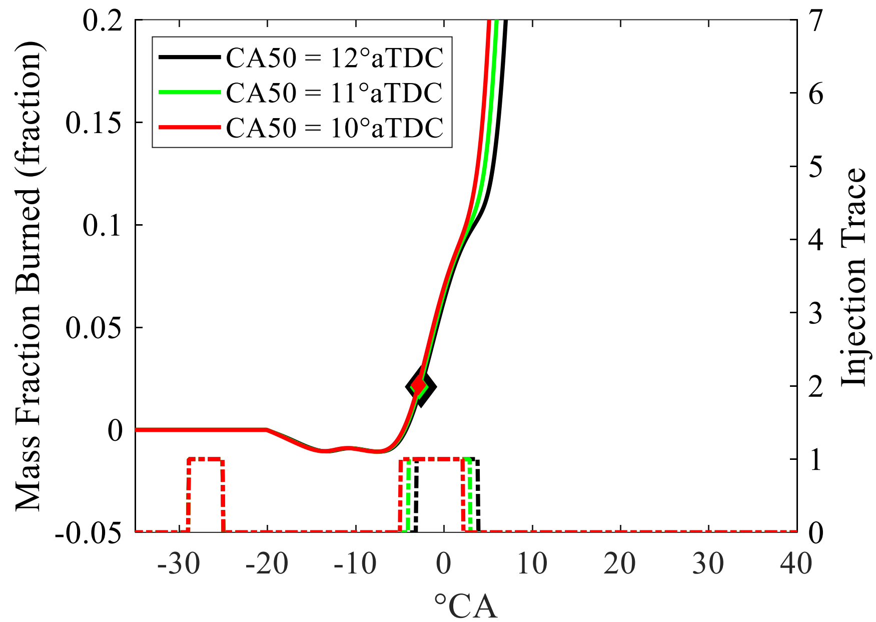

Figure 4.26. Mass Fraction Burned with CA02 plotted with diamond markers as well as the DI injection traces for 1500 RPM 4.6 bar BMEP, P66 RON 80 fuel

The effects of the ignition delay can be both beneficial and detrimental to the performance of the engine. The increased ignition delay of the lower reactivity fuels causes increased pressure rise rates which are detrimental to engine durability as well as causing the highest peak cylinder pressures resulting in the highest NOx production. Fuels with the lowest reactivity showed lower ITE in section 4.1.1 at the low loads. The highest ITE was at 80 RON, showing that the higher RON can result in higher ITE at the detriment of low load operation.

5 SI Operation Results

SI operation testing was only performed with RON91 E10 to compare to the baseline fuel for the GCI testing. Limited supply of the Phillips 66 fuels prevented testing them in SI mode. Operation was tested at three different IATs of 35, 45, and 55°C. Elevated temperatures for the load levels was tested to examine the ability of the fuel to operate at similar conditions to GCI, allowing for mode switching. Operation was successful from 30 Nm up to 80 Nm at lambda 1.5. Figure 5.1 shows the difference in ITE of between GCI and SI. Switching to GCI at the lowest possible load is significantly beneficial to ITE. IAT for SI was tested at the same IAT as GCI to enable mode switching. Changing IAT during the mode switch would be difficult to do quickly so being able to operate the engine at the same IAT in both combustion modes will allow the mode switch to happen quickly without misfires in GCI while the intake warms up.

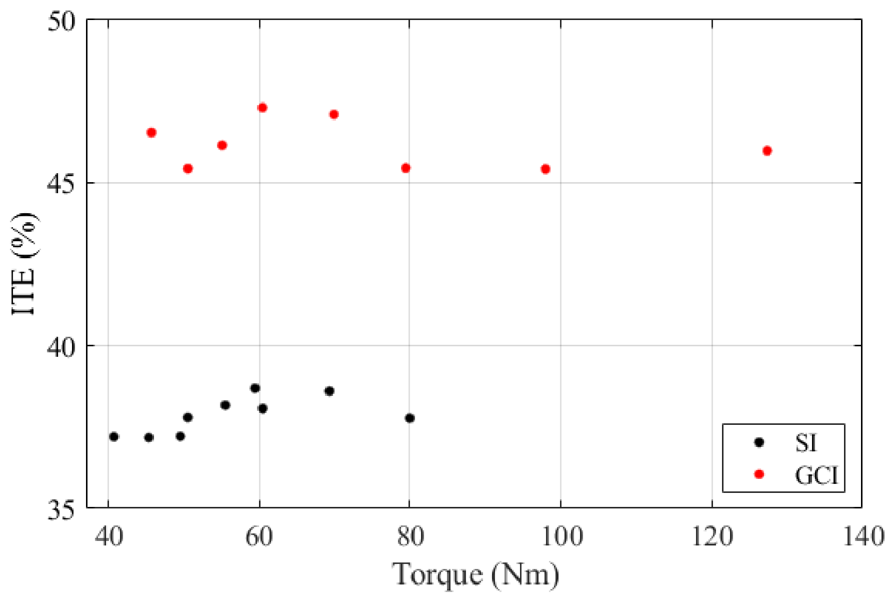

Figure 5.1. ITE comparison of SI vs GCI over a load sweep at 55°C IAT

SI testing completed showed that an overlap in combustion modes of 35 Nm exists between SI and GCI for a given fuel, as well as switching to GCI mode at the lowest possible load will be beneficial to ITE. Extending GCI operation all the way down to idle would not be necessary in a hybrid application due to the ability to upload the combustion engine to the maximum efficiency point for most of it’s operation.

6 Summary and Conclusions

A literature review was conducted to determine the current state of GCI engines. It was found that Delphi was at the cutting edge of this work. The matrix of test points was developed to test the limitations of each fuel in a consistent, controlled manner. Operating at the common testing condition for each fuel allowed for performance metrics such as ITE to be compared across each fuel. The ability of higher reactivity fuels to extend low load operation showed promising results, demonstrating that fuel with a RON of 80 performed the best, yielding high efficiency at low loads which allows low load extension while maintaining the high load performance of a low reactivity fuel, section 4.1.3.

Based upon the results presented from this study, it can be noted that there is potential for overall increased engine efficiency and decreased engine out emissions with the use of fuels with higher reactivity, lower RON, than that of conventional US pump gasoline.

1. Consistent, stable, low load operation was achieved with GCI
2. Fuels with a RON value <80 showed significant low load expansion for GCI compared to the RON 91 E10 baseline
3. Gross ITE of 37% was achieved at 2 bar IMEP, 800 rpm with RON 80
4. RON 80 fuel showed the highest ITE up to 3 bar IMEP, 1200 rpm
5. RON 80 fuel along with IB25 gas showed little difference in ITE at medium-high loads
6. RON 80 fuel showed a lower MPRR at 15 bar BMEP, than the baseline RON 91 E10
7. Increased injection pressure decreased MPRR, especially at high loads
8. Decreasing RON caused NOx to decrease, lower MPRR, lower maximum temperature, lower NOx production
9. Fuels with a RON of 80 showed lowest CO and THC emissions, highest combustion efficiency, higher RON fuels resulted in too much mixing, causing incomplete combustion near the periphery. Fuels with RON less than 80 did not mix well enough, resulting in locally rich combustion
10. Ignition delay trends follow the trend of CO and THC emissions, the steep change from 80 to greater than 90 RON is shown in Figure 4.24
11. SI and GCI operation have an overlap of $\geq$ 35Nm allowing seamless mode switching

6.1 Future Work

Future work for this includes mapping more of the speed load map with the IB25 gas selected. Additional work could be done with optimization and calibration of control maps such as optimization of boost and inlet temperature control as well as applying the use of Exhaust Gas Recirculation, (EGR) to the combustion system to help extend low load as well as assist with control of combustion temperature and emissions formation

control. Continued controls development is needed to optimize the use of the closed-loop combustion control. CA50 control by changing main injection timing works well to maintain combustion stability while IMEP balancing showed to be less effective in the current configuration. IMEP balancing was not used for any of these tests because of the issues faced.

Increased capability with the valve timing will allow for performance to be optimized. Having the ability to change the effective compression ratio will allow for low load expansion as well as using valve overlap to allow hot residuals to remain in the cylinder allowing for GCI at lower loads with lower reactivity fuels without heating the intake air.

Continued testing with the IB25 gas selected to map out the complete operation map would allow for BSFC maps to be generated for comparison to other engines. Based on the collected test data the minimum BSFC region is quite large. Little difference in ITE was seen at 2000 and 2200 rpm testing from 10-15 bar BMEP, 4.1.3.

Determine upper load limit, highest load tested was 15 bar BMEP, promise was seen for significantly higher load operation with the IB25 gas. MPRR was not near the limit with the higher reactivity fuel. Higher speed of 4000 rpm would allow for a comparison to examine the EGT limitations of the higher reactivity fuel and to examine if there is a significant limitation induced compared to the baseline RON 91 E10 fuel.

Determining an effective after-treatment solution for the system to meet tailpipe emissions targets is also required to be able to operate with the unique low exhaust temperature characteristics of GCI as well as lean SI. Opportunity for decreased engine out emissions with optimization of engine tuning also shows potential for improvements.

7 References

[1] Environmental Protection Agency, "Environmental Protection Agency - 40 CFR Parts 86 and 600," US Government, Washington DC, 2021.

[2] National Highway Traffic Safty Administration, "NHSTA News," 1 April 2022. [Online]. Available: https://www.nhtsa.gov/press-releases/usdot-announces-new-vehicle-fuel-economy-standards-model-year-2024-2026. [Accessed 4 4 2022].

[3] US Department of Energy, "energy.gov," US Department of Energy Office of Energy, Efficiency, and Renewable Energy, 2020. [Online]. Available: https://www.energy.gov/eere/bioenergy/co-optima-research. [Accessed 27 October 2021].

[4] U.S. Department of Energy, "The Road Ahead Toward a Net-Zero-Carbon Transportation Future," U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, 2021.

[5] P. Zoldak and S. Zhu, "Hyundai Multi-Mode GCI Engine," US DOE, 2021.

[6] J. b. Heywood, Internal Combustion Engine Fundamentals, Second ed., McGraw-Hill Education, 2018.

[7] B. Wu, Q. Zhan, X. Yu, G. Lv, X. Nie and S. Liu, "Effects of Miller cycle and variable geometry turbocharger on combustion and emissions in a steady and transient cold process," *Applied Thermal Engineering,* vol. 118, pp. 621-629, 2017.

[8] H. Hao, F. Liu, Z. Liu and F. Zhao, "Compression ignition of low-octane gasoline: Life cycle energy consumption and greenhouse gas emissions," *Applied Energy,* vol. 181, pp. 391-398, 2016.

[9] R. Hanson, D. Splitter and R. Reitz, "Operating a Heavy-Duty Direct-Injection Compression-Ignition Engine with Gasoline for Low Emissions," *SAE Technical Paper 2006-01-3385,* 2009.

[10] G. T. Kalghatgi, P. Risberg and H.-E. Angstrom, "Advantages of Fuel with High Resistance to Auto-Igntion in Late-Injectiong, Low-temperature, Compression Ignition Combustion," *SAE Technical Paper 2006-01-3385,* 2006.

[11] M. Sellnau, J. Sinnamon, K. Hoyer and H. Husted, "Gasoline Direct Injection Compression Igntions (GDCI) - Diesel-like Efficicency with Low CO2 Emissions," *SAE Technical Paper 2011-01-1386,* 2011.

[12] M. Sellnau, M. Foster, K. Hoyer, W. Moore, J. Sinnamon and H. Husted, "Developement of a Gasoline Direct Injection Compression Ignition (GDCI) Engine," *SAE International 2014-01-1300,* 2014.

[13] M. Sellnau, J. Sinnamon, K. Hoyer and H. Husted, "Full-Time Gasoloine Direct-Injection Compression Igntion (GDCI) for High Efficiency and Low NOx and PM," *SAE International 2012-01-0384,* 2012.

[14] M. C. Sellnau, J. Sinnamon, K. Hoyer, J. Kim, M. Cavotta and H. Husted, "Part-Load Operationg of Gasoline Direct-Injection Compression Ignition (GDCI) Engine," *SAE International 2013-01-0272,* 2013.

[15] K. S. Hoyer, M. Sellnau, J. Sinnamon and H. Husted, "Boost System Developement for Gasoline Direct-Injection Compression-Ignition (GDCI)," *SAE international 2013-01-0928,* 2013.

[16] M. Sellnau, K. Hoyer, W. Moore, M. Foster, J. Sinnamon and W. Klemm, "Advancement of GDCI Engine Technology for US 2025 CAFE and Tier 3 Emsissions," *SAE Technical Paper 2018-01-0901,* 2018.

[17] M. F. W. M. J. S. K. H. W. K. Mark Sellnau, "Pathway to 50% Brake Thermal Efficiency Using Gasoline Direct Injection Compression Ignition," *SAE Advances and Current Practices in Mobility* , vol. I, no. 4, 2019.

[18] K. Cho, E. Latimer, M. Lorey, D. J. Cleary and M. Sellnau, "Gasoline Fuels Assessment for Delphi’s Second Generation Gasoline Direct-Injection Compression Igntion (GDCI) Multi-Cylinder Engine," *SAE Technical Paper 2017-01-0743,* 2017.

[19] M. Sellnau, W. Moore, J. Sinnamon, K. Hoyer, M. Foster and H. Husted, "GDCI Multi-Cylinder Engine for High Fuel Efficiency and Low Emissions," *SAE Technical Paper 2015-01-0834,* 2015.

[20] Toyota Motor Corporation, "2.0 - Liter Dynamic Force Engine, a New 2.0 - liter Direct-Injection, inline 4-cylinder Gasoline Engine," 29 February 2018. [Online]. Available: https://global.toyota/en/mobility/tnga/powertrain2018/engine/. [Accessed 4 April 2022].

[21] J. H. M. S. N. F. S. Z. N. R. J. a. P. Z. Antowan Zyada, "Demonstration of Better than Diesel Efficiency and Soot Emissions using Gasoline Compression Ignition in a Light Duty Engine with a Fuel Pressure Limitation," *SAE Technical Paper 2021-01-0518,* 2021.

[22] AVL, "AVL," [Online]. Available: https://www.avl.com/-/gp15dk. [Accessed 28 10 2021].

[23] J. d. Naber, J. R. Blough, D. Frankowski, M. Goble and J. E. Szpytman, "Alaysis of Combustion Knock Metrics in Sprak-Ignited Engines," in *SAE World Congress*, Detroit, 2006.

[24] Hyundai, MTU, Phillips 66, *Co-Optimized Light Duty Multi-Mode Engine, Annual Merit Review 2020, FT:087,* US Department of Energy, Office of Energy Efficiency and Renewable Energy, 2020.

[25] WM International Engineering, "WM International Engineering," [Online]. Available: https://www.wminternational-engineering.com/home. [Accessed 4 4 2022].

A Cylinder Pressure instrumentation

A.1 Piezo Electric Pressure Transducers

For cylinder pressure transducers AVL GP15DK transducers were used. These transducers have the following specifications collected from the AVL specifications sheet, [22], Table A.1. The transducers were mounted between the exhaust valves perpendicular to the fire deck.

Table A.1. AVL GP15DK cylinder pressure transducer specification

Specifications:	
Pressure range	0-500 bar
Sensitivity, (Nominal)	10 pC/bar
Calibration ranges	0-80 bar 0-150 bar 0-300 bar
Natural Frequency	170 kHz
Load change drift	7 mbar/ms
Linearity	≤ ± 0.3%

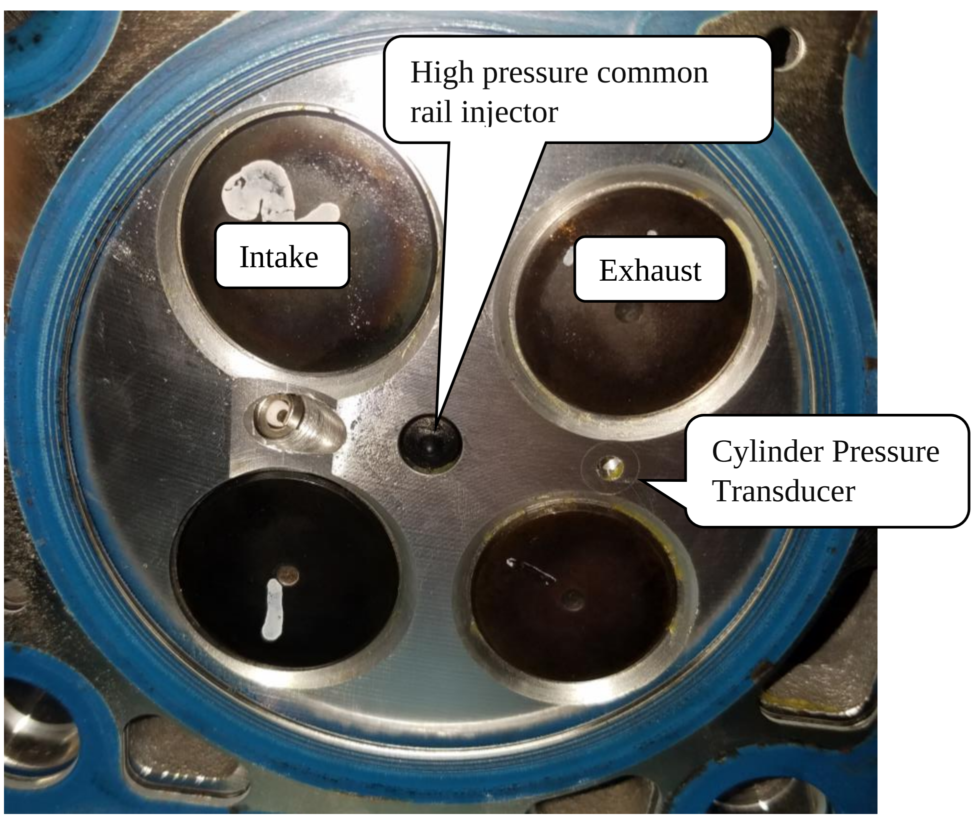

Figure A.1. Cylinder Head instrumented with pressure transducer and an added spark plug

A.2 BEI Optical Encoder

360 PPR BEI optical encoder model: XH20DB-37-SS-360-ABZC-28V/V-SM18 was used to phase cylinder pressure with crank angle pictured in Figure A.2.

Figure A.2. BEI Optical Encoder

A.3 AND CAS

CAS was the combustion analyzer used to interpret the cylinder pressure. CAS was also used to log other signals such and MAP and Exhaust pressure relative to crank angle. The charge amplifier used was a DSP 1108 with a cutoff frequency of 50kHz and a medium time constant.

B Emissions Analysis

B.1 Horiba 5 gas analyzer

The Horiba model MEXA-1600D 5-Gas bench was utilized to measure dry exhaust gas emissions from the engine. The measurements were taken downstream of the turbocharger through a heated sample line, into a heated filter, and then another heated line to the bench. Table B.1 lists the exhaust gas constituents measured and the methods used for detection. Note that NO_2 is not measured directly but is converted to NO and then measured with the same chemiluminescence method used to measure the NO.

Table B.1. Horiba 5-Gas Bench Analyzer Detection methods

Exhaust Gas Constituent	**Detection Method**
O_2	Magneto-Pneumatic detection
CO_2	Non-dispersive infrared
CO	Non-dispersive infrared
NO	Chemiluminescence
NO_2	NO_2 to NO converter, Chemiluminescence
Total Hydrocarbons	Flame Ionization (FID)

B.2 Cummins OEM NOx Sensor

Cummins model 5293295RX NOx sensor was in the exhaust stream and read via CAN to NI Veristand. This sensor reads out O_2 concentration as well as NO_x. These values numbers were used to compare with the Horiba 5 gas bench and followed closely, especially for the NOx Figure B.1.

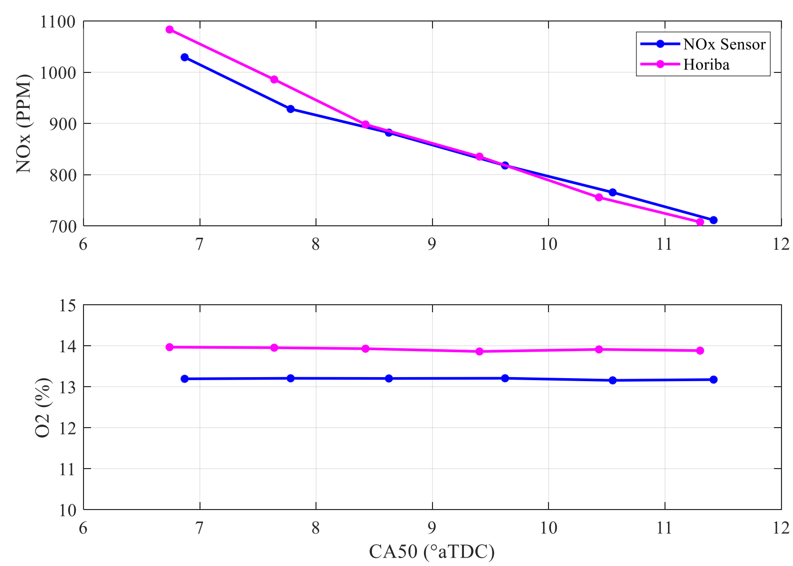

Figure B.1. NOx sensor and Horiba Comparison across a CA50 Sweep for RON 91 E10 at 1500 rpm, 4.6 bar BMEP

C Control Point Repeatability

C.1 Motoring Control Points

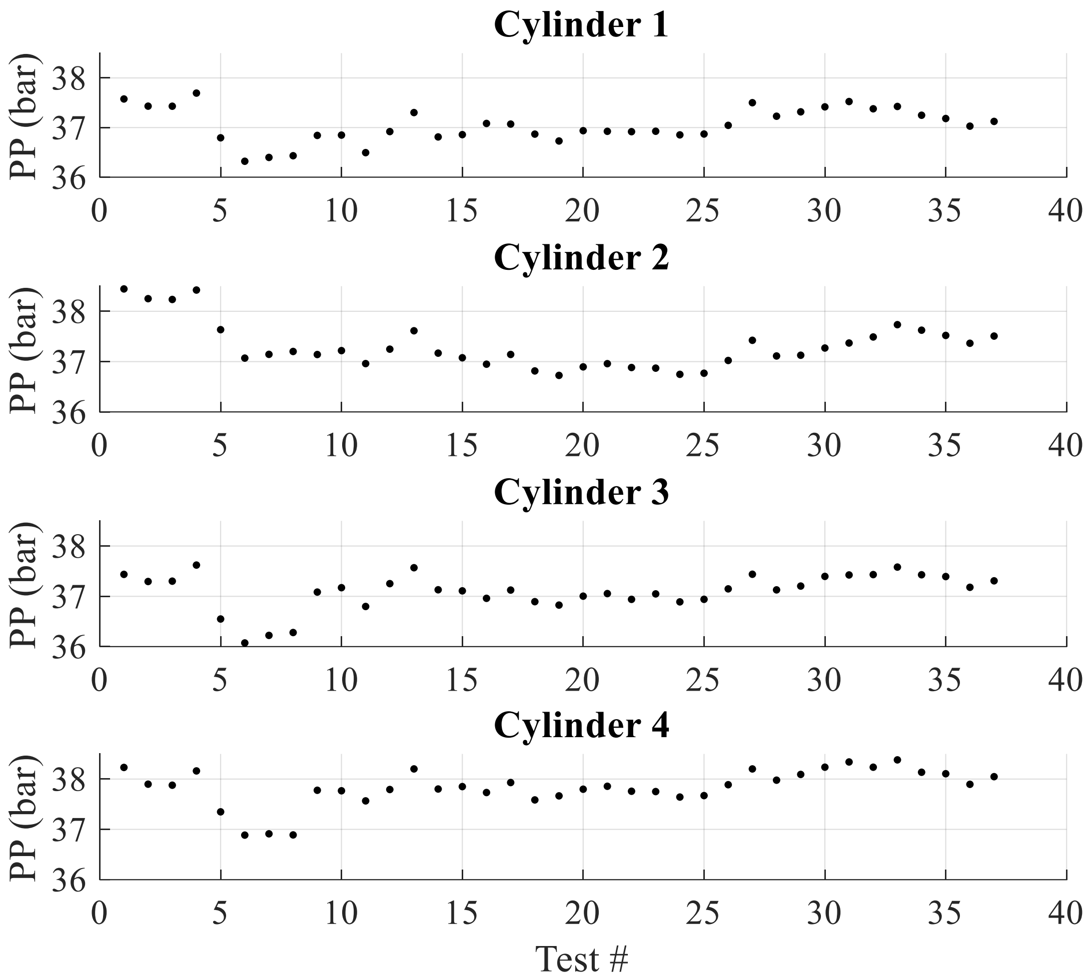

Figure C.1. Motoring Peak Cylinder pressure control point, 1500 rpm, 95 kPa MAP

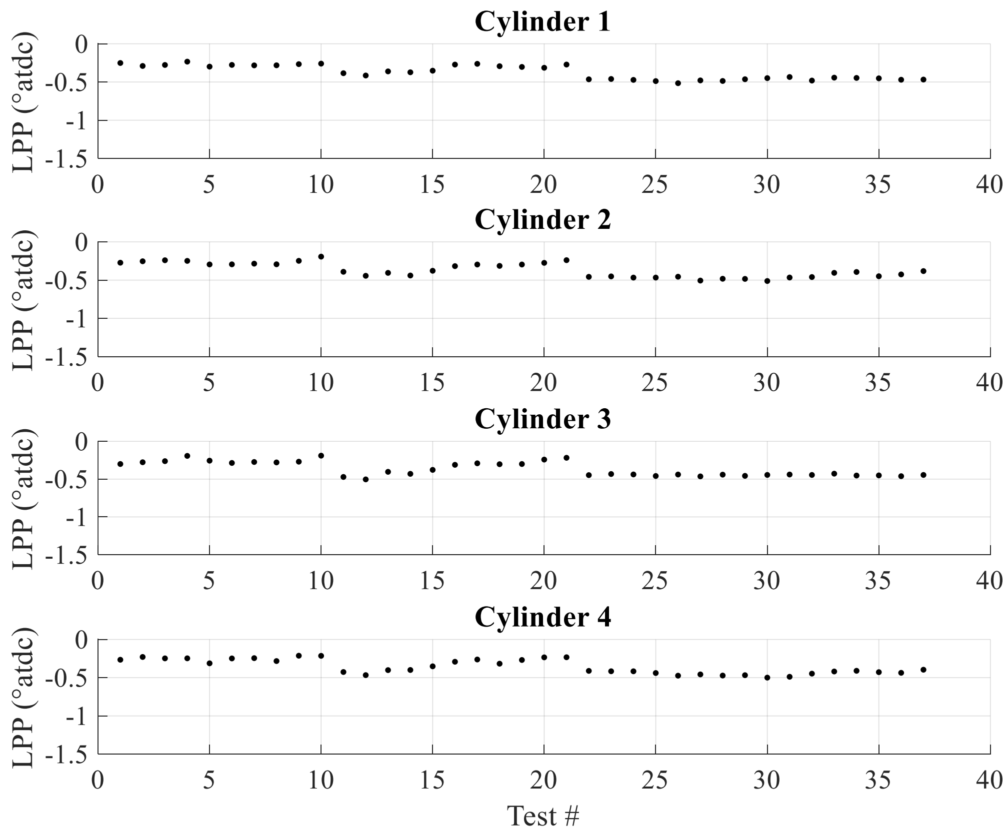

Figure C.2. Location of peak cylinder pressure, 1500 rpm, 95 kPa MAP control point

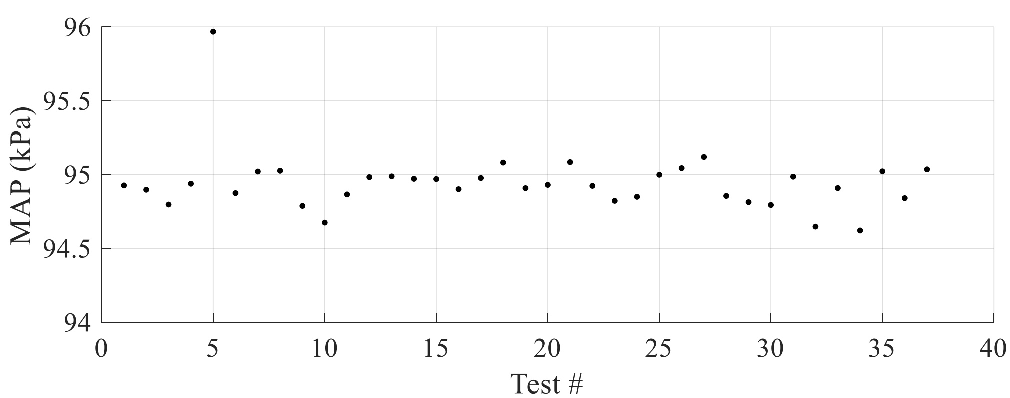

Figure C.3. MAP at 1500 rpm, 95 kPa MAP control point

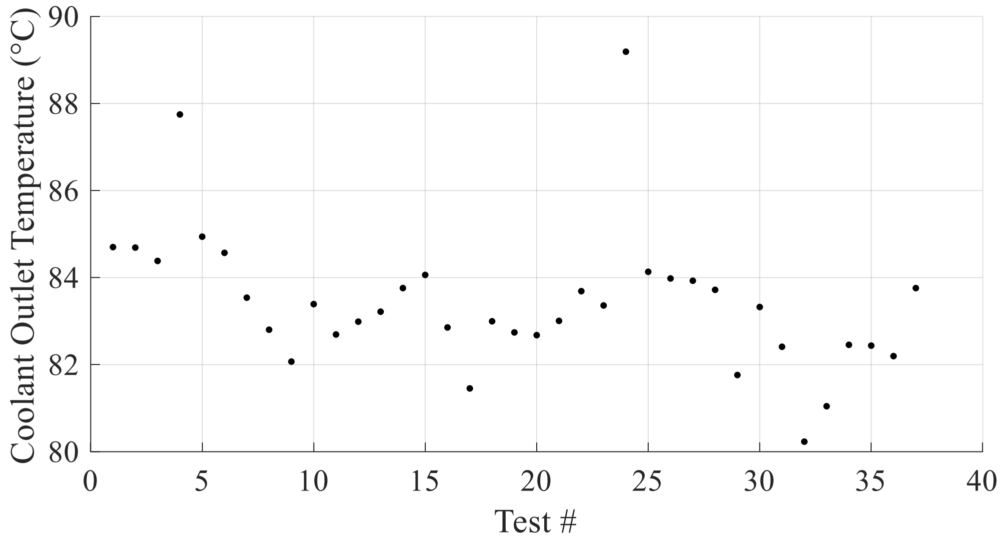

Figure C.4. Coolant outlet temperature at 1500 rpm 95 kPa MAP control point

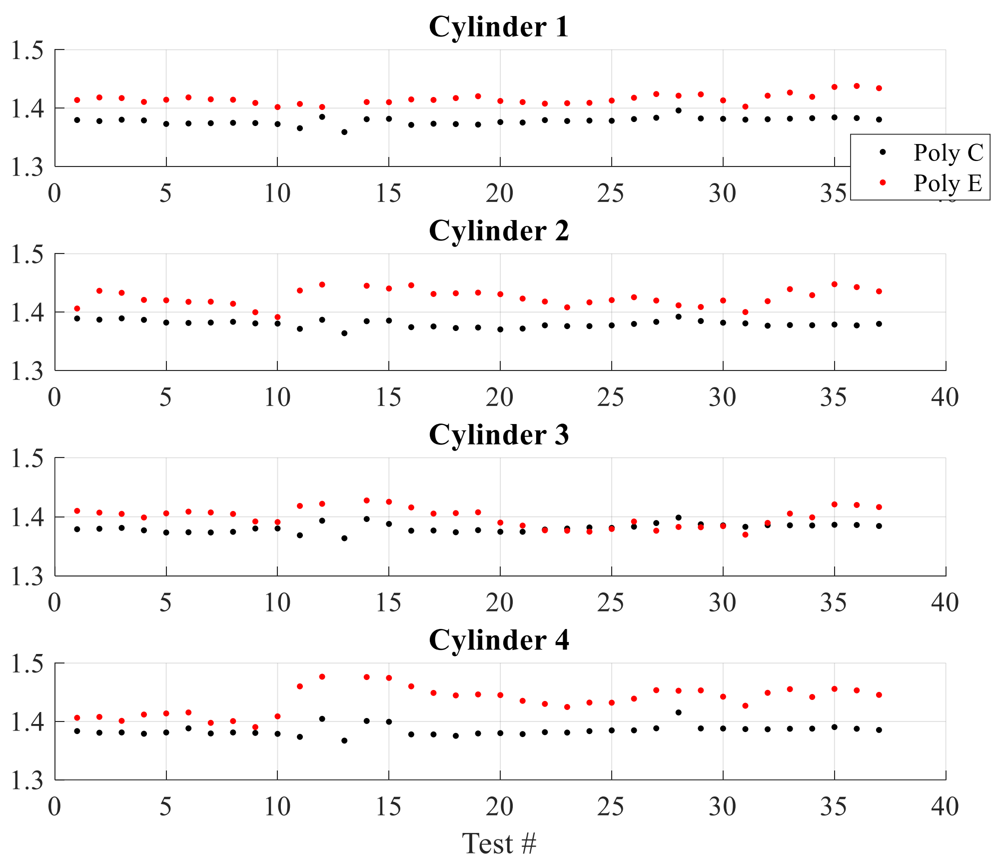

Figure C.5. Polytropic for each cylinder at 1500 rpm, 95 kPa MAP control point

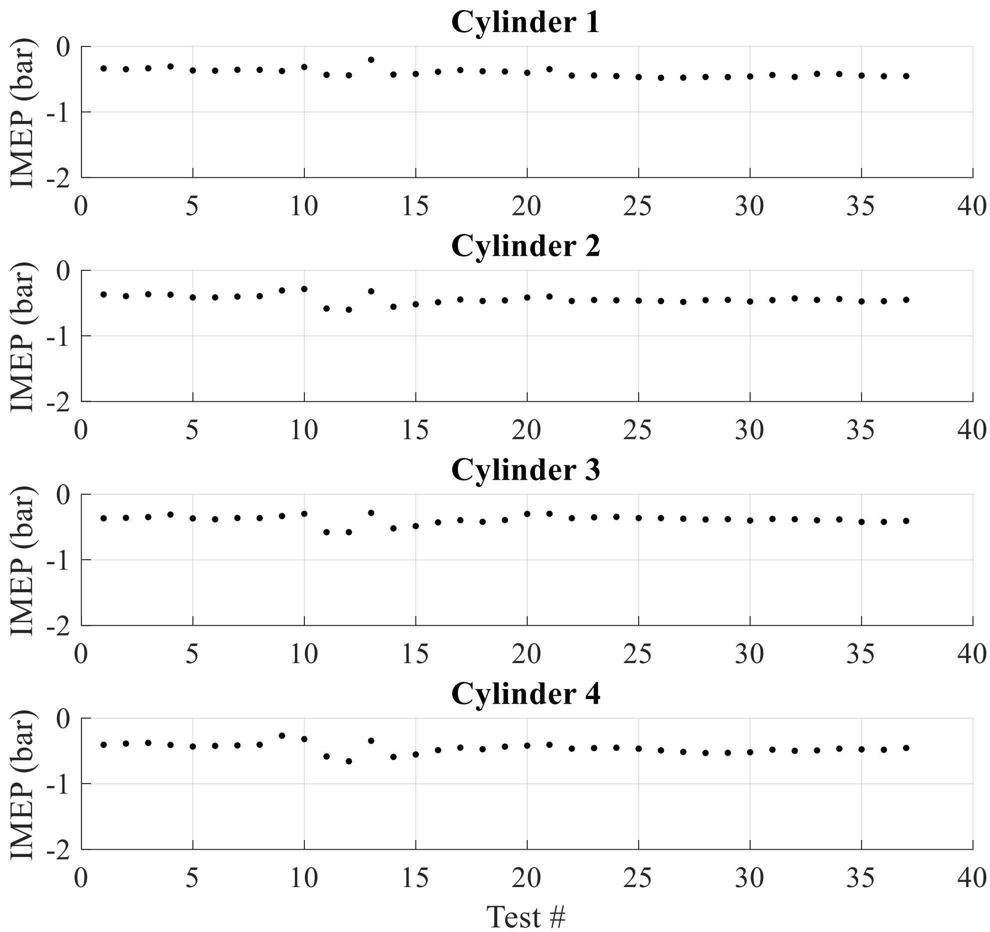

Figure C.6. Motoring IMEPg at 1500 rpm, 95 kPa motoring control point

C.2 Firing Control Points

Firing control points shown in this chapter are from the RON91 E10 test days only to show the repeatability of measurements across the entire project. Each test day the motoring control point was done the same and the firing point was done at the same conditions but with the test fuel for that given day.

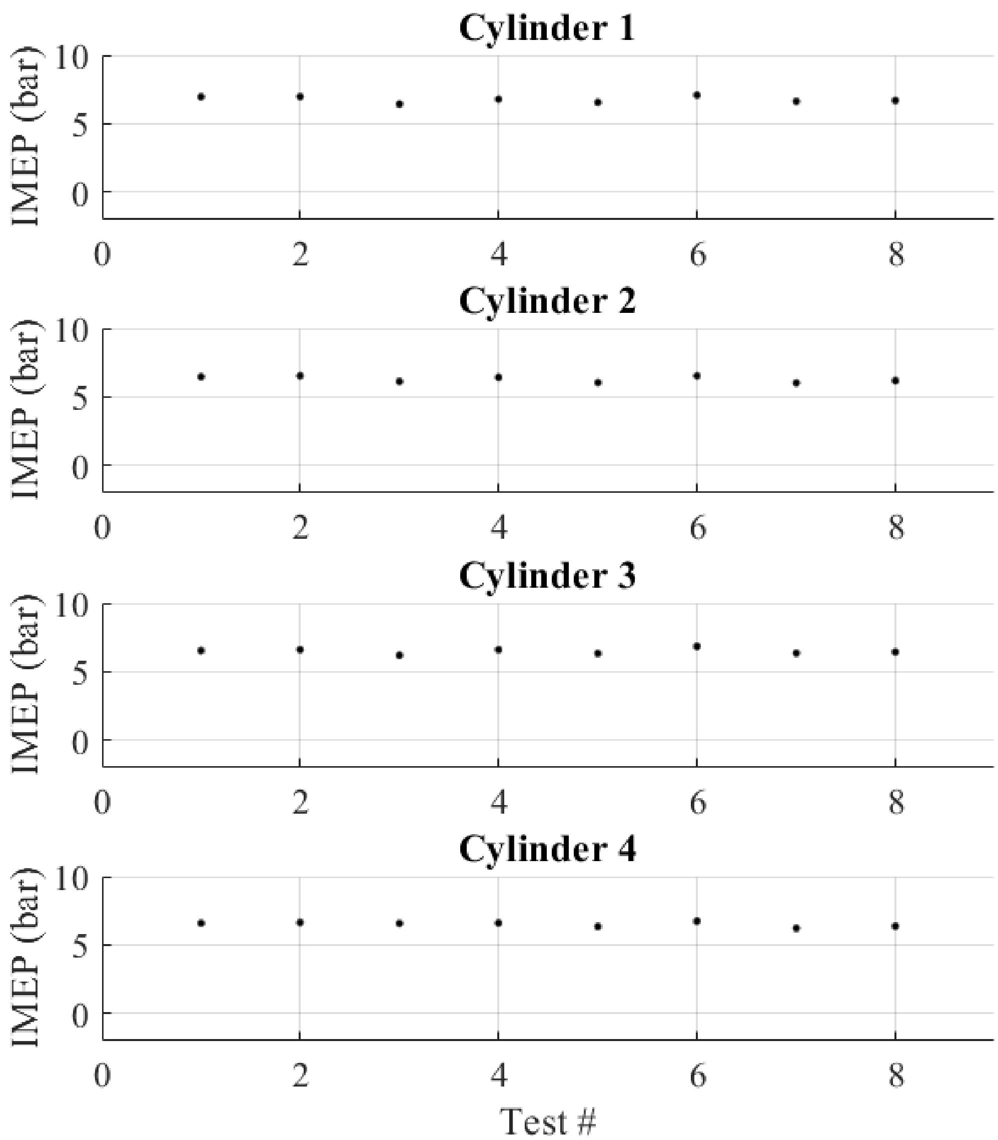

Figure C.7. Firing control point IMEPg for RON 91 E10

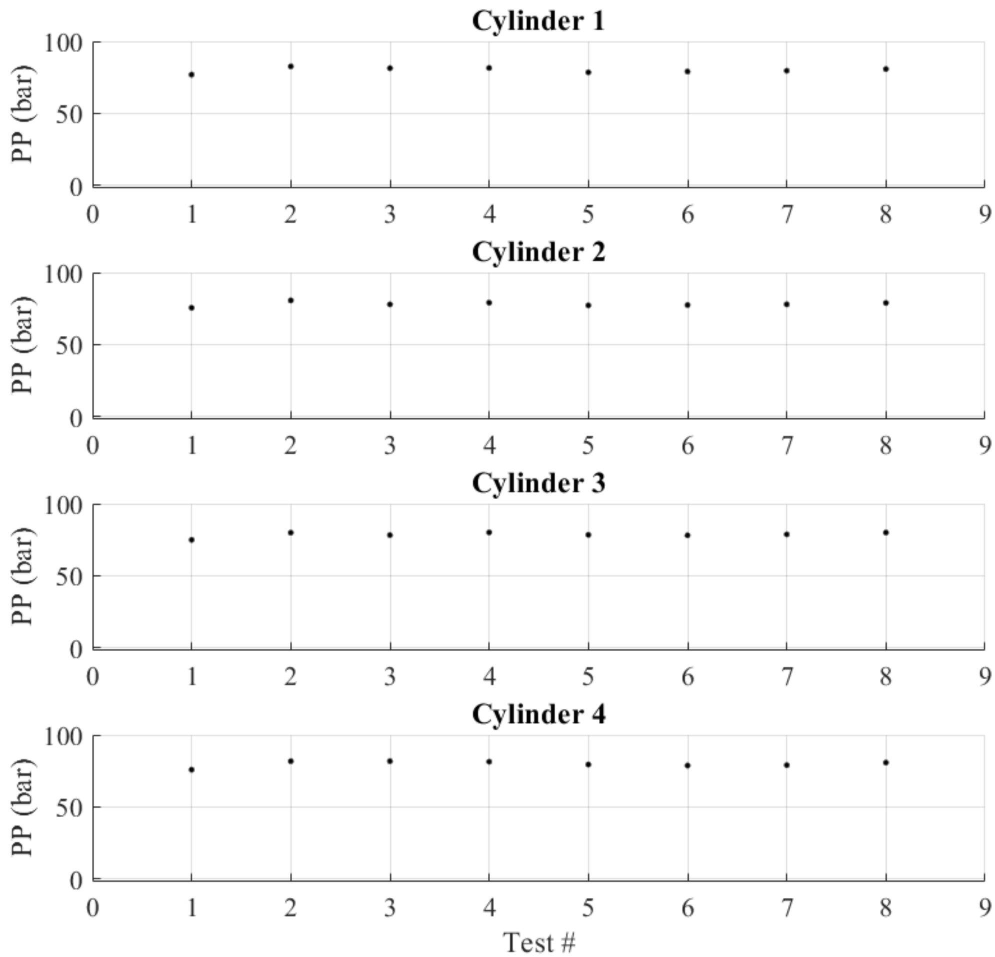

Figure C.8. Peak Pressure for firing control point

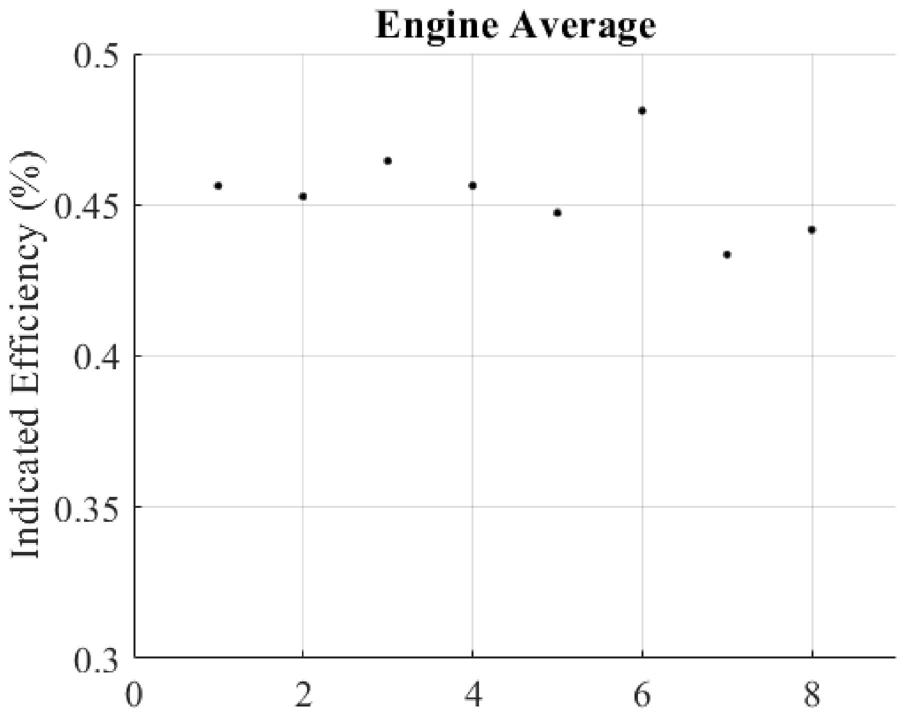

Figure C.9. ITE for firing control point

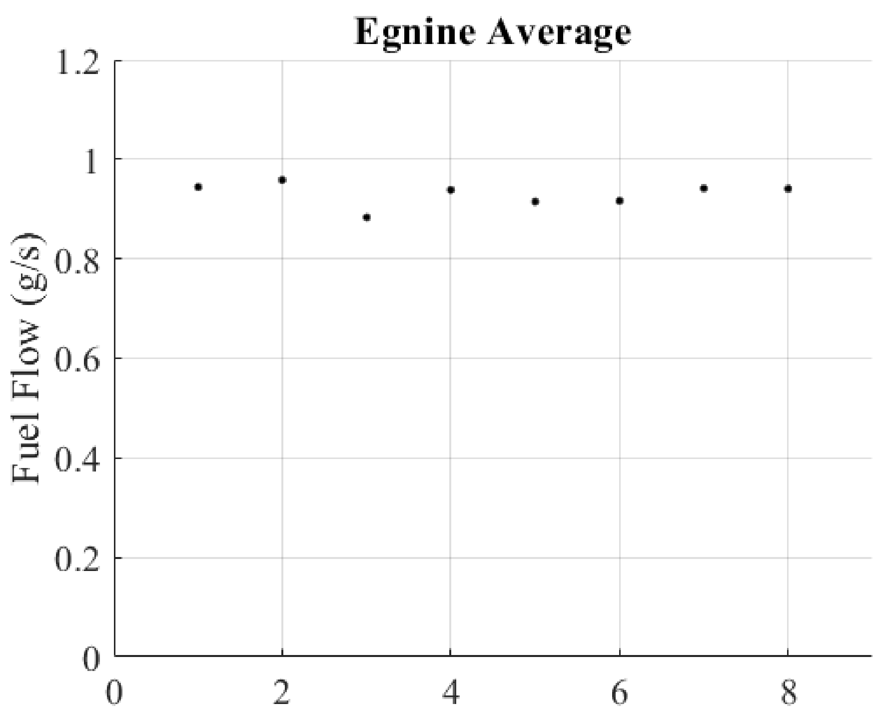

Figure C.10. For firing control point

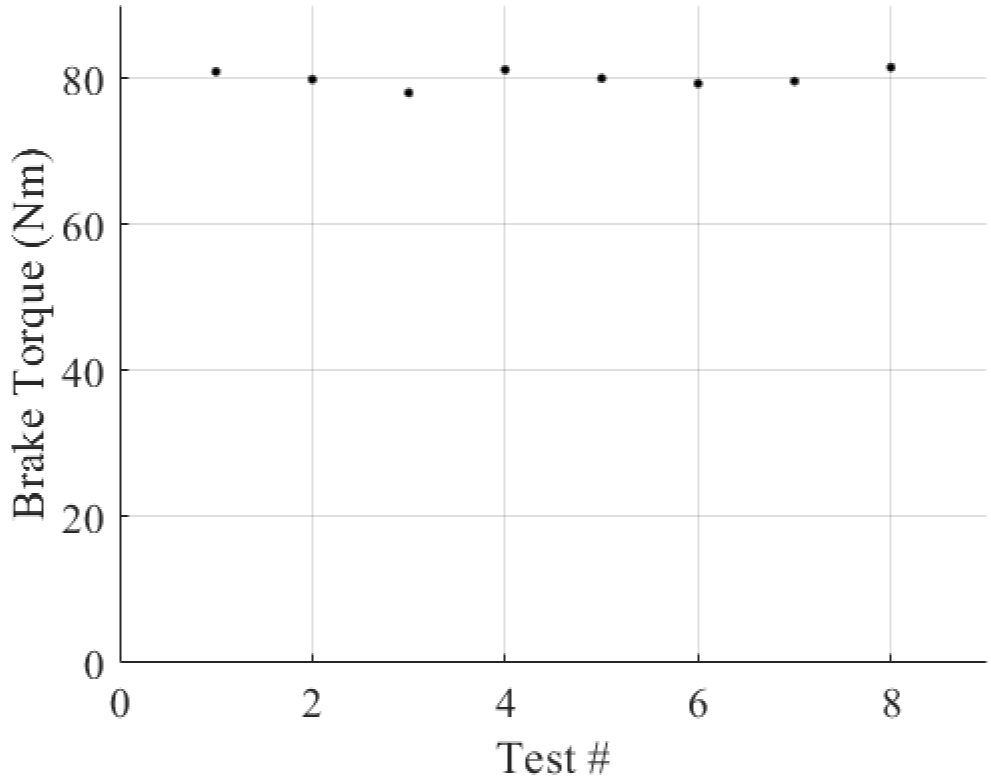

Figure C.11. Brake Torque for firing control point

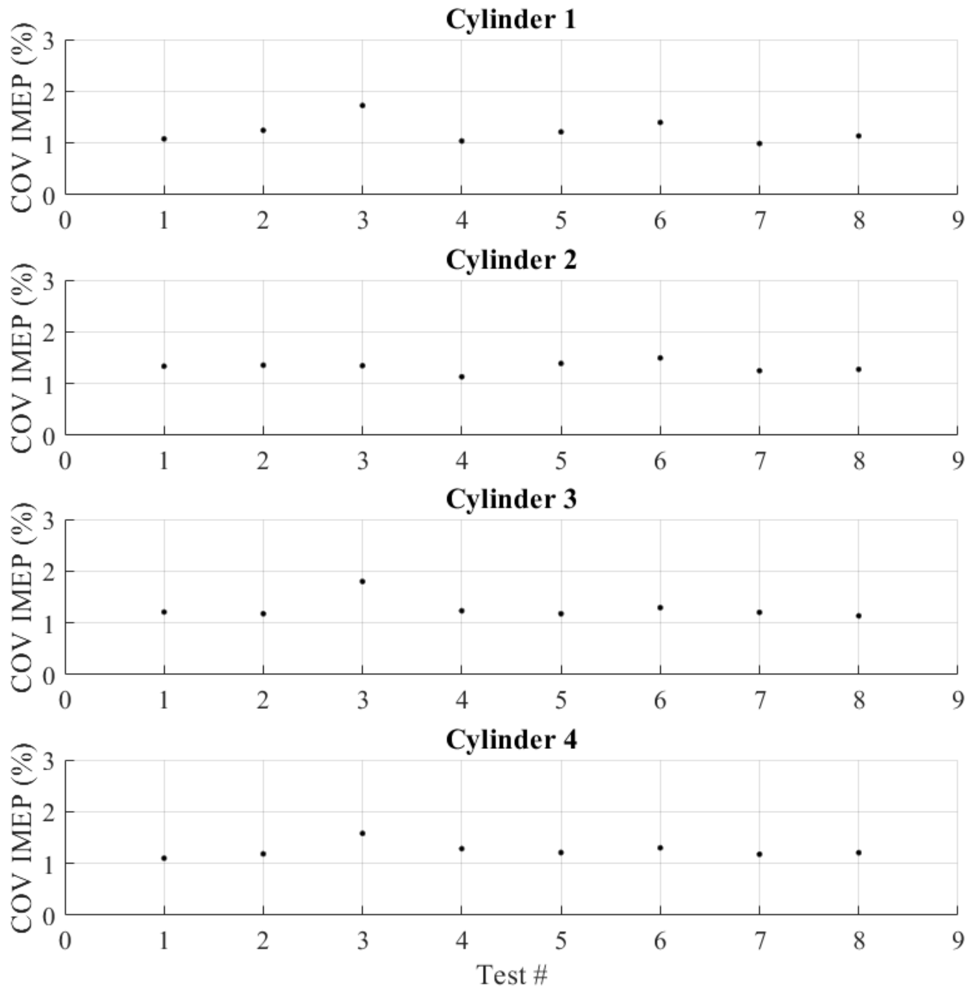

Figure C.12. COV of IMEP for firing control point

D Heat Release Analysis Calculations

D.1 Cylinder Pressure Referencing

Due to the lack of sensitivity of the cylinder pressure transducers, a dual referencing method had to be used to reference the cylinder pressure. This meant that the cylinder pressure was pegged during the intake stroke and the exhaust stroke to the MAP and the turbine inlet pressure at the corresponding angular positions, Figure D.1, choosing a location early in the exhaust stroke and late in the intake stroke, points were chosen from those two windows. With these two reference points for each cycle, a spline interpolation was used between each of the consecutive points. Resulting in a continuous reference pressure vector, the same length as the pressure vector. Taking the difference between the two resulted in an offset which was applied to the raw pressure signal.

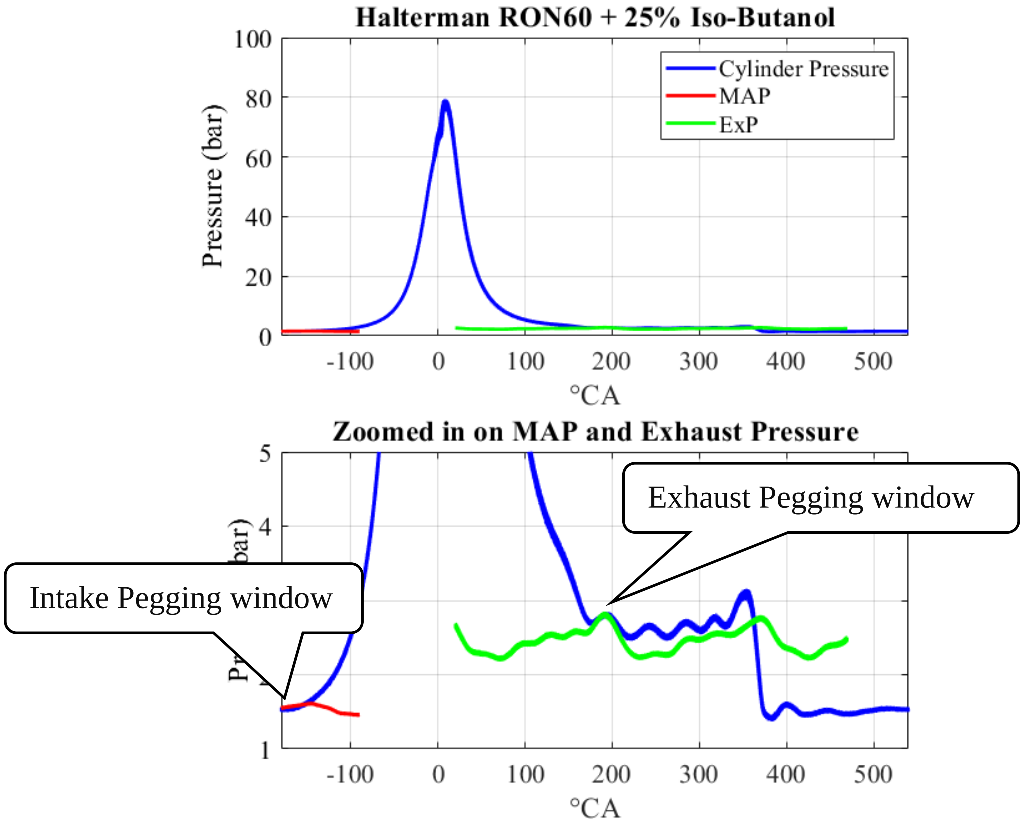

Figure D.1. Dual Cylinder pressure pegging illustration

D.2 Pressure and Heat Release Analysis

Heat release analysis was done with the relationship found in [6] Eq. 10.6 where the ratio of specific heats was found during compression and expansion and transitioned from compression to expansion centered around TDC over a 10 CAD window.

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma-1} * p\left(\frac{dV}{d\theta}\right) + \frac{1}{\gamma-1} * V\left(\frac{dp}{d\theta}\right) \qquad \text{Equation D.1}$$

E Hydra SCRE Spark Ignited, knock limit experiments

To mimic the spark ignited performance of the high compression ratio multi-cylinder engine the piston in the Riccardo Hydra single-cylinder research engine (SCRE) at MTU was changed to raise the compression ratio to 15.3:1. The purpose of the testing on the SCRE was to determine the upper load range of the Phillips 66 blended fuels in spark-ignited mode at lambda 1.

Engine specifications of the MTU SCRE are shown in Table E.1. The engine is under square with a longer stroke than the diameter of the bore. Valve timing was independently controlled, and the intake and exhaust camshafts could be advanced and retarded as needed. They each have ~60°CA of authority.

Table E.1. MTU SCRE Engine Specifications

Attribute	**unit**	**Value**
Bore	mm	86.0
Stroke	mm	94.6
Connecting Rod Length	mm	153.0
Compression Ratio	-	15.3

For the experiments conducted on the SCRE the testbed was configured as shown in Figure E.1. Direct fuel injection during the intake stroke was used for the fuel delivery and the injection pressure was 100 bar. Cam phasing was held at the maximum volumetric efficiency point, the exhaust camshaft centerline was at -110°aTDC gas exchange and the intake was at 130°aTDC gas exchange. This is a late intake valve closing configuration with the intake valve closing ~90°bTDC.

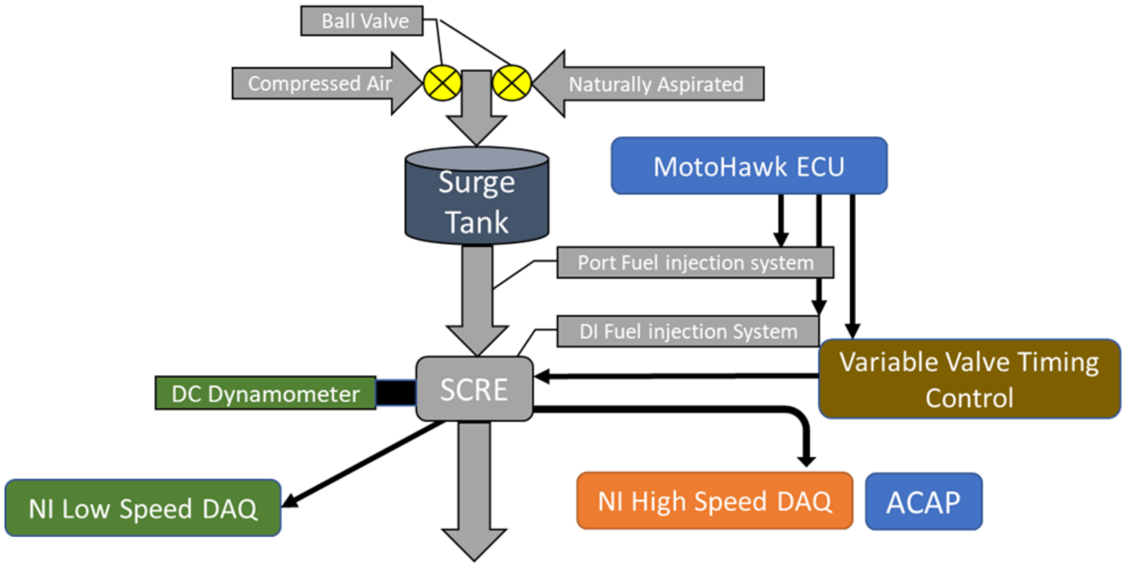

Figure E.1. MTU SCRE Testbed configuration

E.1 Test Matrix

The test matrix for these experiments included two engine speeds, 1500 and 2000 rpm. At each speed, three loads were tested, 3.3, 4, and 5 bar NMEP. To determine the combustion phasing limits, an MBT CA50 location of 8°aTDC was used and the knock limit of 150 kPa pk-pk in the 95^{th} percentile. There were 600 cycles recorded at each point to ensure accurate knock statistics. Injection of the fuel was done with a Bosch gasoline direct injector at a pressure of 100 bar. The intake air temperature was atmospheric, ~25°C.

E.2 Test Results

E.2.1 Knock limit Determination

To determine what knock level should be used as a limit for advancing combustion so testing was required. When measuring knock levels on this engine, an NI high-speed data acquisition system was used to log the cylinder pressure and apply a bandpass filter. Once the pressure is filtered, the peak-peak amplitude of that cycle can be measured. Throughout the previous 100 cycles, statistical analysis was applied to find the 95^{th} peak-peak amplitude of the 95^{th} percentile of knock. As mentioned in [23], knock is a stochastic phenomenon that needs to be analyzed as such. There can be high knocking cycles that will not impact the average knock level but could still be damaging to the engine.

Determining the knock limit required experiments to be carried out at varying knock levels. As the knock level increases, the rate at which it increases is exponential. Figure E.2 shows the exponential fit over the 95^{th} percentile knock amplitude of 600 cycle data sets recorded at each spark advance. The solid black horizontal line shows the 150 kPa

peak to peak knock level on each plot. Four different speed load points were tested and a common knock limit of 150 kPa peak to peak was chosen. As it can be seen, at that level, the amount of increase in knock increases quickly as the spark is advanced further. The knock was audible at these levels as well, it is common to see higher amplitudes reached on other engines but due to the one-off nature of this engine and to avoid damage to the engine this level was used as the limit.

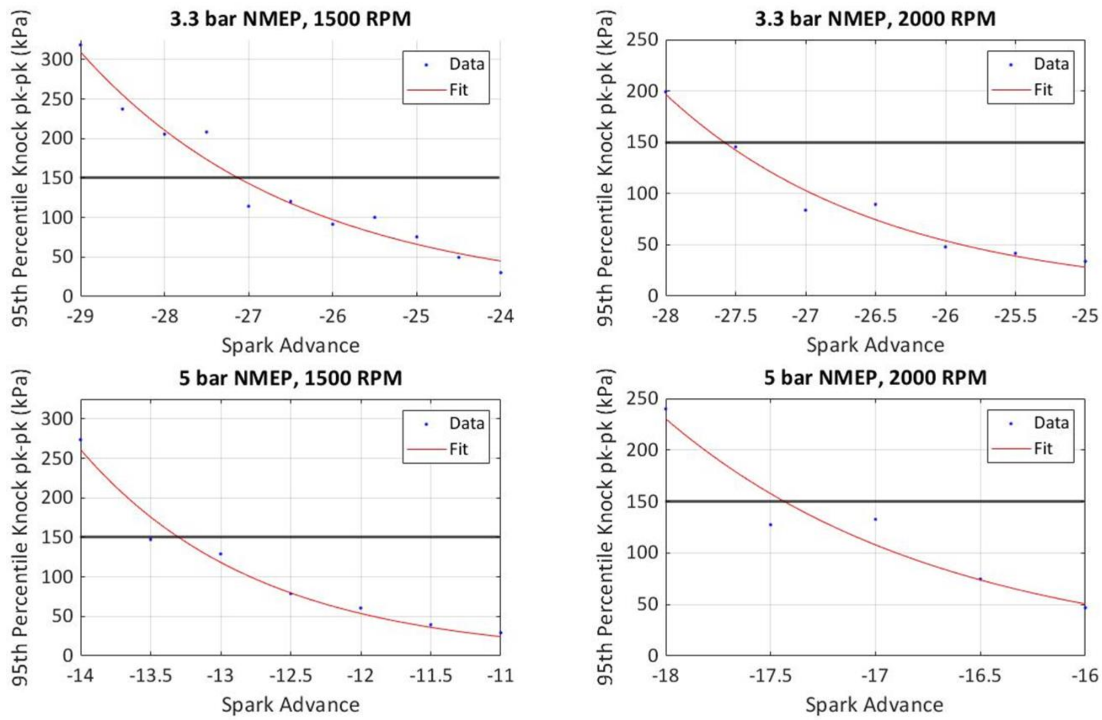

Figure E.2. Knock limit determination, knock levels over a spark sweep

E.2.2 Fuel Reactivity Effects

Testing was successfully done on three different fuels with different RONs of 70, 80, and 90. A RON60 blend was tried but the operation was unsuccessful, with high knock levels and combustion stability problems. Figure E.3 displays the results from the experiments at each speed and each load. As load increases, combustion becomes more knock limited as expected. Even at the lowest load, the RON70 was relatively knock limited with the standard valve timing shown in the top row of Figure E.3. At the highest load, 5 bar NMEP, the RON70 knock limited combustion phasing was at >26°aTDC, far from the 8°aTDC that was being used as MBT. Showing a severe deficit in efficiency due to combustion being so retarded.

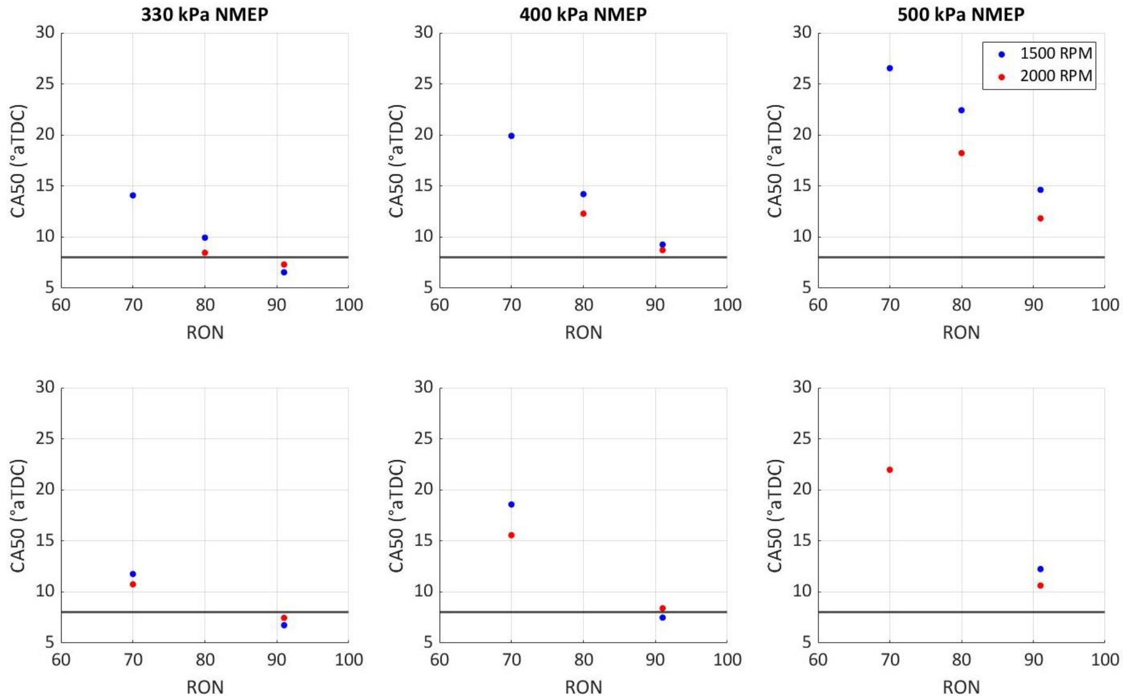

Figure E.3. Fuel Effects on combustion phasing, top row: IMOP of 130° aTDC GE, bottom row: IMEP of 140° aTDC GE

The results of the experiments are continued in Figure E.4, the COV of IMEPg for the RON 70 is greater than 5%. The RON80 yields combustion with a COV of less than 5% for each of the loads. These experiments were intended to assist in choosing a fuel desirable for the multi-mode engine. A desirable fuel will have the highest reactivity possible allowing for SI mode to extend to a medium load. This will allow for the combustion mode transition to be at a load that is easily operated at in each combustion mode.

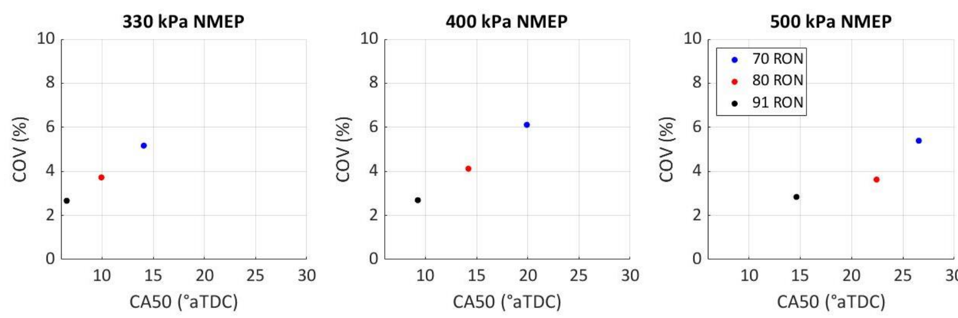

Figure E.4. Fuel effect on COV of IMEPg at 1500 rpm and IMOP of 130° aTDC GE

These experiments yielded results that showed that the RON 80 would be the best fuel based on these results. The results showed that the RON 80 did not impact the upper limit of SI mode greatly and it should yield an easy transition to compression ignition at 5 bar NMEP.

F Fuel System

To maintain the high-pressure diesel injection system along with supplying the port fuel injection system, the fuel system was complex in comparison to normal systems. Mass flow measurements also were required to be made to the lump sum of fuel supplied to the system to know what the fuel consumption rate was.

F.1 Fuel System Schematic

The system consisted of two 12 VDC inline fuel pumps, the first pump was to draw the fuel from the tank. This pump drew the fuel from the cell and pushed it through a fuel pressure regulator set at 1 bar. Once the fuel passed through the regulator it entered a micro-motion Coriolis flow meter where the mass flow measurements were made. This is pressure is what the fuel returns to when relieved from the common rail shown in Figure F.1. The fuel returning from the common rail and from the pressure regulator before the high-pressure fuel pump was cooled to 20°C to prevent valorization. When relieving gasoline from a high pressure of 250-350 bar to 1 bar, there is a lot of heat in the fuel from the work being done on it in the high-pressure pump. This causes instant fuel vaporization in the fuel lines. The vapor bubbles in the lines have a much lower density than the liquid fuel resulting in errors in the mass flow measurement. This system was revised multiple times with different accumulators added, temperatures varied etc. to minimize the error in the measurement.

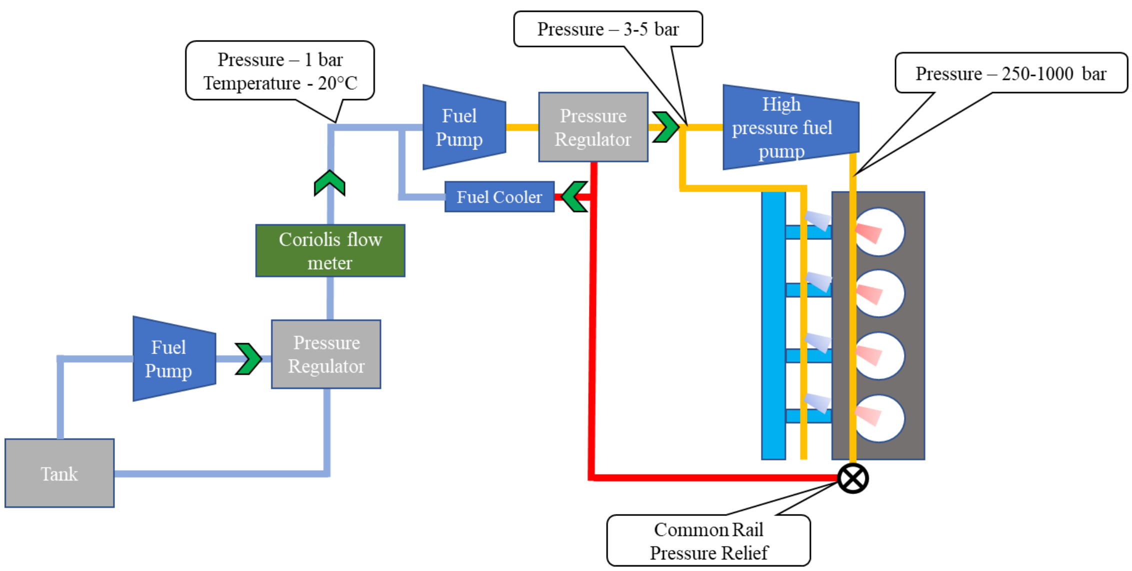

Figure F.1. Fuel system schematic

G Engine Conditioning system

G.1 Engine Coolant Pre-Heater

For preheating of the engine coolant, a 10kW Tempco immersion heater was inserted into the cooling system shown in Figure G.1**Error! Reference source not found.**. To Circulate the coolant while the engine was not spinning a circulation pump for a boiler system in a home was used. A double-acting pneumatic ball valve was installed to direct the coolant through the circulation pump when the engine water pump is not in use. This also can be used if an engine does not have a water pump, ie and SCRE.

Figure G.1. Engine coolant pre-heater and circulation system configuration

To heat the coolant there is one relay, shown in the electrical panel in Figure G.2, that controls both the air solenoid valve and the circulation pump. A 12VDC digital signal is sent from a relay in the test cell control cabinet to the 12 VDC solid-state relay which in turn electrifies the 120 VAC single phase circulation pump and solenoid valve simultaneously. This configuration ensures the pump is on if the valve is shut. For control of the 480VAC 3-phase immersion heater, a Watlow SCR heater controller was used. This modulates the 3-phase electricity sinusoidal waves based on a 4-20mA duty cycle input. For example, if 25% is requested then for every 4 sine waves, the heater is on for one and off for 3. To disable the 480 VAC to the heater there is a contactor with overload protection. This contactor has a 120 VAC coil which is actuated by the other solid-state relay in the same fashion as the circulation system described previously. In the circuit to the coil, the built-in thermal switch in the heater is, allowing for the contactor to be disabled if the heater overheats the coolant in the event the pump is unable to circulate the coolant for some reason.

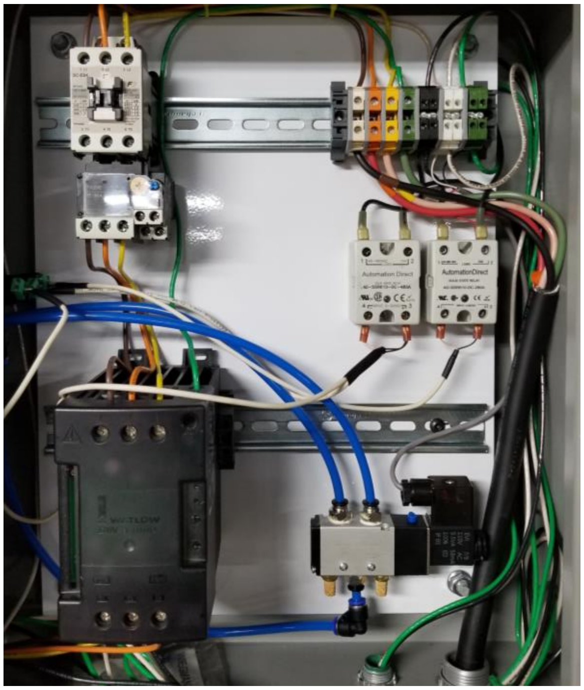

Figure G.2. Engine coolant pre-heater and circulation system electrical panel

G.2 Oil and Charge air heater cart

The oil and charge air heater cart consists of two immersion heaters and two pumps. To control the 480 VAC immersion heaters there are Watlow SCR controllers like the engine coolant pre-heater. The electrical control for the two heaters is the same as the coolant pre-heater with a contactor and solid-state relays along with the thermal switches in the heaters preventing over-temperature situations, Figure G.3.

Figure G.3. Oil and charge air conditioning cart electrical configuration

The cart consists of a 5-gallon aluminum tank for the charge air heating portion. The tank contains the immersion heater and has a 1.1 bar radiator cap to allow for pressurization to be able to reach liquid temperatures above boiling shown in Figure G.4. A circulation pump for an in-home boiler system is used in the system as well to circulate the coolant used as a working fluid to transfer the heat from the electric heater to the heat exchanger in the intake.

The oil pre-heating system consists of a Moroso dry sump pump driven by a 3hp AC electric motor. One stage of the pump is used to circulate the engine oil from the engine cart and through the 2.5” diameter pipe containing the immersion heater. From the immersion heater, the oil enters an oil filter before returning to the engine cart Figure G.4.

Figure G.4. Oil and charge air heater cart

H Copyright documentation

H.1 Multi-Mode Operation Map, Figure 1.1, Copyright Agreement

Zach Stanchina <zjstanch@mtu.edu>

Tue, Jul 12, 10:24 AM (2 days ago)

to Shengrong

Sheng,

I would like to use the following figure from the AMR 2021 presentation published online in my thesis's goals and objectives section in my thesis.

image.png

Can I have permission for the use of this material? I am just confirming for copyright reasons.

- Zach

Zachary Stanchina

Michigan Technological University

Mechanical Engineering - Graduate Student

Advanced Power Systems Research Center - GRA

Phone: (906)-396-6576

Email: zjstanch@mtu.edu

Shengrong Zhu

Tue, Jul 12, 8:07 PM (2 days ago)

to me

Hi Zach,

Yes. You could reference it as needed: Zoldak, P.S., Zhu, S., "Hyundai multi-mode GCI engine," Annual Merit Review, Vehicle Technologies Office, Department of Energy, June 21-24, 2021.

Thank you.

Best Regards,

Sheng

Zach Stanchina <zjstanch@mtu.edu>

Wed, Jul 13, 9:45 AM (1 day ago)

to Shengrong

Thank you Sheng.

H.2 Trend of Emissions with Equivalence ratio, Figure 2.1, Copyright agreement

Order Date15-Jun-2022

Order License ID1208937-1

ISBN-139781260116106

Type of UseRepublish in a thesis/dissertation

PublisherMcGraw-Hill Education

PortionImage/photo/illustration

LICENSED CONTENT

Publication TitleInternal Combustion Engine Fundamentals 2E

Author/EditorHeywood, John

Date05/10/2018

LanguageEnglish

CountryUnited States of America

RightsholderMcGraw Hill LLC

Publication TypeBook

REQUEST DETAILS

Portion TypeImage/photo/illustration

Number of images / photos / illustrations1

Format (select all that apply)Print, Electronic

Who will republish the content?Academic institution

Duration of UseLife of current and all future editions

Lifetime Unit QuantityMore than 2,000,000

Rights RequestedMain product

DistributionWorldwide

TranslationOriginal language of publication

Copies for the disabled?Yes

Minor editing privileges?No

Incidental promotional use?No

CurrencyUSD

NEW WORK DETAILS

TitleAn Experimental Study of Fuel Selection for a Multi-Mode, Spark Ignited - Gasoline Compression Ignition Engine

Instructor nameDr. Jeffrey Naber

Institution nameMichigan Technological University

Expected presentation date2022-05-06

ADDITIONAL DETAILS

Order reference numberThesis

The requesting person / organization to appear on the licenseZachary Stanchina

REUSE CONTENT DETAILS

Title, description or numeric reference of the portion(s)Figure 11.2

Editor of portion(s)N/A

Volume of serial or monographN/A

Page or page range of portion601-605

Title of the article/chapter the portion is from11.1 Nature and Extent of Problem

Author of portion(s)Heywood, John

Issue, if republishing an article from a serialN/A

Publication date of portion2018-05-10

RIGHTSHOLDER TERMS AND CONDITIONS

It is the responsibility of the user to verify that the text, figures, images and other material that they wish to use are owned by McGraw Hill LLC. McGraw Hill LLC can only grant permission for the material that they own. Please check the caption of any figures, images, charts, etc., as well as any credits pages at the front or back of the book. McGraw Hill LLC may restrict the portion of the title that may be used.

SPECIAL RIGHTSHOLDER TERMS AND CONDITIONS

Fee waived for Educational Thesis Duration of Use: Current Edition ONLY Lifetime Unit Quantity: 10,000 ONLY

Marketplace Order General Terms and Conditions

The following terms and conditions (“General Terms”), together with any applicable Publisher Terms and Conditions, govern User’s use of Works pursuant to the Licenses granted by Copyright Clearance Center, Inc. (“CCC”) on behalf of the applicable Rightsholders of such Works through CCC’s applicable Marketplace transactional licensing services (each, a “Service”).

1)Definitions.For purposes of these General Terms, the following definitions apply:

“License” is the licensed use the User obtains via the Marketplace platform in a particular licensing transaction, as set forth in the Order Confirmation.

“Order Confirmation” is the confirmation CCC provides to the User at the conclusion of each Marketplace transaction. “Order Confirmation Terms” are additional terms set forth on specific Order Confirmations not set forth in the General Terms that can include terms

applicable to a particular CCC transactional licensing service and/or any Rightsholder-specific terms.

“Rightsholder(s)” are the holders of copyright rights in the Works for which a User obtains licenses via the Marketplace platform, which are displayed on specific Order Confirmations.

“Terms” means the terms and conditions set forth in these General Terms and any additional Order Confirmation Terms collectively.

“User” or “you” is the person or entity making the use granted under the relevant License. Where the person accepting the Terms on behalf of a User is a freelancer or other third party who the User authorized to accept the General Terms on the User’s behalf, such person shall be deemed jointly a User for purposes of such Terms.

“Work(s)” are the copyright protected works described in relevant Order Confirmations.

2)Description of Service.CCC’s Marketplace enables Users to obtain Licenses to use one or more Works in accordance with all relevant Terms. CCC grants Licenses as an agent on behalf of the copyright rightsholder identified in the relevant Order Confirmation.

3)Applicability of Terms.The Terms govern User’s use of Works in connection with the relevant License. In the event of any conflict between General Terms and Order Confirmation Terms, the latter shall govern. User acknowledges that Rightsholders have complete discretion whether to grant any permission, and whether to place any limitations on any grant, and that CCC has no right to supersede or to modify any such discretionary act by a Rightsholder.

4)Representations; Acceptance.By using the Service, User represents and warrants that User has been duly authorized by the User to accept, and hereby does accept, all Terms.

5)Scope of License; Limitations and Obligations.All Works and all rights therein, including copyright rights, remain the sole and exclusive property of the Rightsholder. The License provides only those rights expressly set forth in the terms and conveys no other rights in any Works

6)General Payment Terms.User may pay at time of checkout by credit card or choose to be invoiced. If the User chooses to be invoiced, the User shall: (i) remit payments in the manner identified on specific invoices, (ii) unless otherwise specifically stated in an

Order Confirmation or separate written agreement, Users shall remit payments upon receipt of the relevant invoice from CCC, either by delivery or notification of availability of the invoice via the Marketplace platform, and (iii) if the User does not pay the invoice within 30 days of receipt, the User may incur a service charge of 1.5% per month or the maximum rate allowed by applicable law, whichever is less. While User may exercise the rights in the License immediately upon receiving the Order Confirmation, the License is automatically revoked and is null and void, as if it had never been issued, if CCC does not receive complete payment on a timely basis.

7)General Limits on Use.Unless otherwise provided in the Order Confirmation, any grant of rights to User (i) involves only the rights set forth in the Terms and does not include subsequent or additional uses, (ii) is non-exclusive and non-transferable, and (iii) is subject to any and all limitations and restrictions (such as, but not limited to, limitations on duration of use or circulation) included in the Terms. Upon completion of the licensed use as set forth in the Order Confirmation, User shall either secure a new permission for further use of the Work(s) or immediately cease any new use of the Work(s) and shall render inaccessible (such as by deleting or by removing or severing links or other locators) any further copies of the Work. User may only make alterations to the Work if and as expressly set forth in the Order Confirmation. No Work may be used in any way that is defamatory, violates the rights of third parties (including such third parties' rights of copyright, privacy, publicity, or other tangible or intangible property), or is otherwise illegal, sexually explicit, or obscene. In addition, User may not conjoin a Work with any other material that may result in damage to the reputation of the Rightsholder. User agrees to inform CCC if it becomes aware of any infringement of any rights in a Work and to cooperate with any reasonable request of CCC or the Rightsholder in connection therewith.

8)Third Party Materials.In the event that the material for which a License is sought includes third party materials (such as photographs, illustrations, graphs, inserts and similar materials) that are identified in such material as having been used by permission (or a similar indicator), User is responsible for identifying, and seeking separate licenses (under this Service, if available, or otherwise) for any of such third party materials; without a separate license, User may not use such third party materials via the License.

9)Copyright Notice.Use of proper copyright notice for a Work is required as a condition of any License granted under the Service. Unless otherwise provided in the Order Confirmation, a proper copyright notice will read substantially as follows: "Used with permission of [Rightsholder's name], from [Work's title, author, volume, edition number and year of copyright]; permission conveyed through Copyright Clearance Center, Inc." Such notice must be provided in a reasonably legible font size and must be placed either on a cover page or in another location that any person, upon gaining access to the material which is the subject of a permission, shall see, or in the case of republication Licenses, immediately adjacent to the Work as used (for example, as part of a by-line or

footnote) or in the place where substantially all other credits or notices for the new work containing the republished Work are located. Failure to include the required notice results in loss to the Rightsholder and CCC, and the User shall be liable to pay liquidated damages for each such failure equal to twice the use fee specified in the Order Confirmation, in addition to the use fee itself and any other fees and charges specified.

10)Indemnity.User hereby indemnifies and agrees to defend the Rightsholder and CCC, and their respective employees and directors, against all claims, liability, damages, costs, and expenses, including legal fees and expenses, arising out of any use of a Work beyond the scope of the rights granted herein and in the Order Confirmation, or any use of a Work which has been altered in any unauthorized way by User, including claims of defamation or infringement of rights of copyright, publicity, privacy, or other tangible or intangible property.

11)Limitation of Liability.UNDER NO CIRCUMSTANCES WILL CCC OR THE RIGHTSHOLDER BE LIABLE FOR ANY DIRECT, INDIRECT, CONSEQUENTIAL, OR INCIDENTAL DAMAGES (INCLUDING WITHOUT LIMITATION DAMAGES FOR LOSS OF BUSINESS PROFITS OR INFORMATION, OR FOR BUSINESS INTERRUPTION) ARISING OUT OF THE USE OR INABILITY TO USE A WORK, EVEN IF ONE OR BOTH OF THEM HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES. In any event, the total liability of the Rightsholder and CCC (including their respective employees and directors) shall not exceed the total amount actually paid by User for the relevant License. User assumes full liability for the actions and omissions of its principals, employees, agents, affiliates, successors, and assigns.

12)Limited Warranties.THE WORK(S) AND RIGHT(S) ARE PROVIDED "AS IS." CCC HAS THE RIGHT TO GRANT TO USER THE RIGHTS GRANTED IN THE ORDER CONFIRMATION DOCUMENT. CCC AND THE RIGHTSHOLDER DISCLAIM ALL OTHER WARRANTIES RELATING TO THE WORK(S) AND RIGHT(S), EITHER EXPRESS OR IMPLIED, INCLUDING WITHOUT LIMITATION IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. ADDITIONAL RIGHTS MAY BE REQUIRED TO USE ILLUSTRATIONS, GRAPHS, PHOTOGRAPHS, ABSTRACTS, INSERTS, OR OTHER PORTIONS OF THE WORK (AS OPPOSED TO THE ENTIRE WORK) IN A MANNER CONTEMPLATED BY USER; USER UNDERSTANDS AND AGREES THAT NEITHER CCC NOR THE RIGHTSHOLDER MAY HAVE SUCH ADDITIONAL RIGHTS TO GRANT.

13)Effect of Breach.Any failure by User to pay any amount when due, or any use by User of a Work beyond the scope of the License set forth in the Order Confirmation and/or the Terms, shall be a material breach of such License. Any breach not cured within 10 days of written notice thereof shall result in immediate termination of such License without further notice. Any unauthorized (but licensable) use of a Work that is terminated immediately upon notice thereof may be liquidated by payment of the Rightsholder's

ordinary license price therefor; any unauthorized (and unlicensable) use that is not terminated immediately for any reason (including, for example, because materials containing the Work cannot reasonably be recalled) will be subject to all remedies available at law or in equity, but in no event to a payment of less than three times the Rightsholder's ordinary license price for the most closely analogous licensable use plus Rightsholder's and/or CCC's costs and expenses incurred in collecting such payment.

14)Additional Terms for Specific Products and Services.If a User is making one of the uses described in this Section 14, the additional terms and conditions apply:

a)Print Uses of Academic Course Content and Materials (photocopies for academic coursepacks or classroom handouts).For photocopies for academic coursepacks or classroom handouts the following additional terms apply:

i) The copies and anthologies created under this License may be made and assembled by faculty members individually or at their request by on-campus bookstores or copy centers, or by off-campus copy shops and other similar entities.

ii) No License granted shall in any way: (i) include any right by User to create a substantively non-identical copy of the Work or to edit or in any other way modify the Work (except by means of deleting material immediately preceding or following the entire portion of the Work copied) (ii) permit "publishing ventures" where any particular anthology would be systematically marketed at multiple institutions.

iii) Subject to any Publisher Terms (and notwithstanding any apparent contradiction in the Order Confirmation arising from data provided by User), any use authorized under the academic pay-per-use service is limited as follows:

A) any License granted shall apply to only one class (bearing a unique identifier as assigned by the institution, and thereby including all sections or other subparts of the class) at one institution;

B) use is limited to not more than 25% of the text of a book or of the items in a published collection of essays, poems or articles;

C) use is limited to no more than the greater of (a) 25% of the text of an issue of a journal or other periodical or (b) two articles from such an issue;

D) no User may sell or distribute any particular anthology, whether photocopied or electronic, at more than one institution of learning;

E) in the case of a photocopy permission, no materials may be entered into electronic memory by User except in order to produce an identical copy of a Work before or during the academic term (or analogous period) as to which any particular permission is granted. In the event that User shall choose to retain materials that are the subject of a photocopy permission in electronic memory for purposes of producing identical copies more than one day after such retention (but still within the scope of any permission granted), User

must notify CCC of such fact in the applicable permission request and such retention shall constitute one copy actually sold for purposes of calculating permission fees due; and

F) any permission granted shall expire at the end of the class. No permission granted shall in any way include any right by User to create a substantively non-identical copy of the Work or to edit or in any other way modify the Work (except by means of deleting material immediately preceding or following the entire portion of the Work copied).

iv) Books and Records; Right to Audit. As to each permission granted under the academic pay-per-use Service, User shall maintain for at least four full calendar years books and records sufficient for CCC to determine the numbers of copies made by User under such permission. CCC and any representatives it may designate shall have the right to audit such books and records at any time during User's ordinary business hours, upon two days' prior notice. If any such audit shall determine that User shall have underpaid for, or underreported, any photocopies sold or by three percent (3%) or more, then User shall bear all the costs of any such audit; otherwise, CCC shall bear the costs of any such audit. Any amount determined by such audit to have been underpaid by User shall immediately be paid to CCC by User, together with interest thereon at the rate of 10% per annum from the date such amount was originally due. The provisions of this paragraph shall survive the termination of this License for any reason.

b)Digital Pay-Per-Uses of Academic Course Content and Materials (e-coursepacks, electronic reserves, learning management systems, academic institution intranets).For uses in e-coursepacks, posts in electronic reserves, posts in learning management systems, or posts on academic institution intranets, the following additional terms apply:

i) The pay-per-uses subject to this Section 14(b) include:

A)Posting e-reserves, course management systems, e-coursepacks for text-based content,which grants authorizations to import requested material in electronic format, and allows electronic access to this material to members of a designated college or university class, under the direction of an instructor designated by the college or university, accessible only under appropriate electronic controls (e.g., password);

B)Posting e-reserves, course management systems, e-coursepacks for material consisting of photographs or other still images not embedded in text,which grants not only the authorizations described in Section 14(b)(i)(A) above, but also the following authorization: to include the requested material in course materials for use consistent with Section 14(b)(i)(A) above, including any necessary resizing, reformatting or modification of the resolution of such requested material (provided that such modification does not alter the underlying editorial content or meaning of the requested material, and provided that the resulting modified content is used solely within the scope of, and in a manner consistent with, the particular authorization described in the Order Confirmation and the

Terms), but not including any other form of manipulation, alteration or editing of the requested material;

C)Posting e-reserves, course management systems, e-coursepacks or other academic distribution for audiovisual content,which grants not only the authorizations described in Section 14(b)(i)(A) above, but also the following authorizations: (i) to include the requested material in course materials for use consistent with Section 14(b)(i)(A) above; (ii) to display and perform the requested material to such members of such class in the physical classroom or remotely by means of streaming media or other video formats; and (iii) to "clip" or reformat the requested material for purposes of time or content management or ease of delivery, provided that such “clipping” or reformatting does not alter the underlying editorial content or meaning of the requested material and that the resulting material is used solely within the scope of, and in a manner consistent with, the particular authorization described in the Order Confirmation and the Terms. Unless expressly set forth in the relevant Order Conformation, the License does not authorize any other form of manipulation, alteration or editing of the requested material.

ii) Unless expressly set forth in the relevant Order Confirmation, no License granted shall in any way: (i) include any right by User to create a substantively non-identical copy of the Work or to edit or in any other way modify the Work (except by means of deleting material immediately preceding or following the entire portion of the Work copied or, in the case of Works subject to Sections 14(b)(1)(B) or (C) above, as described in such Sections) (ii) permit "publishing ventures" where any particular course materials would be systematically marketed at multiple institutions.

iii) Subject to any further limitations determined in the Rightsholder Terms (and notwithstanding any apparent contradiction in the Order Confirmation arising from data provided by User), any use authorized under the electronic course content pay-per-use service is limited as follows:

A) any License granted shall apply to only one class (bearing a unique identifier as assigned by the institution, and thereby including all sections or other subparts of the class) at one institution;

B) use is limited to not more than 25% of the text of a book or of the items in a published collection of essays, poems or articles;

C) use is limited to not more than the greater of (a) 25% of the text of an issue of a journal or other periodical or (b) two articles from such an issue;

D) no User may sell or distribute any particular materials, whether photocopied or electronic, at more than one institution of learning;

E) electronic access to material which is the subject of an electronic-use permission must be limited by means of electronic password, student identification or other control permitting access solely to students and instructors in the class;

F) User must ensure (through use of an electronic cover page or other appropriate means) that any person, upon gaining electronic access to the material, which is the subject of a permission, shall see:

a proper copyright notice, identifying the Rightsholder in whose name CCC has granted permission,

a statement to the effect that such copy was made pursuant to permission,

a statement identifying the class to which the material applies and notifying the reader that the material has been made available electronically solely for use in the class, and

a statement to the effect that the material may not be further distributed to any person outside the class, whether by copying or by transmission and whether electronically or in paper form, and User must also ensure that such cover page or other means will print out in the event that the person accessing the material chooses to print out the material or any part thereof.

G) any permission granted shall expire at the end of the class and, absent some other form of authorization, User is thereupon required to delete the applicable material from any electronic storage or to block electronic access to the applicable material.

iv) Uses of separate portions of a Work, even if they are to be included in the same course material or the same university or college class, require separate permissions under the electronic course content pay-per-use Service. Unless otherwise provided in the Order Confirmation, any grant of rights to User is limited to use completed no later than the end of the academic term (or analogous period) as to which any particular permission is granted.

v) Books and Records; Right to Audit. As to each permission granted under the electronic course content Service, User shall maintain for at least four full calendar years books and records sufficient for CCC to determine the numbers of copies made by User under such permission. CCC and any representatives it may designate shall have the right to audit such books and records at any time during User's ordinary business hours, upon two days' prior notice. If any such audit shall determine that User shall have underpaid for, or underreported, any electronic copies used by three percent (3%) or more, then User shall bear all the costs of any such audit; otherwise, CCC shall bear the costs of any such audit. Any amount determined by such audit to have been underpaid by User shall immediately be paid to CCC by User, together with interest thereon at the rate of 10% per annum from the date such amount was originally due. The provisions of this paragraph shall survive the termination of this license for any reason.

c)Pay-Per-Use Permissions for Certain Reproductions (Academic photocopies for library reserves and interlibrary loan reporting) (Non-academic internal/external business uses and commercial document delivery).The License expressly excludes the uses listed in Section (c)(i)-(v) below (which must be subject to separate license from the applicable

Rightsholder) for: academic photocopies for library reserves and interlibrary loan reporting; and non-academic internal/external business uses and commercial document delivery.

i) electronic storage of any reproduction (whether in plain-text, PDF, or any other format) other than on a transitory basis;

ii) the input of Works or reproductions thereof into any computerized database;

iii) reproduction of an entire Work (cover-to-cover copying) except where the Work is a single article;

iv) reproduction for resale to anyone other than a specific customer of User;

v) republication in any different form. Please obtain authorizations for these uses through other CCC services or directly from the rightsholder.

Any license granted is further limited as set forth in any restrictions included in the Order Confirmation and/or in these Terms.

d)Electronic Reproductions in Online Environments (Non-Academic-email, intranet, internet and extranet).For "electronic reproductions", which generally includes e-mail use (including instant messaging or other electronic transmission to a defined group of recipients) or posting on an intranet, extranet or Intranet site (including any display or performance incidental thereto), the following additional terms apply:

i) Unless otherwise set forth in the Order Confirmation, the License is limited to use completed within 30 days for any use on the Internet, 60 days for any use on an intranet or extranet and one year for any other use, all as measured from the "republication date" as identified in the Order Confirmation, if any, and otherwise from the date of the Order Confirmation.

ii) User may not make or permit any alterations to the Work, unless expressly set forth in the Order Confirmation (after request by User and approval by Rightsholder); provided, however, that a Work consisting of photographs or other still images not embedded in text may, if necessary, be resized, reformatted or have its resolution modified without additional express permission, and a Work consisting of audiovisual content may, if necessary, be "clipped" or reformatted for purposes of time or content management or ease of delivery (provided that any such resizing, reformatting, resolution modification or “clipping” does not alter the underlying editorial content or meaning of the Work used, and that the resulting material is used solely within the scope of, and in a manner consistent with, the particular License described in the Order Confirmation and the Terms.

15)Miscellaneous.

a) User acknowledges that CCC may, from time to time, make changes or additions to the Service or to the Terms, and that Rightsholder may make changes or additions to the Rightsholder Terms. Such updated Terms will replace the prior terms and conditions in the order workflow and shall be effective as to any subsequent Licenses but shall not apply to Licenses already granted and paid for under a prior set of terms.

b) Use of User-related information collected through the Service is governed by CCC's privacy policy, available online at www.copyright.com/about/privacy-policy/.

c) The License is personal to User. Therefore, User may not assign or transfer to any other person (whether a natural person or an organization of any kind) the License or any rights granted thereunder; provided, however, that, where applicable, User may assign such License in its entirety on written notice to CCC in the event of a transfer of all or substantially all of User's rights in any new material which includes the Work(s) licensed under this Service.

d) No amendment or waiver of any Terms is binding unless set forth in writing and signed by the appropriate parties, including, where applicable, the Rightsholder. The Rightsholder and CCC hereby object to any terms contained in any writing prepared by or on behalf of the User or its principals, employees, agents or affiliates and purporting to govern or otherwise relate to the License described in the Order Confirmation, which terms are in any way inconsistent with any Terms set forth in the Order Confirmation, and/or in CCC's standard operating procedures, whether such writing is prepared prior to, simultaneously with or subsequent to the Order Confirmation, and whether such writing appears on a copy of the Order Confirmation or in a separate instrument.

e) The License described in the Order Confirmation shall be governed by and construed under the law of the State of New York, USA, without regard to the principles thereof of conflicts of law. Any case, controversy, suit, action, or proceeding arising out of, in connection with, or related to such License shall be brought, at CCC's sole discretion, in any federal or state court located in the County of New York, State of New York, USA, or in any federal or state court whose geographical jurisdiction covers the location of the Rightsholder set forth in the Order Confirmation. The parties expressly submit to the personal jurisdiction and venue of each such federal or state court.

H.3 Phi-T Copyright agreement, Figure 2.2

This Agreement between Mr. Zachary Stanchina ("You") and Elsevier ("Elsevier") consists of your license details and the terms and conditions provided by Elsevier and Copyright Clearance Center.

License Number	5283780777388
License date	Apr 07, 2022
Licensed Content Publisher	Elsevier

Licensed Content Publication	Applied Thermal Engineering
Licensed Content Title	Effects of Miller cycle and variable geometry turbocharger on combustion and emissions in steady and transient cold process
Licensed Content Author	Binyang Wu,Qiang Zhan,Xiaoyang Yu,Guijun Lv,Xiaokun Nie,Shuai Liu
Licensed Content Date	May 25, 2017
Licensed Content Volume	118
Licensed Content Issue	n/a
Licensed Content Pages	9
Start Page	621
End Page	629
Type of Use	reuse in a thesis/dissertation
Portion	figures/tables/illustrations
Number of figures/tables/illustrations	1
Format	both print and electronic
Are you the author of this Elsevier article?	No
Will you be translating?	No
Title	An Experimental Study of Fuel Selection for a Multi-Mode, Spark Ignited - Gasoline Compression Ignition Engine
Institution name	Michigan Technological University
Expected presentation date	May 2022
Order reference number	Thesis_figure
Portions	Fig. 1. The combustion paths in Φ-T map.
Requestor Location	Mr. Zachary Stanchina N2097 Lahaie Dr. VULCAN, MI 49892 United States Attn: Zach Stanchina
Publisher Tax ID	98-0397604
Total	0.00 USD

Terms and Conditions

INTRODUCTION

1. The publisher for this copyrighted material is Elsevier. By clicking "accept" in connection with completing this licensing transaction, you agree that the following terms

and conditions apply to this transaction (along with the Billing and Payment terms and conditions established by Copyright Clearance Center, Inc. ("CCC"), at the time that you opened your Rightslink account and that are available at any time at http://myaccount.copyright.com).

GENERAL TERMS

2. Elsevier hereby grants you permission to reproduce the aforementioned material subject to the terms and conditions indicated.

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

4. Reproduction of this material is confined to the purpose and/or media for which permission is hereby given.

5. Altering/Modifying Material: Not Permitted. However figures and illustrations may be altered/adapted minimally to serve your work. Any other abbreviations, additions, deletions and/or any other alterations shall be made only with prior written authorization of Elsevier Ltd. (Please contact Elsevier's permissions helpdesk here). No modifications can be made to any Lancet figures/tables and they must be reproduced in full.

6. If the permission fee for the requested use of our material is waived in this instance, please be advised that your future requests for Elsevier materials may attract a fee.

7. Reservation of Rights: Publisher reserves all rights not specifically granted in the combination of (i) the license details provided by you and accepted in the course of this licensing transaction, (ii) these terms and conditions and (iii) CCC's Billing and Payment terms and conditions.

8. License Contingent Upon Payment: While you may exercise the rights licensed immediately upon issuance of the license at the end of the licensing process for the transaction, provided that you have disclosed complete and accurate details of your proposed use, no license is finally effective unless and until full payment is received from you (either by publisher or by CCC) as provided in CCC's Billing and Payment terms and conditions. If full payment is not received on a timely basis, then any license preliminarily granted shall be deemed automatically revoked and shall be void as if never granted. Further, in the event that you breach any of these terms and conditions or any of CCC's Billing and Payment terms and conditions, the license is automatically revoked and shall be void as if never granted. Use of materials as described in a revoked license, as well as any use of the materials beyond the scope of an unrevoked license, may constitute copyright infringement and publisher reserves the right to take any and all action to protect its copyright in the materials.

9. Warranties: Publisher makes no representations or warranties with respect to the licensed material.
10. Indemnity: You hereby indemnify and agree to hold harmless publisher and CCC, and their respective officers, directors, employees and agents, from and against any and all claims arising out of your use of the licensed material other than as specifically authorized pursuant to this license.
11. No Transfer of License: This license is personal to you and may not be sublicensed, assigned, or transferred by you to any other person without publisher's written permission.
12. No Amendment Except in Writing: This license may not be amended except in a writing signed by both parties (or, in the case of publisher, by CCC on publisher's behalf).
13. Objection to Contrary Terms: Publisher hereby objects to any terms contained in any purchase order, acknowledgment, check endorsement or other writing prepared by you, which terms are inconsistent with these terms and conditions or CCC's Billing and Payment terms and conditions. These terms and conditions, together with CCC's Billing and Payment terms and conditions (which are incorporated herein), comprise the entire agreement between you and publisher (and CCC) concerning this licensing transaction. In the event of any conflict between your obligations established by these terms and conditions and those established by CCC's Billing and Payment terms and conditions, these terms and conditions shall control.
14. Revocation: Elsevier or Copyright Clearance Center may deny the permissions described in this License at their sole discretion, for any reason or no reason, with a full refund payable to you. Notice of such denial will be made using the contact information provided by you. Failure to receive such notice will not alter or invalidate the denial. In no event will Elsevier or Copyright Clearance Center be responsible or liable for any costs, expenses or damage incurred by you as a result of a denial of your permission request, other than a refund of the amount(s) paid by you to Elsevier and/or Copyright Clearance Center for denied permissions.

LIMITED LICENSE

The following terms and conditions apply only to specific license types:
15. **Translation**: This permission is granted for non-exclusive world **English** rights only unless your license was granted for translation rights. If you licensed translation rights you may only translate this content into the languages you requested. A professional translator must perform all translations and reproduce the content word for word preserving the integrity of the article.
16. **Posting licensed content on any Website**: The following terms and conditions apply as follows: Licensing material from an Elsevier journal: All content posted to the web site must maintain the copyright information line on the bottom of each image; A hyper-text must be included to the Homepage of the journal from which you are licensing at http://www.sciencedirect.com/science/journal/xxxxx or the Elsevier homepage for books at http://www.elsevier.com; Central Storage: This license does not include permission for a scanned version of the material to be stored in a central repository such as that provided by Heron/XanEdu.
Licensing material from an Elsevier book: A hyper-text link must be included to the Elsevier homepage at http://www.elsevier.com . All content posted to the web site must maintain the copyright information line on the bottom of each image.

Posting licensed content on Electronic reserve: In addition to the above the following clauses are applicable: The web site must be password-protected and made available only to bona fide students registered on a relevant course. This permission is granted for 1 year only. You may obtain a new license for future website posting.

17. **For journal authors:** the following clauses are applicable in addition to the above:

Preprints: A preprint is an author's own write-up of research results and analysis, it has not been peer-reviewed, nor has it had any other value added to it by a publisher (such as formatting, copyright, technical enhancement etc.).

Authors can share their preprints anywhere at any time. Preprints should not be added to or enhanced in any way in order to appear more like, or to substitute for, the final versions of articles however authors can update their preprints on arXiv or RePEc with their Accepted Author Manuscript (see below).

If accepted for publication, we encourage authors to link from the preprint to their formal publication via its DOI. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help users to find, access, cite and use the best available version. Please note that Cell Press, The Lancet and some society-owned have different preprint policies. Information on these policies is available on the journal homepage.

Accepted Author Manuscripts: An accepted author manuscript is the manuscript of an article that has been accepted for publication and which typically includes author-incorporated changes suggested during submission, peer review and editor-author communications.

Authors can share their accepted author manuscript:

immediately

via their non-commercial person homepage or blog

by updating a preprint in arXiv or RePEc with the accepted manuscript

via their research institute or institutional repository for internal institutional uses or as part of an invitation-only research collaboration work-group

directly by providing copies to their students or to research collaborators for their personal use

for private scholarly sharing as part of an invitation-only work group on commercial sites with which Elsevier has an agreement

After the embargo period

via non-commercial hosting platforms such as their institutional repository

via commercial sites with which Elsevier has an agreement

In all cases accepted manuscripts should:

link to the formal publication via its DOI

bear a CC-BY-NC-ND license - this is easy to do

if aggregated with other manuscripts, for example in a repository or other site, be shared in alignment with our hosting policy not be added to or enhanced in any way to appear more like, or to substitute for, the published journal article.

Published journal article (JPA): A published journal article (PJA) is the definitive final record of published research that appears or will appear in the journal and embodies all value-adding publishing activities including peer review co-ordination, copy-editing, formatting, (if relevant) pagination and online enrichment.

Policies for sharing publishing journal articles differ for subscription and gold open access articles:
Subscription Articles: If you are an author, please share a link to your article rather than the full-text. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help your users to find, access, cite, and use the best available version.
Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.
If you are affiliated with a library that subscribes to ScienceDirect you have additional private sharing rights for others' research accessed under that agreement. This includes use for classroom teaching and internal training at the institution (including use in course packs and courseware programs), and inclusion of the article for grant funding purposes.
Gold Open Access Articles: May be shared according to the author-selected end-user license and should contain a CrossMark logo, the end user license, and a DOI link to the formal publication on ScienceDirect.
Please refer to Elsevier's posting policy for further information.
18. **For book authors** the following clauses are applicable in addition to the above: Authors are permitted to place a brief summary of their work online only. You are not allowed to download and post the published electronic version of your chapter, nor may you scan the printed edition to create an electronic version. **Posting to a repository:** Authors are permitted to post a summary of their chapter only in their institution's repository.
19. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of the complete thesis and include permission for Proquest/UMI to supply single copies, on demand, of the complete thesis. Should your thesis be published commercially, please reapply for permission. Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.

Elsevier Open Access Terms and Conditions
You can publish open access with Elsevier in hundreds of open access journals or in nearly 2000 established subscription journals that support open access publishing. Permitted third party re-use of these open access articles is defined by the author's choice of Creative Commons user license. See our open access license policy for more information.
Terms & Conditions applicable to all Open Access articles published with Elsevier:
Any reuse of the article must not represent the author as endorsing the adaptation of the article nor should the article be modified in such a way as to damage the author's honour or reputation. If any changes have been made, such changes must be clearly indicated.
The author(s) must be appropriately credited and we ask that you include the end user license and a DOI link to the formal publication on ScienceDirect.

If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source it is the responsibility of the user to ensure their reuse complies with the terms and conditions determined by the rights holder.
Additional Terms & Conditions applicable to each Creative Commons user license:
CC BY: The CC-BY license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article and to make commercial use of the Article (including reuse and/or resale of the Article by commercial entities), provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, indicates if changes were made and the licensor is not represented as endorsing the use made of the work. The full details of the license are available at http://creativecommons.org/licenses/by/4.0.
CC BY NC SA: The CC BY-NC-SA license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article, provided this is not done for commercial purposes, and that the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, indicates if changes were made and the licensor is not represented as endorsing the use made of the work. Further, any new works must be made available on the same conditions. The full details of the license are available at http://creativecommons.org/licenses/by-nc-sa/4.0.
CC BY NC ND: The CC BY-NC-ND license allows users to copy and distribute the Article, provided this is not done for commercial purposes and further does not permit distribution of the Article if it is changed or edited in any way, and provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, and that the licensor is not represented as endorsing the use made of the work. The full details of the license are available at http://creativecommons.org/licenses/by-nc-nd/4.0. Any commercial reuse of Open Access articles published with a CC BY NC SA or CC BY NC ND license requires permission from Elsevier and will be subject to a fee.
Commercial reuse includes:
Associating advertising with the full text of the Article
Charging fees for document delivery or access
Article aggregation
Systematic distribution via e-mail lists or share buttons
Posting or linking by commercial companies for use by customers of those companies.
20. **Other Conditions**:
v1.10