DYNAMIC MODELING AND CONTROL OF A MULTI-MODE COMBUSTION ENGINE

By

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Dedication

To my beloved father (Muhammad Amir Malik), my mother, brother and sister.

Contents

List of Figures

List of Tables

Preface

This dissertation is submitted for the partial fulfillment of the Doctorate Degree in Mechanical Engineering-Engineering Mechanics. In this dissertation, two major aspects have been investigated: 1) Dynamic modeling and control of low temperature combustion modes, 2) Dynamic modeling and control of a multi-mode combustion engine. The research work is conducted under the supervision of Dr. Mahdi Shahbakhti and Dr. Jeffrey D. Naber. Some chapters of this dissertation have already been published in peer reviewed journal and conferences. Part of this work is submitted for peer review. The copyrights permissions of the published work are provided in Appendix C. The author's contributions in this dissertation are as follows:

Chapter 2 of this dissertation provides an extensive literature review on modeling and control of different low temperature combustion modes and multi-mode engine operation. This material is published by Springer as a book chapter.

Chapter 3 - "Closed-loop predictive control of a multi-mode engine including homogeneous charge compression ignition, partially premixed charge compression ignition, and reactivity-controlled compression ignition modes" is published in SAE International Journal of Fuels and Lubricants. Experimental data were provided by Kaushik Kannan and Dr. Seyfi Polat. Dynamic model for reactivity-controlled compression ignition mode was provided by Akshat Raut.

Chapter 4 - 'Data-driven modeling and control of cyclic variability of an engine operating in low temperature combustion modes" is presented at Modeling, Estimation and Control Conference (MECC), 2021.

Chapter 5 - "Machine learning approaches for identification of heat release shapes in a low temperature combustion engine for control applications" is submitted to Control Engineering Practice for peer review.

Chapter 6 - "Control oriented modeling of SI-RCCI-SI mode switching" will be submitted to International Journal of Engine Research for peer review. This work is based on development of dynamic modeling of a multi-mode engine and model validations at steady state and transient engine conditions.

Chapter 7 - "Model predictive control of SI-RCCI-SI mode switching" is submitted to Modeling, Estimation and Control Conference (MECC), 2023. This work focuses on the development of gain scheduling model predictive controller for a multi-mode engine.

Chapter 8 - "RCCI-SI mode transition control" addresses the challenges of mode switching operation. This chapter contains the updated model and controller for

RCCI-SI mode switching. This work will be submitted to Applied Thermal Engineering for peer review.

Data collection, analysis, dynamic modeling, designing and implementation of model predictive controllers were completed by Sadaf Batool. Dr. Jeffrey Naber and Dr. Mahdi Shahbakhti provided the experimentation facilities, guidance and technical comments on the manuscripts. Dr. Jeremy Worm and Dr. Nathir Rawashdeh provided feedback on the dissertation.

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List of Abbreviations

aTDC	After Top Dead Center
bTDC	Before Top Dead Center
CAD	Crank Angle Degrees
CI	Compression Ignition
DI	Direct Injection
EOM	End of Main Heat Release
HCCI	Homogeneous Charge Compression Ignition
HR_{early}	Fraction of early heat release
HR_{late}	Fraction of late heat release
HRR	Heat Release Rate
ICE	Internal Combustion Engine
KNN	K Nearest Neighbors
LHV	Lower Heating value of Fuel
LPV	Linear Parameter Varying
LTC	Low Temperature Combustion
MIMO	Multi Input Multi Output
NOx	Nitrogen Oxides
PFI	Port Fuel Injection

PM	Particulate Matter
PPCI	Partially Premixed charge Compression Ignition
RCCI	Reactivity Controlled Compression Ignition
SI	Spark Ignition
SOM	Start of Main Heat Release
SVM	Support Vector Machines
BD	Burn Duration (CAD)
CA10	Crank Angle for 10% Heat Release (CAD aTDC)
CA50	Combustion Phasing (CAD aTDC)
CA90	Crank Angle for 90% Heat Release (CAD aTDC)
COV_{IMEP}	Coefficient of Variation of Indicated Mean Effective Pressure (%)
DI	Direct Injection (%)
EGR	Exhaust Gas Recirculation (%)
FQ	Fuel Quantity (mg/cycle)
T_{man}	Intake Manifold Air Temperature (K)
IMEP	Indicated Mean Effective Pressure (kPa)
MPRR	Maximum Pressure Rise Rate (MPa/CAD)
m_{iso}	Mass of Iso-Octane (mg/cycle)
m_{nhep}	mass of N-Heptane (mg/cycle)
N	Engine Speed (RPM)
NMEP	Net Mean Effective Pressure (kPa)

P	Pressure (kPa)
PR	Premixed Ratio (-)
PFI	Port Fuel Injection (%)
P_{man}	Manifold Pressure
P_{max}	Maximum In-cylinder Pressure
R	Gas Constant (kJ/KgK)
SOI	Start of Injection (CAD bTDC)
SOC	Start of Combustion (CAD aTDC)
T_{max}	Maximum In-cylinder Gas Temperature (K)
$\theta_{P_{max}}$	Location of Maximum Pressure
ϕ	Equivalence Ratio

Abstract

Low temperature combustion (LTC) offers high thermal efficiency and low engine-out nitrogen oxides (NOx) and particulate matter (PM) emissions. Homogeneous charge compression ignition (HCCI), partially premixed charge compression ignition (PPCI) and reactivity-controlled compression ignition (RCCI) are the common LTC modes studied in this research. The primary barrier to implementing the LTC modes in on-road vehicles is their limited operating range due to high cyclic variability and excessive pressure rise rates. The feasible operating range of the LTC modes is only a subset of the speed-load range of the conventional spark ignition (SI) engine. Therefore, a multi-mode engine concept operating in one or more LTC modes and SI mode is a viable option to improve engine performance in terms of efficiency and emissions. The goal of this dissertation is to develop model-based closed loop control of an SI-RCCI-SI multi-mode engine.

Control-oriented models and predictive controllers for HCCI, PPCI and RCCI modes are developed to simultaneously control combustion phasing and engine load for an optimal operation of a multi-mode engine. Cyclic variability in HCCI and RCCI modes are modeled using machine learning classification algorithms. Nonlinear model predictive controllers are developed for HCCI and RCCI modes to control combustion phasing and engine load while constraining cyclic variability below 3%. Furthermore,

LTC engine operation faces challenges of excessive pressure rise rates that can damage the hardware. To this end, supervised machine learning classification algorithms are developed to model the heat release type which is used as a scheduling variable to develop data-driven model for an LTC engine. Model predictive controller is then developed to control combustion phasing and engine load while constraining maximum pressure rise rate below 8 bar/CAD.

RCCI mode offers good control over the combustion event by modulating the start of injection timing of high reactivity fuel and adjusting the premixed ratio of the dual fuels. Therefore, this research focuses on SI-RCCI-SI multi-mode engine concept. The aim of this research is to achieve smooth SI-RCCI-SI mode switching operation at different engine loads and speed. A dynamic model for SI-RCCI-SI multi-mode engine is developed and validated for different transient conditions. The model includes the mode switching dynamics as well as actuator dynamics. A model-based predictive controller framework is developed for SI-RCCI-SI mode switching. The mode switching controller showed good performance during mode transitions and steady state engine operation. The controller is capable of tracking the desired combustion phasing and engine load during mode switching while maintaining λ near stoichiometry in SI mode and constraining maximum pressure rise rate below 8 bar/CAD in RCCI mode.

Chapter 1

Introduction

Environmental protection agencies around the world have set the stringent regulations for engine-out emissions and vehicle fuel economy for light and heavy duty vehicles. Due to the stringent regulations, automotive manufacturers have shifted the focus towards the development of hybrid electric vehicles and electric vehicles. According to the U.S. Energy Information Administration, the new light-duty vehicles running solely on internal combustion engines (ICE) will still contribute 81% of the market share by 2050 [45]. Hybrid electric and plug-in hybrid electric vehicles also use ICE. Thus, the market share of new vehicles using ICE will go up to 85% [45]. This motivates researchers to investigate and improve the advanced combustion technologies. Advanced combustion technologies include low-temperature combustion (LTC) that offers better thermal efficiency compared to conventional spark ignition (SI) engines and reduced engine-out emissions compared to conventional diesel combustion (CDC) engines. The common LTC modes are Homogeneous Charge Compression Ignition (HCCI), Partially Premixed Charge Compression Ignition (PPCI), Premixed Charge Compression Ignition (PCCI), and Reactivity Controlled Compression Ignition (RCCI). These LTC modes offer high thermal efficiency and ultra-low nitrogen oxides (NOx) and particulate matter (PM) emissions. However, combustion control, maximum pressure rise rate, cyclic variations, and limited operating range are the common challenges of the LTC modes. Therefore, this study focuses on the development of control strategies to achieve the desired low temperature combustion modes and to develop closed-loop predictive controller framework for a multi-mode combustion engine.

LTC combustion modes provide promising solutions to engine-out emission problems with comparable thermal efficiencies of diesel engines. LTC modes operate under wide open throttle (WOT) condition, thus pumping losses are minimized. But due to limited operating range of HCCI, PCCI, PPCI and RCCI, the applications of these combustion modes are limited in on- road vehicle engines. To avail the benefits, coupling of LTC modes together with SI or CI combustion modes is required. Therefore, many researchers are focusing on the development of mode switching strategy for a multi-mode engine.

1.1 The Necessity of a Multi-Mode Engine

High thermal efficiency and low engine-out NOx and PM emissions make LTC modes appealing. However, the operating range of LTC modes is only a subset of speed-load range of the conventional SI engine. This limits the applications of LTC modes. The majors factors that limit the operating region of LTC modes are unstable combustion due to high dilution and very high pressure rise rates causing damage to the engine [46]. High load LTC operation results in abrupt heat release rates which leads to high pressure rise rates and NOx formation [47]. Excessive pressure rise rates lead to audible noise causing engine knock. Combustion phasing also affects the pressure rise rate in the LTC modes. An early combustion phasing results in rapid heat release rate causing excessive pressure rise rates. High pressure rise rates can be avoided by retarding the combustion phasing. However, the retard in combustion phasing is limited due to the auto-ignition limit of the air-fuel mixture which may lead to misfire [48]. The late combustion phasing reaching the auto-ignition limits increase the cyclic variations.

Engine speed also limits the operating range of the LTC modes. At low engine speed, the combustion event results in late phasing due to heat transfer losses. While at high engine speeds, the cylinder charge has less time for heat transfer, resulting in advance combustion phasing [48]. LTC modes cannot be achieved at cold start condition.

Therefore, a multi-mode engine is a viable option to benefit from the LTC modes and provide full speed and load range by coupling one or more LTC modes to the conventional spark ignition or compression ignition engine.

1.2 Overview of Multi-Mode Combustion Engine

Several mode switching studies have been carried out. These studies are listed in Table 1.1. HCCI, PPCI, CDC, CDF and RCCI are homogeneous charge compression ignition, partially premixed charge compression ignition, conventional diesel combustion, conventional dual fuel combustion and reactivity controlled compression ignition, respectively. Researchers have mostly investigated the SI-HCCI-SI mode switching. SI-HCCI-SI mode switching studies can be categorized as rule based [10, 34, 49, 50] and model-based [12, 13, 51, 52] studies.

Table 1.1
Mode Switching Studies

Sr. #	**Mode Switching**
1	SI-HCCI-SI
2	HCCI-PPCI
3	PPCI-CDC
4	CDC-RCCI-CDC
5	CDF-RCCI

Tian et. al. carried out SI-HCCI mode switching by separately controlling cam profile and throttle (due to slow air dynamics). For SI to HCCI mode switching, cam profile was first switched to negative valve overlap (NVO) while WOT was achieved later. From HCCI to SI mode switching, throttle was closed from WOT to the required throttle position in SI mode before switching the cam from NVO to PVO. During SI mode, split injection strategy was adopted where 80% of the fuel was injected at 100 CAD aTDC during intake stroke while 20% of fuel was injected at 250 CAD aTDC during compression stroke [11]. Li et. al. implemented HCCI, assisted spark stratified compression ignition (ASSCI) and SI for low, medium (upper limit of HCCI) and high load demands, respectively. HCCI to ASSCI mode switch was carried out by decreasing the NVO duration when the high load limit of HCCI was reached. ASSCI mode was switched to SI mode when the upper load limit of ASSCI was reached. ASSCI to SI mode switching was carried out by changing the NVO to PVO. Frequent mode transitions between ASSCI and SI modes were avoided by adding hysteretic area [14].

Singh et. al. carried out CI-PCCI-CI mode switching. Engine was operated in PCCI mode for low to medium loads and in CI mode for higher load demands. CI combustion mode was employed for the engine warm-up. CI to PCCI mode switching was done by varying the pilot and main injection timings followed by the addition of exhaust gas recirculation (EGR). PCCI mode employed 15% EGR throughout the operation. Due to increased maximum pressure rise rates, start of main injection timing was modulated which increased HC and CO emissions. PCCI operation was limited due to engine knocking. Thus, PCCI-CI mode switching was carried out by changing the injection strategy to that of CI and cutting off the EGR. The study shows the potential of implementing PCCI-CI mode switching in commercial applications [53].

Indrajuana et. al. implemented open-loop and closed-loop control strategies for the RCCI-CDF mode switching with natural gas and diesel fuels using high pressure EGR [17]. Fuel quantities, start of injection (SOI), variable turbine geometry (VGT), and EGR fractions were used to control IMEP, CA50, EGR ratio, blend ratio (BR) and dp (difference of intake and exhaust manifold pressure). The study suggested that closed-loop mode switching strategy showed better performance. This mode-switching controller does not cover transient operation [17].

Nakayama et. al. studied CDC-PPCI-CDC mode transition. During CDC to PPCI mode transition, NOx spikes were observed while soot spikes were observed from PPCI to CDC mode switching. The study suggested that retarding CA50 and adding EGR help in reducing NOx during CDC-PPCI mode transition [54]. An open-loop CDC-RCCI mode switching study was carried out to overcome RCCI challenges at cold start and high load operation [16]. EGR was increased from 28.5% to 50% from CDC to RCCI mode switching. CDC-RCCI mode switching resulted in decreased NOx and soot emisisons [16]. To the best of authors' knowledge, this is the first study based on the closed-loop control of SI-RCCI-SI mode switching.

1.3 Motivation

Reactivity controlled compression ignition (RCCI) is among the advanced LTC technologies which provide high thermal efficiency and low engine-out NOx and PM emissions. RCCI mode offers low combustion temperatures that prevent NOx formation and reduce heat transfer losses [1]. In addition, higher specific heat ratios improve the efficiency of work extraction [1]. However, low combustion temperatures limit the oxidation of CO and THC, and complete combustion; thus, resulting in higher CO and THC emissions. In RCCI mode, a portion of the fuel is injected during the intake stroke which allows significant air-fuel premixing and a portion of fuel is injected during the compression stroke. Globally lean air-fuel mixture helps in avoiding particulate matter (PM) formation [1]. Furthermore, RCCI mode is operated at wide open throttle (WOT) which reduces the pumping losses. Besides the advantages, the RCCI mode offers a limited operating range. High cyclic variability at low load and high maximum pressure rise rates (MPRR) at high load confines the feasible operating range of the RCCI mode. Therefore, the engine maps of SI mode are compared with the optimal RCCI operating range for the indicated specific fuel consumption (ISFC) and engine-out CO, THC and NOx emissions. Based on the comparison, RCCI mode showed lower ISFC and NOx emissions as compared to SI mode. However, CO and THC emissions are observed to be higher in SI mode. CO and THC emissions in RCCI mode can be reduced by advancing start of injection timing of n-heptane. A multi-mode engine seems to be a viable option which can provide lower fuel consumption and lower engine out NOx emissions as compared to conventional SI engine. Therefore, RCCI mode is coupled to a conventional SI engine to improve the engine performance. To the best of author's knowledge, it is the first model-based closed-loop study carried out for SI-RCCI-SI mode switching.

1.4 Outline of the Dissertation

Chapter 2 presents detailed literature review on different low temperature combustion modes, control strategies to address the challenges offered by different LTC modes, and open-loop and closed-loop control of multi-mode combustion engines.

Chapter 3 is based on the development of a unified model predictive control framework for HCCI, PPCI and RCCI modes to control combustion phasing and engine load based on the optimal engine map.

In chapter 4, supervised machine learning algorithms are used to model cyclic variations in HCCI and RCCI combustion modes. Cyclic variations in IMEP are determined by computing coefficient of variation of indicated mean effective pressure COV_{IMEP}. Nonlinear model predictive controllers are developed for HCCI and RCCI modes to constrain COV_{IMEP} below 3% while controlling combustion phasing and

IMEP.

Chapter 5 is the extension of research carried out by Sitaraman et. al. [55]. Two different machine learning classification models are developed for classification of heat release rates. Three different machine learning classification algorithms including decision tree, K-nearest neighbors (KNN), and support vector machines (SVM), are used to develop a model to identify the type of combustion events based on the normalized heat release data. This model can be used for online or offline identification of the heat release rate type. Similarly, three supervised machine learning algorithms are also used to develop a model using start of combustion (CA10), burn duration (BD), start of injection (SOI), premixed ratio (PR), fuel quantity (FQ) and intake air temperature (IAT) as feature vectors to determine the type of heat release event. This classification model is used to develop linear parameter varying system to achieve closed-loop control of LTC engine. Model predictive controller is developed using the heat release type as scheduling variable to control CA50 and IMEP while constraining MPRR below 8 bar/CAD.

Chapter 6 is based on the dynamic modeling of SI-RCCI-SI mode switching. The dynamic mode-switching model is validated for steady state and transient conditions. This chapter also provides comparison of SI and RCCI engine operation on the basis of indicated specific fuel consumption and engine-out CO, THC and NOx emissions.

Chapter 7 explains the development of model predictive controller with state estimator for SI-RCCI-SI mode switching. This chapter also includes simulation and experimental results for the mode switching controller for optimal engine operation.

Chapter 8 explains the challenges associated to RCCI-SI mode switching. This chapter also provides the improvement in the dynamic mode switching model. The performance of the improved model predictive controller is experimentally validated and the results are presented in chapter 8. Chapter 9 includes the major findings of the current research and future work.

Chapter 2

Multi-mode low temperature combustion (LTC) and mode switching control[1]

2.1 Abstract

Low temperature combustion (LTC) modes offer high thermal efficiency and low engine-out NOx and soot emissions. The common LTC modes include homogeneous charge compression ignition (HCCI), partially premixed charge compression

[1]Originally published in Advanced Combustion for Sustainable Transport. Energy, Environment, and Sustainability, Springer

ignition (PPCI), and reactivity-controlled compression ignition (RCCI). To realize these promising LTC modes, optimal combustion control of the engine in each LTC mode is required. This will re-quire precise control of combustion phasing and engine load, while constraining engine variables including peak in-cylinder gas pressure, maximum pressure rise rate, high intensity ringing or knock, and coefficient of variation of indicated mean effec-tive pressure (IMEP) to allow safe and stable combustion. This chapter explains state-of-the-art of LTC engine control, includ-ing dynamic modeling, model predictive combustion control, experimentation, and implementation of real-time closed loop combustion controllers.

A well-recognized limitation of LTC engines is a constrained op-timal operating range. To this end, multi-mode engines are de-sired. These include i) multi-mode LTC engines with mode tran-sition among LTC modes, e.g., dual mode HCCI-RCCI engine, or triple mode HCCI-PPCI-RCCI engine, and ii) multi-mode en-gines including LTC and conventional combustion modes, e.g., dual mode HCCI-SI (spark ignition) engines or dual mode RCCI-CDC (conventional diesel combustion) engines. These demands for innovative combustion controllers that capture the engine transient dynamics such as in-cylinder air-fuel ratio vari-ations or residual gas temperature variations during mode transi-tions. This chapter introduces multi-mode LTC engines and ex-plains controller development for these engines.

2.2 Introduction

Environmental protection agencies around the world, such as Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) in U.S., European Environmental Agency (EEA), Ministry of Ecology and Environment the People's Republic of China, etc. have set the stringent regu-lations for greenhouse gas (GHG) emissions and vehicle fuel economy for light and heavy-duty vehicles. These regulations have compelled the automobile manufacturers to explore the advanced combustion strategies. Advanced combustion technologies including low temperature combustion (LTC) are renowned for high thermal efficiency and low engine-out emissions. Light duty vehicles contribute towards the maximum consumption of fuel in transportation sector. The recent projections by the U.S. Energy Information Administration forecast that the new light duty vehicles running solely on IC engines would contribute to 81% of the U.S. market share by 2050 [45]. Hybrid electric and plug-in hybrid electric vehicles also use ICE. This leads to market share increase to 85% when hybrid electric and plug-in hybrid electric vehicles are also included [45]. The transportation sector is one of the major contributors towards the GHG emissions. Therefore, increasing fuel conversion efficiency of ICEs by the use of multi-mode LTC engines will al-low reduction in GHG emissions. Furthermore, biofuels produce much lower GHG emissions; thus, providing much cleaner combustion as compared to gasoline fueled vehicles. Given the fuel flexibility of multi-mode engines, they can run with different biofuels. Biofuels have a potential of reducing GHG emissions for sus-tainable transportation [56, 57]. LTC strategies using biofuels offer reduced GHG emissions together with high thermal efficiency [58, 59, 60] When compared to the per-formance of diesel fueled homogeneous compression ignition engine, biodiesel fuel resulted in reduced HC and CO emissions at low load while reduction in smoke emissions was observed at high load operation [60]. Singh et. al. compared the performance of conventional diesel combustion (CDC) and premixed charge compression ignition (PCCI). The study was extended to the performance com-parison of diesel fueled CDC and PCCI modes with a blend of biodiesel with min-eral diesel (B20) fuel together with the open-loop CDC-PCCI mode switching. The results showed that PCCI led to significant reduction in NOx and particulate emis-sions when compared to CDC operation using both fuels. However, diesel fueled PCCI mode produced higher concentrations of SO2, HCHO, etc. B20-fueled PCCI operation offered relatively lower concentrations of unregulated emissions [58]. In addition, non-fossils based fuel can be accommodated with already existing vehi-cle powertrains without any engine changes [56]. Therefore, multi-mode LTC en-gines contribute to sustainable transportation via three major areas i) offering higher fuel conversion efficiency compared to conventional SI and CI engines, ii) broadening engine speed and load range with high fuel conversion efficiency, and iii) possibility to run with a range of renewable fuels.

The common LTC modes include homogeneous charge compression ignition (HCCI),

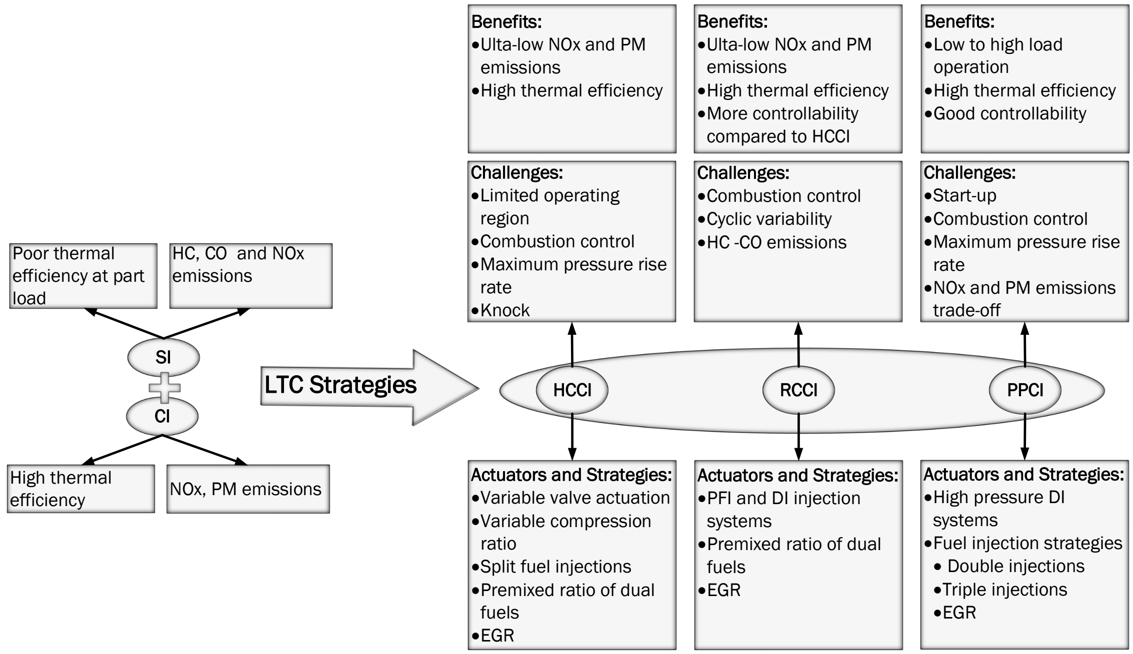

Figure 2.1: Benefits and limitations of common LTC modes

premixed charged compression ignition (PCCI), partially premixed charged compression ignition (PPCI) and reactivity controlled compression ignition (RCCI). In HCCI, fuel is injected during intake stroke which provides enough time to mix homogeneously with air. The air-fuel mixtures undergo autoignition at the end of compression stroke. This mode offers high thermal efficiency and ultra-low NOx emissions. However, it is often prone to excessive pressure rise rates (MPRR) which cause engine knocking. The low load of HCCI is limited by misfire or partial burn while the higher load limitation of HCCI is mainly due to the high MPRR and knocking [61]. These drawbacks can be abated by introducing different levels of air-fuel premixing. Premixed or partially premixed mixtures are formed by varying the fuel injection timings and using high levels of dilution. This introduces the desired ignition delay and increased in-cylinder mixing [62]. Lower compression ratio, high injection pressure, exhaust gas recirculation (EGR) and enhanced mixing can be used to achieve the desired ignition delay [63]. In literature, ignition delay is either defined as the crank angle difference between start of injection and start of combustion [62] or the crank angle difference between start of injection and crank angle where 50% of total heat release occurs [64]. NOx formation can be avoided by increasing the ignition delay [64] In addition, MPRR can be prevented by using multiple fuel injections and high intake pressure [64]. Dual fuel application in LTC has also been focus of research. Reactivity controlled compression ignition (RCCI) is one such combustion mode which uses duel fuels of different reactivity. Usually a low reactivity fuel is injected via port fuel injector (PFI) and high reactivity fuel is injected via direct injector (DI). Premixed ratio of the fuels and injection timing of high reactivity fuel provides better control on the combustion phasing. A brief overview of the common LTC modes is shown in Fig. 2.1.

High local equivalence ratio and high local temperature in CDC leads to the formation of NOx and soot [1]. Unlike CDC, LTC modes generally involve lean premixed mixtures which reduce the local fuel rich zones. Therefore, very high peak in-cylinder gas temperatures are avoided in the LTC modes that helps in restricting NOx and particulate matter (PM) formation [1]. The comparison of emissions between LTC strategies and CDC can be seen in Fig. 2.2. A homogeneous reactor simulations were carried out for different equivalence ratio and temperature in [1]. Figure 2.2

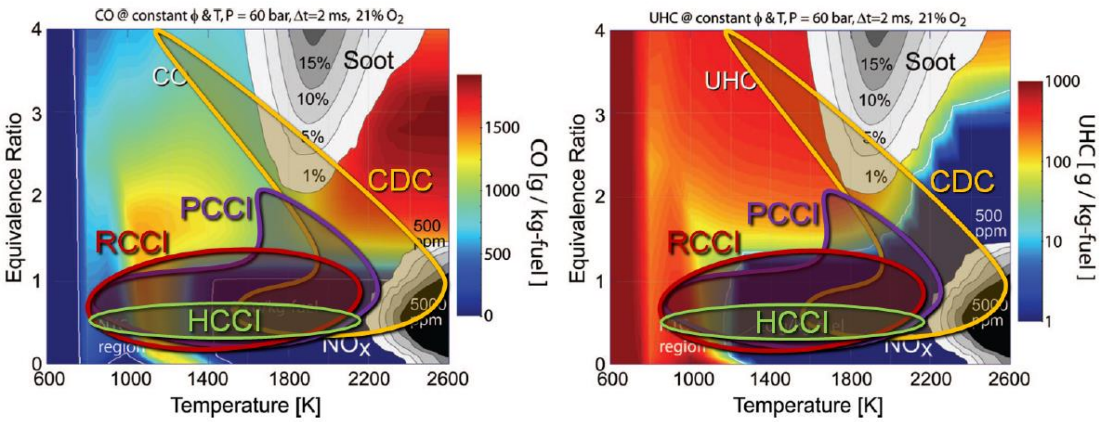

Figure 2.2: Contours of various combustion strategies and emissions (i.e., NOx, soot, CO and unburned HC) from homogeneous reactor simulation with n-heptane and air at different equivalence ratios and temperatures [1]

also shows the relationship between NOx, soot, HC and CO emissions for different equivalence ratios and temperatures for the LTC modes.

Closed-loop control of LTC modes is important to ensure stable and safe engine operation while achieving high thermal efficiency and ultra low engine-out emissions. The variables to be controlled in LTC modes include combustion timing (CA50), indicated mean effective pressure (IMEP), maximum pressure rise rate (MPRR), peak in-cylinder pressure (P_{max}), exhaust gas temperature (T_{exh}) and coefficient of variation of indicated mean effective pressure (COV_{IMEP}). Control of combustion timing is essentially done to achieve maximum work output from the engine and to avoid high pressure rise rates, partial burns or misfires. An early heat release can result in too high pressure rise rates which may cause engine to knock. Moreover, too late combustion events can lead to incomplete combustion which produces high levels of carbon monoxide (CO) and unburned hydrocarbons (HC). In addition, low temperature combustion event typically results in low exhaust gas temperatures as low as 120 °C which limits the effective performance of the oxidation catalyst in the aftertreatment system [65]. Therefore, control of exhaust temperature is important in the LTC modes. The stochastic nature of combustion event can be ascertained by the variations in the engine load output. High cyclic variations in IMEP (COV_{IMEP} $> 5\%$) produce fluctuations in engine torque and speed that affect the drivability, noise, vibration and harshness (NVH) performance of a vehicle. Thus, COV_{IMEP} is determined over the steady state engine operation and is constrained below 5%.

2.2.1 Limitations of LTC Operation

LTC modes are prone to limitations in terms of load and speed operating range, engine-out emissions and thermal efficiency. Despite the high thermal efficiency, ultra-low engine-out emissions and low cyclic variability, HCCI application is limited owing to the limited operating range. The majors factors that limit the operating region of HCCI engine are misfiring due to high dilution and very high pressure rise rates causing high noise levels [46]. Misfiring limits the low load operation of HCCI. Misfires are highly likely with too much dilution which result in insufficient temperatures required for ignition initiation. Similarly, misfire or partial burn occurs at high speed engine operation due to decrease in the available time required for the combustion onset [46]. High load and high speed HCCI operation faces aspirating limitations. Moreover, lack of dilution in the high load HCCI operation causes very high combustion rates which leads to excessive pressure rise rates bringing forth the engine knocking problem with audible noises and NOx formation [47].

Moreover, partially premixed compression ignition mode seems a promising solution to operate a compression ignition engine with gasoline in mid to high load range with high thermal efficiency and low NOx and soot emissions[64]. In [64], high load upto 15 bar was achieved with single gasoline fuel injection by using exhaust gas recirculation (EGR), boosting, late fuel injections and fuel injection pressures upto 1100 bar. Multiple fuel injection strategy can be helpful in curbing high pressure rise rates [66]. In [67], PPCI operating range was extended from idle to full load conditions. The performance was characterized on the basis of thermal efficiency and emissions. The study showed 50% brake efficiency at full load condition with low NOx, soot, CO and HC emissions. However, the poor thermal efficiency of the PPCI operation makes it less favorable for idle engine operation despite the low NOx and zero soot emissions [67]. Therefore, coupling the LTC modes for better thermal efficiency and low engine-out emissions seems an appropriate solution.

2.2.2 Benefits of Multi-Mode Operation

The major drawback of LTC modes is their limited operating region. Coupling one or more LTC modes with either SI or CI mode can provide an efficient and clean engine operation. Prior studies [68, 69] conducted on HCCI mode indicated the possibility of HCCI application for passenger cars by coupling it with the conventional spark ignition gasoline engine, owing to the limited operating region of HCCI. It was anticipated that this would provide diesel engine like fuel economy at idle and light load along with low emissions [69]. It was observed that LTC modes offer higher thermal efficiency; thus, requiring less amount of fuel for the same desired power output compared to the conventional SI engine. Multi-mode (CSI-HCCI) engine tested on dyno confirmed 10-15% improvements in fuel economy in the drive cycle [51].

HCCI, RCCI and PCCI combustion modes offer less NOx, soot, CO and unburned HC emissions as can be seen in Fig. 2.2. It can be clearly seen that CO and HC emission levels from LTC modes are much lower when compared to that of CDC. CDC and SI engine require 3-way catalytic converter for exhaust aftertreatment. However, NOx and soot formation can be prevented in LTC modes with proper control. This can be observed in Fig. 2.2, the operating range of the three LTC modes lie outside NOx and soot formation regions which provide advantage over CDC. In [51], the comparison of HCCI engine operation with the baseline SI engine has shown 36% reduction in NOx formation. Therefore, a multi-mode engine concept has a potential to meet the stringent emission regulations and the targeted fuel economy in the on-road vehicles. This can be achieved with an optimized mode switching operation with controlled combustion event while minimizing load fluctuations and engine-out emissions. Mode switching operation can be achieved by optimized adjustments of actuators.

2.2.3 Optimal Control of Multi-Mode LTC Engine

Combustion events in LTC modes are predominantly governed by the chemical kinetics. The combustion initiation is very sensitive to the temperature and pressure changes at the start of compression stroke [70]. HCCI mode does not offer direct control over the combustion process [26]. The thermodynamic state of the air-fuel charge in HCCI is dependent on the residual gas fraction trapped in the cylinder. By precise control of diluents and intake air states, combustion timing can be controlled in HCCI [71]. In dual fuel HCCI operation, premixed ratio of two fuels can also be used as a control knob [31]. In PPCI and RCCI modes, the timing of direct injection of fuel provides better control over combustion timing and rate of heat release. However, LTC modes are susceptible to high pressure rise rates which can cause engine knocking. That is why, closed-loop optimal control is the best choice for LTC engines.

Similar challenges are faced during mode switching which depends on combustion process dynamics, cyclic coupling, actuator dynamics and direction of the mode switch. The common challenges encountered during mode transitions are shown in Fig. 2.3. Mode switching challenges can be wielded by precise actuation. High cyclic variations, high MPRR, partial burns or even failed mode transition can occur due to the poor choice of control parameters [70]. Mode switching dynamics vary significantly with the direction of transition. This difference is quite evident in SI-HCCI-SI mode switching. HCCI to SI mode switching is considered simple because the SI mode does not predominantly depend on the previous cycle [52]. However, SI to HCCI mode switching is difficult because of the residual gas coupling dynamics [52]. The very first cycle after mode transition usually results in complete combustion accompanied by the high rate of heat release and advanced combustion due to the high temperature of residuals trapped from the last SI cycle [52]. This advanced combustion resulted in low engine work. It was also observed by Roelle et. al. that the cycles after mode transition are prone to misfire [52]. This was explained on the basis of heat transfer losses together with less initial chemical energy which lead to reduced engine work and unstable HCCI [52]. Therefore, residual gas coupling dynamics must be accounted for a successful SI to HCCI mode switching. This requires optimal control over the process to retain appropriate amount of hot residuals to avoid excessive MPRR and to avoid misfire in the subsequent cycles. Although, HCCI to SI mode switching does not involve cyclic coupling but it can still face challenges of unstable combustion.

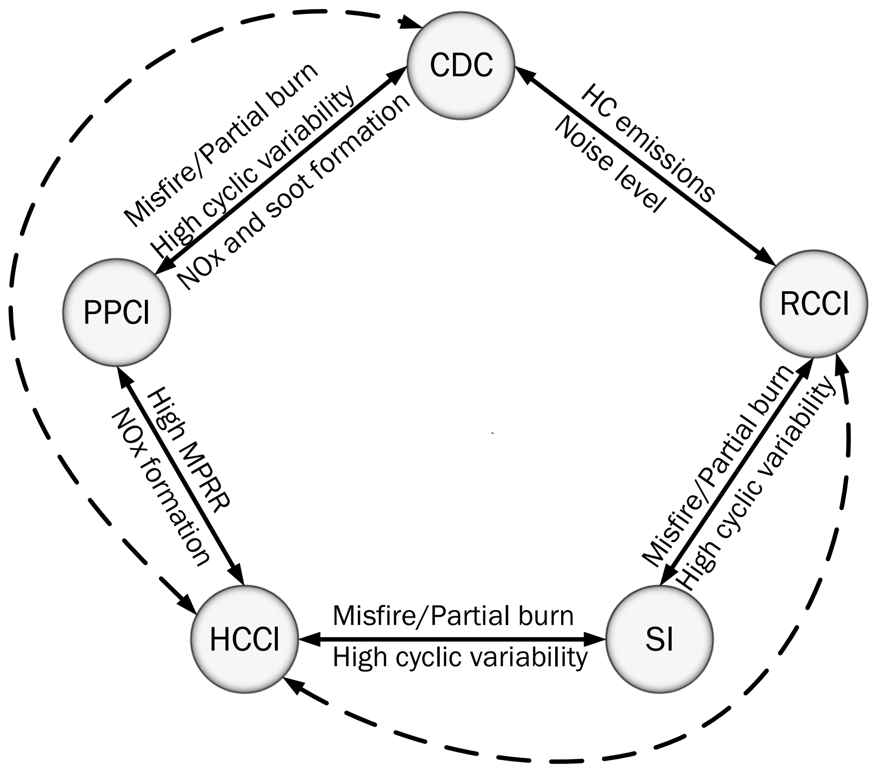

Figure 2.3: Possible mode switching and complications

This is mainly because of the actuator dynamics. HCCI is operated under lean conditions with wide open throttle (WOT) while SI requires stoichiometric air-fuel ratio which is commonly achieved with throttle position control for the required amount of intake air. Studies have shown that throttle response is a major factor behind an unsuccessful HCCI to SI mode transition event [50, 72]. This is because of the slower intake manifold filling dynamics compared to that of valve profile switching. Therefore, it is important to take the actuator dynamics into account. This indicates the necessity of a model-based controlled mode switching event accounting for all the dynamics involved.

A multi-mode engine running in HCCI and PPCI mode using external EGR does not involve throttle dynamics and cyclic coupling. However, HCCI to PPCI mode transition still require optimal actuation to avoid excessive MPRR and NOx formation. Furthermore, transition from LTC-CDC result in engine load fluctuations, high MPRR and high engine noise levels [73]. In [54], potential challenges in CDC-PPCI-CDC mode switching were NOx and soot spikes which was prevented by proper control of fuel injection and air management. Therefore, it is imperative to investigate all the dynamics involved in mode transition. The dynamics can be based on the cyclic coupling, actuator responses or direction of mode transition. A model-based control strategy proves to be the best choice for a stable and smooth transition. Furthermore, mode switching needs finite amount of time to stabilize. Thus, a multi-mode engine should be capable of smooth and fast transitions with minimum load fluctuations. A controlled mode switching assures continuous power delivery while avoiding misfire and safe engine operation. In addition, controlled combustion leads to an optimal combustion phasing which prevents high pressure rise rates; thus, constraining engine noise levels. Appropriate control actions by adjusting the injecting timing, injection duration and split fuel injection help in smooth transition and reduced combustion noise [73].

2.3 Controlled Variables

Controlled variables or parameters are the quantities to be controlled to ensure fuel efficient, stable and safe engine operation while meeting engine-out emission constraints. The challenges associated with the LTC modes can be addressed by implementing optimal control strategies. Model-based controllers are capable of providing optimized control over the LTC process by controlling combustion phasing, engine load, maximum pressure rise rate, coefficient of variation of indicated mean effective pressure (COV_{IMEP}) and exhaust gas temperature. Optimal control of these parameters help in expanding the operating range of LTC modes. A brief introduction of the controlled variables is as follows:

2.3.1 Combustion Phasing

Combustion phasing (CA50) can be defined as the crank angle by which 50% of heat is released. Integrated Arrhenius Rate Threshold, Shell auto-ignition and Modified knock integral models can predict the start of combustion in LTC modes. The start of combustion is important but not sufficient to explain the combustion process because of varying burn duration of combustion events happening at the same operating conditions. Therefore, CA50 is controlled to enable an optimal combustion event.

Wiebe function is commonly used to predict CA50 for model-based control. Feedback from the measured in-cylinder pressure is commonly used to calculate the heat release that provides the combustion phasing. Alternately, in-cylinder ion current sensor can also be used as a feedback sensor but its performance is limited under lean air-fuel mixtures. Other indirect methods used for the calculation of combustion phasing include measurements from microphones and knock sensors [74] and on-board torque sensors [75].

Combustion phasing is one of the most important parameters to be controlled. Variations in CA50 can result in increased or decreased of engine work output, maximum pressure rise rate and emissions. Proper combustion phasing results in maximum brake torque, low maximum pressure rise rates, low NOx and unburned hydrocarbon emissions. HCCI mode lacks the direct control over the combustion process; therefore, it is indirectly controlled by varying the variable valve actuation to trap the required residual gas fraction or using external exhaust gas recirculation [36]. Furthermore, intake air temperature can also be used to control combustion phasing. To address the slow response of intake air heating actuation, fast thermal management system has been developed and tested for the closed loop control of combustion phasing [5]. Combustion phasing can also be controlled with variable compression ratio [46, 71]. In dual fuel application, premixed ratio of the two fuels provides an effective mean to control the combustion phasing [31]. In PPCI and RCCI modes, the timing of directly injected fuel is used to control combustion phasing along with EGR [7, 8].

2.3.2 Engine Load

The main purpose of running an engine is to obtain the desired power output. Engine load output is often termed as indicated mean effective pressure (IMEP) or net mean effective pressure (NMEP) as it can be easily computed from the in-cylinder pressure trace. Sometimes, peak pressure is considered related to engine load and therefore controlled [76]. The total amount of fuel injected in each cycle is used to control IMEP. It is important to control the engine load along with the control of combustion phasing. Partial or incomplete burn in an engine cycle results in lower IMEP which is usually followed by high IMEP due to the unburned fuel available from the previous cycle [50]. This results in high coefficient of variation of IMEP. Simultaneous control of CA50 and IMEP can help in constraining the coefficient of variation of IMEP below 5%.

2.3.3 Exhaust Gas Temperature

One of the drawbacks of the LTC modes is the production of carbon monoxide (CO) and unburned hydrocarbons (HC) which can be reduced using three-way oxidation catalysts. Due to higher thermal efficiency of LTC engines, most of fuel energy is released during expansion stroke; thus, leaving less exhaust gas energy compared to conventional SI and CI engine. In addition, combustion temperature is low in LTC modes due to lean burn or highly diluted engine operation. These lead to low exhaust gas temperature in LTC modes. These combustion temperatures can be as low as 120 °C that typically require a light off temperature of well above 200 °C [65]. This low exhaust gas temperature limits the performance of oxidation catalysts. Therefore, it is important to control the exhaust gas temperature to meet the light-off requirement of the aftertreatment system. In [77], artificial neural network modeling was used to predict exhaust gas temperature for ethanol fueled HCCI operation. It was observed that the variations in combustion parameters such as start of combustion (SOC), burn duration (BD) and maximum in-cylinder pressure (Pmax) were not effectively correlated with variations of exhaust gas temperature. However, exhaust gas temperature was strongly correlated with IMEP and constant-volume adiabatic flame temperature [77]. In [31], exhaust gas temperature is controlled along with CA50 and IMEP for HCCI engine using intake manifold pressure, octane rating and mass of fuel as control variables.

2.3.4 Maximum Pressure Rise Rate

Maximum pressure rise rate (MPRR) is a measure of engine noise level. In LTC modes, a portion of the air-fuel mixture undergoes autoignition which can result in very high pressure rise rates. Therefore, MPRR is usually constrained below 8 bar/CAD in order to prevent the engine from knocking and controlling engine noise level [19]. In HCCI mode, the homogeneous air-fuel mixture undergoes autoignition at multiple points inside the cylinder which results in rapid heat release rates causing very high MPRR. That is why, MPRR is an important engine safety parameter to be controlled. Advanced combustion phasing and shorter burn duration in HCCI lead to high MPRR and engine ringing [78]. In addition, a strong correlation was found between the engine noise level and in-cylinder peak pressure and in-cylinder pressure variation for HCCI mode [79]. In PPCI and RCCI modes, split fuel injections are used to control MPRR along with EGR. By controlling CA50 after TDC, the rate of heat release can be controlled thus preventing MPRR. MPRR in RCCI mode can be reduced by increasing the combustion duration which can be achieved by using the fuels with large difference in their reactivity [80].

2.3.5 Engine-out Emissions

In LTC modes, combustion temperatures are low which helps in preventing the formation of NOx. Diesel fuelled PPCI operation requires low compression ratio and excess amount of EGR for low NOx and soot emissions but it results in low thermal efficiency and high CO and unburned HC emissions [67]. In [64], gasoline fuelled PPCI operation showed very low NOx and soot formation without EGR. In [63], running the engine near stoichiometric conditions lead to soot formation with high levels of CO and unburned HC emissions despite the high thermal efficiency, low NOx and MPRR. Advancing the start of injection of fuel increases fuel stratification; thus, increasing the soot level in PPCI [63]. It was suggested that using high octane number fuels can introduce longer ignition delay which helps in reducing soot formation [63]. Furthermore, it was argued that improving the injection system can decrease the soot levels by employing higher injection pressures [63]. Using advanced injection system with common rail pressure upto 2400 bar and EGR in excess of 50% , full load PPCI operation was achieved with low NOx, soot and CO emissions simultaneously [67]. Transient PPCI operation with gasoline fuel can also lead to high MPRR and soot formation [81]. In order to satisfy low emission levels, double injection strategy has been effective in constraining NOx and soot along with MPRR in PPCI operation [7]. In HCCI mode, HC and CO emissions are strongly correlated with the combustion phasing [82]. Bidarvatan et. al. developed grey-box predictive model to constrain the CO, HC and NOx emissions in HCCI operation [83, 84].

Combustion phasing can also be regulated for low engine-out emissions [64]. In addition, adding EGR as diluent helps in the prevention of NOx but can lead to soot formation due to reduced oxygen concentration [54]. Moreover, high fuel injection pressure improves the air-fuel mixing quality which prevents soot formation [67]. Longer ignition delay provides more mixing time for air-fuel mixing which prevents soot formation [67]. A study showed that proper selection of spray angle, decreasing the injection pressure and premixed ratio while advancing the start of injection timing can significantly reduce HC and CO emissions in RCCI engine operation [85].

2.3.6 $\mathrm{COV_{IMEP}}$

Cycle to cycle variability in combustion event is indicated by $\mathrm{COV_{IMEP}}$. The COV_{IMEP} is a measure of variability in $IMEP$ for a number of consecutive engine cycles at steady state operating conditions. It is defined as the ratio of standard deviation of $IMEP$ to the mean of $IMEP$, given by:

$$COV_{IMEP}(\%) = \frac{\sigma_{IMEP}}{\mu_{IMEP}} \times 100. \tag{2.1}$$

where, μ_{IMEP} and σ_{IMEP} are the mean and standard deviation of $IMEP$, respectively.

High cyclic variability results in engine speed fluctuations and increases engine-out emissions [86]. Noise, vibration and harshness (NVH) performance of a vehicle is affected by high $\mathrm{COV_{IMEP}}$ [87]. LTC modes, operated under ultra-lean conditions, are prone to high $\mathrm{COV_{IMEP}}$. Therefore, combustion cyclic variations are need to be controlled to enable stable engine operation while maximizing thermal efficiency and reducing engine-out emissions. Engine operating cycles undergoing partial burn or misfire result in high cyclic variations.

Kalghatgi et. al. showed a linear regression model using $CA50$ and equivalence ratio (ϕ) to differentiate low and high cyclic variability for HCCI combustion [61]. In order to understand the cyclic variation in HCCI mode, a study by Shahbakhti et. al. identified three distinct patterns of cyclic variations in combustion peak pressure, IMEP and ignition timing [88]. These patterns included normal cyclic variations, periodic cyclic variations and misfired ignition variations. More cyclic variations were observed in the second stage of heat release for different primary referenced fuel (PRF) blends as compared to the first stage of heat release. The study also identified that cyclic variations were highly dependent on the start of combustion timing [88]. Low $\mathrm{COV_{IMEP}}$ can be achieved in HCCI mode by using low exhaust gas recirculation (EGR) rate, high equivalence ratio and high intake temperature [89]. Hellstrom et. al. regulated CA50 using proportional integral (PI) and linear quadratic Gaussian (LQG) controllers to reduce cyclic variability in HCCI engine operation [38]. Bahri et. al. developed artificial neural network model to detect the misfire cycles for ethanol fueled HCCI operation [90]. In RCCI mode, $\mathrm{COV_{IMEP}}$ can be reduced by retarding the injection timing, increasing the injection pressure and using boosted intake pressure [91]. CA50 can be adjusted to ensure stable RCCI combustion by limiting COV_{IMEP} for varying load and speed conditions [21]. Data-driven classification models for $\mathrm{COV_{IMEP}}$ have also been developed for HCCI and RCCI mode. Model predictive controllers (MPC) were developed for HCCI and RCCI modes to limit $\mathrm{COV_{IMEP}}$ below 3% while regulating CA50 and IMEP [92].

2.4 Control Actuators

2.4.1 Variable Valve Actuation

Variable valve actuation (VVA) provides degrees of freedom for cam phasing on intake cam shaft, exhaust cam shaft, cam profile switching or combinations of cam phasing and cam profile switching. VVA can provide variable valve timing and variable valve lift. This helps in achieving the LTC modes by controlling the effective compression ratio and adjusting the amount of residual gas trapped inside the cylinder.

LTC operation is sensitive to charge conditions at intake valve closing (IVC). The charge temperature can be controlled by varying the IVC and exhaust valve closing (EVC) timings. Early or late IVC results in reduced effective compression ratio [2]. This can be understood by the fact that compression process begins when the piston starts moving from bottom dead center (BDC) to the top dead center (TDC). Reduction in effective compression ratio as a result of retarding the IVC is intuitive. However, the effective compression ratio in the case of early IVC during the expansion stroke is complicated to comprehend. The in-cylinder charge pressure is essentially equal to the intake pressure at the IVC. In case of early IVC, the cylinder charge undergoes expansion as the piston moves towards the BDC. This reduces the in-cylinder

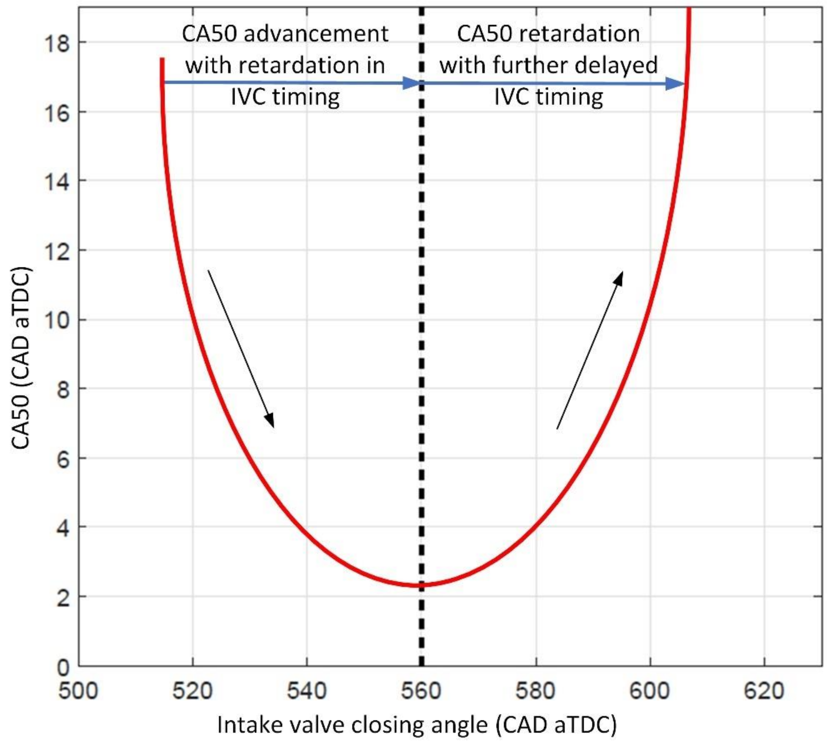

Figure 2.4: Effect of intake valve closing timing on CA50 (aTDC) in HCCI operating mode [2]

pressure below the intake pressure. When the piston starts moving towards the TDC, the in-cylinder charge undergoes compression in which a portion of compression work is utilized in bringing the pressure of the charge gases equal to the intake pressure thus resulting in overall reduced effective compression. Figure 2.4 shows effect of variations in the IVC timing on CA50.

Negative valve overlap (NVO) can be used to trap the required amount of residual gas fraction in the cylinder by altering the EVC. With an early EVC and late intake valve opening (IVO), the residual gases undergo recompression. In-cylinder pressure of HCCI operation with NVO causing an exhaust recompression can be seen in Fig. 2.5. Combustion phasing in HCCI mode can be controlled by varying the EVC to achieve exhaust recompression [27]. The amount of trapped residual gas affects the bulk gas temperature and dilution rate in the cylinder. Increasing NVO increases the amount of trapped residual gas fraction which results in advanced combustion timing. However, the amount of residual gases are reduced for high load engine operation to reduce the charge temperature to control the combustion timing. This results in reduced dilution which leads to advanced combustion and very high pressure rise rates. Another strategy used to retain the residual gases in the cylinder is exhaust re-breathing which is achieved by re-opening the exhaust valve during the intake stroke. This helps in the reinduction of hot exhaust gases in the cylinder. Low load in PPCI operation can be achieved using NVO [93].

2.4.2 Fuel Injection System

Port fuel injectors and direct injectors are used in LTC engines to adjust fuel injections and fuel-air equivalence ratio. Injection variables include fuel injection timing, fueling amount, number of injections and injection pressure. Different fuel injection strategies are used to realize LTC combustion modes. For homogeneous air-fuel mixture, fuel is injected during the intake stroke for HCCI via PFI or DI. For dual fuel HCCI, usually double PFI systems are used for fuel injection. Premixed ratio of two fuels provides

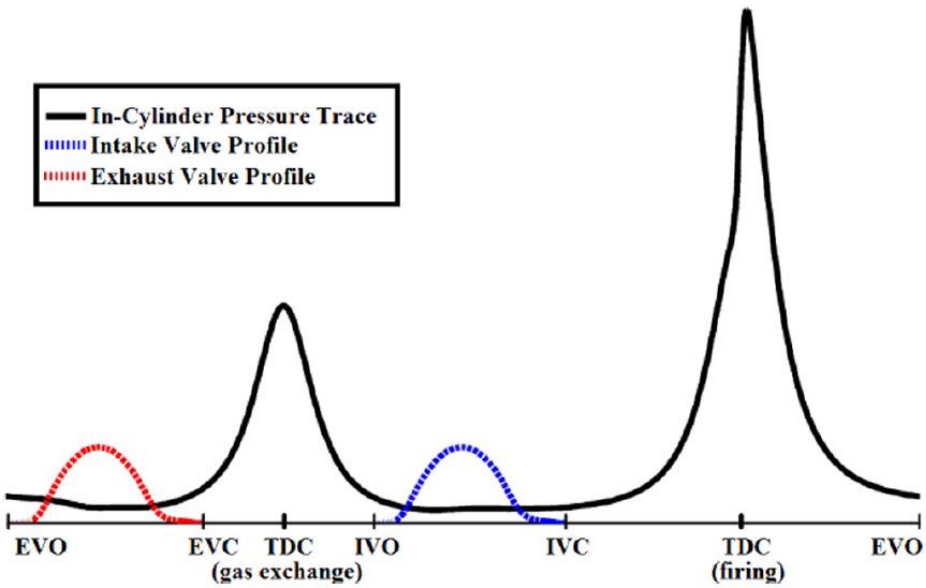

Figure 2.5: A typical in-cylinder pressure trace of exhaust recompressed HCCI operation due to NVO (Source: [3], p. 10)

a control knob over the combustion phasing. HCCI mode can use DI system with split fuel injection strategy. Split fuel injection strategy includes main and pilot fuel injections. Less amount of fuel is injected during the exhaust recompression stroke of HCCI operation which provides a better control over CA50 [4]. The effect of pilot injection timing with a constant main injection timing on CA50 can be seen in Fig. 2.6.

RCCI mode is realized by injecting two fuels of different reactivity levels. Low reactivity fuel is injected via PFI during the intake stroke while high reactivity fuel is injected via DI during the compression stroke. The injection timing of high reactivity fuel provides a good control over combustion phasing. However, premixed ratio of two fuels can also be adjusted to control CA50.

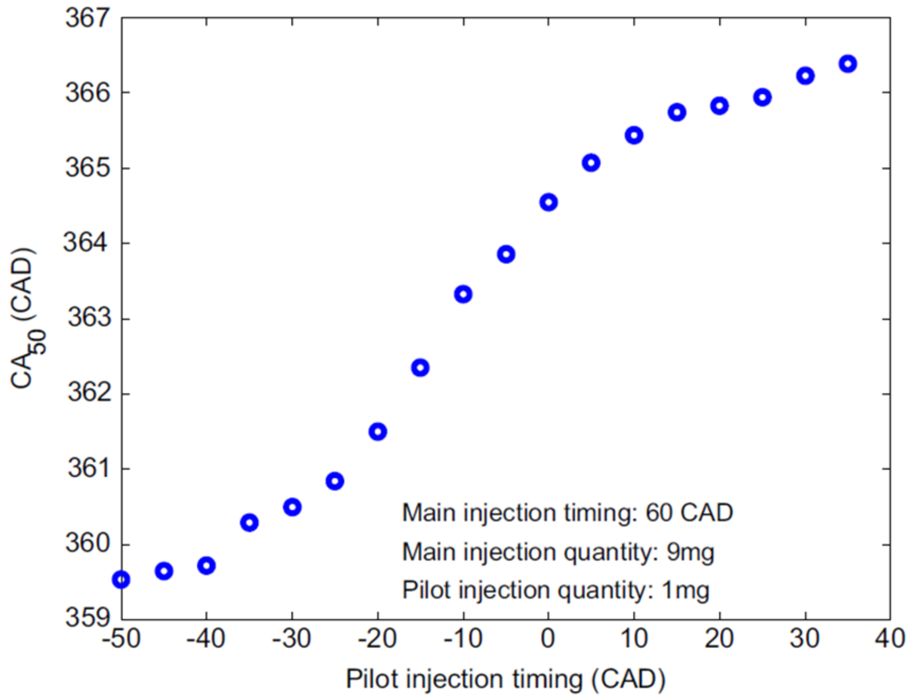

Figure 2.6: Effect of pilot injection during exhaust recompression on CA50 of an HCCI engine (Source: [4], p. 423)

Multiple fuel injection strategy with pilot injection during early compression stroke results in lower cyclic variations, lower smoke, NOx and maximum heat re-lease rate compared to single injection in GCI engine [94]. Kalghatgi et. al. stud-ied the effect of single and double gasoline injections on heat release rate in the PPCI engine operation using 25% EGR, 2 bar intake pressure and 40 °C intake temperature [94]. The results for a single gasoline injection case and two cases with double fuel injections with constant pilot and main injection timings were discussed. For double injection cases, the pilot injection fueling rate was varied while keeping the main injection fueling rate constant. Double injection was help-ful in attaining higher IMEP, lower NOx, smoke, HC and maximum heat release rate, compared to single injection [94]. It was observed that increased pilot fueling rate in double injection led to increased smoke [94]. Yang et. al. used pilot injection timing to control soot emissions while pilot fueling rate was used to control MPRR for PPCI operation using 80% gasoline and 20% n-heptane [81]. In addition, high fuel injection pressure can also be helpful in reducing soot emissions [63].

2.4.3 Fast Thermal Management (FTM)

Intake air heating is usually employed to realize the LTC modes. Intake air heating affects the combustion in LTC mode but due to the slow response, it can not be used to control the combustion phasing on cycle-to-cycle basis. Fast thermal management (FTM) can heat the intake air quickly and can be used for control purposes. FTM system consists of a heat exchanger to extract the heat from the hot exhaust gases. The hot air and cold air are then mixed after the heat exchanger to attain the desired temperature of the intake air. The amount of hot and cold air is controlled by the throttle valves. Figure 2.7 shows the schematic of fast thermal management system used for closed-loop control of HCCI mode in reference [5]. In [5], CA50 was controlled by changing the inlet air temperature using fast thermal management. For a step change of CA50 from 1 to 9 CAD (aTDC), it took 8 engine cycles for CA50 to reach the desired value using fast thermal man-agement. The inlet air temperature was decreased from 190 °C to 136 °C to retard CA50 to 9 CAD (aTDC). Moreover, it

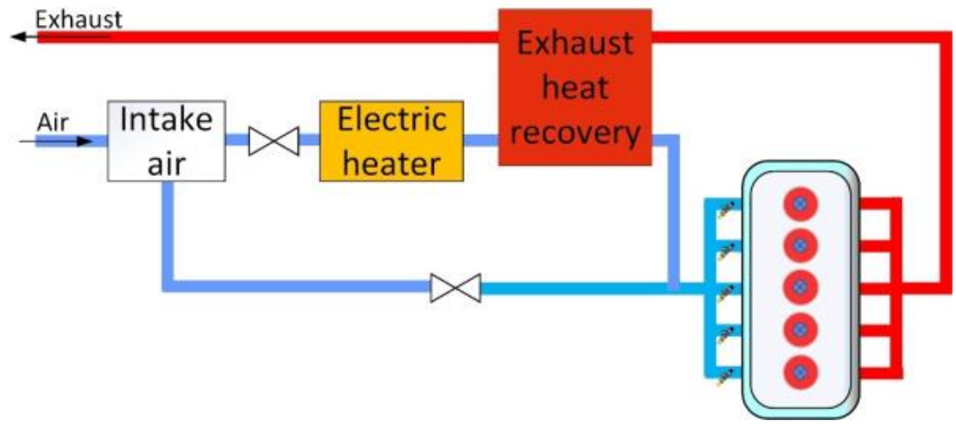

Figure 2.7: Schematic of a fast thermal management system used for closed-loop control of HCCI mode [5]

took 14 engine cycles for CA50 to reach the desired value using variable compression ratio (VCR). FTM proved to be a faster control actuator in controlling CA50 by changing inlet air temperature as com-pared to VCR [5]. LTC is sensitive to air-fuel mixture temperature and cylinder wall tempera-tures. To this extent, adding a capability of precise control of coolant and oil tem-peratures should enhance the capability to control LTC combustion. However, the time scale will be in the order of seconds; thus, coolant and oil temperature control cannot be used for cycle-by-cycle combustion control, while they can be used for steady-state engine operation control.

2.4.4 Exhaust Gas Recirculation (EGR)

NOx formation can be prevented by further reducing the combustion temperature in LTc modes. This can be done by either running the engine under lean condition, premixed or with EGR. High levels of cool EGR can delay autoignition; thus, resulting in retarded CA50. Late heat release occurs during expansion stroke with retarded CA50 decreases the overall combustion temperature; therefore, reduces the NOx formation [64]. Further improvements can be achieved by optimizing injector design, swirl and multiple fuel injection strategy [64].

2.4.5 Intake Air Pressure Boosting System

Intake air pressure is increased either by using a turbocharger or a supercharger. In LTC modes, intake boosting is usually done to extend the load range [95]. The load range of 5-16 bar was achieved for PPCI operation in a heavy duty engine by using boosting, low pressure EGR and triple fuel injections per cycle [20]. Variable geometry turbocharger (VGT) was used to maintain the intake manifold pressure at a desired value for the required engine load [20]. Kalghatgi et. al. investigated diesel and gasoline PPCI operation for low NOx and smoke emissions by using EGR at 2 bar intake air pressure using turbocharger [94]. Shen et. al. investigated the effects of EGR and intake air boosting on PPCI operation using diesel, gasoline and ethanol fuels [96]. It was observed that increasing EGR led to prolonged ignition delay and reduced MPRR while increasing boost resulted in reduced ignition delay and increased MPRR. Increasing EGR became insignificant at high boost levels. It was suggested that reduced intake pressure or increased EGR could help in keeping low NOx emissions [96]. However, this could result in high CO, unburned HC and soot emissions [96].

2.5 LTC Control

Combustion control in LTC modes is very important. Both open-loop and closed-loop control have been used for the LTC modes. Feedback or closed-loop control refers to the control frameworks that adjust engine control variables based on real-time engine feedback. LTC controllers are grouped into two categories: model-free controllers (e.g., PI, PD, PID, etc.) and model-based controller (e.g., LQI, MPC, etc.). Model-based controllers are more appropriate for LTC mode switching. This is because they can incorporate understanding of the engine mode transition dynamics and actuator dynamics through control-oriented models. First, a dynamic LTC mode is defined by its mathematical model then control system is designed for the LTC mode. In order to control the combustion event in the LTC engines, control platforms are usually designed for tracking mode in which reference signals are provided and the system has to follow the desired trajectory.

Open-loop control provides the control action without any feedback knowledge of the plant performance because the control framework has no information about the plant outputs. To control the LTC modes, we need to track the desired combustion phasing and load while it is necessary to keep MPRR and peak in-cylinder pressures below a certain limit. This could be possible with a closed-loop control system in which the information about the parameters of interest is acquired from the LTC engine and fedback to the controller for appropriate action. This is critical for multi-mode LTC engines since different modes have different in-cylinder mixture requirements that affect the engine performance. This is particularly important during mode transitions since the engine can easily become unstable (e.g., misfire) if not controlled properly. Moreover, the nonlinear and complex behavior of some of the engine actuators makes it necessary to design a closed-loop LTC control. The controller frameworks employed in LTC mode studies can be divided into two categories namely, model-free and model-based control systems. These systems are discussed in the following sections.

2.5.1 Model-Free Closed-Loop Control Systems

Model-free closed-loop control systems are based on feedback measurement signals and present control laws that do not directly include a model of the system dynamics.

The most common of these controllers include proportional control, derivative control and integral control actions. Derivative control can never be used alone while proportional and integral control actions can used individually or combined together. The common combined controllers include PD, PI or PID controllers. Better performance can be achieved by combining two or three control actions together. Increasing gain of the proportional controller often yields shorter settling time and smaller steady state error while integral action ensures zero steady state error. Derivative action corresponds to the rate of change of the error signal and provides a component proportional to the derivative of error signal. However, derivative action stops once the error becomes constant. Derivative action usually lead to a noisy operation because of the amplification of the signal noise; therefore, a low-pass filter is usually used. The other reason of using a low pass filter is to prevent saturation of the controller by avoiding the integrator windup.

Earlier studies on the control of LTC modes include model-free control framework implementation. These controllers are manually tuned and relatively simple to design. In [5], two PID controllers were designed to control CA50 and IMEP in HCCI mode by using fast thermal management to heat the intake air and adjusting fuel quantity, respectively. This study also showed the regulation of CA50 using variable compression ratio. Similarly, Olsson et. al. implemented two PID controllers for CA50 and IMEP control. Gain scheduled CA50 controller was designed as a function of sensitivity of CA50 to the octane number [24]. CA50 was controlled by adjusting the premixed ratio of two fuels while total fuel quantity injected per cycle was used to control IMEP [24]. The study showed the possible control of dual fuel operated HCCI engine [24]. CA50 and IMEP are interdependent and therefore, one parameter affects the other. This issue was highlighted in [24] while controlling CA50 and IMEP simultaneously. The performance of IMEP controller was compromised by making it slower than CA50 controller to effectively control CA50.

PID controllers are often single-input single-output (SISO) control systems. PID controllers often use a simple transfer function in which gains are tuned manually to achieve the desired performance. Given no model of system dynamics, PID controllers controllers are not robust. In addition, these controllers require substantial calibration efforts for disturbance rejection and cannot provide optimal control action. On the contrary, model based controllers can offer better performance by taking the interdependence of the engine parameters into account.

2.5.2 Model-Based Closed-Loop Control Systems

Model based controllers use the mathematical model of the LTC mode under consideration. The system dynamics, actuators dynamics and engine outputs can be well explained by the mathematical models that can be integrated into controller design. Model-based controllers can handle multi-input multi-output (MIMO) systems. In reality, mathematical models cannot exactly imitate the real systems. Therefore, robust controllers are designed to handle the inaccuracies or uncertainties in the engine models with minimal performance degradation. Linear quadratic regulator (LQR), linear quadratic Gaussian (LQG), linear quadratic integral (LQI), H_2 optimal control, sliding mode control, adaptive control and model predictive controllers are the commonly used linear optimal control techniques in LTC modes. Controllers, such as model predictive controller, sliding mode control, etc., can also be used for nonlinear control actions. Non-linear model-based controllers have also been developed for LTC modes as will be explained in subsequent sections.

2.5.2.1 HCCI Control

HCCI mode does not offer direct control over the combustion process. Combustion in HCCI undergoes auto-ignition at multiple points which result in very short burn duration and excessive MPRR. Therefore, it is important to control the combustion process in HCCI mode. In HCCI mode, the charge composition at the IVC is a dominant factor that affects the combustion timing in HCCI mode [97]. The commonly used actuators for the control of combustion timing in HCCI mode include variable valve actuation, variable compression ratio, inlet air heating, fuel injection strategies and premixed ratio of dual fuel. The widely used actuator for HCCI mode realization is the use of VVA. Residual gas fraction trapped in the cylinder and effective compression ratio are varied using VVA to adjust the combustion phasing effectively. Increased negative valve overlap (NVO) traps hot residual gases from the previous cycle which results in advanced combustion phasing. Varying the intake valve closing can change the combustion phasing because of the variation in the effective compression ratio. Shaver et. al. designed an H_2 optimal controller based on a two-input and two output state space model to control CA50 and peak pressure by varying IVC and EVC to attain the desired residual gas fraction and effective compression ratio [71]. Strandh et. al. compared the performance of model based controllers i.e., LQG and MPC with PID controller for CA50 control using VVA. The three controllers show good performance with MPC being the best one for CA50 control by adjusting IVC. The study suggested that HCCI control was limited using IVC alone as the control actuator; therefore, inlet air conditioning is required [2]. A sensitivity analysis carried out on HCCI identified that start of combustion is more sensitive to the variations in the mixture temperature as compared to the variation in EGR [98]. In [4], EVC timing together with pilot fuel injection timing during the exhaust recompression were used to control CA50. Bidarvatan et. al. developed discrete sliding mode controller based on the physics based control oriented model of HCCI engine [31]. This study [31] controlled exhaust gas temperature along with CA50 and IMEP. An HCCI combustion event can result in very low exhaust gas temperature which can affect the performance of 3-way catalytic converter. Octane number (ON), mass of fuel injected and intake manifold pressure were adjusted to control CA50, IMEP and exhaust gas

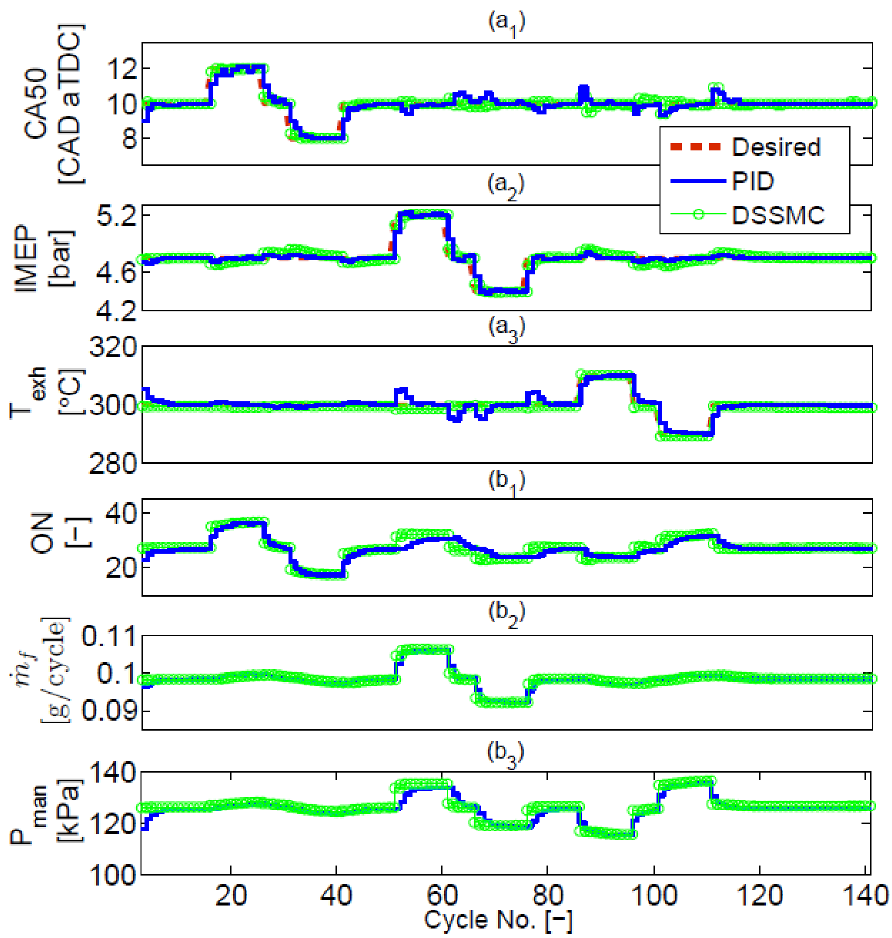

Figure 2.8: Control of HCCI mode using PID and discrete sliding mode controller. a_x are the plant outputs while b_x are the control inputs (Source: [6], p. 173)

temperature as shown in Fig. 2.8. The controller showed good tracking performance while tracking the plant outputs with settling time of 1 engine cycle and zero steady state error.

Model predictive control (MPC) framework is a control technique which optimizes the control action over a finite time horizon in future. MPC can handle constraints on states, inputs and outputs. Constraints on MPRR, peak in-cylinder pressure, emissions, and physical limits of engine actuators make MPC a favorable framework to optimally control the LTC modes. The only drawback of MPC is its relatively long computational time. HCCI operation in a heavy duty 6-cylinder Volvo diesel engine using dual fuels (i.e., ethanol and n-heptane) was controlled by an MPC [26]. A MIMO MPC framework using system identification model was used to control combustion phasing, IMEP and maximum pressure rise rate using IVC timing, amount of fuel injected, intake air temperature and engine speed as inputs [26]. Combustion phasing and load were simultaneously controlled together with the constraint on cylinder pressure on cycle-to-cycle basis in an HCCI engine [26]. The effects of separate constraints on inputs and plant outputs have been studied for an HCCI engine actuated with VVA. A MIMO MPC framework was used to control combustion phasing and IMEP [30]. This study [30] suggested that the constraints on the outputs were sufficient to avoid ringing and misfire. Nonlinear MPC was developed for dual fuel HCCI operation to control CA50 and IMEP while constraining COV_{IMEP} below 3%. The nonlinear model for COV_{IMEP} of HCCI mode was based on a data-driven classification technique. The controller was capable of regulating CA50 to ensure stable HCCI operation by maintaining COV_{IMEP} below 3% [92].

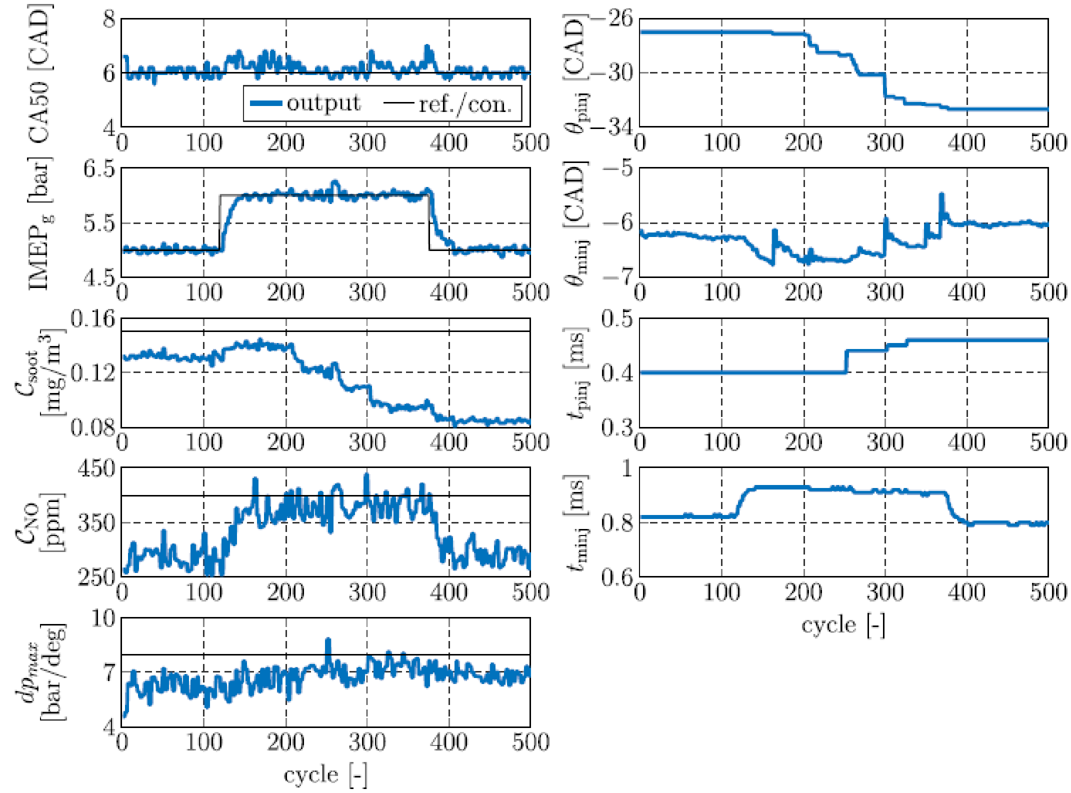

Figure 2.9: Experimental results for control of PPCI mode in Scania D13 heavy-duty multi-cylinder engine using MPC with constraints on soot, NOx and maximum pressure rise rate. Subplots on the left side show the MPC outputs and state observer outputs. Subplots on right show the corresponding control actions (Source: [7], p. 9)

2.5.3 PPCI Control

Unlike HCCI, partially premixed charge compression ignition engine provides a direct control over CA50 by adjusting the injection timing of the fuel. Engine load is controlled by the total amount of fuel injected in the cycle. Model predictive controller has widely been used in closed-loop control of PPCI operation owing to the fact that MPC provides optimal control with constraints handling. Based on the experimental studies, control oriented models for PPCI are developed for model based control [7, 20]. One such study is conducted by Yang et. al. in which a double Wiebe function is used to model the combustion event [7]. For dual fuel PPCI operation, the developed MPC not only controlled CA50 and IMEP but also constrained NOx, soot and MPRR below 400 ppm, 0.15 mg/m^3 and 8 bar/CAD, respectively. Duration of main fuel injection was used to control IMEP. To counter the effect of increased main injection duration, the timing of main fuel injection manipulated the combustion phasing as shown in Fig. 2.9. The control action to limit NOx emissions can be explained by the fact that when pilot injection advances, it prolongs the mixing period which results in a leaner low stratified mixture. This leads to a more premixed combustion thus limiting the NOx formation. Furthermore, increased amount of pilot injection also results in reduced NOx emission as observed in [94]. However, heat release rate increases due to advanced pilot injection timing and increased pilot fuelling rate [7]. From the combined effect of the control actions, soot was significantly reduced while limiting NOx and MPRR [7].

Closed-loop control of PPCI in a heavy duty engine delivered 5 bar to 16 bar engine load by utilizing intake air boosting, low pressure EGR and triple fuel injections per cycle [20]. The desired CA50, intake pressure and EGR flow were determined from the engine load and speed performance. MPC was developed for controlling

CA50, intake pressure and EGR flow using main injection timing, variable geometry turbocharger valve and EGR flow valve [20]. However, engine load was controlled by using feedforward and PI controllers using fuel injection duration as manipulated variable [20].

2.5.4 RCCI Control

Reactivity control compression ignition mode usually employs port fuel injection system for low reactivity fuel while high reactivity fuel is injected via a DI system. The premixed ratio of two fuels, also known as blend ratio can be used to control combustion phasing. In addition, injection timing of high reactivity fuel can also effectively control combustion phasing. Gasoline and diesel [23], iso-octane and n-heptane [99], gasoline and ethanol [100], natural gas (NG) and diesel [22] are some of the dual fuels used to achieve RCCI. Either physics-based or data driven control oriented models are used for MIMO control of RCCI engines. In [22], a robust MIMO feedback controller was developed to control NG-diesel RCCI operation using diesel injection timing and total amount of fuel as manipulated variables to control ignition delay and engine load, respectively. NOx and HC emissions depend on ignition delay and blend ratio. Too long ignition delay and high blend ratio resulted in low combustion efficiency and even misfire. Thus, blend ratio along with ignition delay were controlled to avoid misfire and reduced NOx formation. The controller was based on the multi-zone

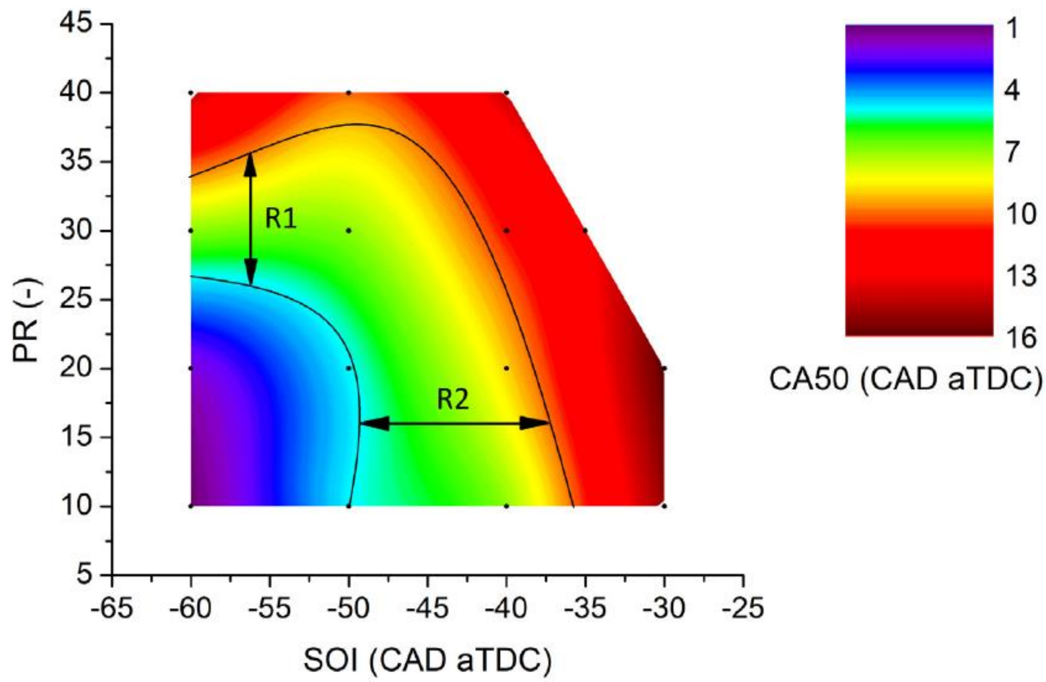

Figure 2.10: Sensitivity map of CA50 w.r.t premixed ratio of iso-octane and n-heptane and SOI of n-heptane for control of an RCCI engine (Source: [8], p. 140)

combustion model [22].

Raut et. al. developed a physics-based control oriented model to control RCCI mode [8]. RCCI operation was realized with iso-octane and n-heptane fuels. Two control knobs were identified for combustion phasing control based on the sensitivity map shown in Fig. 2.10. Either premixed ratio (PR) of the fuels or start of injection (SOI) of n-heptane was selected as a control knob for combustion phasing based on the sensitivity map. At constant engine speed, intake manifold temperature and pressure, PR and SOI sweeps were conducted to determine the sensitivity of CA50 corresponding to each control knob, see 2.10. Figure 2.11 shows the schematic for a designed MPC controller for RCCI engine based on the sensitivity of CA50 w.r.t PR and SOI. Gain scheduled MIMO MPC controllers were developed to control CA50 by adjusting either PR or SOI timing based on the sensitivity and IMEP by adjusting amount of total fuel injected. Data-driven RCCI model was developed by Irdmousa et. al. using support vector machine (SVM) to obtain linear parameter varying (LPV) models as a function of fuel quantity. MPC was then developed based on the LPV models to control CA50 in RCCI engine operation [41]. MPRR in RCCI operation can be constrained using MPC as shown in [101] by constraining MPRR $\leq$ 6 bar/CAD. Based on SVM, an RCCI model was developed using premixed ratio as a scheduling parameter to obtain LPV models [101].

For high thermal efficiency and low NOx and soot emissions, Gaussian process regression was used for optimization of RCCI [43]. Feedforward controller based on data-driven model used nested particle swarm optimization to maximize gross IMEP for fixed amount of fuel injection while satisfying constraints on MPRR, NOx, PM, CO and HC [43]. It is important to prevent the cyclic variability in RCCI mode below 3% for stable engine operation. In [92], SVM classification technique was used to develop COV_{IMEP} model for RCCI mode. Based on the model, a nonlinear MPC was developed for RCCI operation. SOI, PR and fuel quantity were used to simultaneously control CA50 and IMEP while constraining COV_{IMEP} below 3%.

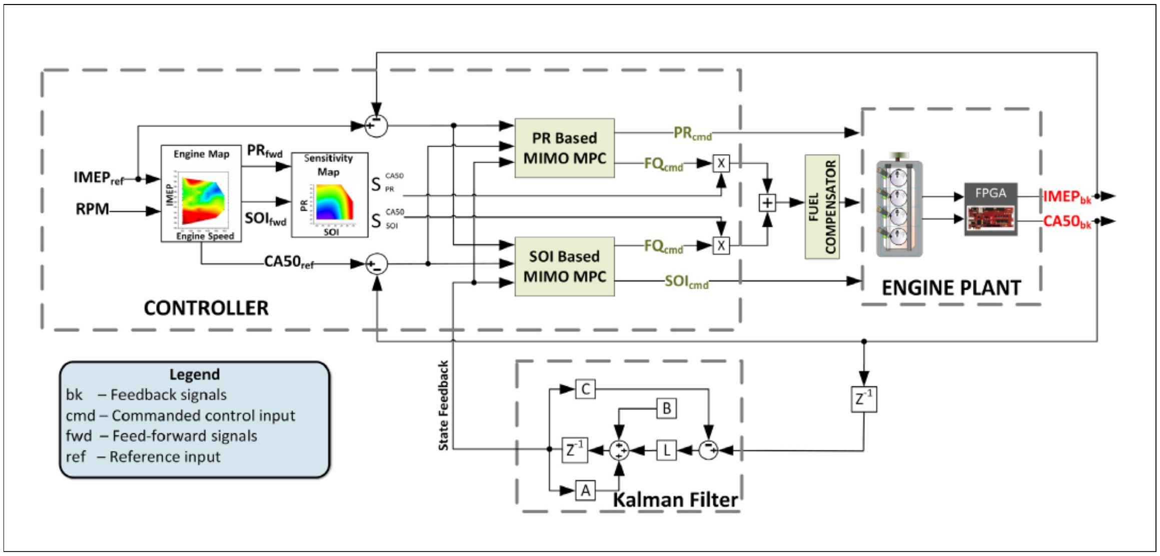

Figure 2.11: Schematic of a designed MPC for RCCI control (Source: [8], p. 140)

2.6 Mode Switching Control

To take the full advantage of LTC modes, multi-mode combustion engine is a viable solution to increase engine speed and load for broad engine applications. This will require developing robust mode switching control strategies. The most common multi-mode engine concept is based on SI and HCCI mode switching. Other multi-mode engines include HCCI-PPCI-CDC, CDC-RCCI, and conventional dual fuel combustion to RCCI mode, as shown in Fig. 2.3. In a multi-mode engine, conventional SI or CI mode is often necessary for engine startup and high load requirements. However, multi-mode engine challenges depend on the modes and type of actuators being used. The common multi-mode engine challenges are summarized in Fig. 2.12.

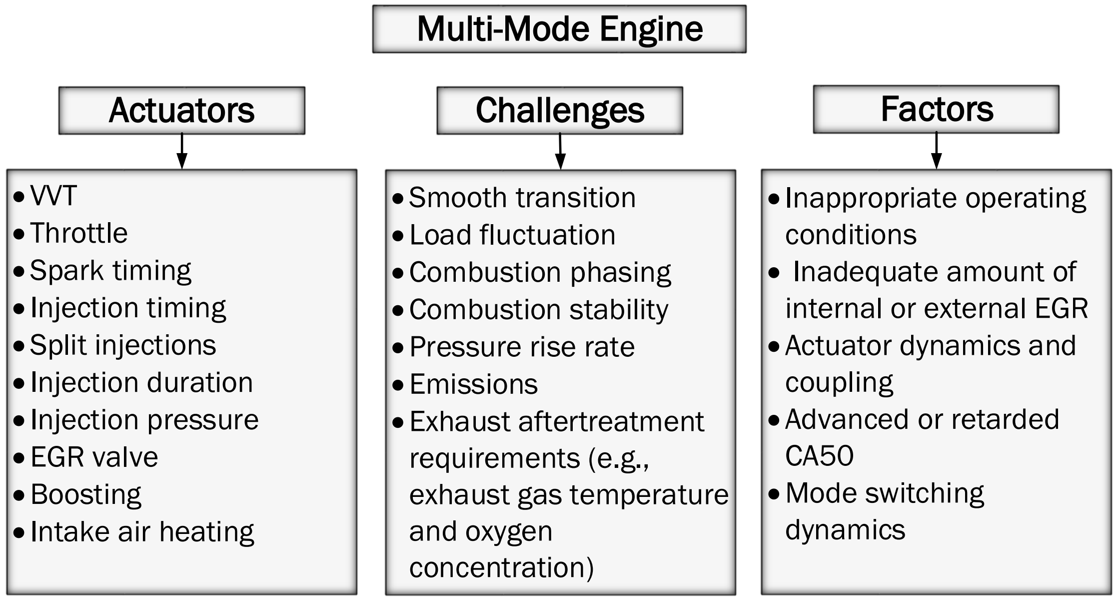

Figure 2.12: Common multi-mode engine actuators, challenges and associated factors

Ultra-low emissions of LTC modes makes a multi-mode engine desirable. Properly controlled mode switching operation can result in minimum load fluctuations and reduced emissions in LTC modes, as observed in [51]. CO, unburned HC, NOx and soot spikes can occur during mode switching operation. These undesirable emissions can be avoided by a controlled mode switching operation. Increase in dilution helps in avoiding NOx while insufficient in-cylinder oxygen concentration often leads to soot emissions. Therefore, it usually results in a trade-off between NOx and soot emissions. However, soot formation can be prevented by increasing injection pressure, injection rate and boost pressure. While NOx emissions can be avoided by using split fuel injections and controlling injection timing together with the amount of dilution. The common mode switching emission challenges and possible countermeasures are listed

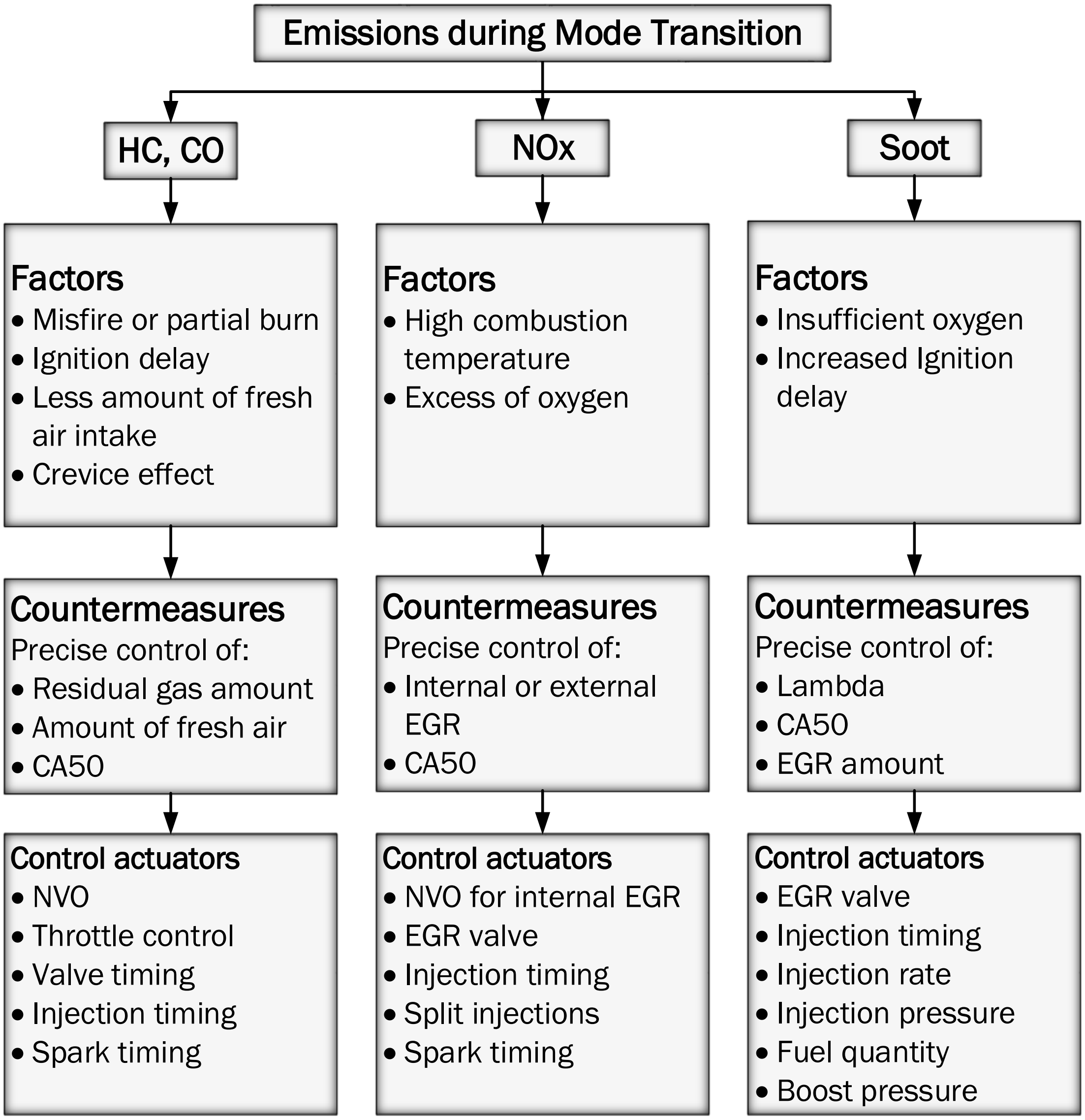

Figure 2.13: Common multi-mode engine-out emission challenges and possible solutions

in Fig. 2.13.

2.6.1 SI-HCCI-SI Mode Switching

In a SI-LTC engine, SI mode is necessary for engine startup. After the engine warm-up, SI mode is switched to HCCI mode for an efficient low load engine operation with low engine-out emissions. Mode switching from HCCI to SI is required to achieve high engine load and speed. HCCI operation at high engine speed is likely to undergo misfire or partial burn due to decrease in the available time required for the combustion onset [46]. Furthermore, HCCI operation at high load causes very high combustion rates which leads to excessive pressure rise rates due to the lack of dilution [47]. Moreover, because of low pumping loses and use of three way catalyst for the exhaust aftertreatment, the performance of SI mode is comparable to HCCI mode at high load [47]. Thus, researchers suggested the viable concept of SI-HCCI-SI dual mode engine for a full speed-load engine operation. Several rule-based and model-based studies using open-loop and closed-loop control have been conducted on mode switching to develop a multi-mode engine. The challenges in mode switching operation of SI-HCCI multi-mode engine and suggested solutions are shown in Fig. 2.14. To extend the operating range and to avoid frequent mode transition and misfired cycles, assisted spark stratified compression ignition (ASSCI) mode can be effective for successful mode transition between SI and HCCI modes. In ASSCI mode, fuel is directly injected before spark initiation to form a locally rich charge near spark plug. This leads to a two-stage combustion resulting from flame propagation and

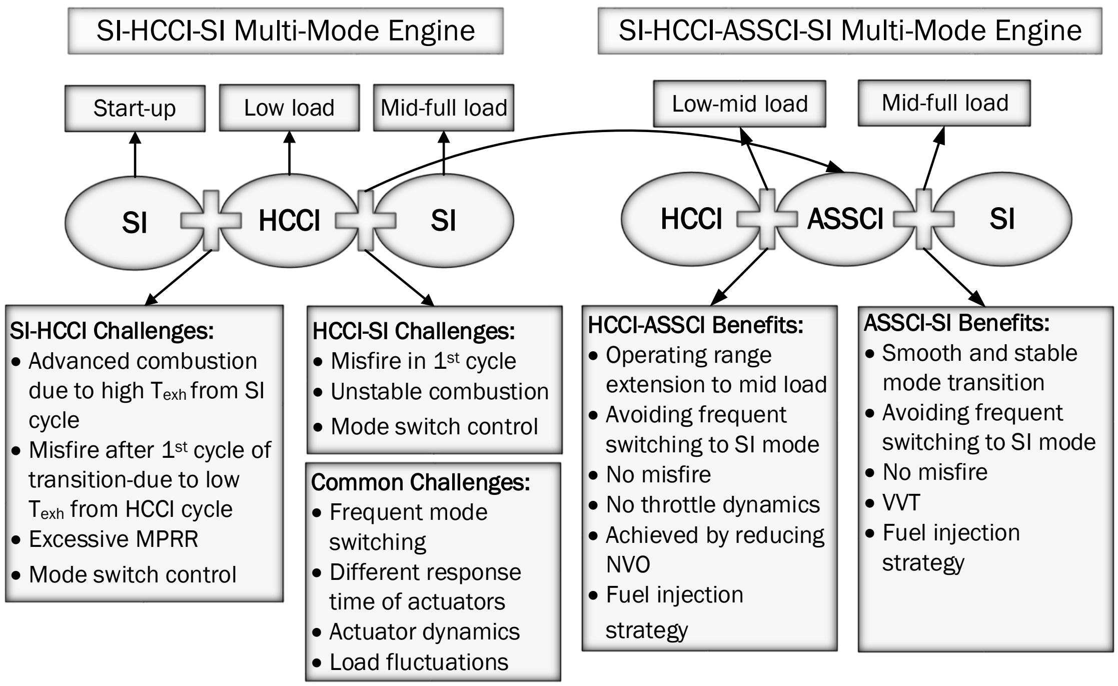

Figure 2.14: Challenges associated with SI-HCCI-SI mode transition and benefits of introducing ASSCI mode in HCCI-SI mode switching

compression ignition [14].

2.6.1.1 Rule-Based Mode Switching

The actuators used to realize SI-HCCI-SI mode switching may include throttle, variable valve timing, cam profile switch (CPS) system and phaser, DI and PFI injectors, spark plug, external EGR and variable compression ratio. The mode switching strategies can be grouped as a single step or two steps based on the actuator dynamics. A single step mode switching strategy is the one in which all the actuators are set to the required set points simultaneously and mode switching is achieved in a single engine cycle. While two step strategy is the one in which mode transition takes place in two steps by activating the actuators based on their response time. In [11], based on the actuator dynamics, cam profile switching and throttle position were changed in two steps for successful SI-HCCI-SI mode transitions.

HCCI operation can be realized with variable compression ratio (VCR) engine actuated either by varying VVT or tilting the cylinder head [47]. In [47], an in-cylinder pressure sensor was used to provide combustion phasing feedback sampled with a fast data acquisition processor board. HCCI to SI mode transition in a multi-cylinder engine with VCR by tilting the monohead was not successful in the study done by Hyvonen et. al. [47]. The possible reason can be the fact that HCCI operates at high compression ratio with air as dilution while SI requires substantially low compression ratio and stoichiometric air-fuel ratio which was not possible to achieve from one engine cycle to the next cycle due to the hardware limitations used in [47].

The main challenge in mode switching is the precise setting of the control parameters. Poor choice of control parameters can cause high cyclic variability, high MPRR or even failed mode transition [70]. Multi-mode engine realized with VVT can often result in successful mode switching using single step strategy. SI-HCCI-SI mode transition carried out on a Volvo 5-cylinder engine was successful with electronic valve timing control without throttling. For SI to HCCI mode switching, valve timings were changed to achieve NVO to retain hot residual gases from the SI cycle. HCCI is more sensitive to the temperature and pressure at IVC. SI-HCCI was easily realized with NVO resulting in an early combustion timing. Too advanced combustion in first few cycles of SI-HCCI mode transition resulted in reduced load, causing load fluctuations [70]. When HCCI mode was stabilized after a few cycles, the resulting NMEP was higher than that of the SI mode because of higher thermal efficiency [70]. Combustion stability was affected by the variation in NVO during SI-HCCI mode switching. IVC did not significantly affect CA50 but an early IVC had a positive impact on the fuel consumption in a Volvo 5-cylinder engine [70]. HCCI operation with early intake valve closure resulted in 12% reduced fuel consumption as compared to SI operation at the same load. From HCCI to SI mode transition, valve timings were changed from NVO to normal valve overlap. HCCI to SI mode transition has proved to be more robust.

VVT is an effective control actuator to realize HCCI operation and mode switching. However, there still exists probability of misfire during mode switching. It is hard to stabilize the combustion event after a misfire because the unburnt fuel from the previous cycle accumulates and results in advanced combustion and high pressure rise rates in the subsequent cycle. Furthermore, the first cycle of SI to HCCI mode switching results in successful combustion followed by a cycle with misfire [9, 52]. This is essentially due to cyclic coupling of the hot residuals gases from SI cycle that helps in initiating auto-ignition in the first HCCI cycle. While the residuals trapped from the first transition cycle should be sufficient enough to sustain the HCCI combustion in the subsequent cycles [9]. A stable combustion cycle followed by a misfiring event was observed in [9] during single step SI-HCCI mode switching. Therefore, two-step strategy was developed for a successful and stable mode switching operation. In [9], intake and exhaust valve timings were adjusted to switch from SI to HCCI mode while running both modes under wide open throttle condition to avoid manifold dynamics associated with the throttle control. Kistler 6125 pressure transducer was used for combustion feedback. Spark assistance at TDC was provided during the transition. To avoid misfiring, IVC timing was changed to an intermediate value in the first HCCI cycle followed by the desired IVC timing while EVC timing was changed in one step which resulted in robust transition from SI to HCCI mode. For HCCI to SI, EVC and IVC valve timings were retarded to trap required mass of fresh air. Figure 2.15 shows successful SI-HCCI mode transitions running un-throttled in dual modes using VVT.

For a successful mode switching event, it is very important to understand the effect of different actuators on the coupling of SI and HCCI modes. In addition, SI-HCCI-SI transition dynamics strongly vary depending on the direction of switch and operating conditions. It is important to identify the actuator response times and the coupling dynamics of different actuators. Throttle response has major effect on the mode switching performance even more than valve profile switching [50, 72]. For instance, a slow or fast throttle response can lead to a misfire [72]. HCCI to SI mode transition

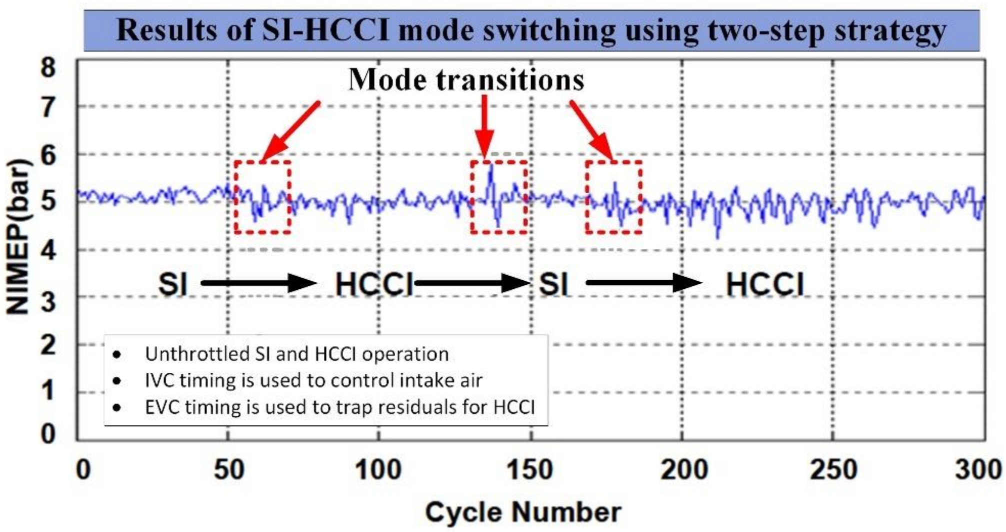

Figure 2.15: SI-HCCI mode transitions at 1500 rpm and 5 bar NMEP in single cylinder engine with electromagnetic VVT system [9]

is considered to be relatively easy because of no cyclic coupling through the residual gas [49, 52]. However, it is not always true because different actuators exhibit different dynamics during mode switching and their response times vary. In [50], SI-HCCI mode transition was successfully accomplished in one engine cycle using throttle control, VVT, cam profile switching and phasing at three different operating conditions. However, mode switch from HCCI to SI was unsuccessful in three different cases with different control strategies [50]. The main reason was slow moving throttle valve which took 5-6 engine cycles to move from WOT to 45% position. Failed mode transition in [72] corroborates the dependence on the direction of mode switching, actuator dynamics and response times of actuators.

In [72], the actuators' dynamics were investigated during SI-HCCI-SI mode switching. It was observed that the intake manifold pressure response changed at a faster rate as compared to the rate of internally trapped residual gases in SI-HCCI transition. The different response timings of throttle and VVT lead to misfire during mode switching. However, the dynamics were opposite for the HCCI-SI mode switch. Therefore, a two-step mode switching strategy was utilized with an intermediate operating point. In the first step, NVO and throtle opening were slightly increased. NVO was further increased for a stable HCCI operation along with wide open throttle (WOT) in the second step. An accurate NVO period and throttle position are essentially the key factors in mode transition. It was emphasized that a successful combustion event at an intermediate condition can only be possible by retaining precise amount of residuals and fresh air. The intermediate operating point was susceptible to abnormal combustion event because of the following two reasons:

- High internal residuals reduces combustion speed in SI combustion event that leads to prolonged combustion and reduced IMEP. If the internal residual gases are high enough compared with the stable SI operation then it can cause misfire.
- Low internal residual gases can not promote auto-ignition.

Optimal spark timing and use of secondary injection can be helpful during mode transition. Advanced spark timing can suppress the effect of hot residual gases on the combustion in SI mode[72]. A second injection during transition creates stratification

[72]. In [72], an overlapped timings of second injection and the spark resulted in a combustion event with combined effect of flame propagation and auto-ignition. This strategy resulted in a successful SI-HCCI mode switching.

A two-step strategy for HCCI-SI mode switching resulted in stable transition by taking the actuator dynamics into account. Firstly, throttle opening was reduced and stoichiometric air-fuel ratio was maintained. Secondly, NVO was reduced along with further reduction in throttle opening. Additionally, second fuel injection with advanced spark timing was employed which helped in achieving a successful combustion event with auto-ignition and flame propagation [72]. Combustion event occurring during a mode transition is a hybrid of typical SI and HCCI operations [72]. Similar observation was made in [10] where the mode switching operation utilized variable valve timing and lift without throttling. The mass fraction burn (MFB) profile of the transitioning cycle showed two different slopes as shown in Fig. 2.16. A portion of the MFB curve with smaller slope corresponds to the typical SI event with slow heat release rate and the second portion of the MFB curve with larger slope can be associated with the faster heat release rate which is characteristic of an HCCI event from SI-HCCI mode switch [10]. This study used two ECUs, an EFI ECU to control fuel injection, ignition and air-fuel ratio while the other ECU to control intake and exhaust valve timing and lifts [10].

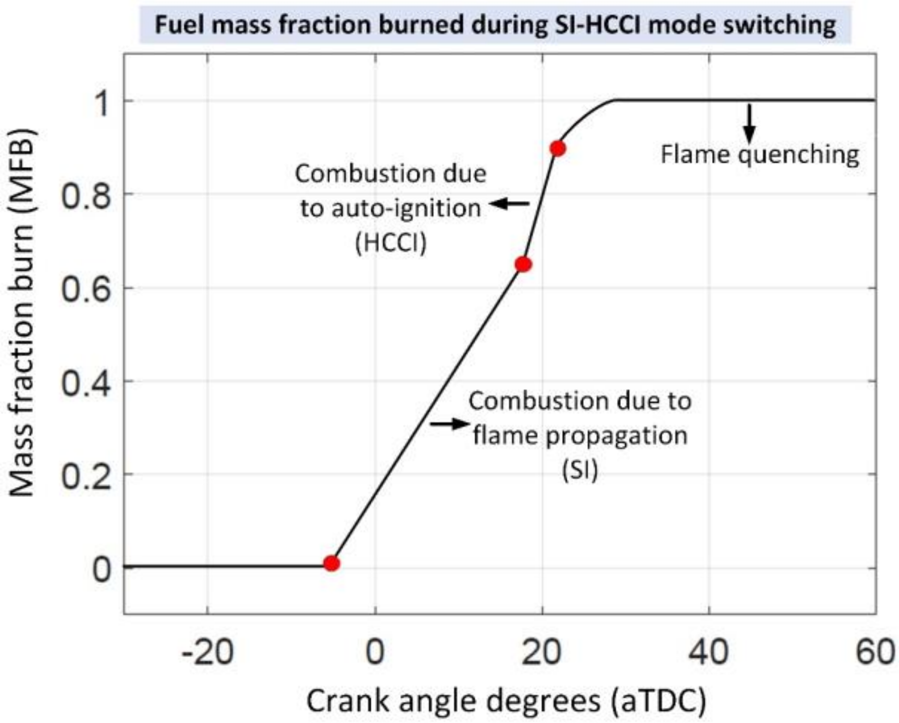

Figure 2.16: Mass fraction of burn (MFB) fuel during SI-HCCI mode transition [10]

Cam profile switching and phasing has also been used as a control actuator for multi-mode engines realization using VVT and throttle control. Low lift profile with NVO is used for HCCI operation while SI mode is realised with positive valve overlap and high valve lift. However, the dynamics of actuators in this case must be taken into account to ensure stable mode switching. A study on SI-HCCI mode switching was conducted on gasoline direct injection engine equipped with throttle position, variable valve timing and lift profiles [11]. For SI to HCCI mode transition, cam profile was switched, following by the opening of throttle to wide open position. For HCCI to SI switch; however, throttle position was closed first followed by the cam profile switching

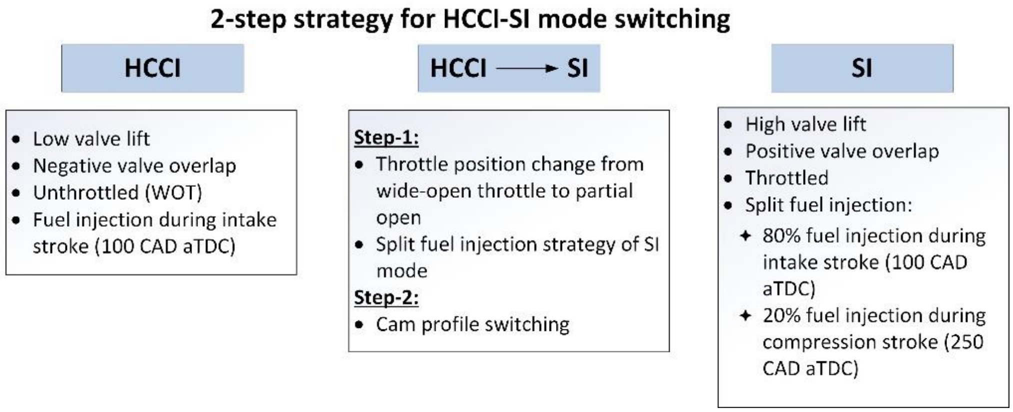

Figure 2.17: Two-step strategy for SI-HCCI mode transition [11]

in the subsequent cycle as shown in Fig. 2.17. Spark assistance was provided through out the mode switching process [11]. In addition to the two-step strategy used for a stable mode switching operation, another strategy has also been suggested. In this strategy, two fuel injections were used for normal SI operation. Main injection took place at 100 ° CAD aTDC and pilot injection at 250° CAD aTDC in compression stroke to provide rich zone near spark plug. SI to HCCI switch failed because of delayed response of cam switching while fuel injection strategy was already switched to HCCI. The cam profile switch delay was prevented by switching the cam earlier in the last SI cycle to trap enough hot residuals for the first HCCI cycle followed by the change in fuel injection strategy. From SI to HCCI mode transition, low valve lift and short valve timings wth NVO could retain less amount of fresh air which resulted in more THC emissions while NOx was reduced dramatically as shown in Fig. 2.18. However, the resulting HCCI cycles showed stable engine operation without knocking. Combustion phasing is usually advanced in HCCI mode because of the hot trapped residual gases from the previous SI cycle which leads to high peak cylinder pressure and MPRR [11]. For HCCI to SI mode transition, the last four HCCI cycles before the switch were operated under NVO with the SI split fuel injection strategy. This helped in handling the high-lift cam switching. In this way a smooth and stable HCCI to SI mode switch was achieved. Though, there was a slight increase in THC emissions for the engine cycle number 82 and beyond as seen in Fig. 2.18.

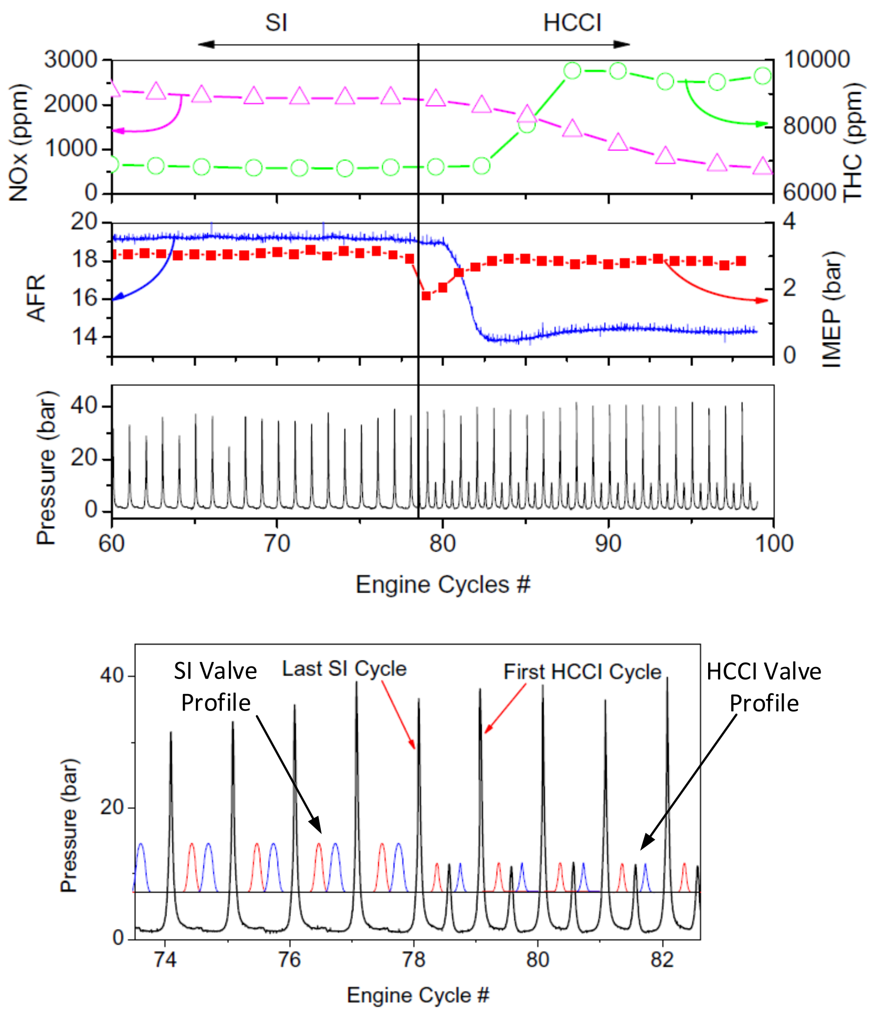

Figure 2.18: SI-HCCI mode transition in a 2-cylinder gasoline direct injection engine [11]

Combustion in HCCI is rapid with high rate of heat release because of multiple autoignition points thus leading to high maximum pressure rise rate [102]. From SI to HCCI mode transition, temperature of trapped exhaust gases and cylinder walls are high which results in advanced combustion timing of HCCI producing very high MPRR. External EGR can be used to reduce the audible knocking during transition [102]. Secondary fuel injection during the compression stroke of SI-HCCI mode transition effectively reduce the rate of heat release and combustion noise without any additional dilution [103]

2.6.1.2 Model-Based Mode Switching

Multi-mode engine performance for high thermal efficiency and low emissions is contingent on mode switching event. A successful mode switching operation takes a few cycles to stabilize and provide a steady state load output [70]. In rule-based mode switching approach, actuators' sequence are determined either through trial and error basis or using look-up tables. In case of misfired cycles during mode switching, engine power-output fluctuates leading to high cyclic variability and it takes more time to stabilize the steady state mode operation with increased engine-out emissions; thus, losing the thermal efficiency and low emission targets. On the contrary, a model-based mode switching approach takes the cyclic coupling dynamics of the combustion modes and actuator dynamics into account. This not only reduces the calibration efforts but also provides a robust control over the mode switching process. The common modelling approaches used for model-based mode switching include semi-empirical models, physics-based models and finite state machine models. Furthermore, mode switching is a tricky task which can result in unacceptable engine operation with slight change in the operating conditions. Therefore, either feedforward control or closed-loop transition control must be adopted. One such example of semi-empirical model-based mode transition was implemented for SI-HCCI-SI switching. In [51], multi-cylinder gasoline engine was operated in SI and HCCI modes by modifying the intake cam phaser to provide high and low lift profiles and AVL electro-hydraulic valve actuation (EHVA) system was added at exhaust valve of each cylinder. EHVA system ensures fully flexible valve timing, and being able to vary valve opening, duration and valve lift. Closed-loop combustion control was implemented for both SI and HCCI modes while model-based open-loop SI-HCCI-SI mode transitions were carried out. At low load, SI mode was switched to HCCI and back to SI mode using transition algorithm. This algorithm stored the valve closing timing for the first HCCI cycle after transitioning from SI mode and for steady state HCCI operation. Mode transition function was developed based on the stored valve timings and shape function. Model based corrections were made with the help of semi-empirical function based on load-temperature history of mode transition at different operating conditions [51]. For instance, if mode was switched from SI to HCCI at high load, the exhaust gases would be at higher temperature as compared to the mode switching at idle conditions

[51]. Closed-loop combustion control was activated after a few cycles of mode transition. Mode switching from SI to HCCI resulted in significantly reduced NOx because of lower exhaust gas temperature in HCCI mode [51]. Furthermore, MPRR less than 8 bar/CAD was observed during mode switching from SI to HCCI with the transition algorithm. Experimental results showed 36% reduction in NOx when compared with the conventional gasoline engine operation [51].

Physics-based SI-HCCI mode switching model for a light duty engine was developed for an efficient transition [52]. Actuators used to accomplish mode transition were variable valve timing and duration. Residual affected HCCI operation is very sensitive to the residual gas temperature. Hot residual gases from SI cycle are less dense which reduce the total mass being inducted [52]. Moreover, advanced auto-ignition occurs in the HCCI cycle which can be explained by the fact that heat transfer losses increase with early ignition thus, decreasing not only the available work but also less initial chemical energy which leads to unstable HCCI combustion following the transition [52]. Therefore, control of residual gases to be trapped during transition becomes imperative from SI to HCCI switch [52]. With proper valve timing control, mode switching can be made efficient and effective. The model developed in [52] incorporated the intake and exhaust manifold dynamics, combustion kinetics and heat transfer for SI and HCCI modes and the switching dynamics. This model was also capable of capturing the exhaust gas temperature dynamics of SI to HCCI mode switching. The model demonstrated successful mode switching while maintaining constant combustion phasing and work output. This model provided a pathway for closed-loop mode switching controller for constant combustion phasing and work output [52].

Finite state machine can be used for modelling the SI-HCCI-SI mode switching. It can also be used to develop a discrete-time switching model based on the continuous-time system dynamics. One such study was carried out by Karagiorgis et. al. [12]. Complete engine cycle was modelled into five mutually exclusive discrete-time subsystems. Each subsystem was modelled as continuous-time differential equation from intake air-flow dynamics to the exhaust. Look-up tables were provided to determine temperature and concentration dependent thermodynamic properties. State and charge gas concentrations computed by each subsystem were stored to set the initial values for the next cycle. Two strategies for SI-HCCI switching were employed in this study. First strategy used cam profile switching followed by changing throttle position to WOT and valve timing. Fuel injection strategy in HCCI mode used pilot injection during NVO and main injection during intake stroke. In this strategy, the last SI cycle ran in lean condition which led to partial burn while the subsequent HCCI cycle showed advanced auto-ignition with rapid combustion. The second strategy was carried out at fixed valve timing and spark timing during mode transition. However, binary valve lift was switched to low lift for HCCI with phased throttle opening. Fuel amount, injection timing and fuel split ratio were adjusted. The developed model for mode switching was able to capture transition dynamics as shown in Fig. 2.19.

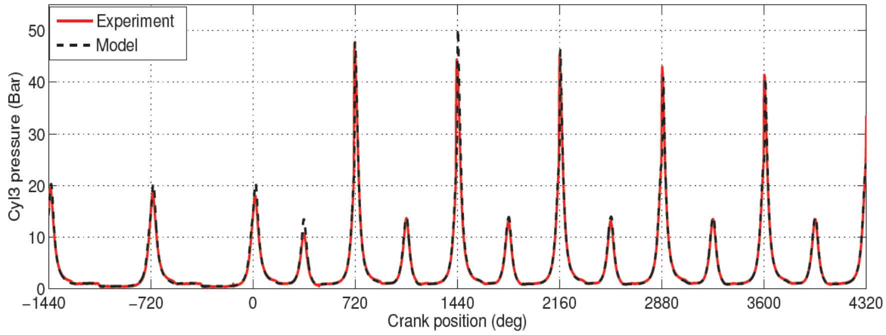

Figure 2.19: Comparison of experimental SI-HCCI mode transition with the model predictions at 1500 RPM and 2.62 bar IMEP for a 2.0L, 4-cylinder GDI Ford engine [12]

Model-based SI-HCCI-SI mode transition for an engine equipped with cam profile switching and phasing system was developed in [13]. Steady state experimental data was used to parameterize the model for a wide range of conditions to include the operating points pertinent to cam switching used for mode transition. First, open-loop mode switching was carried out to study the dynamics during the transition. For SI-HCCI mode switching, throttle was switched to WOT before cam switching while maintaining constant load and AFR. Low lift was achieved by switching the intake and exhaust cams simultaneously during the final SI cycle. Spark timing was fixed at 20 CAD aTDC. EVC timing and start of injection timings were retarded for the first HCCI cycle to retard CA50. However, first HCCI cycle still resulted in advanced combustion timing and high MPRR because of high temperature of residuals from the SI event [13]. Second cycle of HCCI was retarded because of the low exhaust gas temperature from the previous cycle. The third cycle of HCCI showed significantly enlarged peak pressure after TDC during recompression indicating recompression heat release rate (RCHR) of unburnt fuel from the main combustion event of the previous HCCI cycle [13]. Combustion timing was advanced in the third HCCI cycle due to RCHR and early fuel injection; thus, stabilizing HCCI combustion. Based on transient data of mode switching, model was augmented with additional parameter to counter the transient effects. Comparing the model performance with the experimental data during transition, a correction factor was introduced for the residual gas temperature. This correction factor was tuned to match the CA50 of only first HCCI cycle after transitioning from SI mode as shown in Fig. 2.20. This correction factor was computed by back-calculation from the data using Newton-Raphson inversion by matching CA50. This can be computationally expensive for real-time application but this needs to be computed only once for a new mode switch [13]. Moreover, recursive least squares and simplified projected gradient algorithms along with stochastic counterpart can be used to tune the correction parameter for real-time applications [13]. Significant improvements in developed model were observed for the conditions where steady state data was not available [13].

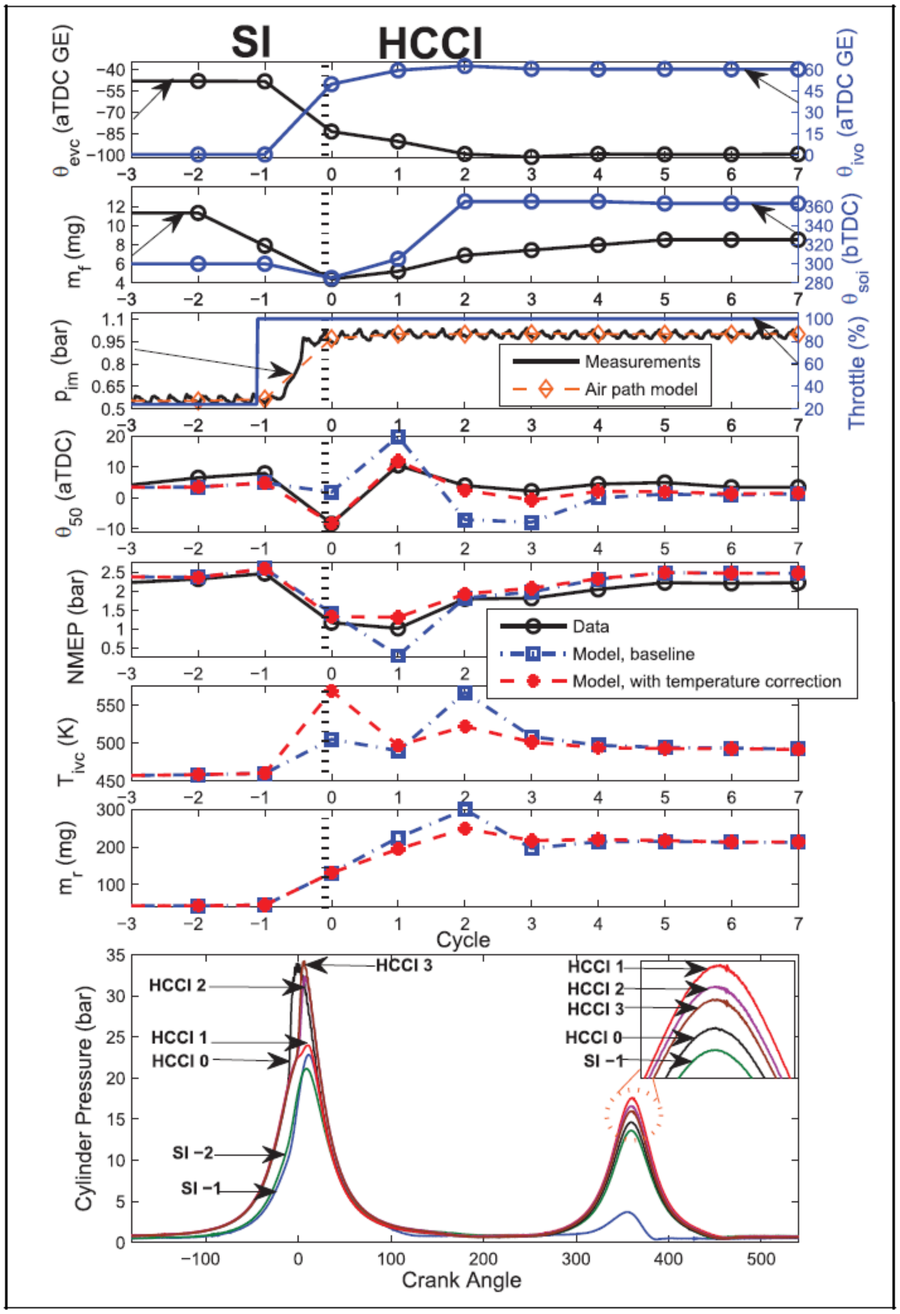

Figure 2.20: Comparison of experimental open-loop SI-HCCI mode transition with the model prediction on cycle-to-cycle basis for a 2.0L, 4-cylinder engine. SI-1 represents the final SI cycle while HCCI 0 represents the first HCCI cycle [13]

2.6.2 HCCI-ASSCI-SI Mode Switching

Due to HCCI limited speed-load operation and to avoid frequent mode switching by switching cam profile, VVT and throttle control, a new mode was introduced to bridge the gap between low load HCCI and high load SI operation [14]. This mode is named as assisted spark stratified compression ignition (ASSCI) in which fuel is directly injected before spark initiation to form a locally rich charge near spark plug. Multi-point autoignition is followed by the flame propagation which leads to two staged combustion [14]. ASSCI offers low pressure rise rate because of two-stage combustion resulting from flame propagation and compression ignition [14]. HCCI operation was achieved with NVO and WOT conditions. When the requested load exceeded the HCCI mode limit, NVO was reduced to achieve ASSCI without switching back to SI mode as shown in Fig. 2.21. Furthermore, hysteresis was introduced for a region to avoid frequent mode switching between ASSCI and SI which involved cam profile switch. In [14], split fuel injection in HCCI mode was used with one injection during recompression leading to fuel reforming and the second injection during intake for homogeneous air-fuel mixture. For ASSCI, one injection during intake stroke and the second injection during compression stroke for stratification were used. SI mode was realized with single injection during intake stroke. An open-loop transition was carried out from HCCI-ASSCI-SI modes. Spark assistance was provided at fixed timing (24 CAD bTDC) during mode switching.

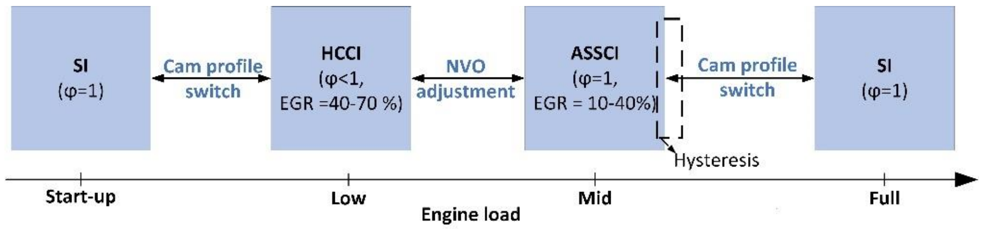

Figure 2.21: SI-HCCI-ASSCI-SI multi-mode engine and the corresponding combustion characteristics [14]

ASSCI was achieved at stoichiometric conditions with reduced amount of internal EGR. First step involved closing the throttle from WOT to the ASSCI position. In second step, fuel strategy was changed from HCCI to ASSCI mode requirement and NVO was reduced to reduce the amount of internal EGR. The first cycle resulted in reduced IMEP because of the retarded combustion timing which can be explained by the delayed response of the NVO [14].

For ASSCI to SI mode switch, fuel injection rate was increased first while spark timing was fixed at 24 CAD bTDC. Fuel injection strategy from ASSCI (50% fuel injection during intake stroke and 50% during compression stroke) was shifted to SI with split injections (60% fuel injection during intake stroke and 40% in compression stroke). Smooth and stable mode switching was completed in 2-3 engine cycles without misfire.

ASSCI mode extended the operation range of the engine under NVO from 3.5 bar to 6.5 bar IMEP. But this study did not account for the benefits of fuel consumption by comparing SI to ASSCI operation. Furthermore, there is no information about NOx emissions during ASSCI mode operation. However, this strategy confirms smooth and stable mode switching without any misfire or unstable combustion [14].

2.6.3 HCCI-PPCI Mode Switching

Partially premixed charge compression ignition is proved to be a promising LTC combustion mode for mid to full load operation with low NOx and soot emissions [20]. Research group at Lund University explored the mode transition between HCCI and PPCI modes in a heavy duty engine. In [15], HCCI to PPCI mode transition was achieved by varying start of injection of fuel from intake stroke to near TDC. Furthermore, external EGR and inlet air heating were also used to keep the combustion phasing constant [15]. Unlike SI-HCCI mode switching, HCCI-PPCI mode switching did not include cam profile switching and throttle control challenges that were reported in [15].

Li et. al. studied the effect of SOI, intake air heating and EGR on mode switching and identified the important control knobs for each mode and the transitioning period. Intake air temperature and SOI sweeps were conducted with and without EGR for a constant CA50 [15]. Effects of SOI and intake air temperature on the combustion events with EGR can be divided into five zones to explain the sensitivities to CA50, as can be seen in Fig. 2.22. A 'spoon' shaped trend was observed for intake air temperature as a function of SOI for maintaining a constant CA50 with 55% EGR [15]. The injection timings during the intake stroke and early compression stroke created a homogeneous air-fuel mixture resulting in HCCI combustion. The required intake air temperature increased in zone 1, possibly due to the fuel spray vaporization cooling effect on the inducted charge during the intake stroke. Required intake air temperature in zone 2 is independent of SOI [15]. CA50 was not significantly sensitive to the variations in SOI in zones 1 and 2. However, CA50 was highly sensitive to the variations in SOI and intake air temperature in zones 3 to 5 [15]. It is common intuition that increase in intake air temperature advances the combustion phasing. A later SOI in zones 3 and 5 retarded CA50; therefore, intake air temperature was increased to maintain constant CA50. SOI around -60 CAD aTDC in zone 3 showed a pit where the required intake air temperature was decreased because of the fuel spray was entering into the piston bowl [15]. Fuel injections in zone 4 result in fuel stratification providing a local rich region which required low intake temperature. SOI from -50 to -45 CAD aTDC lead to increased HC emissions because a portion of fuel spray hit the top-land. When compared to the case with EGR, similar trends of SOI and intake temperature sensitivities were found without EGR with slight differences. The overall intake air temperature requirement was low without using EGR. In addition, zone 3 (crevice effect zone) and zone 4 (charge stratification) required much lower temperature compared to the case with EGR. The study suggested that SOI was an effective control knob for CA50 for zones 3 to 5. However, intake air temperature was the only option to control CA50 in zones 1 and 2 [15]. Furthermore, the maximum global temperature stayed between 1500-1700 K throughout the SOI sweep using EGR which was beneficial for CO oxidation and suppressing NOx [15]. CO and THC were found sensitive to the crevice effect [15]. Overall lower emissions were produced in the case with EGR [15].

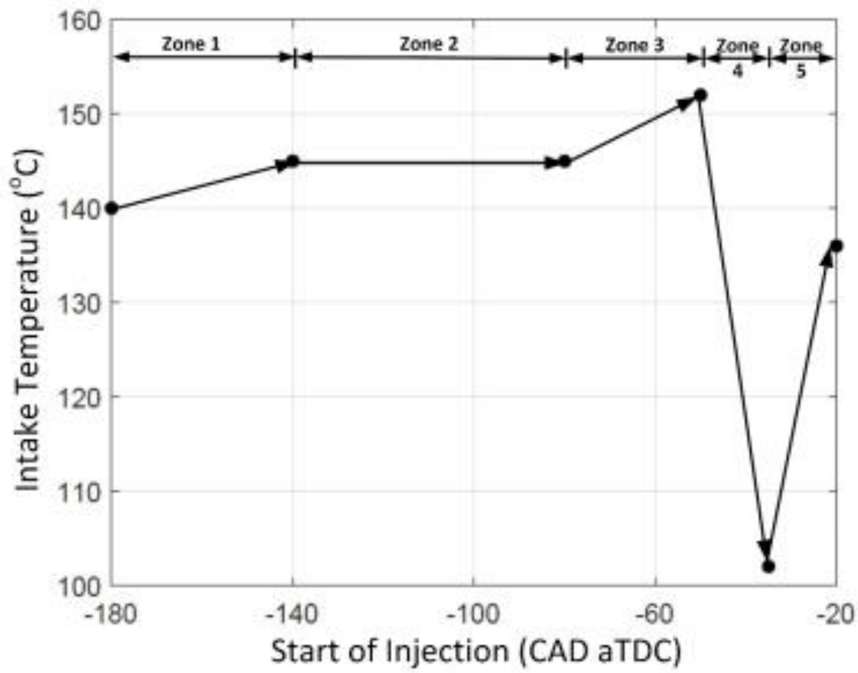

Figure 2.22: Required intake air temperature to maintain CA50 at 3 CAD (aTDC) as a function of SOI for HCCI-PPCI transition for a single cylinder heavy-duty CI engine. Higher T_{in} and lower T_{in} are the perturbations in the intake air temperature for the baseline reference points [15]

Shen et. al. also studied the transition from HCCI to PPCI mode using gasoline-like fuel [104]. HCCI to PPCI mode transition was carried out by using single and double fuel injection strategies, start of injection timing, EGR and intake boost pressure. Single fuel injection during intake stroke resulted in HCCI combustion because of homogeneous air-fuel charge. Fuel injection during late compression stroke resulted in premixed charge compression ignition. Transition period between HCCI and PPCI mode was associated with SOI range from -80 to -45 CAD aTDC. The challenges during this transition zone included excessive MPRR due to rapid burn rate and high NOx emissions. A double fuel injection strategy can be effective in HCCI-PPCI transition. Second injection with 30% of fuel injected very close to TDC can reduce burn rate and increase thermal efficiency while increasing NOx formation. Using EGR, NOx formation can be reduced. But use of EGR results in a trade-off between NOx and soot formation. Increasing boost pressure has a positive impact on reducing soot and HC emissions because of providing more oxygen concentration input to the cylinders. Therefore, split fuel injection strategy, EGR and high boost levels are effective means of controlling combustion and emissions during HCCI-PPCI transition [104].

2.6.4 CDC-PPCI Mode Switching

Mode switching between conventional diesel combustion (CDC) and premixed charge compression ignition is another interesting multi-mode engine concept as shown in Fig. 2.23. The engine runs in CDC mode during start-up and high load requirements.

However, PPCI can be employed during low to medium load range for better efficiency and low emissions [58]. Transition period in CDC-PPCI switching can result in high NOx and soot emissions [54]. Therefore, either rule-based or model-based feedback controlled mode switching strategy is necessary for smooth transition with low MPRR and emission levels. In [54], switching from CDC to PPCI resulted in NOx spike while smoke spike was observed during PPCI to CDC mode switching. A PID controller was used to regulate CA50 while feedforward controller regulated the mode transition by suppressing NOx and soot. NOx increased with advanced CA50 and increased oxygen concentration ($> 17\%$). NOx becomes insensitive to CA50 if oxygen concentration is below 17% [54]. CA50 was adjusted to avoid NOx spike by feedforward action while transitioning from CDC to PPCI when oxygen concentration decreased due to addition of EGR. Soot can be controlled by adjusting fuel injection and amount of air to maintain air-fuel ratio and by avoiding retarded CA50 [54].

Response time of actuators can also affect the mode switching process. Therefore, it is important to take the response time of actuators in account. Fuel injection timing, duration and number of injections can be controlled on cyclic basis. EGR delay can be improved by reducing the EGR path [73]. Fluctuations in power output and MPRR can be reduced by optimizing fuel injection strategy [73]. High fuel injection pressure improves fuel atomization and mixing thus reducing HC emissions [105].

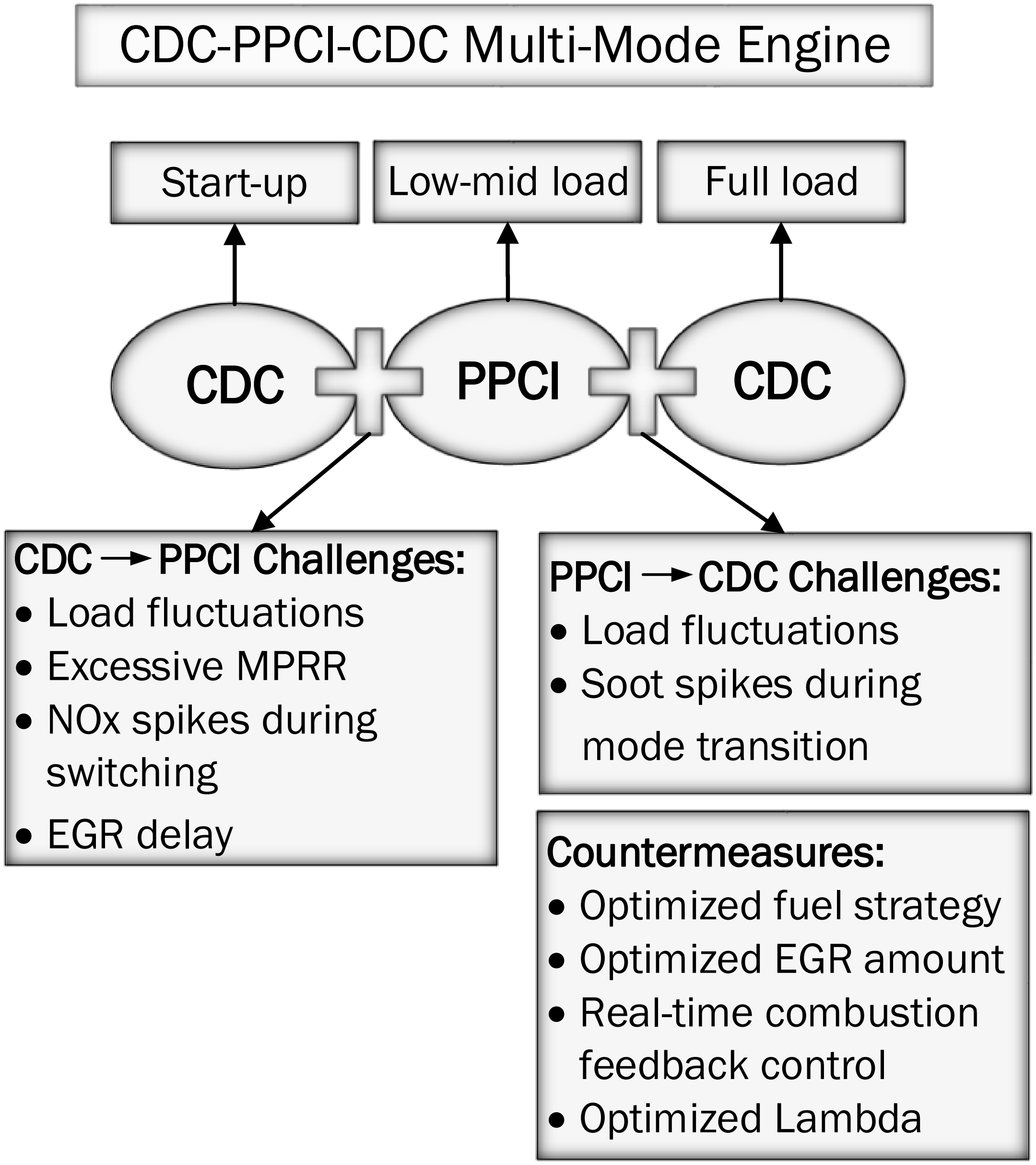

Figure 2.23: Challenges and possible solutions during CDC-PPCI-CDC mode switching

2.6.5 RCCI-CDC Mode Switching

CDC to RCCI mode switching has been investigated at low load engine operations [16]. RCCI mode at low load results in low exhaust gas temperature which is not sufficient for catalytic converter [16]. In addition, appropriate strategies exist for cold start engine operation which make CDC operation more advantageous for cold start condition [16]. Therefore, mode switching between CDC and RCCI is required for cold start and low load operation. Moreover, RCCI operation is limited at high load because of excessive pressure rise rates which requires RCCI to CDC mode transition [16]. Fuels used to realize RCCI mode were nonoxygeneted gasoline (RON96) and ultra-low sulfur diesel (ULSD) while CDC mode used ULSD fuel. Swirl ratio and pedal positions were kept fixed for mode switching operation while two direct injections were used for both CDC and RCCI modes. RCCI mode also used PFI. EGR amount was increased from 28.5% to 50.9% for CDC to RCCI mode transition. Figure 2.24 shows the BMEP during RCCI and CDC mode transitions. RCCI operation showed slight improvement in BMEP as compared to CDC. The mode switching results showed that the combustion phasing and MPRR during mode switching were similar to the baseline RCCI and CDC operations. Furthermore, RCCI operation resulted in lower NOx and PM emissions as shown in Fig. 2.25. Smoke was increased from RCCI to CDC mode switching. HC emissions were observed during first 5 cycles of mode transition to CDC mode. These emissions were linked to the unburned gasoline fuel which was entering the cylinder from the intake fuel puddle. Though the gasoline injections were stopped during RCCI-CDC mode switching [16].

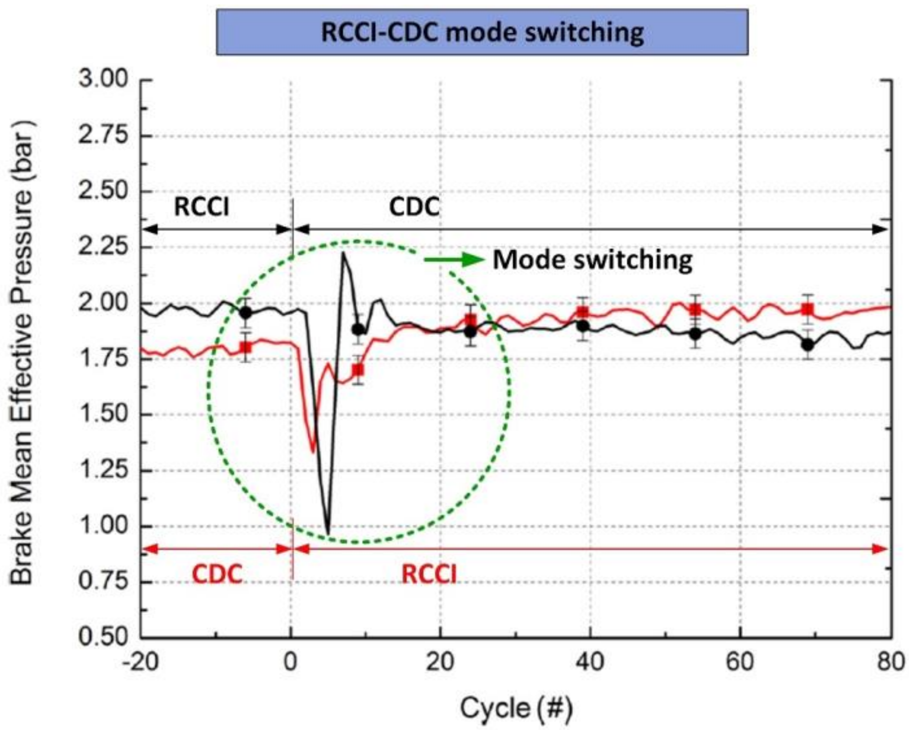

Figure 2.24: BMEP during CDC-RCCI mode switching in a 1.9L, 4-cylinder Euro IV diesel engine [16]

2.6.6 RCCI-CDF Mode Switching

Multi-mode engine concept has also been applied to RCCI and conventional dual fuel (CDF) combustion modes in a heavy duty engine. Dual fuel compression ignition has been used in marine and automotive applications using diesel with either ethanol or natural gas [17]. The performance of CDF engine can further be improved in terms

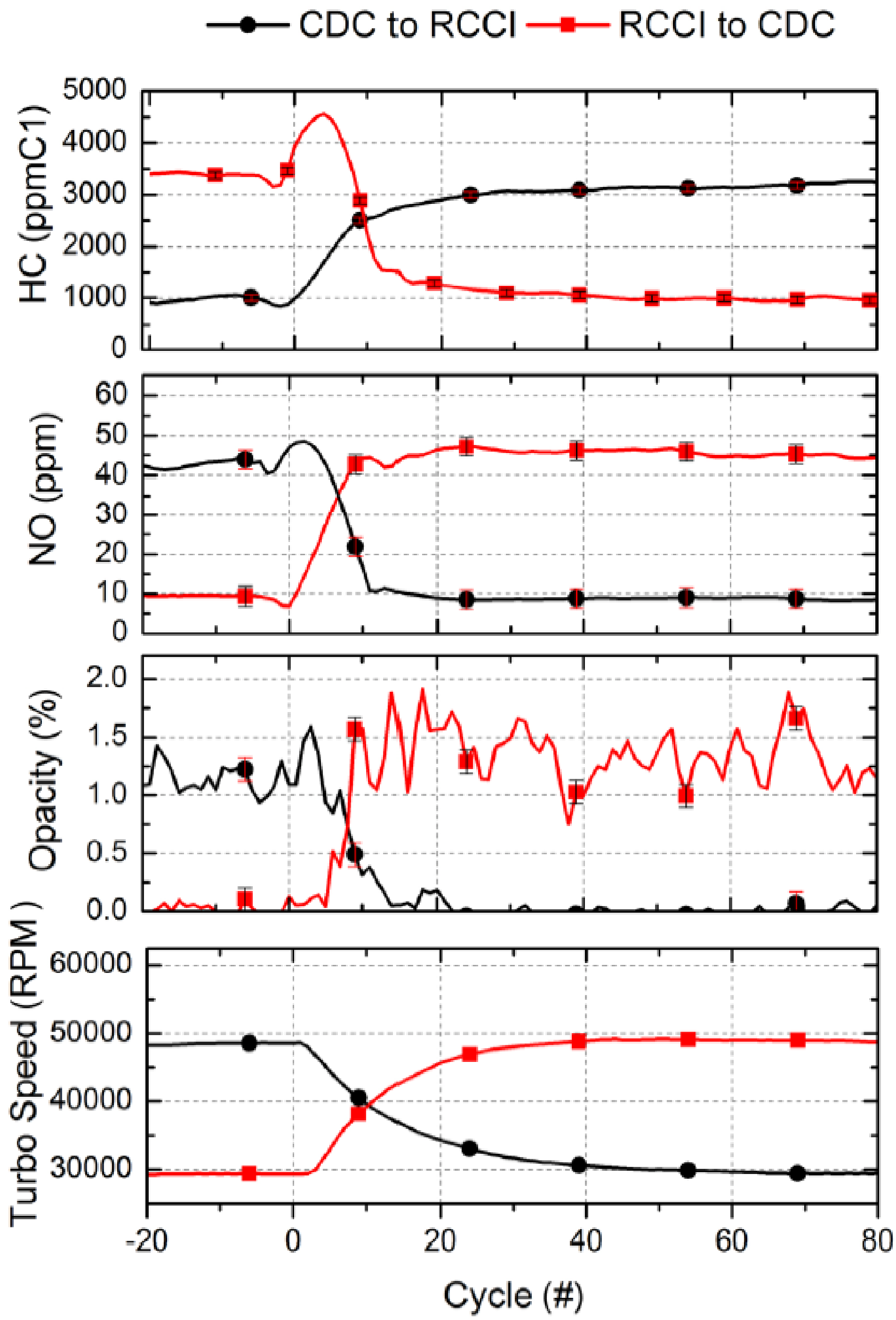

Figure 2.25: Performance results during CDC-RCCI mode switching in a 1.9 litre, 4 cylinder Euro IV diesel engine [16]

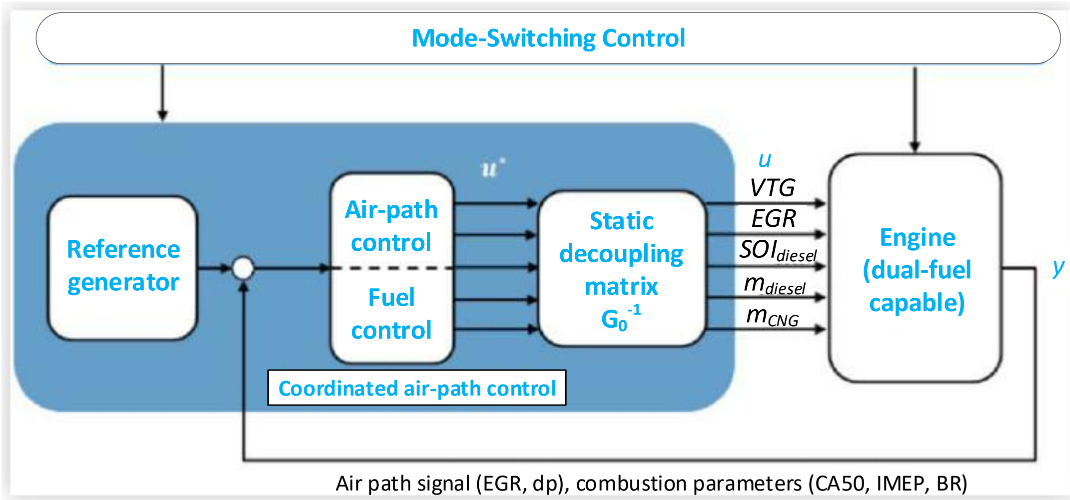

Figure 2.26: CDF-RCCI mode switching schematic for a heavy duty engine [17]

of thermal efficiency and reduced engine-out emissions by coupling it with RCCI [17]. Operating conditions to realize CDF combustion are different than RCCI. That is why, smooth transitions between RCCI and CDF modes are challenging [17]. Thus, a proper control strategy is essential to ensure smooth RCCI-CDF mode switching and emission control.

In [17], open-loop and closed-loop CDF and RCCI mode switching has been studied. CDF and RCCI modes were achieved using high pressure EGR with natural gas and diesel fuels. Mean-value engine modelling approach was used for air-path dynamic model. Two-zone combustion model for CDF and multi-zone RCCI combustion model were used. Schematic for mode switching control is shown in 2.26. Static input-output decoupling was used to account for the different dynamics offered by intake air path and fuel path, and also to address the interdependence of control inputs and engine outputs. By using static decoupling, new control inputs (u^*) were obtained as a linear combination of actual control inputs (u). This resulted in five independent single input-single output (SISO) subsystems. EGR valve and variable-turbine geometry (VTG) were the two available control actuators for air-path control.

Two PI controllers and a feedforward controller were developed to control EGR ratio and the pressure difference (dp) across engine. Air-fuel ratio was not closed-loop controlled. Fuel path control actuator actions included diesel injection timing, diesel quantity and natural gas quantity to control CA50, IMEP and blend ratio. High blend ratio results in reduced fuel consumption and low CO_2 and NOx emissions [17]. RCCI-CDF mode switching was done by controlling the actuators to track CA50, IMEP, blend ratio and pressure rise rate. Closed-loop controller was proved to be a better choice than an open-loop controller.

2.7 Summary

Based on thermal efficiency and engine-out emissions, LTC modes have a potential to meet the stringent fuel economy and emission targets. However, LTC modes are prone to excessive pressure rise rate due to autoignition which must be controlled by adjusting internal or external EGR, fuel injection timings, intake temperature and pressure. High MPRR limits the high load operation in LTC modes. Low load operation in LTC modes is limited due to risk of misfires and partial burns resulting in high engine torque fluctuations, high cyclic variability, HC and CO emissions. Overall, the limited optimal operation of LTC modes compared to conventional SI and CI modes limits the application of these engines. Multi-mode engine is a viable solution to benefit from the high thermal efficiency and ultra-low emissions of LTC modes.

A multi-mode engine can be developed by using conventional SI or CI modes along with one or multiple LTC modes for full load and speed operation. A multi-mode engine can operate in SI mode for start-up and full load operation while LTC mode can operate from low to mid load range. Among LTC modes, PPCI offer the highest load operating range. Each mode of engine operation requires certain inputs to the engine, as shown in Fig. 2.27. The optimal engine mode can be selected based on engine BSFC map and engine-out emission map. The optimization can be done in a high-level combustion optimizer that selects optimal engine mode and determines the desired IMEP and CA50 reference trajectories. Then the feedback combustion controller will adjust engine cycle-by-cycle control inputs, e.g., spark timing, SOI of pilot and main fuel injections, premixed ratio of fuels, valve overlap, etc.

Several researchers have explored SI-HCCI, CDC-PPCI, HCCI-PPCI, HCCI-ASSCI-SI and CDF-RCCI mode switching for an optimal multi-mode engine development.

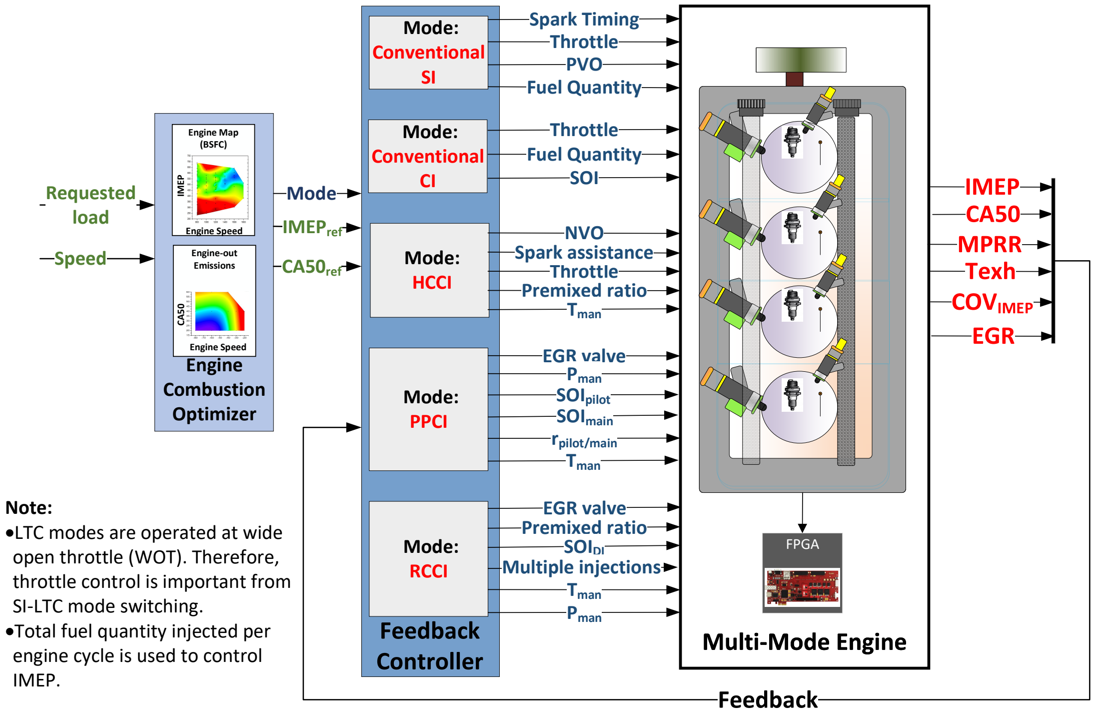

Figure 2.27: Schematic for closed-loop control structure of a multi-mode engine

These studies include rule-based open-loop and model-based closed-loop control of multi-mode engine with increased efficiency and reduced emissions. The common challenges in mode transitioning include misfire, partial burn, advanced combustion causing high pressure rise rates, load fluctuations and engine-out emissions including NOx, soot, HC and CO. These challenges can be successfully addressed by designing optimal mode switching control strategies as discussed in this book chapter. Other emerging studies include electrified LTC powertrains that include mode switching between LTC engine modes and electric/hybrid/electric modes [106].

Chapter 3

Closed-loop Predictive Control of a Multi-Mode Engine Including HCCI, PPCI and RCCI Modes[1]

3.1 Abstract

High thermal efficiency and low engine-out emissions including nitrogen oxides (NOx) and particulate matter (PM) make the low temperature combustion (LTC) favorable for use in engine technologies. Homogeneous charge compression ignition (HCCI),

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partially premixed compression ignition (PPCI) and reactivity-controlled compression ignition (RCCI) are among the common LTC modes. These three LTC modes can be achieved on the same dual fuel engine platform; thus, an engine controller can choose the best LTC mode for each target engine load and speed. To this end, a multi-mode engine controller is needed to adjust engine control variables for each LTC mode.

This paper presents model-based control development of a 2.0-liter multi-mode LTC engine for cycle-to-cycle combustion control. The engine is equipped with port fuel injectors (PFI) and direct injectors (DI). All combustion modes are achieved with dual fuels (iso-octane and n-heptane) under naturally aspirated conditions. Using experimental data, control-oriented models (COMs) are developed for HCCI, PPCI and RCCI combustion modes on a cycle-to-cycle basis. The COMs for HCCI, PPCI and RCCI modes can predict CA50 with average errors of 1.3 CAD, 1.5 CAD and 1 CAD, respectively. The average errors in predicting IMEP for HCCI, PPCI and RCCI modes are 18 kPa, 34 kPa and 43 kPa respectively. Multi-input and multi-output (MIMO) adaptive model predictive controllers (MPC) with linear parameter varying (LPV) models are designed for the LTC modes. Combustion phasing (CA50) and indicated mean effective pressure (IMEP) are controlled by adjusting premixed ratio (PR) of the fuels, start of injection (SOI) timing, and fuel quantity. The results show that the designed model predictive controllers are able to track both CA50 and IMEP in all combustion modes, with average tracking errors of less than 1 CAD and 5.2 kPa, respectively.

3.2 Introduction

Advancements in compression ignition (CI) engine technology have been made to improve efficiency and lowering engine-out emissions. One of the major focus in improving CI engine technology is towards development of advanced combustion modes including Low Temperature Combustion (LTC) technologies. Light duty vehicles (LDVs) account for 52% of fuel consumption in the transportation sector [45]. A recent report by the U.S. Energy Information Administration states that new light duty vehicles running solely on internal combustion engine (ICE) will contribute to 81% of the new vehicles market share by 2050 [45]. This number goes up to 85% when hybrid electric and plug-in hybrid electric vehicles are taken into account as they also use an ICE [45]. Therefore, it is essential to optimize the advanced ICE combustion regimes including LTC modes to improve the fuel economy of LDVs and to meet the stringent emission legislations. However, the application of each LTC mode is limited due to the narrow optimal load operating range. To this end, developing a multi-mode engine is an appropriate option to take the advantages of LTC modes while providing full speed and load operation. This requires development of control-oriented models and optimal control methods for a multi mode LTC engine.

LTC modes generally involve lean premixed mixtures which reduce the local fuel rich zones. Therefore, too high peak in-cylinder gas temperatures are avoided that helps in restricting NOx formation. The LTC combustion processes can offer thermal efficiency comparable to conventional diesel combustion engines [48, 107] and produce NOx, and PM emissions substantially less than conventional CI engines [108, 109]. LTC includes but not limited to Homogeneous Charge Compression ignition (HCCI), Partially Premixed Charge Compression Ignition (PPCI), Premixed Charge Compression Ignition (PCCI), and Reactivity Controlled Compression Ignition (RCCI) combustion modes [18]. LTC modes can be achieved by using a combination of several strategies such as preheating of the inducted air [69, 110], fast thermal management [5], variable valve actuation [111, 112], variable compression ratio [5, 46, 113], exhaust re-compression [112], exhaust gas recirculation (EGR) [19, 20, 69, 110], utilizing dual fuels [20, 107, 114, 115, 116], multiple fuel injections [4, 117], adjusting fuel injection timing [19, 21, 118] and direct dual fuel stratification [114].

Control of combustion process in the LTC modes is important to avoid partial burns, misfires, and unsafe high pressure rise rates and knocking [119]. Different LTC modes are achieved using different strategies. For instance, HCCI mode is more sensitive to the thermodynamic state of the premixed charge (temperature and pressure of the air-fuel mixture) [48, 98]. The mixture in HCCI auto-ignites in the absence of any external trigger such as spark in an SI engine or fuel injection timing in a DI engine [48, 120]. That is why, HCCI combustion event can result in a very rapid rate of heat release causing very high pressure rise rates [120]. This limits the maximum achievable load in an HCCI mode [121]. Therefore, control of HCCI process is important for a safe engine operation to avoid too high pressure rise rates and restrict peak in-cylinder gas pressure. PPCI mode is achieved by injecting the fuel during early compression stroke. Simultaneous reduction of NOx and soot can be achieved by adding high EGR rates in excess of 70% in a low compression ratio diesel engine running in PPCI mode [122]. However, it is difficult to obtain high EGR rates in excess of 70% from the engine's air handling perspective [120]. NOx and smoke can be simultaneously reduced by delaying the heat release to the point where the fuel and air are sufficiently mixed. A study conducted on ethanol PPCI combustion at Lund University achieved low emissions with 40-47% EGR. However, pilot injection timing and pilot to main fuel injection ratio were adjusted to limit the pressure rise rates below 10 bar/CAD [108]. Although, PPCI mode offers low engine-out emissions but the control of combustion timing and heat release rate are challenging. The maximum work output reduces by retarding the heat release, therefore, resulting in a trade-off between thermal efficiency and combustion noise [114].

RCCI mode is realized by using dual fuels of different reactivity levels. This combustion mode offers high thermal efficiency along with low NOx emissions [21, 22, 100]. The ratio of high to low reactivity fuel provides a control over the heat release rate which results in controlled combustion noise levels [114]. Splitter et. al. explored the effect of injections on a low load RCCI operation and found out that double injections reduced CO and HC emissions to 40% [123]. Wu et. al. proposed that combustion phasing can be controlled by changing the PFI fuel ratio during load transients [23].

To ensure stable and controlled combustion, it is imperative to control the combustion phasing and load in the LTC modes. Various studies have been conducted on the modeling and control development of the LTC modes. Overview of prior control studies carried out on LTC modes are presented in Figure 3.1. These studies are grouped into HCCI, PPCI and RCCI combustion modes. Here, a brief review of each group is provided. Combustion phasing and indicated mean effective pressure are the two important control parameters. Combustion in LTC engine is sensitive to the change in the thermodynamic states at intake valve closing, such as intake air temperature, residual gas fraction, etc. Uncontrolled combustion may lead to knocking due to advanced combustion phasing or even a misfire in case of too retarded combustion [22]. CA50 is an important parameter that directly influence IMEP, MPRR, exhaust gas temperature, and CO and unburned HC emissions [3]. Furthermore, partial or incomplete combustion results in lower IMEP. This usually causes the next engine cycle to produce higher IMEP because of the unburned fuel from the previous engine cycle. This leads to increased coefficient of variation of IMEP which affects the noise, vibration, and harshness (NVH) performance of the vehicle. Therefore, it is important to simultaneously control CA50 and IMEP for the optimum and safe engine operation.

LTC modes can be modeled by using computational fluid dynamics (CFD) and detailed kinetic reaction mechanisms to analyze the combustion dynamics and prediction. Wu et. al. proposed that combustion phasing can be controlled by changing the

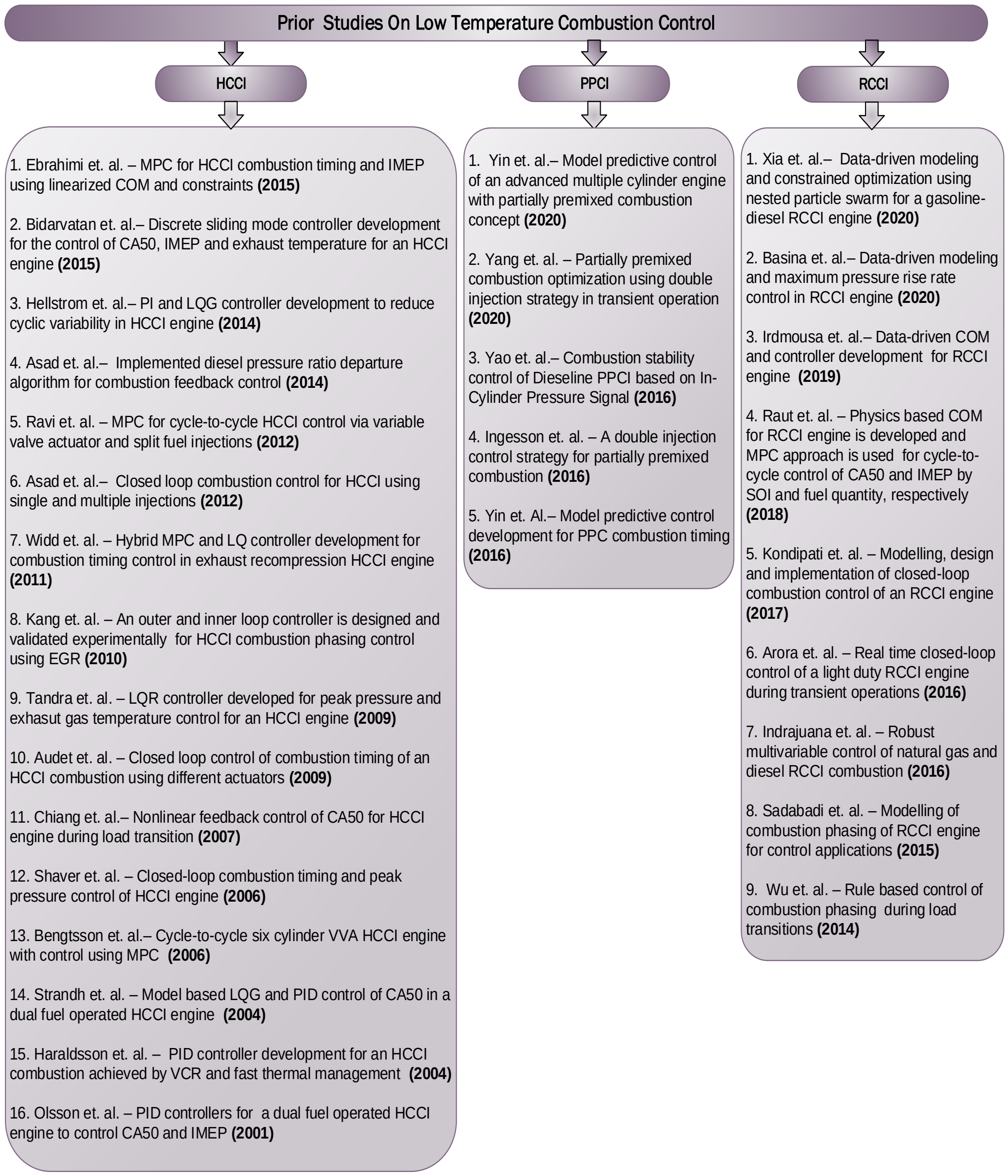

Figure 3.1: Prior studies on the control of LTC modes [4, 5, 7, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44]

PFI fuel ratio during load transients in RCCI mode [23]. A multi-dimensional CFD model coupled with kinetics-based combustion model was used to control combustion phasing during load transition. The computation time of this numerical based study was around 15h for each case, using three central processing units. Eichmeier et. al. developed a zero-dimensional phenomenological RCCI combustion model and the results were compared with experimental data and 3D CFD model. The zero dimensional model was based on reduced order mechanism and each zone was considered as a constant volume reactor. Computational time was sufficiently reduced by running the reaction kinetics parallel and using the iteration scheme. The study mentioned that both the 3D-CFD and zero-dimensional models were highly dependent on the initial conditions at IVC. The zero dimensional model requires an accurate knowledge of the initial conditions The prediction accuracy of the developed zero dimensional model is dependent on the accurate knowledge of the initial conditions [124]. Numerical studies require extensive computational resources and run-time which make them less appropriate for real-time control applications. Therefore, the present study introduces a computationally efficient physics-based control-oriented modeling approach for real-time control of LTC modes on cycle-to-cycle basis.

A wide range of studies have been conducted on control oriented modelling (COM) and controller development for the HCCI mode. Control oriented modelling of the HCCI combustion includes prediction of ignition timing [98, 125], combustion phasing [71, 97, 111, 126, 127], load [83, 125, 127], combustion efficiency [127], exhaust gas temperature and engine-out emissions [83]. Olsson et. al. developed PID controllers for a dual fuel HCCI operation to control heating, combustion timing, and IMEP [24]. Haraldsson et. al. also implemented PID controllers using variable compression ratio and fast thermal heating as manipulated variables for combustion timing control and adjusted fuel quantity for load control [5]. Manual PID and linear quadratic gaussian (LQG) model based controllers were developed for an HCCI engine using dual fuels. Strandh et. al. compared the performance of PID and LQG controllers along with the performance comparison of the feedback signals from pressure and ion current sensors. The study concluded that both controllers worked well for combustion timing control [25].

Bengtsson et. al. used system identification to model an HCCI engine with variable valve actuation. The study incorporated model predictive control (MPC) framework for multi-input multi-output (MIMO) control of an HCCI engine with constraints on control variables and pressure rise rate ($dP/d\theta$) [26]. Widd et. al. compared the performance of hybrid MPC and switched LQ controller for the combustion timing control of the exhaust recompression HCCI. Due to optimal control provided by the MPC over the prediction horizon, MPC response showed no overshoot while the LQ controller response resulted in a large overshoot [27]. Ravi et. al. demonstrated an LQR controller that is developed based on a physics-based two-state COM for an exhaust recompression HCCI combustion mode in a gasoline engine [128]. Shaver et. al. controlled peak pressure and combustion timing using an H_2 optimal controller for a residual-affected HCCI engine. The inducted gas composition and effective compression ratio were used as control knobs [28]. A study conducted by Kang et. al. showed that mass fraction of burned gases in the intake and exhaust ports can also be used to control combustion phasing indirectly in the HCCI mode [29]. Ravi et. al. used MPC framework to control combustion phasing (CA50) and net indicated mean effective pressure (NMEP) for an HCCI engine. This study used variable valve actuation system and split fuel injection strategy to control HCCI. In addition, constraints on the injection timing, cylinder volume at intake and exhaust valve closure and maximum allowable rate of change of valve timings, and air to fuel ratio were implemented. The air-fuel ratio was constrained to avoid too lean or too rich of a mixture. The controller response for tracking NMEP became slower with the application of constraints on the air to fuel ratio [4]. Ebrahimi et. al. implemented MPC to control combustion phasing and load by adjusting valve timing and fueling rate [30]. In order to avoid misfire or ringing, constraints were applied on the combustion phasing and load. Bidarvatan et. al. developed sliding mode controller to control combustion phasing, load and exhaust gas temperature for a stable HCCI engine operation [31]. This robust discrete sub-optimal sliding mode controller performed well in the presence of disturbances and showed no steady state errors.

There are several studies conducted on the modeling and control of PPCI engines. Hall et. al. developed a COM for start of combustion (SOC) prediction for a PCCI engine [129]. Tunestal et. al. used system identification to model PPCI combustion [130]. Yao et. al. developed a closed-loop feedback controller for combustion stability and combustion noise level control for a PPCI engine. Injection timings and EGR

(%) were used to control maximum pressure rise rate (MPRR) and coefficient of variation of IMEP (COV_{IMEP}). MPRR and COV_{IMEP} were chosen as representatives of combustion noise level and combustion stability, respectively [19]. Ingesson et. al. implemented an MPC to limit MPRR while controlling CA50 by adjusting the pilot ratio and timing of main injection for PPCI operation. The fuel being used was composed of 80% gasoline and 20% n-heptane by volume. Split injection (an early pilot injection followed by main injection) strategy was used to reduce ignition delay which resulted in low MPRR [32]. Yin et. al. developed PPCI combustion control system for a heavy duty 13-liter diesel engine using a fuel blend (80% gasoline and 20% n-heptane). A tripple injection strategy was employed along with 45-50% EGR. The study incorporated an MPC controller for a transient load range of 4-15 bar at 1200 rpm. The controller results showed a trade-off between faster response and overshoot [20]. Yang et. al. employed a double injection strategy for PPCI operation. An MPC framework was implemented for CA50 and IMEP control including constraints on MPRR, soot and NOx. The study included a 5 to 8 bar IMEP range of transient PPCI operation at a constant engine speed of 1200 rpm [7].

Researchers have also explored control of RCCI engine operation using various feedback controllers including PI, LQI, and MPC. There are various parameters which can be used to control combustion phasing in the RCCI mode. These parameters include start of injection (SOI), dual fuel premixed ratio (PR), split injections, valve timings, etc. Kondipati et. al. designed a PI controller to control CA50 for an RCCI engine using either PR or SOI as control inputs [33]. Arora et. al. carried out an experimental study on mode switching for RCCI-SI-RCCI [18]. A PI controller along with feed-forward control was implemented for cycle-to-cycle control of CA50 during transient operation [18]. An observer-based LQI controller was developed to control CA50 using PR as the control input. Observer performance under transient RCCI operation was also examined [34]. The results showed no steady state tracking errors and good disturbance rejection performance. Indrajuana et. al. investigated RCCI combustion using natural gas and diesel [22]. RCCI operation was controlled on a cycle-to-cycle basis by using diesel injection timing, diesel fuel quantity and natural gas fuel quantity. A robust MIMO feedback controller was developed for engine load, ignition delay and blend ratio control to achieve low NOx emissions [22]. Raut et. al. implemented multiple model predictive controllers to control engine load and CA50 during transient operation of an RCCI engine [21]. SOI was used as control input for adjusting CA50 while fuel quantity was used to control engine load. Moreover, PR was used as a scheduling variable for switching between multiple MPCs to increase the operating range of the RCCI engine [21]. Irdmousa et. al. developed a data driven COM for an RCCI engine using fuel quantity as the scheduling variable. This study incorporated linear parameter varying (LPV) model along with MPC controller for CA50 control. The controller developed on the data-driven model showed similar response as compared to physic-based MPC [41]. Batool et. al. developed data-driven classification models for COV_{IMEP} for HCCI and RCCI modes [92]. CA50 and IMEP were regulated by designing nonlinear model predictive controller (MPC) frameworks for HCCI and RCCI modes while constraining COV_{IMEP} below 3% [92].

Despite the benefits of high efficiency and ultra low NOx and soot emissions, LTC modes can suffer from a limited load operation. To address this shortcoming, several studies have been conducted on mode switching between LTC and conventional SI and CI modes. Widd et. al. studied SI to HCCI mode switching. A model based controller was designed and its results showed better performance as compared to PI controllers [131]. Roelle et. al. developed a multi-mode combustion model for SI to HCCI transition [52]. Gorzelic et. al. implemented a model-based feedback control for SI-HCCI mode transition [48]. An online parameter adapting algorithm was appended to the model-based control platform to reduce the errors while improving robustness and addressing the cylinder-to-cylinder variability. Nuesch et. al. developed a finite state machine model to capture HCCI-SI mode switching dynamics and fuel penalties [132]. Besides the significant reduction in NOx emissions and improvement in fuel efficiency in the HCCI mode, the mode switching induces penalties in fuel efficiency while meeting the high torque requests.

This paper presents a unified modeling and control platform to adjust combustion phasing and load for three LTC modes on the same engine platform. To the best of the authors' knowledge, this work is the first study undertaken to control three LTC modes with an integrated optimal and predictive control setup. An optimizer selects the best LTC mode and the designed multi-mode MPC combustion controller adjusts SOI, PR and fuel quantity to control CA50 and IMEP. The multi-mode controller focuses on optimal LTC operation in each mode, while mode switching control is outside the scope of this paper. All the three modes are achieved on a single engine. The three different LTC modes are achieved using different strategies and each mode offers different challenges. That is why, it is difficult to have a single controller framework for all the LTC modes. Linear parameter varying (LPV) models are identified to capture the LTC dynamics then LPV models are incorporated into the MPC framework to provide a wide operation range. The designed controllers are also tested for disturbance rejection properties.

The major contributions in this paper include (i) A unified modeling platform is developed to include physics based control-oriented models for the three LTC modes to control the combustion phasing and load for a range of PRs. The models are validated for steady state and transient conditions; (ii) Three multi-input and multi-output adaptive MPC controllers are developed for the LTC modes. In order to address the nonlinear behavior of dual fuel combustion with varying PR and to improve the controller response for a wide range of load operation, LPV models are developed. These LPV models are integrated to the adaptive MPC framework. LPV models are developed for different PRs which capture the nonlinear dynamics of the LTC modes. The LPV models are then used within the adaptive MPC framework to extend the operating range and improve performance of the controller; (iii) The disturbance rejection performance of the developed MIMO adaptive MPC controllers is verified.

The organization of this paper is as follows: Section II explains the experimental setup and the specifications of the engine used to collect the experimental data for LTC modes. This section also includes the operating conditions for each mode. Section III explains the development of control oriented models for each mode on cycle-to-cycle basis. The following section IV focuses on the development of LPV systems and adaptive MPC controllers. MPC controllers and Kalman filters are designed for optimum performance in each mode. Section V presents results and discussions for multi-mode engine operation. The disturbance rejection performance of controllers are also assessed. The last section summarizes the major findings from this study and provide recommendations for future studies.

3.3 Experimental Setup and Engine Data

A GM EcoTec 2.0L engine is used for conducting the experiments, coupled with an AC dynamometer of 460 hp. The original GDI engine with one direct injection (DI) system is modified to include two port-fuel injection (PFI) systems and use the original direct injection (DI) system, as shown in Figure 3.2. Engine specifications are given in Table 3.1. The engine is run at naturally aspirated conditions without exhaust gas recirculation (EGR). PCB piezoelectric pressure transducers are used to measure in-cylinder gas pressure with a resolution of 1 CAD. A dSPACE MicroAutoBox (MABX) is used as the engine control unit. For the real time feedback of combustion parameters, Xilinx Spartan-6 field programmable gate array (FPGA) is used. The intake air is pre-heated to the desired temperature with the help of an external air heater. Merriam MDT500 air flow measurement system is used to measure the mass flow rate of the intake air. Experimental setup of the multi-mode LTC engine is shown in Figure 3.3.

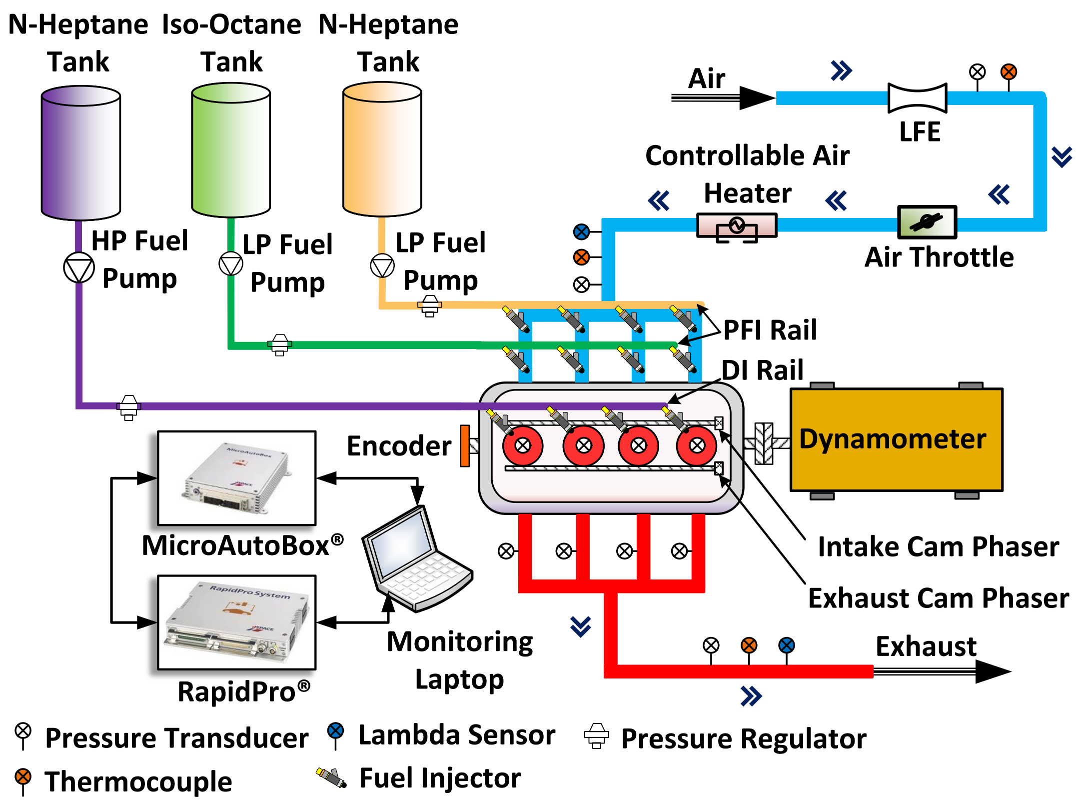

Figure 3.2: Schematic of experimental setup of the LTC engine

The engine is run in three LTC modes including HCCI, PPCI and RCCI by adjusting

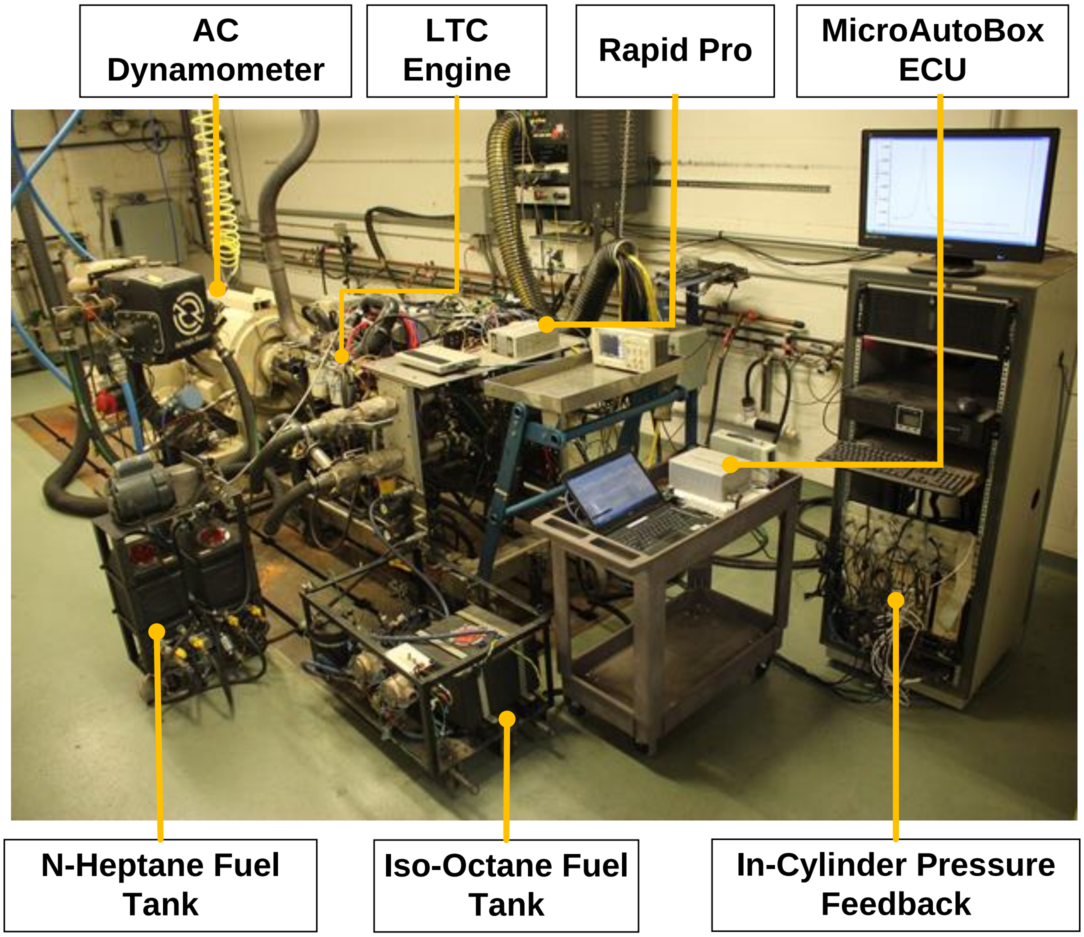

Figure 3.3: Experimental setup of the multi-mode LTC engine

the engine variables and using dual fuels i.e. n-heptane and iso-octane. In HCCI mode, both iso-octane and n-heptane are injected into intake ports during the exhaust stroke of the previous cycle via two PFI systems. While n-heptane is directly injected during the compression stroke for PPCI and RCCI modes. In PPCI mode, the start of injection (SOI) is kept constant at 100 CAD bTDC while in RCCI mode, the SOI of n-heptane is varied. For HCCI, PPCI and RCCI combustion modes, intake air temperature, total fuel quantity and the premixed ratio of fuels are varied. The

Table 3.1
Engine Specifications

Engine Type	GDI, 4 Stroke
No. of Cylinders	4
Cylinder Volume	1998 (cc)
Bore	86 (mm)
Stroke	86 (mm)
Compression Ratio	9.2:1
IVO	25.5/-24.5 (CAD bTDC)
IVC	2/-48 (CAD bBDC)
EVO	36/-14 (CAD bBDC)
EVC	22/-28 (CAD bTDC)
Valve Lift	10.3 (mm)
Max. Engine Power	164 kW @ 5300 rpm
Max. Engine Torque	353 Nm @ 2400 rpm
Intake Valve Diameter	35.17 (mm)
Firing Order	1-3-4-2

premixed ratio (PR) of the two fuels is calculated using the following equation:

$$PR = \frac{\mathrm{m_{iso}LHV_{iso}}}{\mathrm{m_{iso}LHV_{iso}} + \mathrm{m_{nhep}LHV_{nhep}}} \tag{3.1}$$

where, m_{iso} and m_{nhep} are the mass of injected iso-octane and n-heptane, respectively. $\mathrm{LHV_{iso}}$ and $\mathrm{LHV_{nhep}}$ are the lower heating values of iso-octane and n-heptane, respectively.

Performance maps for the LTC modes are shown in Fig. 3.4 on the basis of brake specific fuel consumption (BSFC). Based on the comparison with baseline SI map, HCCI combustion in this engine shows 9% improvement in BSFC at low loads for a speed range of 800-1600 rpm. PPCI mode offers 5% improvement at 6 bar when compared to the baseline SI engine. RCCI combustion shows upto 14% improvement in BSFC for a load range of 6-8 bar as compared to the baseline SI mode. This paper focuses on developing a model based control platform to allow an optimal engine operation in HCCI, PPCI and RCCI modes based on the requested speed and load conditions to offer the best BSFC.

Operating conditions of the data used in this study are shown in Table 5.1. The measured uncertainties in the values of CA50 and IMEP calculated from the experimental data are 1 CAD and 7.7 kPa, respectively [133].

Table 3.2
Range of experimental data used for the COM development of the LTC modes

Parameters	**HCCI**	**PPCI**	**RCCI**
IAT (°C)	40:20:100	40:20:100	40:20:80
P_{man} (kPa)	96	96	96
Engine Speed (RPM)	800	800	1000
PR (-)	0-40	0-40	10-40
SOI (CAD bTDC)	450	100	20-60
Equivalence ratio, ϕ	0.32-0.67	0.3-0.8	0.32-1

In-cylinder gas pressure (solid lines) and the resulting rate of heat release (dotted lines) in the LTC modes are shown in Fig. 3.5 for a sample operating condition for comparison. Combustion in HCCI mode occurs predominantly in two stages because of early injections and the homogeneous air-fuel mixture. First stage heat release corresponds to the low temperature reactions while the high temperature reactions result in the second stage combustion. High temperature heat release (HTHR) followed by low temperature heat release (LTHR) is more abrupt in HCCI mode. Ignition in

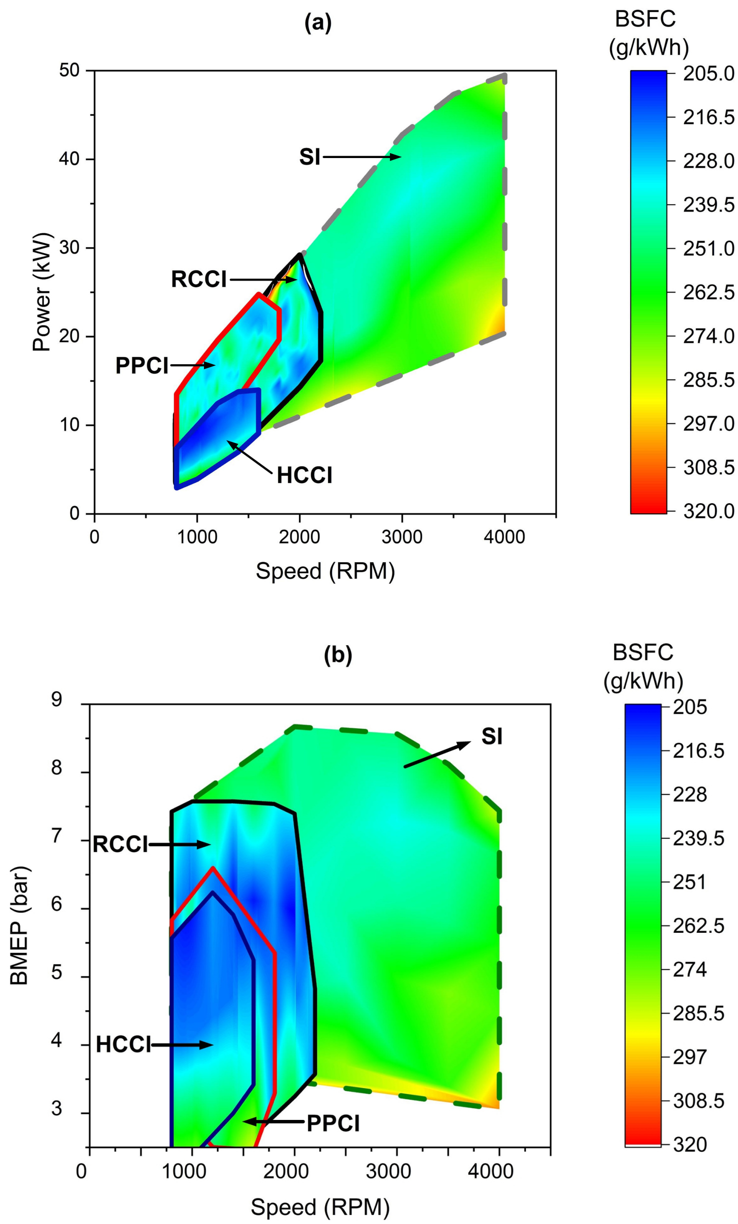

Figure 3.4: Comparison of the engine tested conditions for SI, HCCI, PPCI and RCCI modes

PPCI mode also occurs in two stages. The LTHR in the heat release rate of HCCI mode seems higher than the one in PPCI mode. However, the magnitude of heat released in HCCI mode during low-temperature reactions is lower than that of the

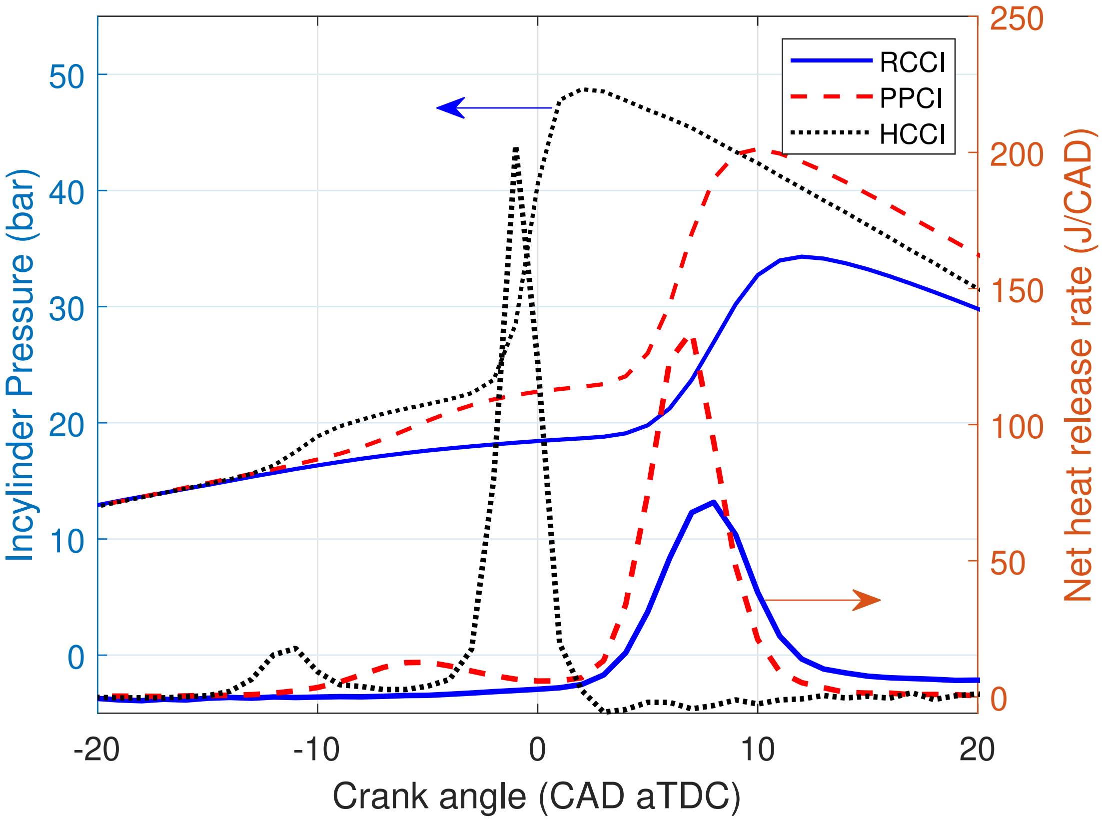

Figure 3.5: Experimental in-cylinder gas pressure and heat release rate in LTC modes (N = 1000 RPM, PR = 20, Tman = 313 K, SOI_{RCCI} = 25 CAD (bTDC), $\Phi = 0.65$)

PPCI mode. The cumulative LTHR in PPCI and HCCI modes are 98 J and 53.4 J, respectively. However, the HTHR in PPCI mode is less rapid that results in relatively late combustion phasing as compared to HCCI mode. Due to late injection of n-heptane, RCCI mode does not exhibit abrupt heat release rate. In addition, combustion in RCCI mode happens in a single stage with late combustion phasing compared to HCCI and PPCI modes. That is why, SOI proves to be an effective control knob in single stage heat release in RCCI combustion along with PR.

3.4 Control Oriented Models for Combustion Modes

Dynamic models of the LTC modes need to represent the entire engine cycle. The process starts from mode selection based on the requested speed and load followed by the intake valve opening (IVO) to exhaust valve closing (EVC) events, as shown in Figure 3.6. This study is based on three different LTC modes, that is why, the particular mode offering the lowest BSFC is first selected from the engine map as shown in Fig. 3.4. Mode 1, 2 and 3 represent HCCI, PPCI and RCCI, respectively. Based on mode number, the particular dynamic model is selected to represent the corresponding engine operation. Step 2 includes the IVO to IVC event. Pressure and temperature of the air-fuel mixture at IVC for all combustion modes are estimated using Eq. (6.19) and Eq. (6.20), respectively. To incorporate cycle to cycle coupling, the temperature at IVC is calculated by taking the residual gas fraction and the residual gas temperature into account.

$$P_{\mathrm{ivc}} = \frac{N^{\mathrm{a}}\phi^{\mathrm{b}}}{T_{\mathrm{m}}^{\mathrm{c}}} P_{\mathrm{m}}, \tag{3.2}$$

$$T_{ivc} = (1 - X_{rg})T_{in} + X_{rg}T_{rg} \tag{3.3}$$

Where, N is engine speed, P_m is the intake manifold pressure, T_m is the intake manifold temperature, ϕ is the fuel-air equivalence ratio, T_{rg} is the residual gas temperature and X_{rg} is the residual gas fraction. X_{rg} for the first cycle is estimated using Eq. (6.41), [116]:

$$X_{rg} = \sqrt{\frac{1}{C}.\frac{\pi\sqrt{2}}{360}.\frac{r_c-1}{r_c}.\frac{OF}{N}.\sqrt{\frac{RT_m|P_{exh}-P_m|}{P_{exh}}}.\left(\frac{P_{exh}}{P_m}\right)^{\frac{k_c+1}{k_c}}} + \frac{1}{C}.\frac{r_c-1}{r_c}.\phi_{tot}\frac{V_{ivo}}{V_d}.\left(\frac{P_{exh}}{P_m}\right)^{\frac{1}{k_c}} \tag{3.4}$$

Where, OF is overlap factor, r_c is compression ratio, R is gas constant, and V_d is displaced volume. C is given by the following:

$$C = \left[1 + \frac{LHV}{c_v T_m \frac{m_t}{m_f}.r_c^{k_c-1}}\right]^{\frac{1}{k_c}} \tag{3.5}$$

Where m_f is the mass of fuel injected and m_t is the sum of mass of air and mass of fuel.

The air-fuel mixture undergoes auto-ignition in the LTC modes [134]. Start of combustion (SOC) is defined as crank angle where 10% of fuel mass is burned. SOC is estimated using a modified knock integral model (MKIM) [97]. The MKIM is calibrated for each combustion mode separately such that the integral becomes 1 at SOC. MKIM is integrated from IVC to SOC for the LTC mode using fuel injected via PFI only, using Eq. (3.6). However, the integral of MKIM is divided into two parts for the LTC modes using both PFI and DI as shown in Eq.(6.43) [21]. The first part in

Eq. (6.43) considers the fuel coming from PFI thus integrating from IVC to SOI and the second part in Eq. (6.43) incorporates the effect of directly injected fuel, hence, integrating from SOI to SOC.

$$\int_{\theta_{ivc}}^{\theta_{soc}} \frac{\phi_k^A}{Bexp\left(\frac{C\left(P_{ivc,k+1}v_c^k\right)^D}{T_{ivc}V_c^k c^{-1}}\right)N_k} d\theta = 1 \tag{3.6}$$

$$\int_{\theta_{ivc}}^{\theta_{soi}} \frac{d\theta}{B_1\phi_{PFI}^{A_1}exp\left(\frac{C_1\left(P_{ivc,k+1}v_c^k\right)^{D_1}}{T_{ivc}V_c^k c^{-1}}\right)N_k} + \int_{\theta_{soi}}^{\theta_{soc}} \frac{d\theta}{B_2(\phi_{PFI}^{A_2}+\phi_{DI}^{A_3})exp\left(\frac{(\frac{C_2}{CN_{mix}+E})\left(P_{ivc,k+1}v_c^k\right)^{D_2}}{T_{ivc}V_c^k c^{-1}}\right)N_k} = 1 \tag{3.7}$$

$$\phi_{DI} = (1-PR).\phi \tag{3.8}$$

$$\phi_{PFI} = PR.\phi \tag{3.9}$$

Where, A, A_1, A_2, A_3, B, B_1, B_2, C, C_1, C_2, D, D_1, D_2 and E are the parameters estimated by calibrating the MKIM for the LTC modes. ϕ, in Eq. (3.6) is the total equivalence ratio of the injected fuels. ϕ_{PFI} and ϕ_{DI} are the equivalence ratios of iso-octane and n-heptane, respectively.

Pressure (P_{soc}) and temperature (T_{soc}) at start of combustion are calculated using a

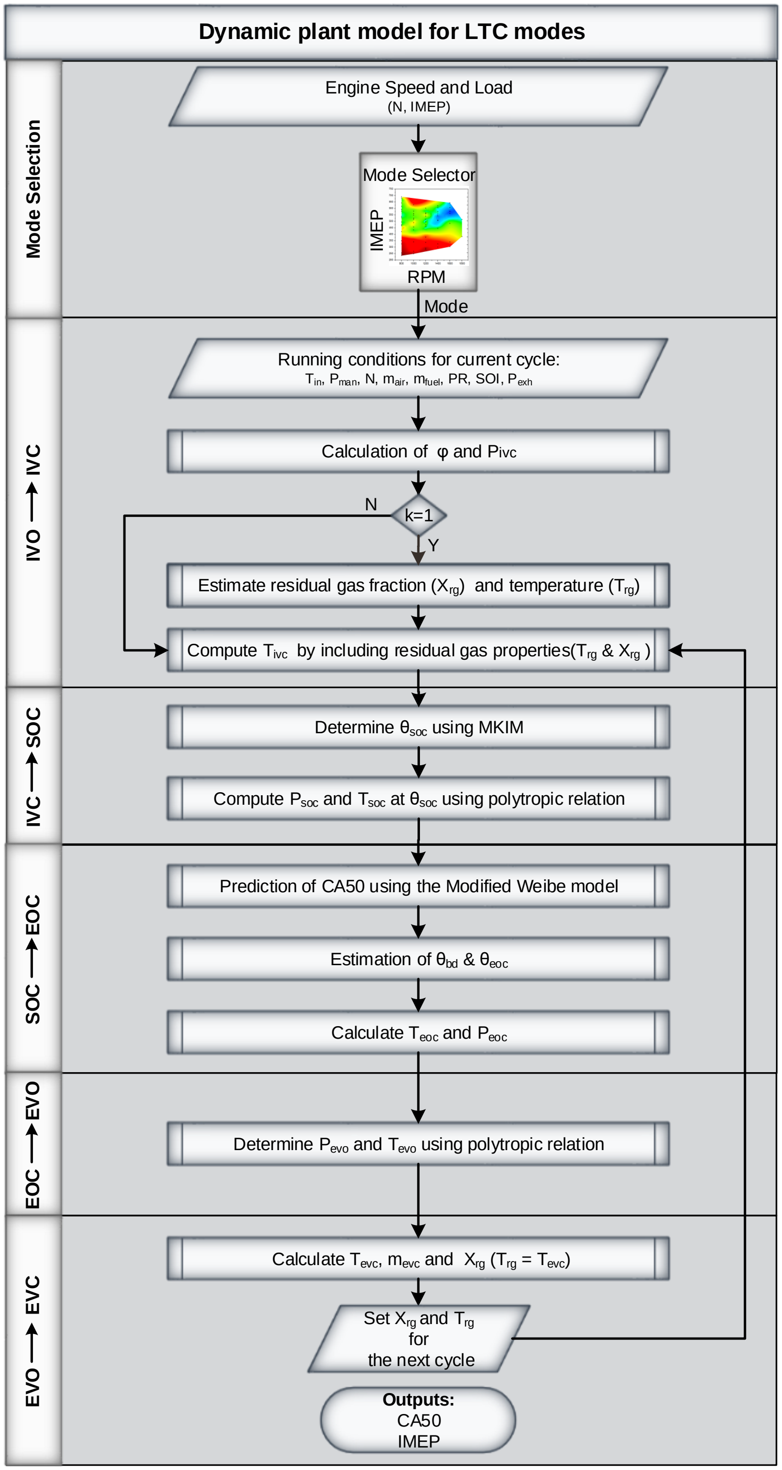

Figure 3.6: Designed multi-mode dynamic model for the LTC engine

polytropic relationship, using Eq. (6.47) and Eq. (6.48).

$$P_{soc} = P_{ivc}\left(\frac{V_{ivc}}{V_{soc}}\right)^{k_c} \tag{3.10}$$

$$T_{soc} = T_{ivc}\left(\frac{V_{ivc}}{V_{soc}}\right)^{k_c-1} \tag{3.11}$$

Where, k_c is the polytropic index of compression. V_{ivc} and V_{soc} are the volumes at intake valve closing and start of combustion, respectively.

Weibe function is parameterized for each LTC mode for the estimation of CA50, using Eq. (6.49). CA50 is defined as the crank angle by which 50% of the fuel mass is burned.

$$x_b(\theta) = 1 - exp\left(-a\left[\frac{\theta - \theta_{soc}}{\theta_d}\right]^n\right) \tag{3.12}$$

$$\theta_d = CD\,(1 + X_d)^x\,\phi^y \tag{3.13}$$

$$X_d = EGR + \frac{X_{rg}}{1 - X_{rg}} \tag{3.14}$$

Where, a and n are the constants calculated by parameterizing the Weibe function. θ_d is the burn duration estimated by using Eq. (6.50). X_{rg} is the residual gas fraction. Temperature at the end of combustion (T_{eoc}) is calculated from the temperature rise due to the fuel burned during combustion, using Eq.(6.53).

$$T_{eoc} = T_{soc} + \Delta\ \mathrm{T} \tag{3.15}$$

$$\Delta T_{comb} = \frac{LHV_f CoC}{(1 + X_{rg})(\phi^{-1} AFR_{st} + 1)C_v} \tag{3.16}$$

$$P_{eoc} = \frac{P_{soc} V_{eoc}}{V_{eoc}} \frac{T_{eoc} R_{eoc}}{T_{soc} R_{soc}} \tag{3.17}$$

Where, CoC is the completeness of combustion, AFR_{st} is the stoichiometric air to fuel ratio. Pressure and temperature at the end of expansion stroke are calculated using polytropic relationship, as shown in Eq. (6.56) and Eq. (6.57), respectively.

$$P_{evo} = \; P_{eoc} \left(\frac{V_{eoc}}{V_{evo}} \right)^{k_e} \tag{3.18}$$

$$T_{evo} = \; T_{eoc} \left(\frac{V_{eoc}}{V_{evo}} \right)^{k_e - 1} \tag{3.19}$$

Where, k_e is the polytropic index of expansion, while V_{evo} and V_{evc} are the volumes at EOC and EVO, respectively. Temperature of the in-cylinder charge at the end of EVC is calculated using Eq. (6.58):

$$T_{evc} = T_{evo} \left(\frac{V_{evo}}{V_{evc}} \right)^{k_e - 1} \tag{3.20}$$

Where, T_{evc} is the temperature at EVC, V_{evo} and V_{evc} in Eq. (6.58) are the volumes at EVO and EVC, respectively. The mass of residual gases (m_{evc}) trapped in the cylinder at EVC is calculated using Eq. (6.59)

$$m_{evc} = \frac{P_{exh} V_{evc}}{R_{evc} T_{evc}} \tag{3.21}$$

Where, P_{exh} is the exhaust pressure, V_{evc}, T_{evc} and R_{evc} are the volume, temperature and gas constant at EVC, respectively. Residual gas fraction (X_{rg}) at the end of engine cycle is calculated using Eq. (3.22).

$$X_{rg} = \frac{m_{evc}}{m_t} \tag{3.22}$$

IMEP is calculated using Eq. (6.60) [83]. m_t is the sum of mass of air, fuel and residual gas fraction of the current cycle.

$$IMEP = m_t \frac{Cv}{V_{dis}} \left(T_{ivc} - T_{soc} \ + T_{eoc} - T_{evc} \right) \tag{3.23}$$

3.4.1 Fuel Transport Dynamics

This work includes fuel injection via PFIs; therefore, it is important to consider the port fuel transport dynamics. The fuel injected via PFI undergoes transport dynamics before entering the cylinder. This transport dynamics of the fuel can be explained by $\tau - X$ model [135]. A portion of the total injected fuel from PFI vaporizes and enters the cylinder directly while the remaining forms puddle in the intake port. The fuel in the puddle evaporates slowly and then enters the cylinder. The rate at which the fuel evaporates from the puddle is proportional to the puddle mass (m_p) and inversely proportional to the evaporation time constant (τ). The amount of fuel entering the cylinder is determined by using Eq. 3.24

$$\dot{m}_{cyl} = \frac{1}{\tau}m_p + (1 - X)\dot{m}_{fi} \tag{3.24}$$

Where, $\dot{m}_{cyl}$ is the mass of fuel entering the cylinder, X is the fraction of the injected fuel which enters the puddle and $\dot{m}_{fi}$ is the rate of total fuel injected.

The measurement dynamics and transport delay associated with the lambda sensor and exhaust gas transport delay to reach the lambda sensor. The lambda sensor can be modeled as a first order dynamic system lag and exhaust gas transport as a time delay. The values of T_L and τ_m are determined by using system identification. Eq. 6.5 shows the transfer function for lambda sensor model in Laplace domain.

$$G(s) = \frac{K_p e^{-sT_L}}{\tau_m s + 1} \tag{3.25}$$

To determine the values of τ and X, the fuel is injected via PFI. System identification is used to determine the values of τ and X using Eq. 3.26.

$$\frac{\dot{m}(s)}{\dot{m}_{fi}(s)} = \frac{(1 + \tau(1 - X)s}{1 + \tau s}\frac{1}{1 + \tau_m s}e^{-sT_L} \tag{3.26}$$

Where, $\dot{m}$ is the amount of the fuel calculated using lambda sensor measurements.

The values of T_L, τ_m, X and τ are determined to be 0.15 s, 0.43 s, 0.09 and 0.06 s, respectively.

3.4.2 Model Validation

The developed dynamic models for HCCI, PPCI and RCCI combustion modes are parameterized and validated based on the steady state experimental data. Half of the experimental data is used for parameterization while the other half is used for the model validation. HCCI PPCI and RCCI model validations for SOC, burn duration (BD), CA50 and IMEP prediction are shown in Figures 3.7, 3.8 and 3.9, respectively.

The developed models are used as virtual plants for design and testing of the controller. For transient validation of HCCI model, step changes in PR and fuel quantity are provided simultaneously. The experimental data and model outputs are compared as shown in Figure 3.10. It can be observed that the model is capable of responding to the step changes in the PR and fuel quantity. Combustion phasing retards with the increase in PR and IMEP increases as fuel quantity increases. The average error in predicting CA50 is 1 CAD while the average error in predicting IMEP is 24 kPa for HCCI. RCCI model is also validated under different transient conditions. Experimental data and model outputs for RCCI mode are compared for two different cases as shown in Figures 3.11 and 3.12. In the first scenario, a step change in SOI is

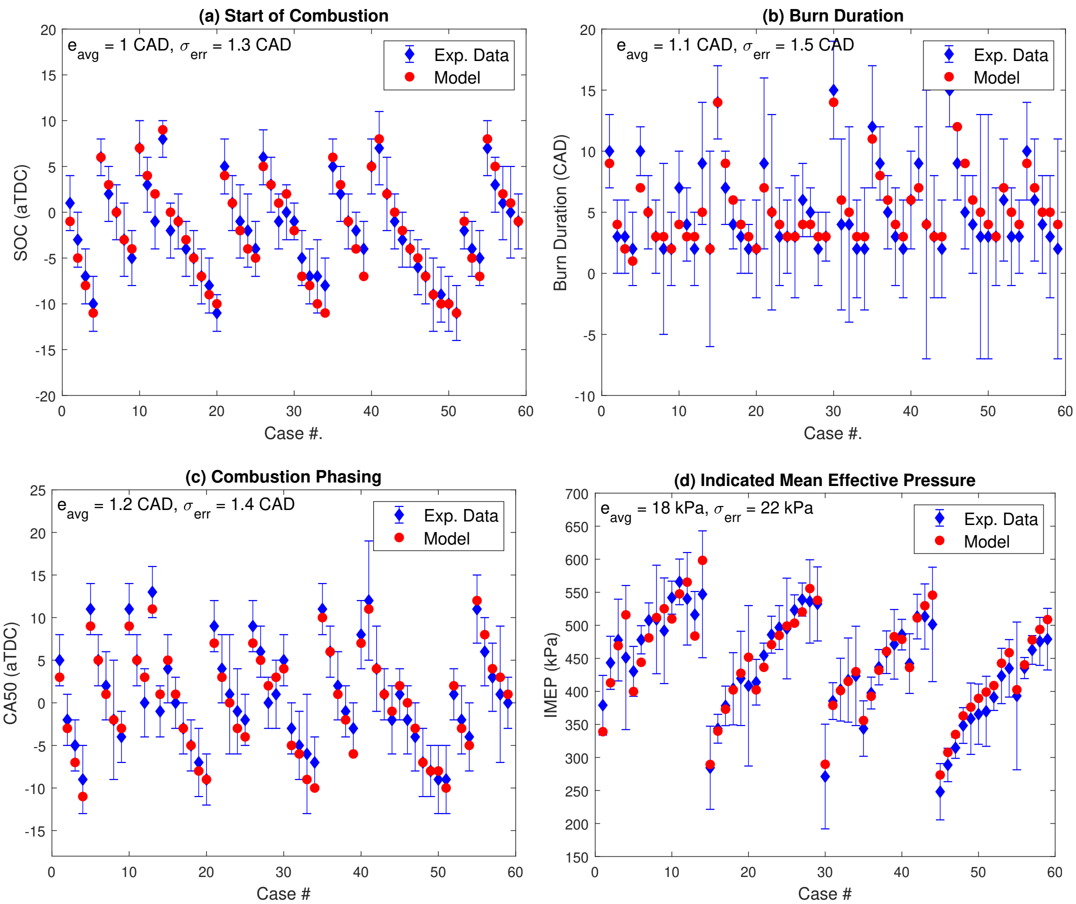

Figure 3.7: Experimental validation for HCCI Model under steady state condition (N = 800 RPM, Tman = 313-373 K, PR =0 - 40). e_{avg} is the average error while σ_{err} is the standard deviation of error

provided while keeping fuel quantity constant for PR of 20. For the second case, SOI of 50 CAD bTDC and PR of 20 are kept constant and fuel quantity is varied. It can be seen that the model predicts CA50 and IMEP with average errors of less than 2 CAD and 37 kPa, respectively for both cases.

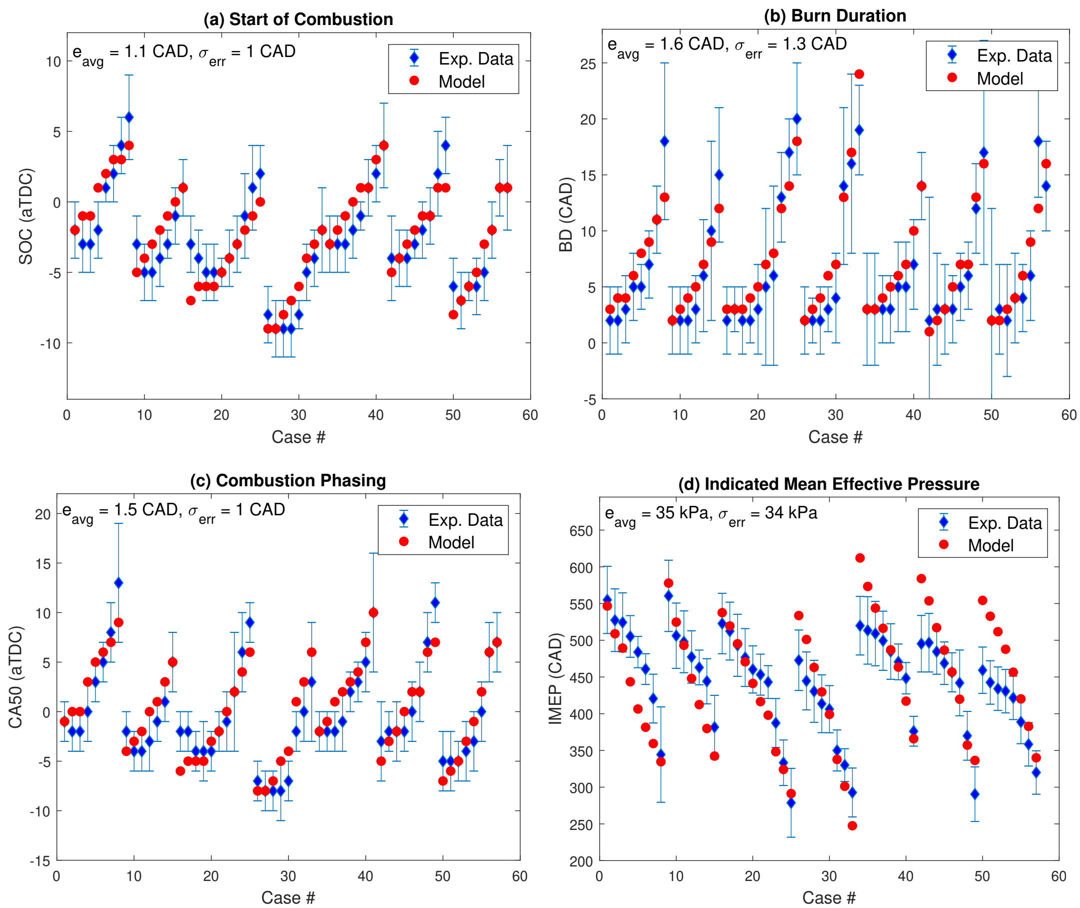

Figure 3.8: Experimental validation for PPCI Model under steady state condition (N = 800 RPM, Tman = 313-373 K, PR =0 - 40). e_{avg} is the average error while σ_{err} is the standard deviation of error

3.5 State-Space Modeling of LTC Modes

The outputs of the nonlinear COM for HCCI and PPCI modes can be represented on cycle to cycle basis as shown in Eq. (3.34) and Eq. (3.35) whereas outputs for RCCI mode can be represented as shown in Eq. (3.36) and Eq. (3.37). The nonlinear models are computationally expensive. Therefore, the developed nonlinear COMs for

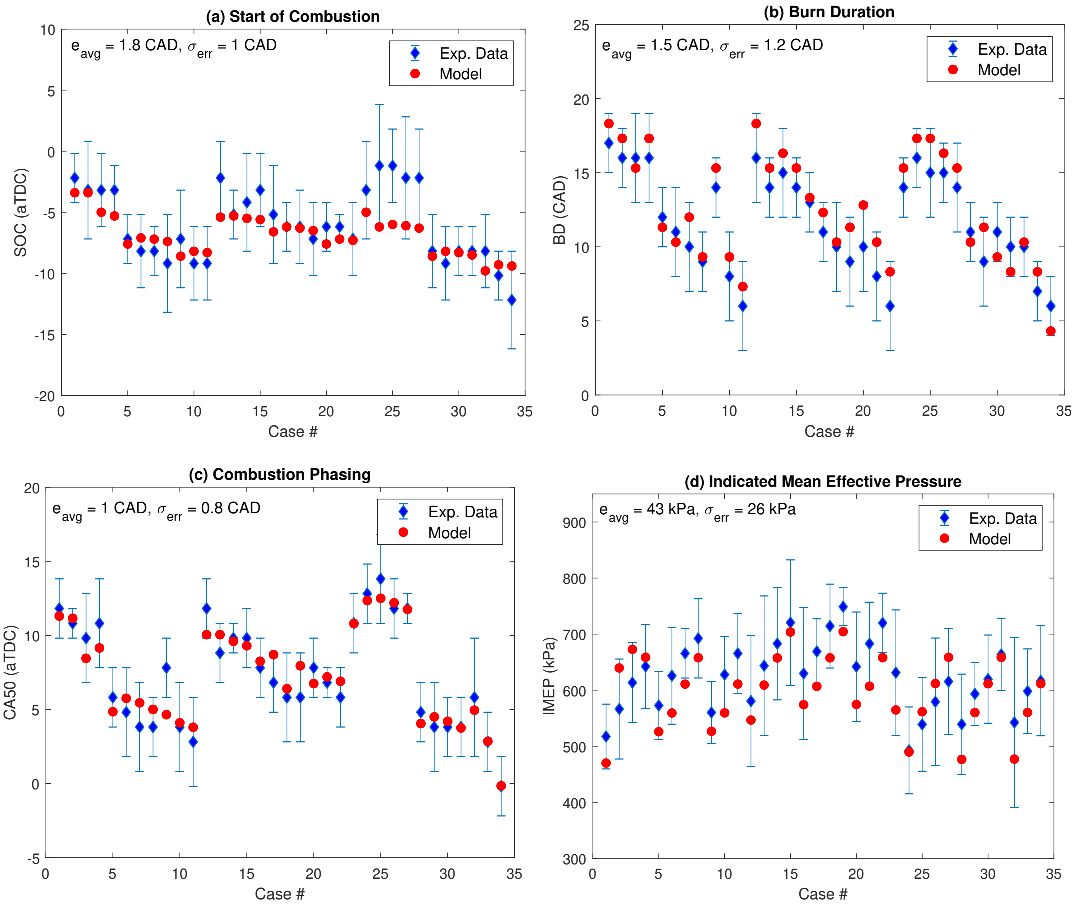

Figure 3.9: Experimental validation for RCCI Model under steady state condition (N = 1000 RPM, Tman = 313 K, PR = 0 - 40, SOI = 20-60 CAD bTDC). e_{avg} is the average error while σ_{err} is the standard deviation of error

CA50 and IMEP control on cycle-to-cycle basis are linearized around the nominal operating conditions for each LTC mode. A nonlinear system is defined by the state and output equations:

$$\dot{x}(t) = f(x(t), u(t)) \tag{3.27}$$

$$y(k) = g(x(t), u(t)) \tag{3.28}$$

Let $(\mathrm{x}_0, \mathrm{u}_0)$ be the states and control inputs at equilibrium point around which the dynamic system is linearized:

$$\delta x(t) = x(t) - x_0 \tag{3.29}$$

$$\delta u(t) = u(t) - u_0 \tag{3.30}$$

$$\frac{\delta x(t)}{dx} = \dot{x} = f(x(t), u(t)) \tag{3.31}$$

By computing Jacobian matrix of Eq. (3.27) w.r.t the states, we obtained:

$$\begin{bmatrix} \delta\dot{x}_1(t) \\ \vdots \\ \delta\dot{x}_4(t) \end{bmatrix} = \begin{bmatrix} \frac{\delta f_1(t)}{x_1} & \dots & \frac{\delta f_1(t)}{x_4} \\ \vdots & \ddots & \vdots \\ \frac{\delta f_4(t)}{x_1} & \dots & \frac{\delta f_4(t)}{x_4} \end{bmatrix}_{(x_0,u_0)} \begin{bmatrix} \delta x_1(t) \\ \vdots \\ \delta x_4(t) \end{bmatrix} + \begin{bmatrix} \frac{\delta f_1(t)}{u_1} & \dots & \frac{\delta f_1(t)}{u_4} \\ \vdots & \ddots & \vdots \\ \frac{\delta f_4(t)}{u_1} & \dots & \frac{\delta f_4(t)}{u_4} \end{bmatrix}_{(x_0,u_0)} \begin{bmatrix} \delta u_1(t) \\ \vdots \\ \delta u_4(t) \end{bmatrix} + \begin{bmatrix} f_1(x_0,u_0) \\ \vdots \\ f_4(x_0,u_0) \end{bmatrix} \tag{3.32}$$

For the equilibrium point (x_0, u_0),

$$\begin{bmatrix} f_1(x_0, u_0) \\ \vdots \\ f_4(x_0, u_0) \end{bmatrix} = 0 \tag{3.33}$$

δx is obtained by solving Eq. (3.32) for δu and x(t) is computed. The linearized equations for the outputs are obtained in the analogous manner.

Based on the performance characterization, the nominal intake air temperatures are chosen to be 80, 40 and 60 °C for HCCI, PPCI and RCCI modes, respectively. Premixed ratio (PR) is used to control CA50 in HCCI and PPCI modes while SOI is used to control CA50 in RCCI mode. IMEP in each LTC mode is controlled by adjusting fuel quantity. In HCCI and PPCI modes, intake air temperature is modelled as disturbance input while PR is modelled as a disturbance input in the RCCI mode.

$$CA50_{k+1} = f(CA50, T_{soc}, P_{soc}, IMEP, PR, FQ, T_m)_k \tag{3.34}$$

$$IMEP_{k+1} = f(CA50, T_{soc}, P_{soc}, IMEP, PR, FQ, T_m)_k \tag{3.35}$$

$$CA50_{k+1} = f(CA50, T_{soc}, P_{soc}, IMEP, SOI, FQ, PR)_k \tag{3.36}$$

$$IMEP_{k+1} = f(CA50, T_{soc}, P_{soc}, IMEP, SOI, FQ, PR)_k \tag{3.37}$$

The states of the MIMO COM of HCCI, PPCI and RCCI are CA50, T_{soc}, P_{soc} and

IMEP. In addition, CA50 and IMEP are the outputs of the MIMO COM of HCCI, PPCI and RCCI.

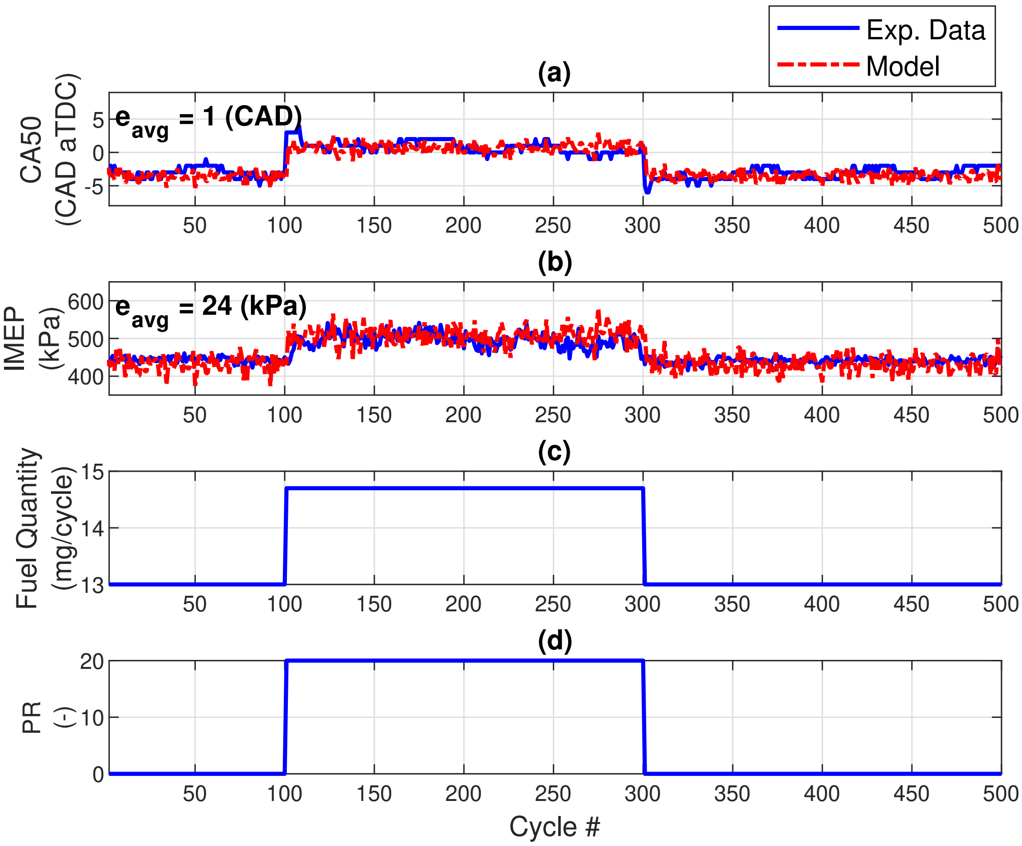

Figure 3.10: Experimental validation for the HCCI COM Model under transient operation (N =800 RPM, Tman = 353K, SOI = 450 CAD bTDC)

The linearization yields the following state space matrices for HCCI model:

$$A = \begin{bmatrix} 0.2067 & -0.1761 & 0.0179 & -0.0586 \\ -0.2798 & 0.0194 & 0.0938 & -0.0638 \\ -3.2405 & -0.6555 & 1.0898 & -1.0923 \\ -0.9657 & 0.7802 & 0.0072 & 0.1506 \end{bmatrix} \tag{3.38}$$

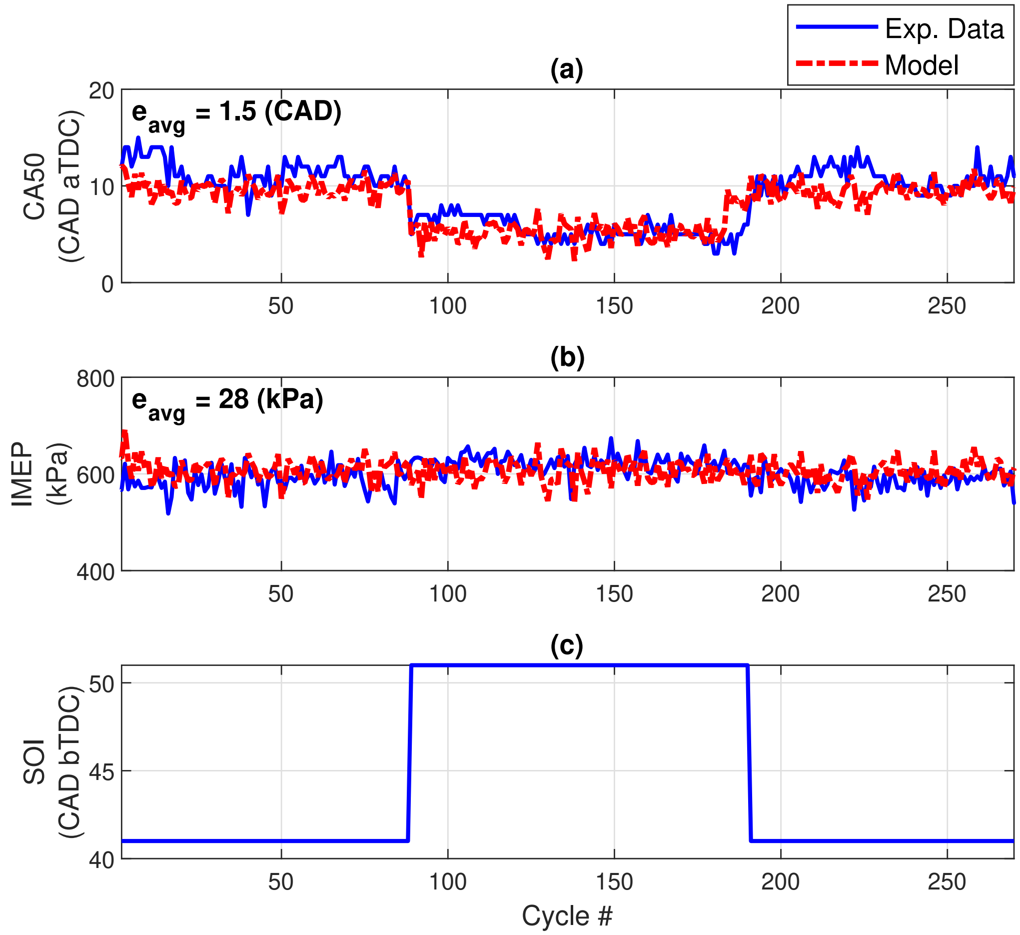

Figure 3.11: Experimental validation for the RCCI COM Model under transient operation due to step change in SOI (N =1000 RPM, Tman = 333K, PR= 20, Fuel quantity =23 mg/cycle)

$$B = \begin{bmatrix} 0.3558 & -1.0438 \\ 0.1957 & -1.2902 \\ 1.8241 & 31.5290 \\ 0.9085 & 30.1506 \end{bmatrix} \tag{3.39}$$

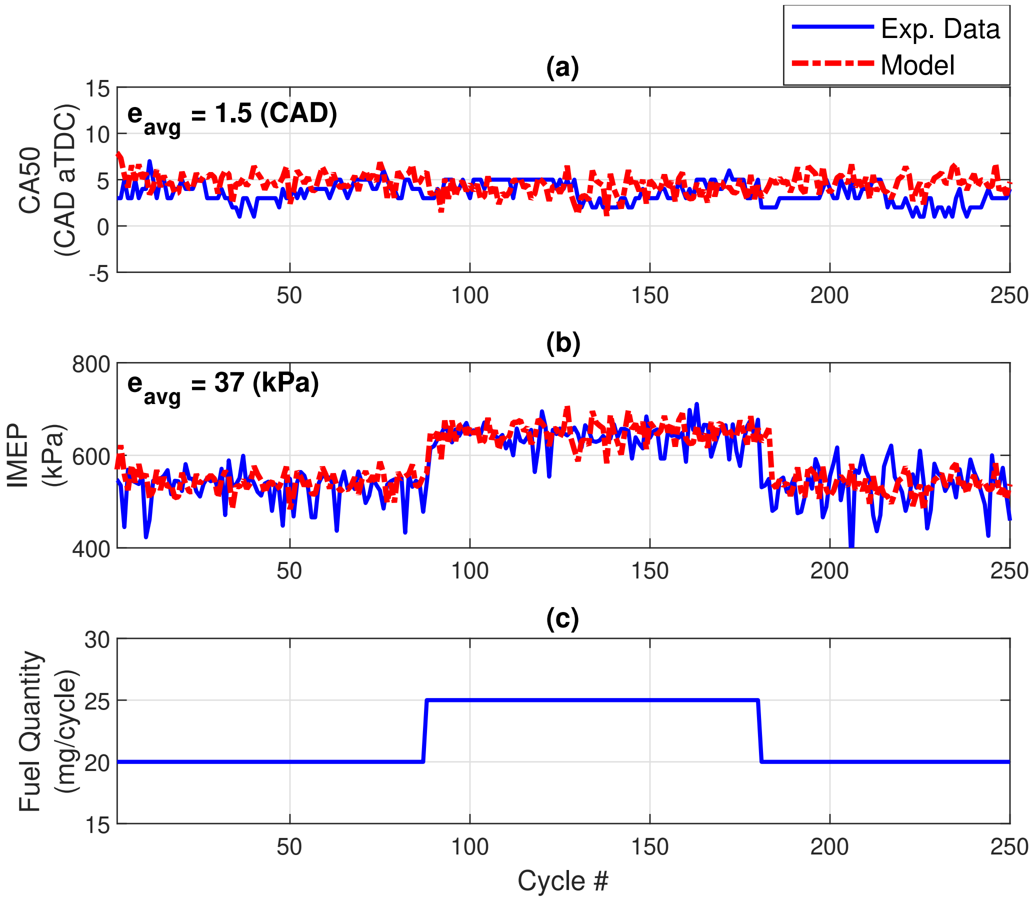

Figure 3.12: Experimental validation for the RCCI COM Model under transient operation due to step change in FQ (N =1000 RPM, Tman = 333K, SOI = 50 CAD (bTDC), PR =20)

$$B_v = \begin{bmatrix} 0.3915 \\ 1.8087 \\ 0.0380 \\ -2.4140 \end{bmatrix} \tag{3.40}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.41}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{3.42}$$

The state space matrices for the PPCI model are as follows:

$$A = \begin{bmatrix} 0.4602 & -0.0516 & -0.0009 & -0.0102 \\ 0.9645 & 0.7823 & 0.0147 & 0.0806 \\ 0.1369 & 0.5456 & 0.8911 & 0.0987 \\ -1.2572 & 0.7840 & 0.0092 & 0.4497 \end{bmatrix} \tag{3.43}$$

$$B = \begin{bmatrix} 0.1810 & -0.4005 \\ -0.2562 & -1.8488 \\ -0.1300 & -1.6146 \\ 0.0705 & 18.0950 \end{bmatrix} \tag{3.44}$$

$$B_v = \begin{bmatrix} 0.0027 \\ 0.5479 \\ -0.8427 \\ -1.3600 \end{bmatrix} \tag{3.45}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.46}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{3.47}$$

Following are the state space matrices after linearizing the RCCI model:

$$A = \begin{bmatrix} 0.0393 & -0.0140 & 0.0052 & 0.0081 \\ -0.2741 & 0.0974 & -0.0361 & -0.0566 \\ -0.3965 & -0.1409 & -0.0523 & -0.0819 \\ 0.3743 & -0.1043 & 0.0493 & -0.0452 \end{bmatrix} \tag{3.48}$$

$$B = \begin{bmatrix} -0.4165 & -0.3176 \\ 0.4479 & 2.4402 \\ 4.2019 & 3.1550 \\ 2.1777 & 28.2946 \end{bmatrix} \tag{3.49}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.50}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{3.51}$$

The linearized systems have been analyzed for open and closed-loop stability. The discrete-time system is said to be asymptotically stable if eigenvalues of the system lie within the unit circle [136]. The eigenvalues of HCCI, PPCI and RCCI are presented in Table 3.3. The eigenvalues of the three LTC modes are within the unit circle; therefore, the systems are open-loop stable. Nyquist stability criteria is used to

Table 3.3
Eigenvalues of linearized discrete-time open-loop system in the three LTC modes

Modes	**Eigenvalues**
HCCI	0.92, -0.04, 0.08, 0.50
PPCI	0.30, 0.95, 0.61, 0.71
RCCI	0.18 + 0i, -0.0002 + 0i, -0.071 ± 0.043i

determine the closed-loop stability of the systems. CA50 is controlled by adjusting the premixed ratio of the dual fuels while IMEP is regulated by controlling the amount of injected fuel quantity. Therefore, transfer functions are determined from inputs to outputs of the system and the frequency response of a unity feedback system is plotted on Nyquist diagram for each LTC mode. According to Nyquist stability criteria, if the contour encircles the entire right half plane is mapped through the transfer functions of the system (G(s)) and unity feedback (H(s)), then the number of closed-loop poles (Z) of the unity feedback system in the right half plane is equal to the number of clockwise revolutions (N) around the point (-1 + 0i) of the mapping minus the number of open-loop poles (P) that lie in the right half plane, i.e., N = Z - P [136].

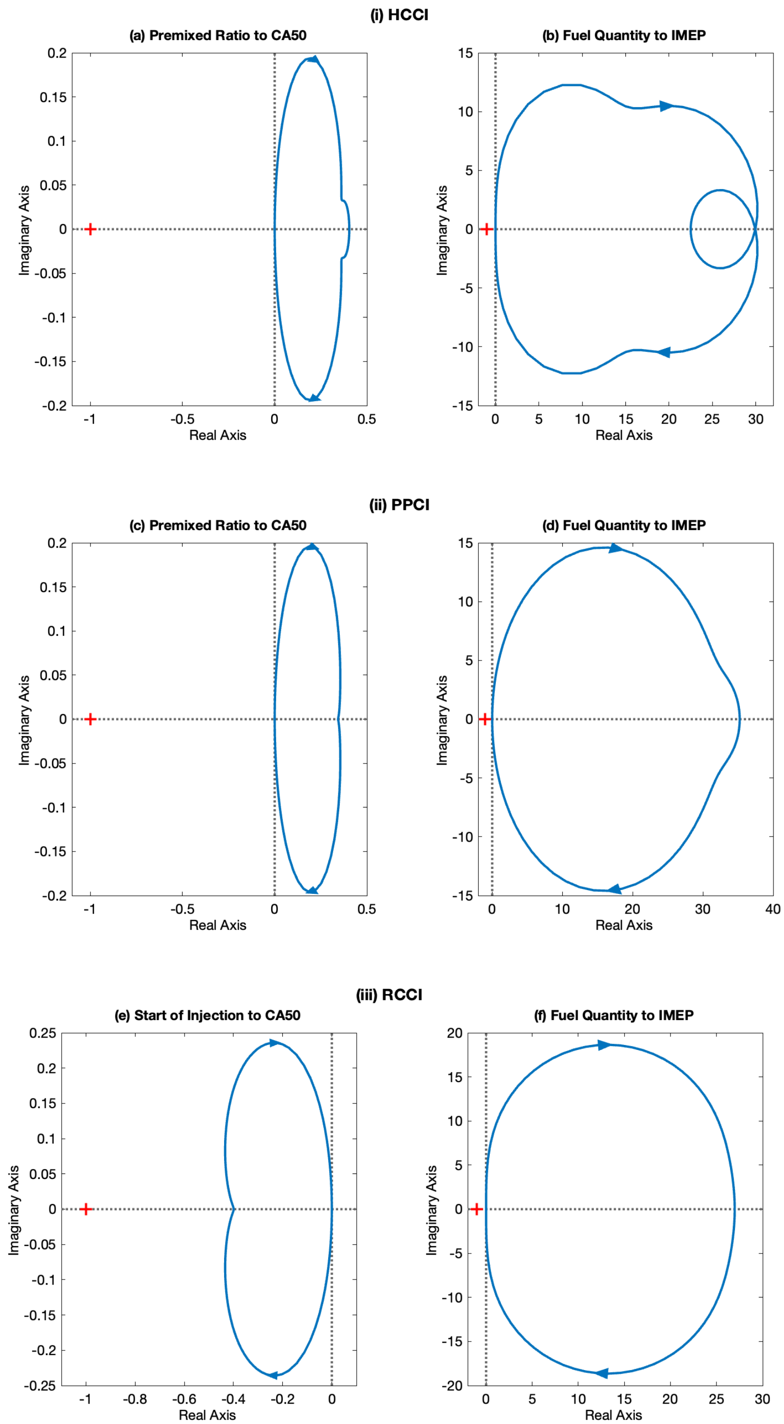

Figure 3.13: Nyquist plots for closed loop stability analysis of i) HCCI, ii) PPCI and iii) RCCI systems

Figures 3.13(a) & 3.13(b) show that the system is closed-loop stable because the open-loop poles of the HCCI system lie in the left half plane and the point (-1 + 0i) lies outside the contour that maps the entire right-half plane. Therefore, HCCI system is closed-loop stable. Based on Nyquist stability criteria, the contour mapped through the transfer functions of the system and unity feedback do not encircle the point (-1 + 0i) and the number of open-loop poles in right half plane (P) = 0, as shown in Fig. 3.13(c) & 3.13(d). This means that no closed-loop pole of PPCI mode exists in the right half plane, thus; the closed-loop system is stable. Nyquist plots of RCCI show that the system is stable as the point (-1+0i) lie outside the contours of the transfer functions, as shown in Fig. 3.13(e) & 3.13(f).

3.6 Controller Development

The LTC modes under study are operated using dual fuels and changing the premixed ratio of two fuels affects the combustion process. Due to the highly non-linear nature of the combustion process, a single MPC can only perform well in a limited region around the nominal operating conditions. Raut et al. developed multiple MIMO MPCs, each MPC capable of achieving the desired CA50 and IMEP for a range of PR. Therefore, PR is used as a scheduling variable to switch between the multiple MPCs to achieve the desired performance [21]. In this study, the limited operating regime of a single MPC is extended without any performance degradation by using the linear parameter varying (LPV) models. The LPV models are capable of capturing the system dynamics which vary as a function of time-varying scheduling parameter. LPV system is represented as a linear state space model with coefficients being the function of a scheduling parameter. In this study, the linear parameter varying models as a function of different values of PR are developed offline for each LTC mode. The LPV models update the internal predictive model at each control interval and is used within an adaptive MPC controller to achieve the nonlinear control. The schematic of designed LPV-MPC system is shown in Figure 3.14. By using LPV models, development of multiple MPCs can be avoided to cover a wide range of engine operation. Hence, the dynamic COM for the LTC modes can be represented in discrete time state space model as a function of PR (scheduling parameter), as shown in Eq. (5.19) and Eq. (8.23).

$$X_{k+1} = A(p)X_k + B(p)U_k \tag{3.52}$$

$$Y_k = C(p)X_k + D(p)U_k \tag{3.53}$$

X, U and Y represent the states, control inputs, and outputs of the system. The states and outputs for the LTC modes are:

$$X = \begin{bmatrix} CA50 & T_{soc} & P_{soc} & IMEP \end{bmatrix}^T \tag{3.54}$$

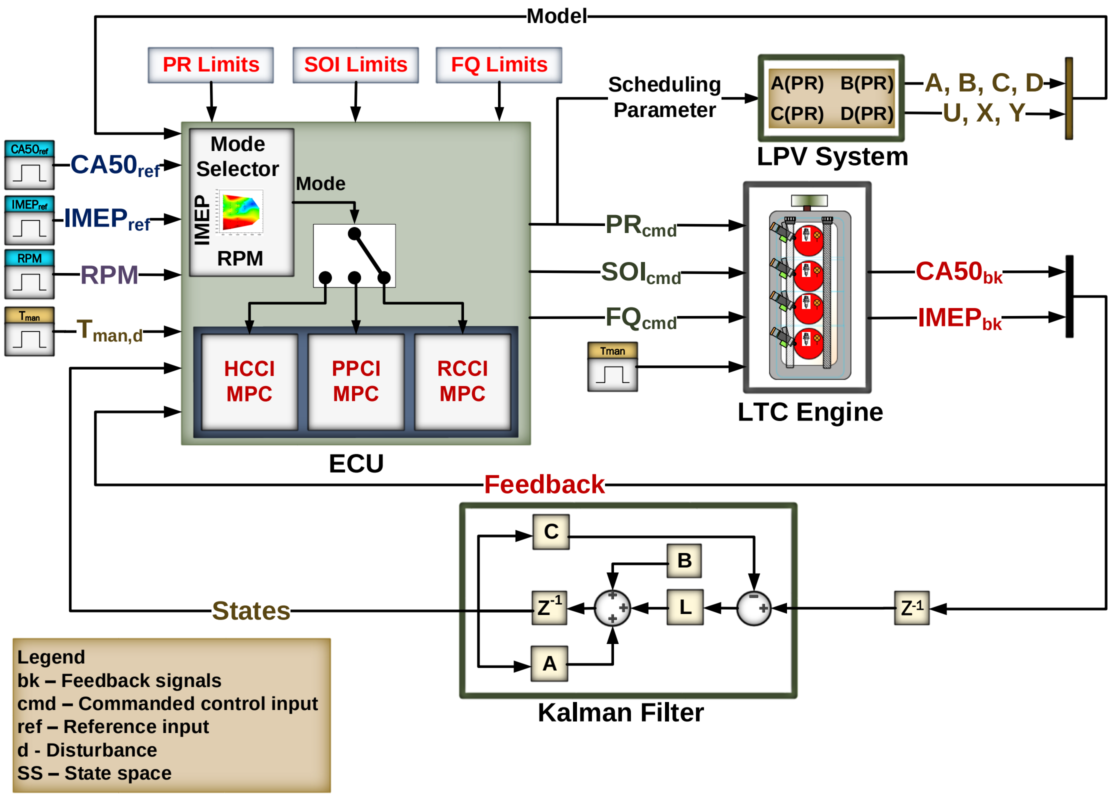

Figure 3.14: Schematic of the designed adaptive MPC combustion controller with LPV systems to control CA50 and IMEP

$$Y = \begin{bmatrix} CA50 & IMEP \end{bmatrix}^T \tag{3.55}$$

Control inputs for HCCI and PCCI modes are represented in Eq. (6.62) while for RCCI, control inputs are presented in Eq. (3.57). PR in Eq. (5.24) is used as a scheduling variable for the LTC modes.

$$U_{HCCI,PPCI} = \begin{bmatrix} PR & FQ \end{bmatrix}^T \tag{3.56}$$

$$U_{RCCI} = \begin{bmatrix} SOI & FQ \end{bmatrix}^T \tag{3.57}$$

$$p_k = \begin{bmatrix} PR \end{bmatrix} \tag{3.58}$$

The problem statement includes an optimal control objective of a MIMO system with a set of constraints on inputs and outputs for each combustion mode. Based on the targeted performance index, MIMO adaptive MPC controllers are developed for each combustion mode. An MPC is a real-time model-based optimization framework which provides flexibility of handling constraints on inputs, outputs and states. An MPC controller requires information about the reference input over the prediction horizon, as shown in Eq. (3.59). For all LTC modes, the prediction and control horizons are chosen to be 5 and 3 engine cycles, respectively. The output of the MPC over the prediction horizon presented in Eq. (3.59), can be simplified in terms of states and control inputs as shown in Eq. (3.60).

$$Y_k = \begin{bmatrix} y(k+1|k & y(k+2|k & y(k+3|k & y(k+4|k & y(k+5|k) \end{bmatrix}^T \tag{3.59}$$

$$Y_k = FX_k + \phi U_k \tag{3.60}$$

where, the matrices F and ϕ are computed by using Eq. (5.10) and Eq. (3.62).

$$F = \begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ CA^4 \\ CA^5 \end{bmatrix} \tag{3.61}$$

$$\phi = \begin{bmatrix} CB & 0 & 0 & 0 & 0 \\ CAB & CB & 0 & 0 & 0 \\ CA^2B & CAB & CB & 0 & 0 \\ CA^3B & CA^2B & CAB & CB & 0 \\ CA^4B & CA^3B & CA^2B & CAB & CB \end{bmatrix} \tag{3.62}$$

The objective function is as follows:

$$J = \sum_{i=1}^{N} [(\Psi - Y_i)^T Q (\Psi - Y_i) + U^T R U] \tag{3.63}$$

where, Q and R are the weight matrices for reference tracking and control variables, respectively. The optimal solution for control signal is given by:

$$U = (\phi^T Q \Phi + R)^{-1} \phi^T Q (\Psi - F X(k)) \tag{3.64}$$

The term $(\phi^T Q\Phi + R)^{-1}\phi^T Q\Psi$ in Eq. (3.64) refers to the set point change. The term $(-\phi^T Q\Phi + R)^{-1}\phi^T QFX$ in Eq. (3.64) corresponds to the state feedback control. Quadratic programming is used to evaluate the cost function for optimal control signal in the presence of constraints. The objective function with active constraints is given by:

$$J = \frac{1}{2}U^T EU + U^T H \tag{3.65}$$

subject to constraints:

$$A_{cons}U = B_{cons} \tag{3.66}$$

where,

$$E = \phi^T Q\phi + R; \quad H = \phi^T Q(\Psi - FX_k) \tag{3.67}$$

The constraints on the manipulated variables for each LTC modes are applied. A_{cons} and B_{cons} matrices are given in Eq. (3.68).

$$A_{cons} = \begin{bmatrix} I_{10\times 10} \\ I_{10\times 10} \end{bmatrix}; \quad B_{cons} = \begin{bmatrix} U_{max} - u(k_i - 1) \\ U_{min} + u(k_i - 1) \end{bmatrix} \tag{3.68}$$

Model predictive controller requires the information about the state variables $(X(k_i))$ at the time (k_i). It is expensive to use the sensors to measure all the states of the LTC engine. Thus, the state variables are estimated via an observer. To this end, a

Kalman filter is used to estimate the unmeasured state variables like T_{soc} and P_{soc} for each mode. The developed adaptive MPC controllers with LPV systems are simulated in Matlab/Simulink.

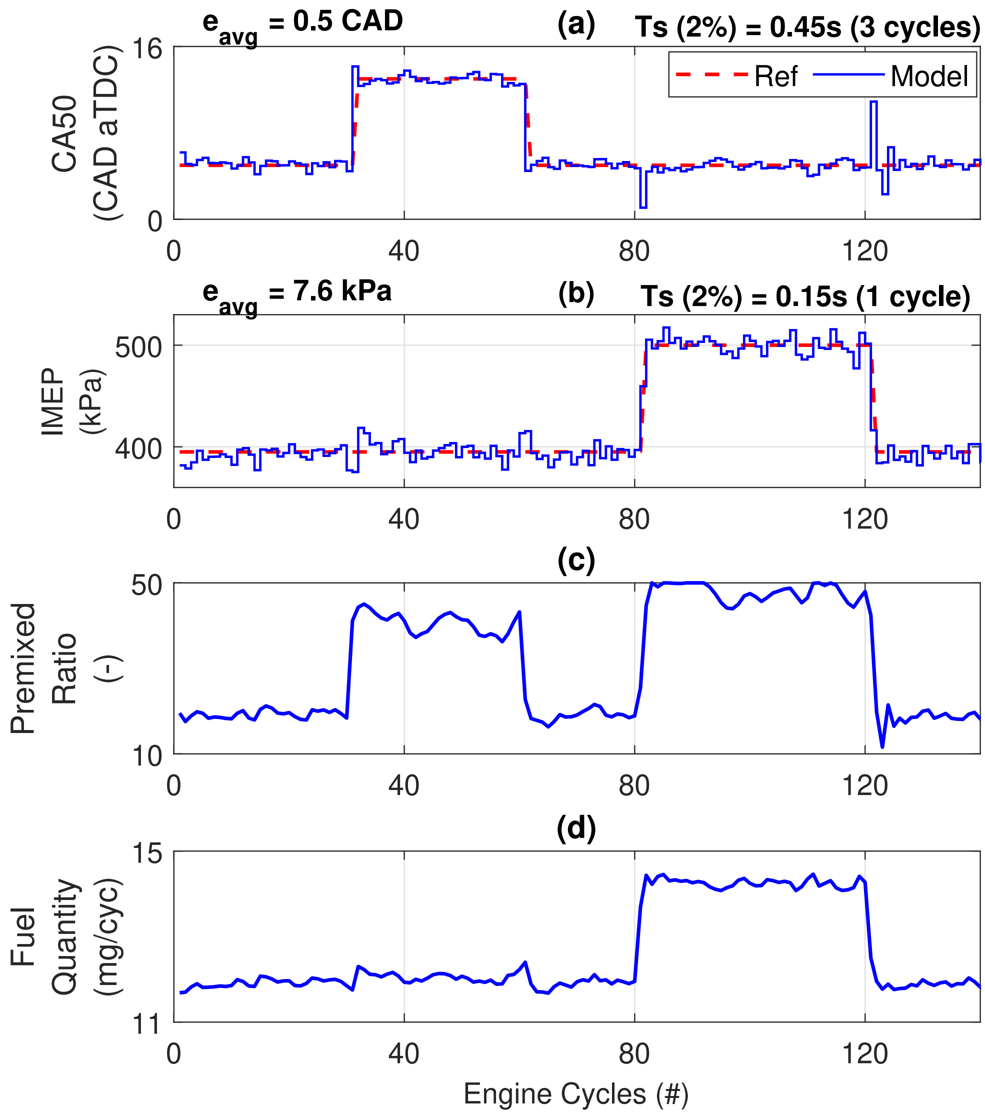

Figure 3.15: Simulation results of MIMO adaptive MPC for step changes in IMEP and CA50 (HCCI mode). Operating conditions: N = 800 RPM, Tman = 353K, Pman = 96 kPa

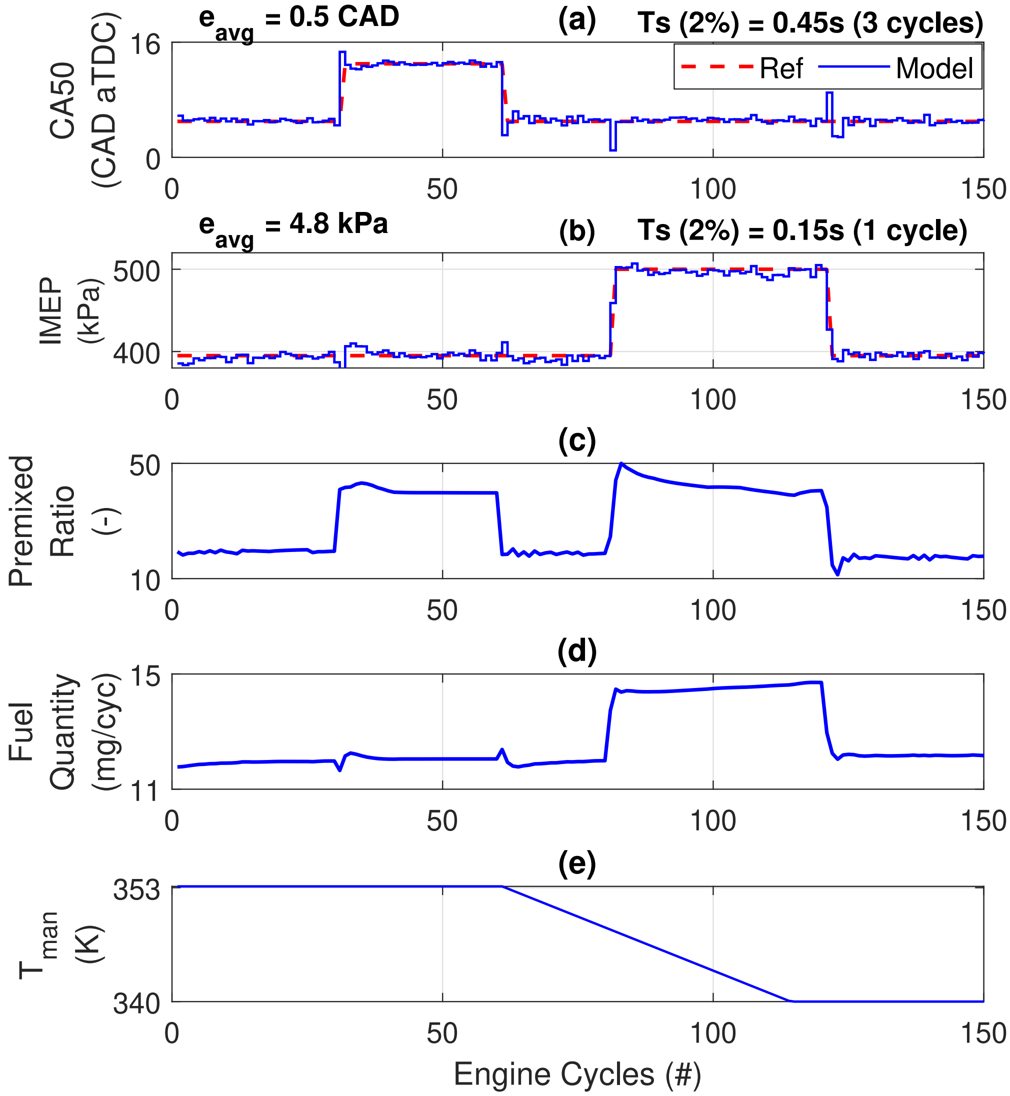

Figure 3.16: Disturbance rejection of MIMO adaptive MPC by varying T_{man} (HCCI mode). Operating conditions: N = 800 RPM, Pman = 96 kPa

3.7 Results and Discussion

The controller developed for HCCI mode is tested by providing step changes in IMEP and CA50. Measurement noise is added to both the outputs in order to account for the measurement noise in real engine setup. The controller response is tested for a step of change of 8 CAD in CA50 and 100 kPa in IMEP. The controller response including the plant outputs and the manipulated variables are shown in Figure 3.15. It takes one engine cycle to attain the targeted CA50 for a step change in CA50. However, CA50 reaches the steady state in 3 engine cycles corresponding to the step change in IMEP. IMEP reaches its targeted value in one engine cycle corresponding to a step change of 100 kPa. The average errors in CA50 and IMEP with added measurement noises are 0.5 CAD and 7.6 kPa, respectively. In addition, the controller outputs remain within the set constraints of the actuators. For instance, when there is a step change in IMEP at engine cycle # 72, PR reaches its maximum value of 50 to maintain CA50 to its optimum value. One of the important performance characteristics of the controller is its disturbance rejection property. Thus, the designed controller is tested in the presence of disturbance input. Intake air temperature is modeled as disturbance input to the plant. A ramp signal for the change in intake air temperature is provided. The controller performance in the presence of disturbance is shown in Figure 3.16. The controller shows good disturbance rejection performance. It takes only one cycle for CA50 and IMEP to regain the steady state performance. In addition, there is no significant impact on the average errors of CA50 and IMEP. Controller performs well in tracking the step changes in CA50 and IMEP in the presence of disturbance input while meeting the set constraints.

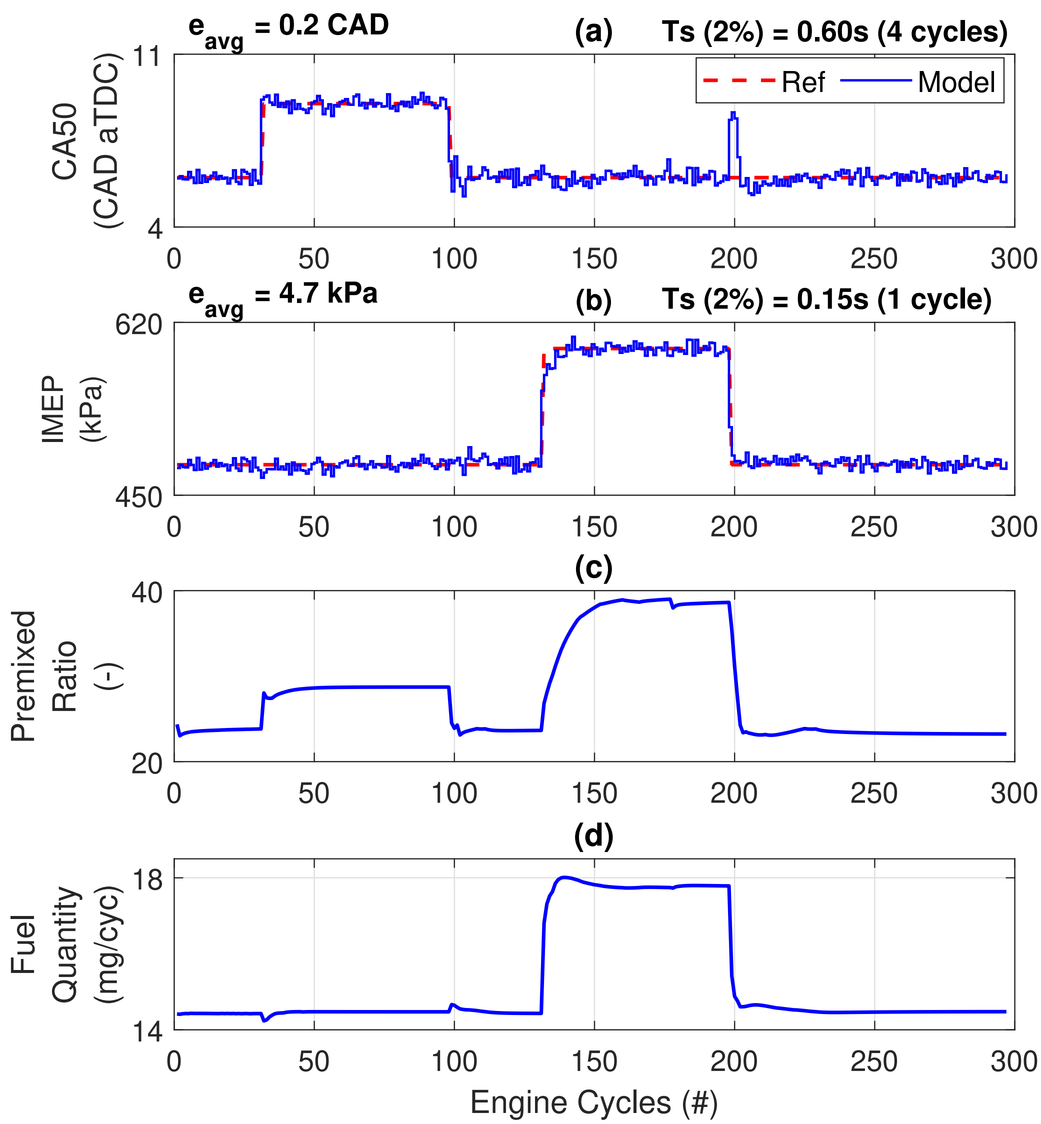

Figure 3.17: Simulation results of MIMO adaptive MPC for step changes in IMEP and CA50 (PPCI mode). Operating conditions: N = 800 RPM, Tman = 313 K, Pman = 96 kPa

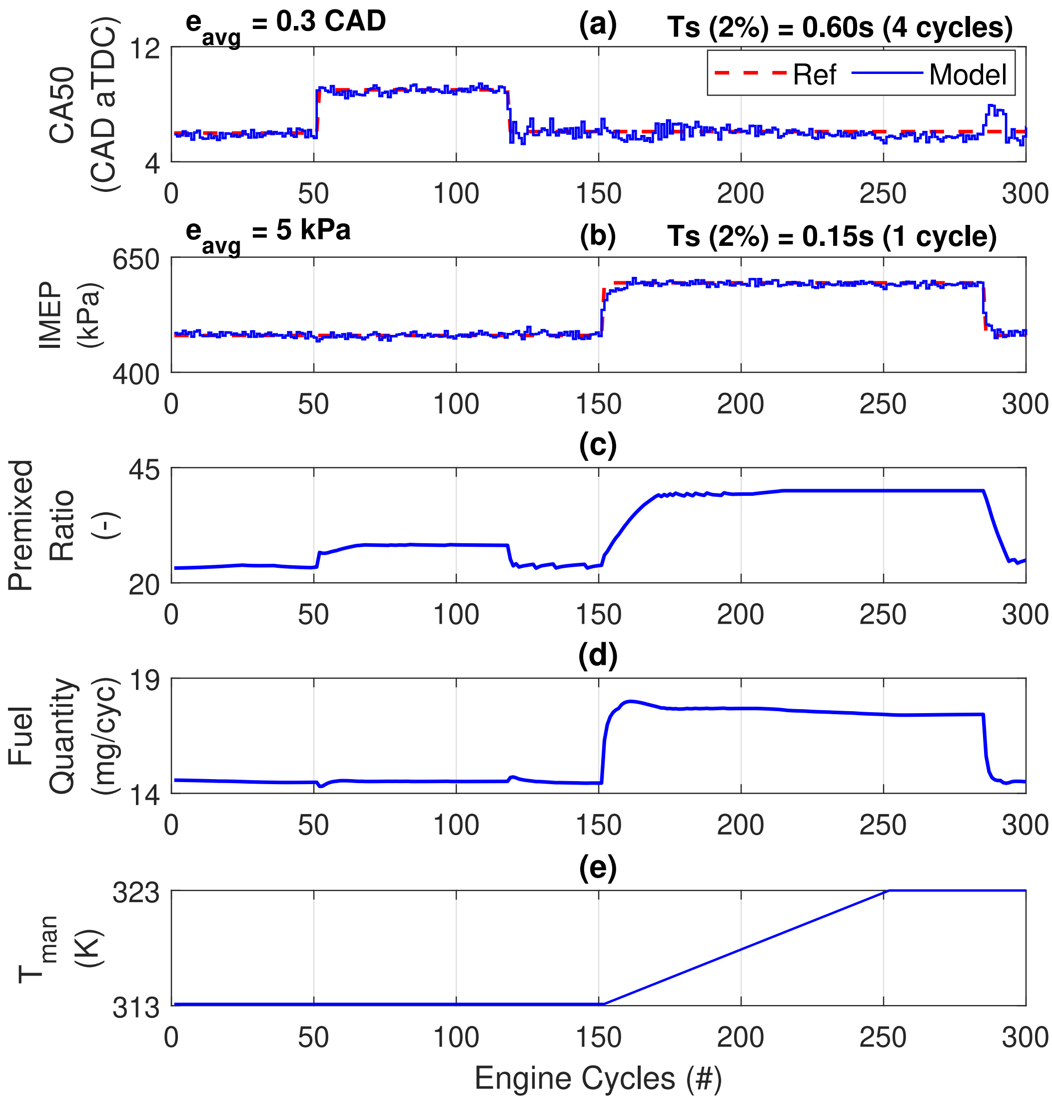

Figure 3.18: Disturbance Rejection of MIMO adaptive MPC by varying T_{man} (PPCI mode). Operating conditions: N = 800 RPM, Pman = 96 kPa

The performance of MPC controller for PPCI mode is validated against the step changes in both CA50 and IMEP. CA50 and IMEP both reach the targeted value in 1 engine cycle against a step change in CA50. However, it takes 4 engine cycles to attain the targeted value of CA50 when there is a step change of 120 kPa in required

IMEP. IMEP takes one engine cycle to gain the steady state for a step change. The controller performance for reference tracking of CA50 and IMEP is shown in Figure 3.17. The average errors in tracking CA50 and IMEP are 0.2 CAD and 4.7 kPa, respectively. The controller performance is also tested in the presence of measured disturbance. The disturbance rejection performance of the controller is shown in Figure 3.18. A ramp change in the intake air temperature and a step change in IMEP are provided simultaneously. The controller is able to reject the disturbance in one engine cycle while it is able to track the targeted CA50 and IMEP.

For RCCI mode, the MPC controller is tested for two different cases. In the first case, MPC controller is tested for the fuel with fixed PR of 20. The controller performance is validated in the presence of two step changes in IMEP at different time steps while tracking the combustion phasing (CA50) to its optimum value. IMEP reaches the target in 1 engine cycle while CA50 takes 2 engine cycles to attain the steady state value. The controller response and plant outputs are shown in Figure 3.19. The average errors in tracking CA50 and IMEP are 0.2 CAD and 5.2 kPa, respectively. In the second case, the MPC controller for RCCI is tested for different PR ranging from 5 to 45. For a step change of 5 in PR, CA50 takes one engine cycle to reach the optimum value while it takes 2 engine cycle for a step change of 10 in PR. However, IMEP regains the reference tracking in 1 engine cycle for both the step changes of 5 and 10 in PR. In addition, a step change of 200 kPa in IMEP is provided to test the controller performance for a range of PR. The controller is capable of tracking CA50

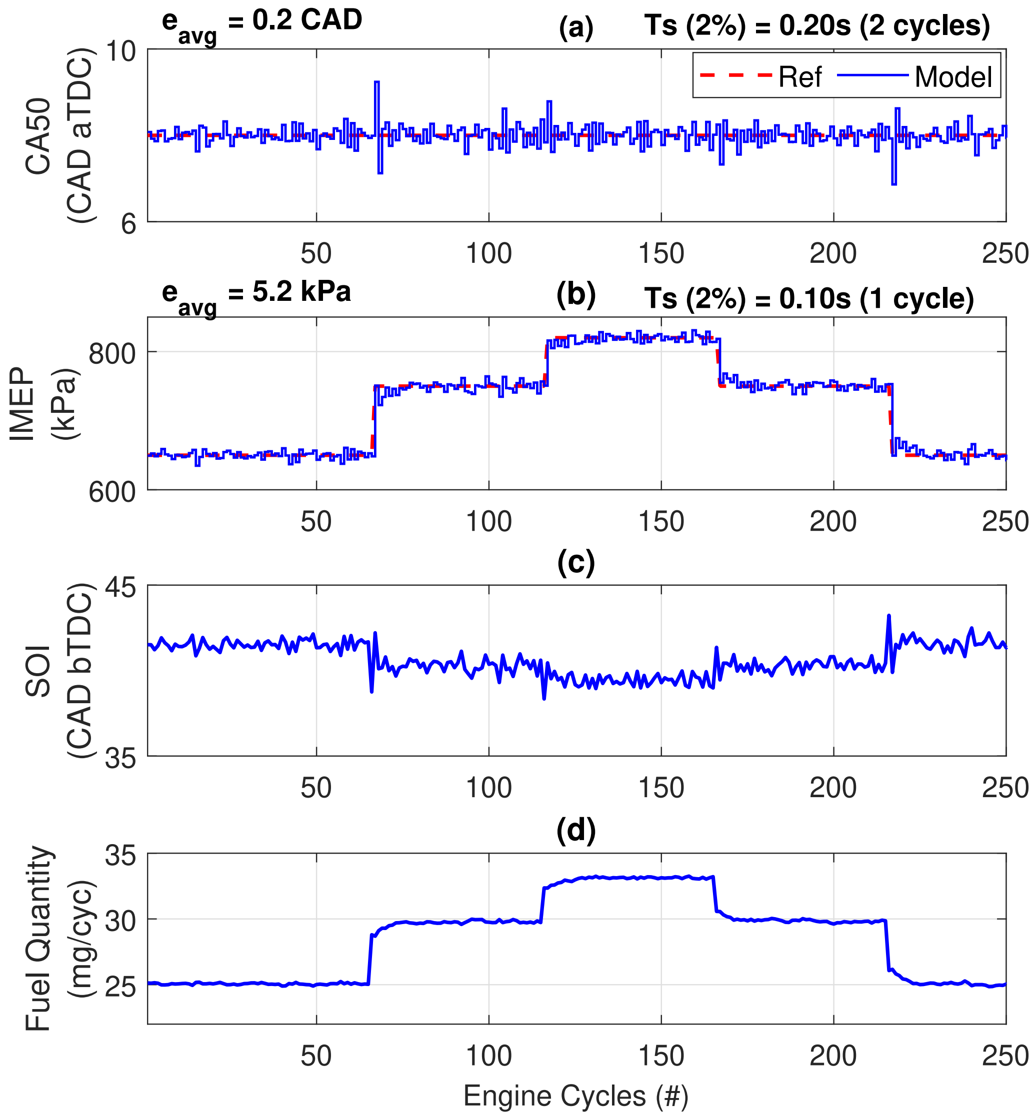

Figure 3.19: Simulation results of MIMO MPC for step changes in IMEP and CA50 (RCCI mode). Operating conditions: PR = 20, N = 1000 RPM, Tman = 333 K, Pman = 96 kPa

and IMEP without any performance degradation as shown in Figure 3.20.

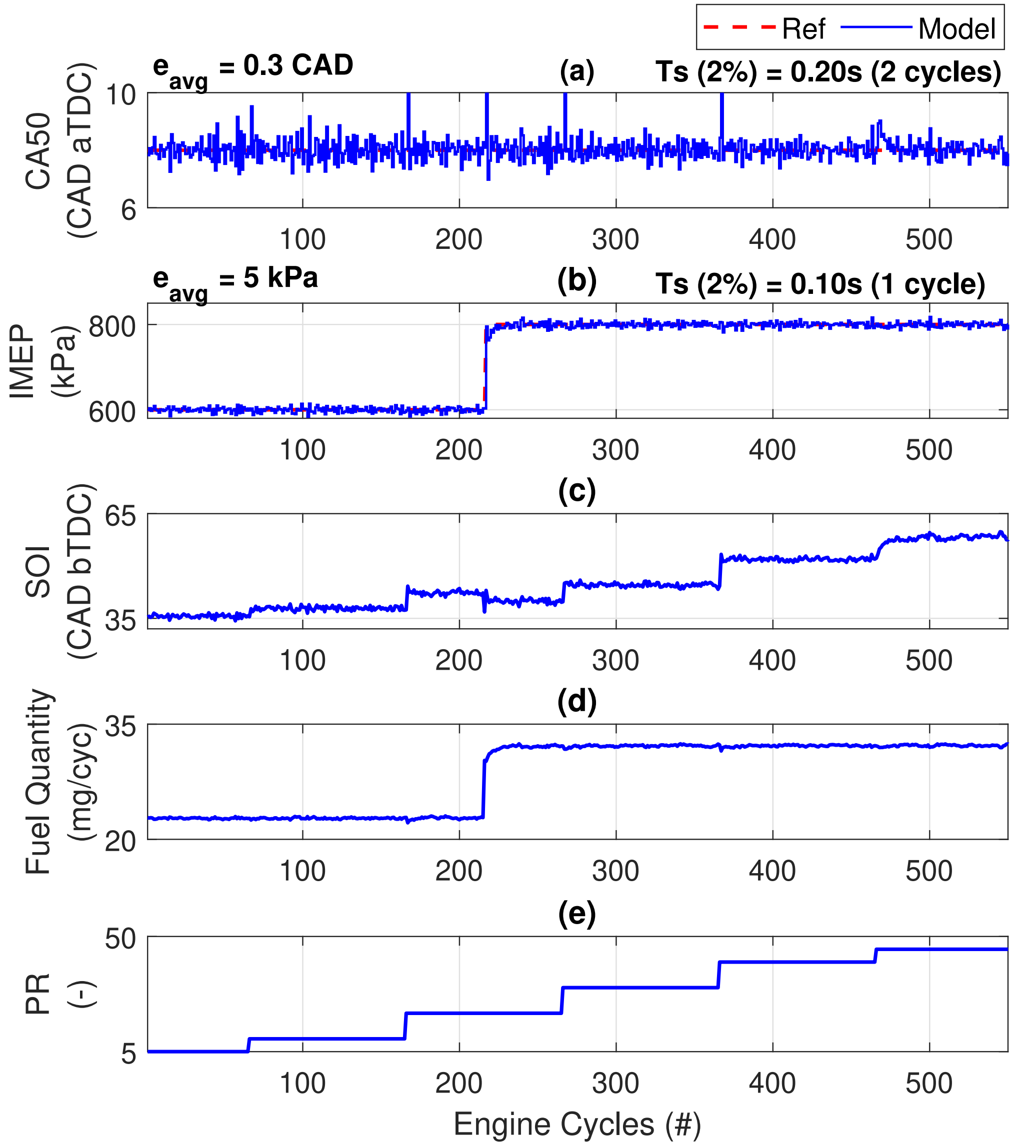

Figure 3.20: Simulation results of MIMO MPC for step changes in PR (RCCI mode). Operating conditions: N = 1000 RPM, Tman = 333K, Pman = 96 kPa

3.8 Summary and Conclusions

This paper presents model based control development of three common low temperature combustion (LTC) modes using dual fuels. The engine controller selects the best combustion regime based on the engine brake specific fuel consumption (BSFC) performance map. An independent combustion controller is developed for each mode which uses linear parameter varying (LPV) models to capture the system dynamics for achieving the non-linear LTC engine control. Major findings from this work for the tested conditions are:

- Discrete time control-oriented models (COMs) and LPV systems are developed as a function of dual fuel premixed ratio for each LTC mode. The steady state and transient validations show that the developed control oriented models are capable of predicting CA50 and IMEP on cycle-to-cycle basis with average errors less than 2 CAD and 37 kPa, respectively for each LTC modes.

- For HCCI mode, the developed adaptive model predictive controller (MPC) uses premixed ratio and fuel quantity to control CA50 and IMEP. Moreover, premixed ratio is also used as a scheduling variable for the LPV system. Results show that the adaptive MPC with LPV system is able to track CA50 and IMEP with average errors of 0.5 CAD and 7.6 kPa, respectively. The controller is also tested for disturbance rejection properties.

- For PPCI mode, CA50 is controlled by adjusting premixed ratio while IMEP is controlled by adjusting fuel quantity. The adaptive MPC controller uses PR as scheduling variable for the LPV models. The controller performs well in the presence of measured disturbance. The average errors in CA50 and IMEP tracking are 0.1 CAD and 1.7 kPa, respectively.

- For RCCI mode, start of injection is used to control CA50 while fuel quantity is used for IMEP control. Premixed ratio is used as a scheduling variable to develop the LPV models. The adaptive MPC is able to track CA50 and IMEP with average errors of 0.2 CAD and 5.2 kPa, respectively.

- The MPC controllers developed for each mode are capable of providing good performance in controlling combustion phasing for any premixed ratio of fuels ranging between 0 and 50. This is because the LPV models with premixed ratio as the scheduling parameter improves the performance of the controller by capturing the system dynamics. A single MPC controller with an LPV plant model works well for a wide range of PR both with and without disturbance inputs.

Overall, developed MPC controllers show promising results for reference tracking of CA50 and IMEP for the dual fuel application in the LTC modes.

Chapter 4

Data-Driven Modeling and Control of Cyclic Variability of an Engine Operating in LTC Modes[1]

4.1 Abstract

Combustion cyclic variability in an internal combustion engine leads to cyclic variations in the engine torque output and emissions. Combustion cyclic variability is often characterized by coefficient of variation of indicated mean effective pressure

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(COV_{IMEP}) that is used as an indicator of combustion stability. These cyclic variations are inevitable and cannot be completely eliminated but can be controlled to allow stable engine operation. This work focuses on control oriented modeling of COV_{IMEP} to limit engine cyclic variations in low temperature combustion (LTC) modes. COV_{IMEP} is generally stochastic in nature; thus, a data-driven approach is used to develop a predictive model of COV_{IMEP} for Homogeneous Charge Compression Ignition (HCCI) and Reactivity Controlled Compression Ignition (RRCI) modes. This work presents the development of a cycle-by-cycle model predictive controller for a 2.0 liter multi-mode LTC engine. Physics-based control-oriented models for combustion phasing (CA50) and IMEP are augmented with the new data-driven COV_{IMEP} model to limit the cyclic variations below 3% for HCCI and RCCI modes. These models are then used to design closed-loop non-linear model predictive controllers to control CA50 and IMEP while constraining COV_{IMEP} to ensure stable engine operation for varying load conditions.

4.2 Introduction

Advanced combustion modes including low temperature combustion offers high thermal efficiency and low engine-out emissions. Premixed mixtures in LTC modes reduce the local fuel rich zones which prevents very high peak in-cylinder gas temperatures that in turn, helps in restricting oxides of nitrogen (NOx) formation. The LTC engines can offer thermal efficiency comparable to the conventional diesel engines [107] and produce NOx, and PM emissions substantially less than conventional diesel engines [108]. This work focuses on the two common LTC modes i.e.; homogeneous charge compression ignition (HCCI) and reactivity controlled compression ignition (RCCI).

Combustion control in the LTC modes is important to avoid knock and too high maximum pressure rise rate, partial burns and misfires. Combustion phasing CA50 and indicated mean effective pressure IMEP are the common controlled parameters in the LTC modes [5, 24, 39]. In addition, combustion in LTC modes is mainly restrained by high cyclic variations and maximum pressure rise rate. Large cyclic variations are usually observed at low loads in LTC modes [19]. That is why, peak pressure [35], peak pressure rise rate [26] and cyclic variability [21, 38] are important control parameters that need to be monitored for safe and stable engine operation.

Combustion variations on cycle-to-cycle basis are indicated by the coefficient of variation of indicated mean effective pressure (COV_{IMEP}). High cyclic variations in IMEP result in engine speed fluctuations and affect the noise, vibration and harshness (NVH) performance of a vehicle [87]. Moreover, cyclic variability increases engine-out emissions [86]. In addition, desirable ultra-lean engine operations with high thermal efficiency are prone to high cyclic variations. Therefore, it is important to minimize combustion cyclic variations to achieve stable combustion in order to allow the maximum thermal efficiency, and lower engine-out emissions. This study focuses on model based control of HCCI and RCCI modes by constraining COV_{IMEP} to limit the cyclic variations in the combustion to ensure stable engine operation.

Several studies have been conducted to evaluate the parameters responsible for these cyclic variations in LTC engines. Peak pressure, location of peak pressure, maximum pressure rise rate, location of maximum pressure rise rate, combustion phasing and burn duration are commonly used to quantify the cyclic variations [137]. Jia et. al. studied the cyclic variations in the LTC modes with main focus on dual fuel RCCI combustion. The study suggested that cyclic variations in RCCI combustion can be reduced by retarding the injection timing, increasing the injection pressure and using boosted intake pressure [91]. Low exhaust gas recirculation (EGR) rate, high equivalence ratio and high intake temperature provide lower cyclic variations in HCCI mode [89]. A study conducted on cyclic variations of combustion parameters for HCCI suggested that the cyclic variations increases by exceeding the research octane number (RON) of the test fuels beyond 40 [138].

Kalghatgi et. al. showed a linear regression model using CA50 and equivalence ratio (ϕ) to differentiate low and high cyclic variability for HCCI combustion [61]. Hellstrom et. al. developed proportional integral (PI) and linear quadratic Gaussian (LQG) controllers to regulate CA50 in order to reduce cyclic variability in HCCI engine operation [38]. In another study, CA50 was adjusted to ensure stable RCCI combustion and limiting COV_{IMEP} for varying load and speed conditions [21].

To the best of the authors' knowledge, this is the first study undertaken to develop a learning based engine cyclic variability classifier to create a predictive model and nonlinear MPC for LTC engines to control load and combustion phasing while stabilizing the engine combustion. This paper focuses on developing an approach to categorize stable and unstable combustion into different classes on the basis of the COV_{IMEP} using supervised learning algorithm for HCCI and RCCI modes. The contributions of this work include:

1. Development of a control oriented predictive model for COV_{IMEP} using supervised learning classification algorithm for HCCI and RCCI combustion modes;
2. Development of a nonlinear MPC for an HCCI engine regulating CA50 to ensure stable combustion while delivering requested IMEP;
3. Development of a nonlinear MPC for an RCCI engine to control CA50, IMEP and constraining COV_{IMEP}.

The organization of this paper is as follows: Section 2 covers the experimental setup, engine specifications and the range of experimental data used in this study. The data driven modelling of COV_{IMEP} for HCCI and RCCI modes is explained in Section 3. In Section 4, nonlinear model predictive controller development is described. The results are presented in Section 5. Section 6 summarizes the major findings of this work.

4.3 Experimental Setup and Data

A GM 2.0L, 4-cylinder gasoline direct injection EcoTec engine coupled with a 460hp AC dynamometer is used in this study. The original engine is modified to include two port-fuel injection (PFI) systems and one direct injection (DI) system, as shown in Fig. 3.3. The engine is run at wide open throttle under naturally aspirated conditions without external exhaust gas recirculation. An air heater is used to pre-heat the intake air to the desired temperature. In-cylinder gas pressure is measured with a resolution of 1 CAD using PCB piezoelectric pressure transducers. A dSPACE MicroAutoBox (MABX) is used as the engine control unit. A Xilinx Spartan-6 field propgrammable gate array (FPGA) is used for the real time feedback of combustion parameters.

The LTC modes are achieved in this engine by adjusting engine control variables and using two fuels including n-heptane and iso-octane. In HCCI mode, both iso-octane and n-heptane are injected during the exhaust stroke of the previous cycle via two PFI systems. While in RCCI mode, iso-octane is injected during intake stroke via PFI and n-heptane is directly injected during the compression stroke. For HCCI and RCCI combustion modes, intake air temperature (IAT), total fuel quantity (FQ) and the premixed ratio (PR) of two fuels are varied. Start of injection (SOI) timing of n-heptane is also varied in RCCI mode. The premixed ratio of the two fuels is calculated using (5.1):

$$PR = \frac{\mathrm{m_{iso}LHV_{iso}}}{\mathrm{m_{iso}LHV_{iso}} + \mathrm{m_{nhep}LHV_{nhep}}} \tag{4.1}$$

where, m_{iso} and m_{nhep} are the mass of injected iso-octane and n-heptane, respectively. $\mathrm{LHV_{iso}}$ and $\mathrm{LHV_{nhep}}$ are the lower heating values of iso-octane and n-heptane, respectively.

Operating conditions of the engine data used in this study are shown in Table 5.1. These include 210 steady state HCCI operating points and 300 steady state RCCI operating points.

Table 4.1
Range of experimental data used in this paper for developing control models for HCCI and RCCI modes

Parameters	**HCCI**	**RCCI**
IAT ($°C$)	40-100	40-80
$\mathrm{P_{man}}$ (kPa)	96	96
Engine Speed (RPM)	800-1600	800-2200
PR (-)	0-40	10-40
SOI (CAD bTDC)	450	20-60
Equivalence ratio, ϕ(-)	0.32-0.67	0.32-1.00

The engine data is recorded for 100 consecutive cycles at different steady state operating conditions. The $\mathrm{COV_{IMEP}}$ is a measure of variability in the IMEP and is defined as the ratio of standard deviation of IMEP to the mean of IMEP. It is calculated by:

$$COV_{IMEP}(\%) = \frac{\sigma_{IMEP}}{\mu_{IMEP}} \times 100. \tag{4.2}$$

where, μ_{IMEP} and σ_{IMEP} are the mean and standard deviation of IMEP, respectively.

The in-cylinder pressure data from all operating conditions are analyzed and combustion parameters are determined. Figure 4.1 shows in-cylinder pressure traces for 100 consecutive engine cycles running in HCCI mode. Figure 4.1 shows unstable combustion with partial burns and misfire in a number of the engine cycles for HCCI mode. This unstable combustion results in very high $\mathrm{COV_{IMEP}}$ of 10.8%.

High cyclic variations may occur due to slower burning cycles which result in reduced work output. In this work, a predictive model is developed to confine the engine cyclic variations below 3%.

4.4 Data-Driven Modeling of $\mathrm{COV_{IMEP}}$

In this work, machine learning classification is used to develop a model to predict engine combustion stability level based on $\mathrm{COV_{IMEP}}$. The data can be classified into three distinct classes based on $\mathrm{COV_{IMEP}}$ to indicate stable, semi-stable and unstable combustion. Each class is provided with combustion stability index (CSI) based on

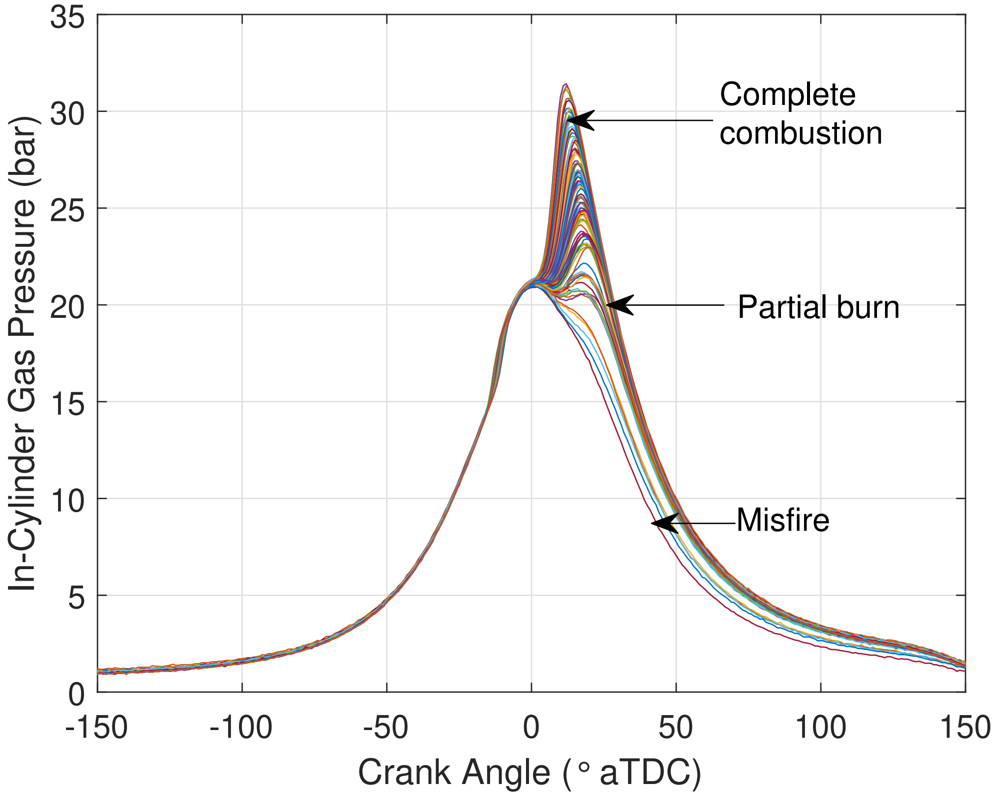

Figure 4.1: In-cylinder pressure traces for 100 consecutive steady-state cycles of HCCI engine operating at FQ = 11.2 (mg/cycle), PR = 20 (-), Tman = 353 (K); COV_{IMEP} = 10.8%, CSI = 3

COV_{IMEP}. The data points with $COV_{IMEP} \leq 3\%$ are grouped into class-I having CSI of 1. These data points showed stable and complete combustion as shown in Fig. 4.2. Class-II consists of data points with $3 < COV_{IMEP} \leq 5\%$ with CSI of 2. These include engine operation with some of the cycles have abnormal combustion (e.g., high MPRR or light knocking) as shown in Fig. 4.3. Depending on engine load, an engine can tolerate COV_{IMEP} by 5% without any major oscillations in torque delivery or vehicle driveability concerns. Therefore, class-II is considered semi-stable. The data points having $COV_{IMEP} > 5\%$ are grouped into class-III with CSI of 3 to represent unstable

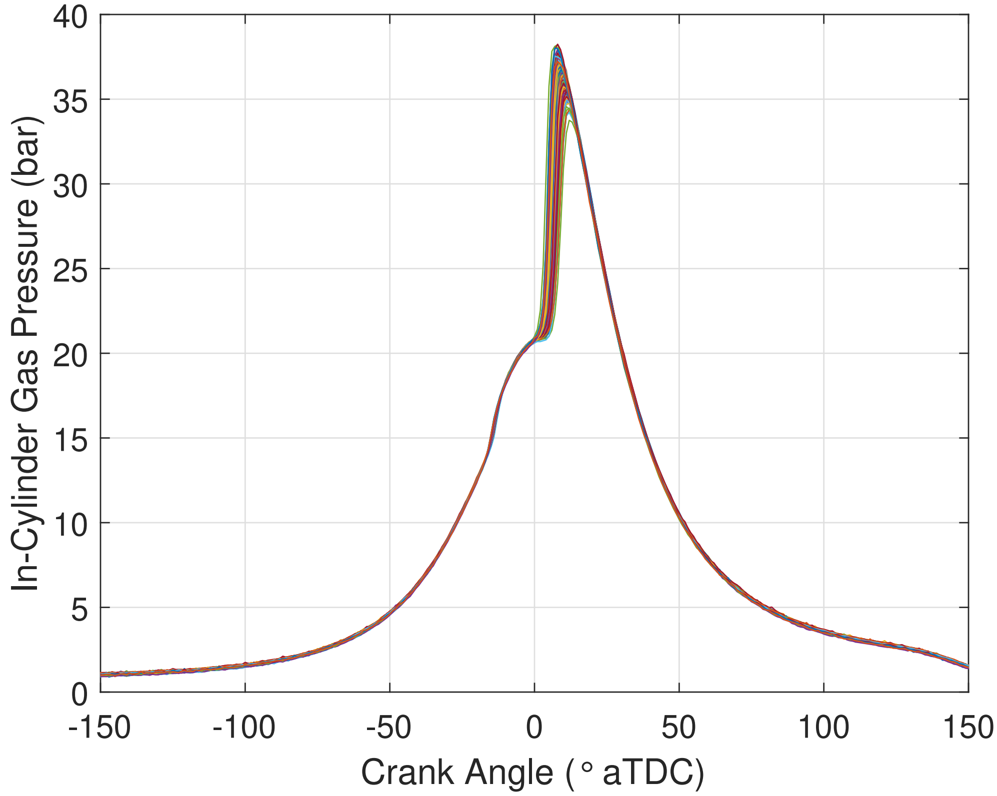

Figure 4.2: In-cylinder pressure traces for 100 consecutive steady-state cycles of HCCI engine operating at FQ = 12.7 (mg/cycle), PR = 40 (-), Tman = 373 (K); COV_{IMEP} = 0.71%, CSI = 1

combustion, see Fig. 4.1. Class-III contains some data points with misfire and/or partial burns. Partial burn usually occurs when the burning rate is sufficiently slow and combustion is not completed by the time exhaust valves open [139].

Classification is a supervised machine learning algorithm which categorizes the data into different classes. There are various algorithms which can be used for classification such as logistic regression, support vector machines (SVMs), neural networks (NN), Naive Bayes, K nearest neighbors (KNN), boosted decision trees and random decision

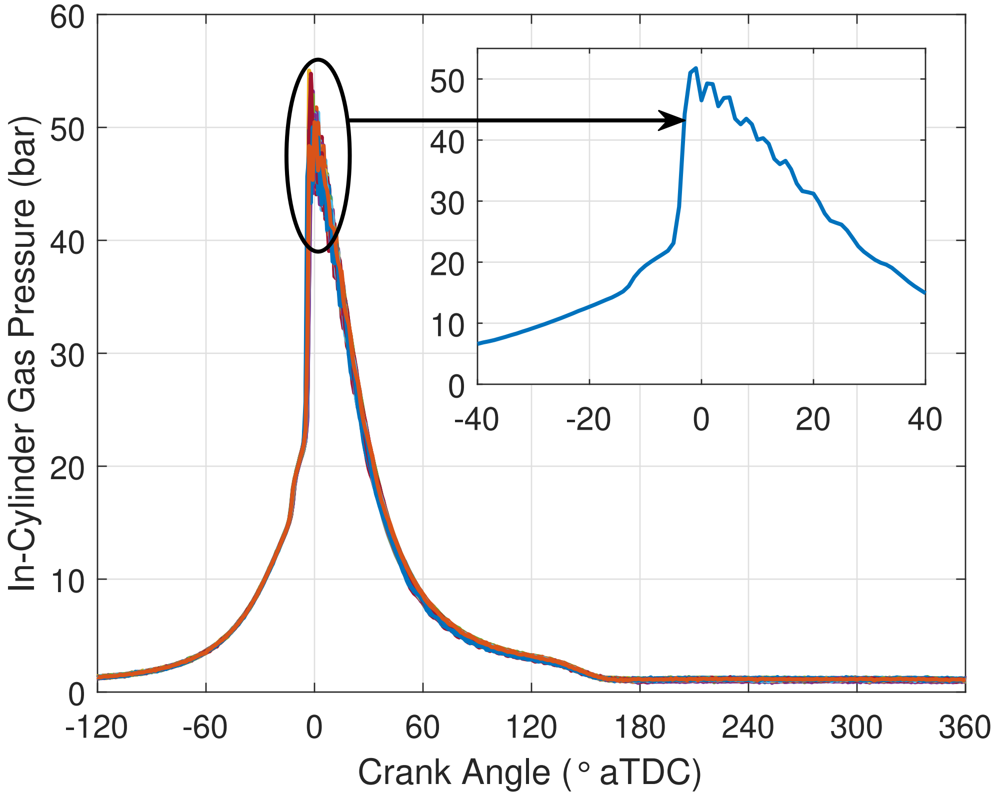

Figure 4.3: In-cylinder pressure traces for 100 consecutive steady-state cycles of HCCI engine operating at FQ = 18.2 (mg/cycle), PR = 0 (-), Tman = 313 (K); COV_{IMEP} = 4.6%, CSI = 2

forests. We investigated SVM, KNN, Naive Bayes and neural networks classifiers and their accuracy were compared. In this study, support vector machine (SVM) is used for multi-class classification based on providing the best prediction accuracy. SVM works well with small data sets [140]. SVM is a vector space based machine learning approach that maximizes the margin between two classes [141]. The COV_{IMEP} predictive modeling is formulated as a non-linear multi-class classification problem as the classes are linearly inseparable. SVM maps the data ($x_i \in R^p$) in the input space

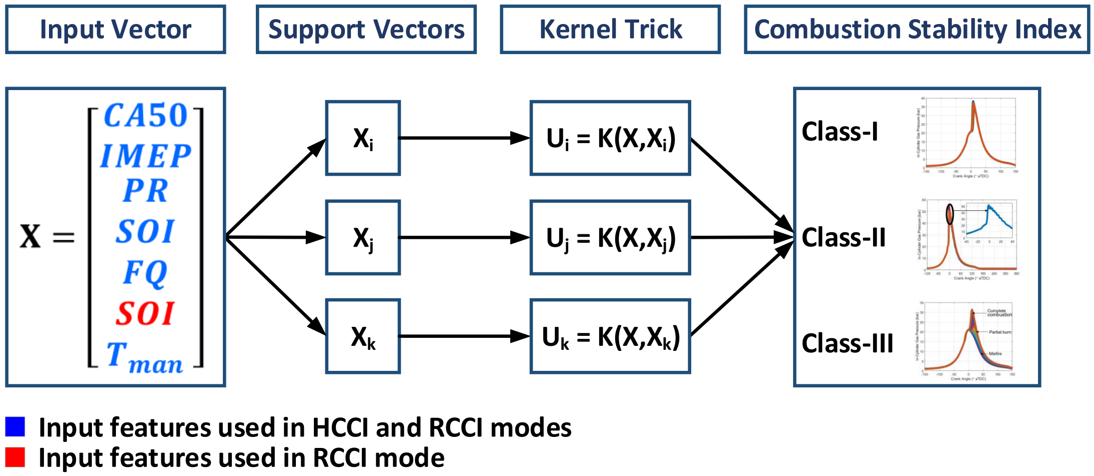

Figure 4.4: Classification of engine combustion stability using support vector machines for COV_{IMEP} data

(X) to a feature space F:

$$F = \{\phi(x) : x_i \in X\} \tag{4.3}$$

$$f(x) = \sum_{i=1}^{N} w_i \phi(x) + \beta_0 \tag{4.4}$$

The linearly inseparable data in the input space (X) can be linearly separated in the feature space (F) [142]. These linear boundaries provide better separation and translates into nonlinear boundaries in the input space (X) [143]. The classifier is given by:

$$G(x) = sign(f(x)) \tag{4.5}$$

Lagrange dual objective function is of the form:

$$L_D = max \sum_{i=1}^{N} \alpha_i - \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} \alpha_i \alpha_j y_i y_j (\phi(x_i), \phi(x_j)) \tag{4.6}$$

Subject to the constraints

$$\sum_j y_j \alpha_j = 0 \tag{4.7}$$

$$0 \leq \alpha_j \leq C \tag{4.8}$$

The dual optimization problem is solved by maximizing L_D using quadratic programming. The solution of the optimization problem is given by:

$$f(x) = \sum_{i=1}^{N} \alpha_i y_i (\phi(x), \phi(x_i)) + \beta_0 \tag{4.9}$$

where, α_i, β_0 and y_i are the Lagrange multipliers, bias and class labels, respectively. C is box constraint to limit the values of Lagrange multiplier.

$$y_i f(x_i) = 1 \tag{4.10}$$

The transformation to feature space (F) and computation of their corresponding inner product can be computationally expensive. Therefore, kernel trick is used to compute the inner products in the feature space without any transformation as shown in Fig. 4.4. This requires a kernel function that can be computed efficiently. Kernel function (K) is a function, such that for all $x_i, x_j \in X$

$$K(x_i, x_j) = \ (\phi(x_i), \phi(x_j)) \tag{4.11}$$

K should be a symmetric positive semi definite function. The commonly used nonlinear kernel functions in the SVM are polynomial (5.18), radial basis (Gaussian) (4.13) and sigmoid (4.14).

$$K(x_i, x_j) = (1 + (x_i, x_j))^d \tag{4.12}$$

$$K(x_i, x_j) = exp(-\gamma||x_i - x_j||^2 \tag{4.13}$$

$$K(x_i, x_j) = tanh(\kappa_1(x_i, x_j) + \kappa_2) \tag{4.14}$$

4.4.1 $\mathbf{COV_{IMEP}}$ Modeling for HCCI Mode

For HCCI, SVM is used to train the model for COV_{IMEP} classification using linear, polynomial and radial basis kernel functions. Combustion parameters including CA50, burn duration (BD), peak pressure (P_{max}), location of peak pressure (θ_{Pmax}), IMEP, maximum pressure rise rate (MPRR), location of maximum pressure rise rate (θ_{MPRR}), premixed ratio (PR), fuel quantity, intake air temperature and engine speed were initially used in developing COV_{IMEP} classifier. CA50 has a linear relationship with (θ_{Pmax}) and (θ_{MPRR}). P_{max}, MPRR and engine speed didn't improve the prediction accuracy of the model. Therefore, this study uses CA50, IMEP, premixed ratio, fuel quantity and intake air temperature as features to develop a control oriented model for the COV_{IMEP} for the HCCI mode as shown in Fig. 4.4. HCCI engine data for 210 different operating conditions are used for training and testing. 72% of data is used for training the model and the remaining 28% is used for testing. The data is standardized before training because of different scales of the predictor variables. Otherwise, the predictor variable with the largest range would dominate. The classification models are tuned by varying the kernel scale and box constraint (C). The choice of C is a trade-off between variance and bias. The models are trained using 10 fold cross validation approach to prevent over-fitting. Sequential minimal optimization is used as a solver for the optimization problem. The radial basis (Gaussian) kernel function (4.13) showed better results as compared to linear and cubic polynomial kernel functions.

The trained classification model consists of three classifiers, one for each class using one-vs-all classification technique. The confusion matrices for the training and test data sets are shown in Fig. 4.5a and 4.5b, respectively. Class-I and II show one misclassified data point for each class while class-III shows 100% accuracy. Overall, the developed model shows 96.5% accuracy in predicting engine CSI (combustion stability index).

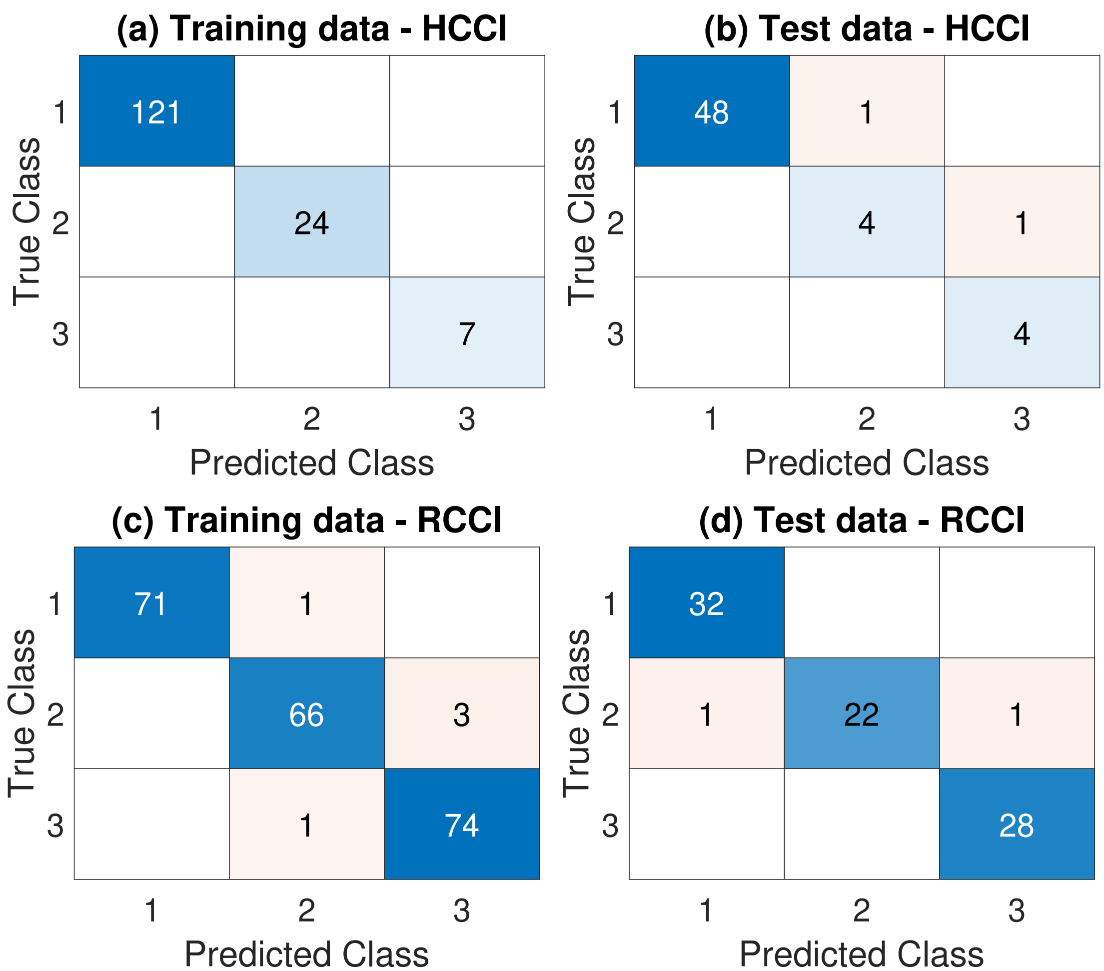

Figure 4.5: Confusion matrix for COV_{IMEP} classification for HCCI and RCCI modes

4.4.2 COV_{IMEP} Modeling for RCCI Mode

Similar to the HCCI mode, COV_{IMEP} classification model for RCCI mode is developed using SVM. The engine variables used in the RCCI mode are the start of injection timing of n-heptane, premixed ratio of fuels, intake air temperature and fuel quantity. Engine data at 300 different steady state operating conditions are used. Similar to the HCCI mode, the COV_{IMEP} for RCCI mode is also grouped into three distinct classes. The COV_{IMEP} prediction for the RCCI mode is modeled using CA50, IMEP, SOI, PR, fuel quantity and intake air temperature as predictors as shown in Fig. 4.4. Addition of P_{max}, MPRR and engine speed as predictors to the model did not improve the prediction accuracy.

72% of the data from three classes are used for training the model and remaining 28% are used for testing. Data standardization, 10 fold cross validation and one-vs-all classification technique are used to train the model. The kernel scale and box constraint are varied to tune the trained model. Three classifiers are trained by solving the objective function using sequential minimal optimization (SMO). The cubic kernel function (5.18) showed better results as compared to linear and Gaussian kernel functions.

Confusion matrices are plotted for both training data set and test data set as shown in Fig. 4.5c and Fig. 4.5d. The trained model has prediction accuracy of 98.7% for class-I, 96% for class-II and 98.5% for class-III. The trained model is validated for 80 different test conditions. The test data for class-I and III show 100% prediction accuracy. However class-II shows two misclassifications with prediction accuracy of 92.8%.

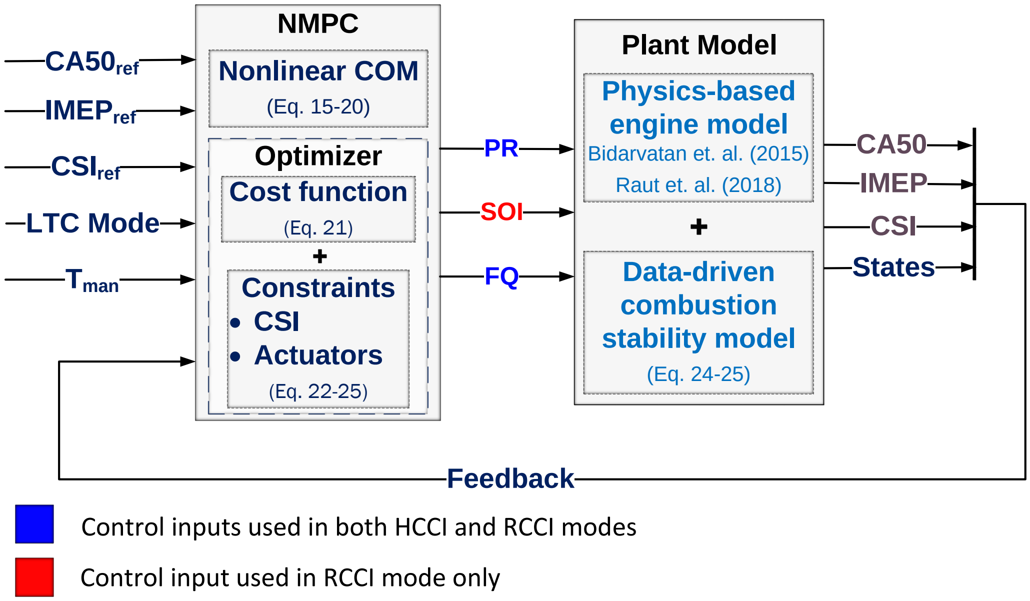

Figure 4.6: Schematic of nonlinear MPC and plant model

4.5 Non-Linear Model Predictive Control Development

To control cycle-by-cycle CA50 and IMEP, experimentally validated control oriented models (COMs) are used from our prior works [21, 31]. The objective of this work is to control CA50 and IMEP while ensuring combustion stability by limiting the COV_{IMEP} below 3%. For both HCCI and RCCI modes, COMs are augmented with data-driven models to constrain COV_{IMEP}. Crank angle for 50% fuel mass fraction burned CA50, temperature at start of combustion (T_{soc}), pressure at start of combustion (P_{soc}) and indicated mean effective pressure IMEP are chosen as the states of the MIMO nonlinear HCCI and RCCI COMs. The outputs for both HCCI and RCCI modes are CA50, IMEP and $\mathrm{COV_{IMEP}}$. The control structure is shown in Fig. 4.6.

The nonlinear COM of HCCI and RCCI modes can be represented as follows:

$$x(k+1) = f(x(k), u(k)) \tag{4.15}$$

$$y(k) = f(x(k) \tag{4.16}$$

where:

$$x = \begin{bmatrix} CA50 & T_{soc} & P_{soc} & IMEP \end{bmatrix}^T \tag{4.17}$$

$$u_{HCCI} = \begin{bmatrix} PR & FQ \end{bmatrix}^T \tag{4.18}$$

$$u_{RCCI} = \begin{bmatrix} SOI & FQ & PR \end{bmatrix}^T \tag{4.19}$$

$$y = \begin{bmatrix} CA50 & IMEP & COV_{IMEP} \end{bmatrix}^T \tag{4.20}$$

The developed COMs are used in a nonlinear model predictive control (NMPC) platform to control the LTC engine in HCCI and RCCI modes. The NMPC uses real-time iterative optimization of the plant model over a finite number of time steps and yields an optimized control strategy for a provided reference input. The first element of the optimal control sequence is provided as a feedback control for the next sampling interval. The prediction and control horizons for both HCCI and RCCI modes are chosen to be 5 and 3 engine cycles, respectively. The cost function is designed by penalizing the control efforts and least square error of reference tracking as shown in (4.21)

$$J = \sum_{k=1}^{N} \frac{1}{2}(Y_k - Rs)^T Q (Y_k - Rs) + U_k^T R U_k \tag{4.21}$$

subject to the constraints on $\mathrm{COV_{IMEP}}$ and actuators limits

$$h(x(k), u(k)) : CSI - 1 = 0 \tag{4.22}$$

$$A_{cons} U \leq B_{cons} \tag{4.23}$$

Combustion stability index (CSI) is used to specify the classes that is based on $\mathrm{COV_{IMEP}}$. Constraint h(x(k),u(k)) is a nonlinear equality constraint on $\mathrm{COV_{IMEP}}$ which is given by (4.24) and (4.25) for HCCI and RCCI modes, respectively.

$$CSI_{HCCI} = h_{HCCI}(x(k), u_{HCCI}(k)) \tag{4.24}$$

$$CSI_{RCCI} = h_{RCCI}(x(k), u_{RCCI}(k)) \tag{4.25}$$

Rs is the reference signal for CA50 and IMEP available for next 5 time steps.

$$Rs = [CA50_{ref} \quad IMEP_{ref}]^T \tag{4.26}$$

Q and R are the tuning weights. Q is a positive semi definite diagonal matrix while

R is positive definite diagonal matrix.

$$A = \begin{bmatrix} -I_{10\times10} \\ \\ I_{10\times10} \end{bmatrix}; \quad B = \begin{bmatrix} U_{min} + u(k_i - 1) \\ \\ U_{max} - u(k_i - 1) \end{bmatrix} \tag{4.27}$$

This nonlinear programming problem (NLP) is solved in Matlab by using "fmincon" command and specifying sequential quadratic programming (SQP) algorithm. SQP solves this minimization problem with an active nonlinear constraint. SQP is an iterative approach to search for a local optimal solution [144]. The QP subproblem is formulated to account for the local properties of the NLP for each iteration step using quasi-Newton method. The subproblem is of the following form:

$$min \; \nabla J^T_{(x_k,u_0)} \Delta U + \frac{1}{2} \Delta U^T H \Delta U \tag{4.28}$$

over $\Delta U \in R^n$

subject to

$$h(x_k, u_0) + \nabla h(x_k, u_0)^T \Delta U = 0 \tag{4.29}$$

$$g(x_k, u_0) + \nabla g(x_k, u_0)^T \Delta U \leq 0 \tag{4.30}$$

The solution of this subproblem is used to form a new iteration.

$$U(j+1) = U(j) + \alpha \Delta U(k) \tag{4.31}$$

where, α is a scale factor that determines the length of the search step in direction of ΔU. α is determined by line search approach subject to the decrease in original NLP merit function.

H is the PD Hessian matrix, computed by taking the second derivative of J(x(k),u(k)) w.r.t U

$$H = 2(\frac{\delta^2 Y}{\delta U^2}|_{(x(k),u_0)})Q(Y - Rs) + 2(\frac{\delta Y}{\delta U}|_{(x(k),u_0)})^T Q(\frac{\delta Y}{\delta U}|_{(x(k),u_0)}) \tag{4.32}$$

4.6 Results and Discussions

4.6.1 Results for RCCI Mode

In RCCI, there are three control knobs available to control combustion. CA50 can be controlled by adjusting either SOI or PR. SOI is used as manipulated variable to control CA50 while premixed ratio is adjusted to provide stable combustion. Fuel quantity is used to control IMEP. Constraint on COV_{IMEP} is added along with the actuator constraints. Figures 4.7 and 4.8 show the controller performance with and without constraint on COV_{IMEP}. During first 300 cycles, the controller is capable of tracking CA50 and IMEP but the optimal solution lies in the region of unstable

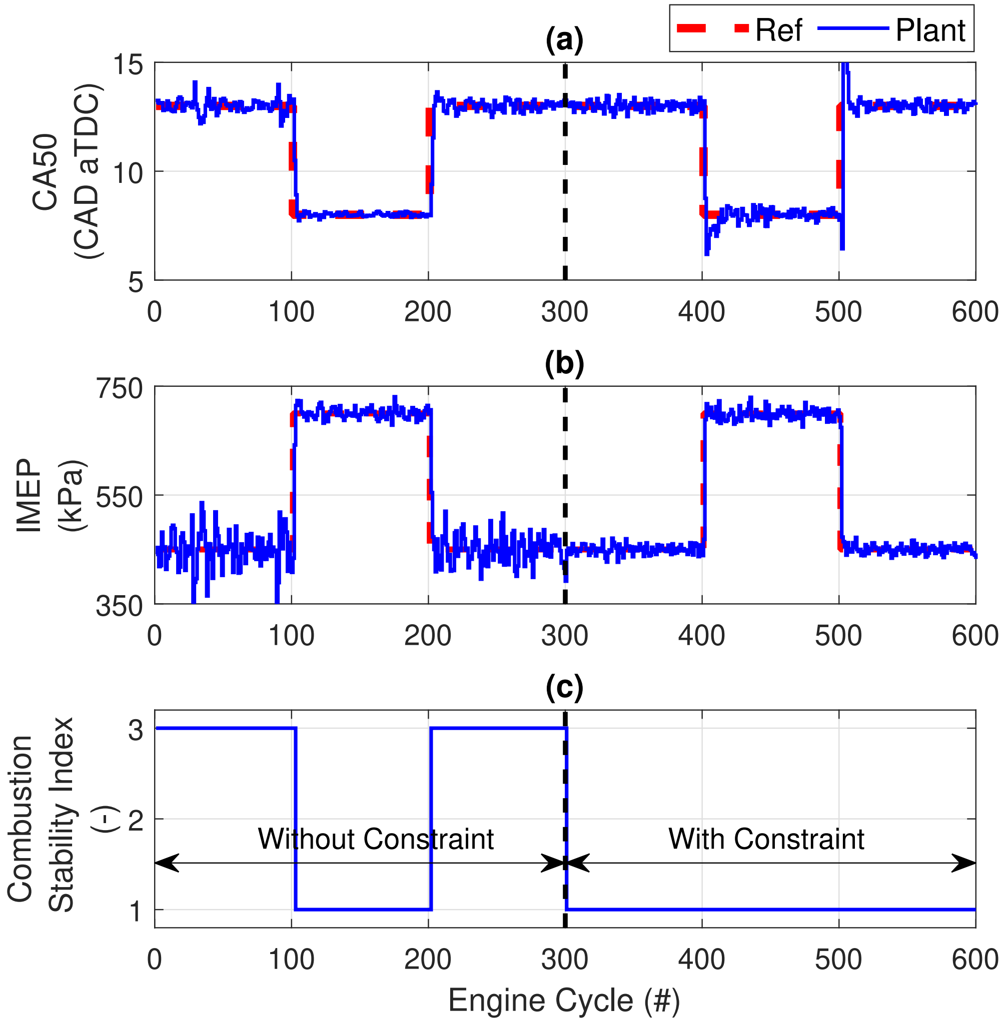

Figure 4.7: Controller response for reference tracking of CA50 and IMEP with and without constraint on COV_{IMEP} for RCCI mode. Combustion stability index of 1, 2 and 3 indicates $COV_{IMEP} \leq 3\%$, $3 < COV_{IMEP} \leq 5\%$ and $COV_{IMEP} > 5\%$, respectively.

combustion as the constraint on COV_{IMEP} is inactive. However, when the constraint on COV_{IMEP} is activated, the controller adjusts the premixed ratio while tracking CA50 and IMEP to provide an optimal solution in the region of stable combustion, as it can be seen in Fig. 4.7 during 300-600 cycles. Moreover, the controller is capable of reference tracking CA50 and IMEP with settling time of one engine cycle.

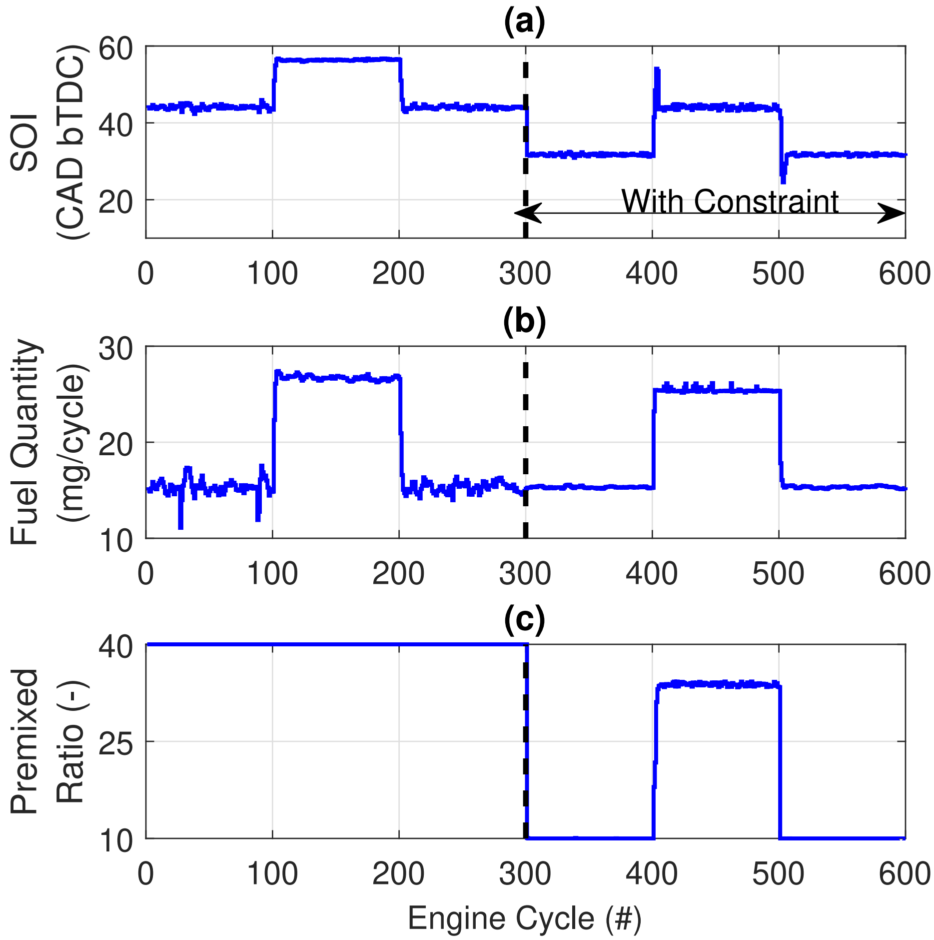

Figure 4.8: Control inputs of the NMPC for the results in Fig. 4.7

4.6.2 Results for HCCI Mode

Nonlinear MPC controller is implemented in Matlab for the reference tracking of CA50 and IMEP while constraining COV_{IMEP} for HCCI mode. The outputs and states are computed using engine plant model and provided as feedback to the controller. In HCCI mode, premixed ratio, fuel quantity and manifold temperature are the available control actuators. Manifold temperature shows very slow response; thus, it cannot be used to control the parameters on cycle-to-cycle basis. PR is used as manipulated variable to control CA50, and IMEP is controlled by adjusting the fuel quantity.

Moreover, COV_{IMEP} model is added to the plant model to predict the combustion stability and to provide feedback to the controller. Figures 4.9 and 4.10 show the controller response for tracking CA50 and IMEP with and without constraint on COV_{IMEP}. For the first 100 cycles, when the IMEP is 250 kPa and CA50 is 13 CAD (aTDC), the model predicts unstable combustion as the combustion stability index is 3. This means that the COV_{IMEP} for these 100 cycles is greater than 5%. For the next 100 cycles, the combustion is stable as CSI is 1 (COV_{IMEP} <3%). However, the controller shows good performance for reference tracking of CA50 and IMEP. It takes one engine cycle to reach the target IMEP while CA50 takes four engine cycles to reach the reference value. For cycles 301-600, the constraint on COV_{IMEP} is activated. The controller tracks IMEP well but it adjusts CA50 such that the combustion stability index remains 1. As it can be seen in Fig. 4.9, when the constraint on COV_{IMEP} becomes active, premixed ratio regulates CA50 to avoid constraint violation. Hence, COV_{IMEP} stays below 3% ensuring stable combustion.

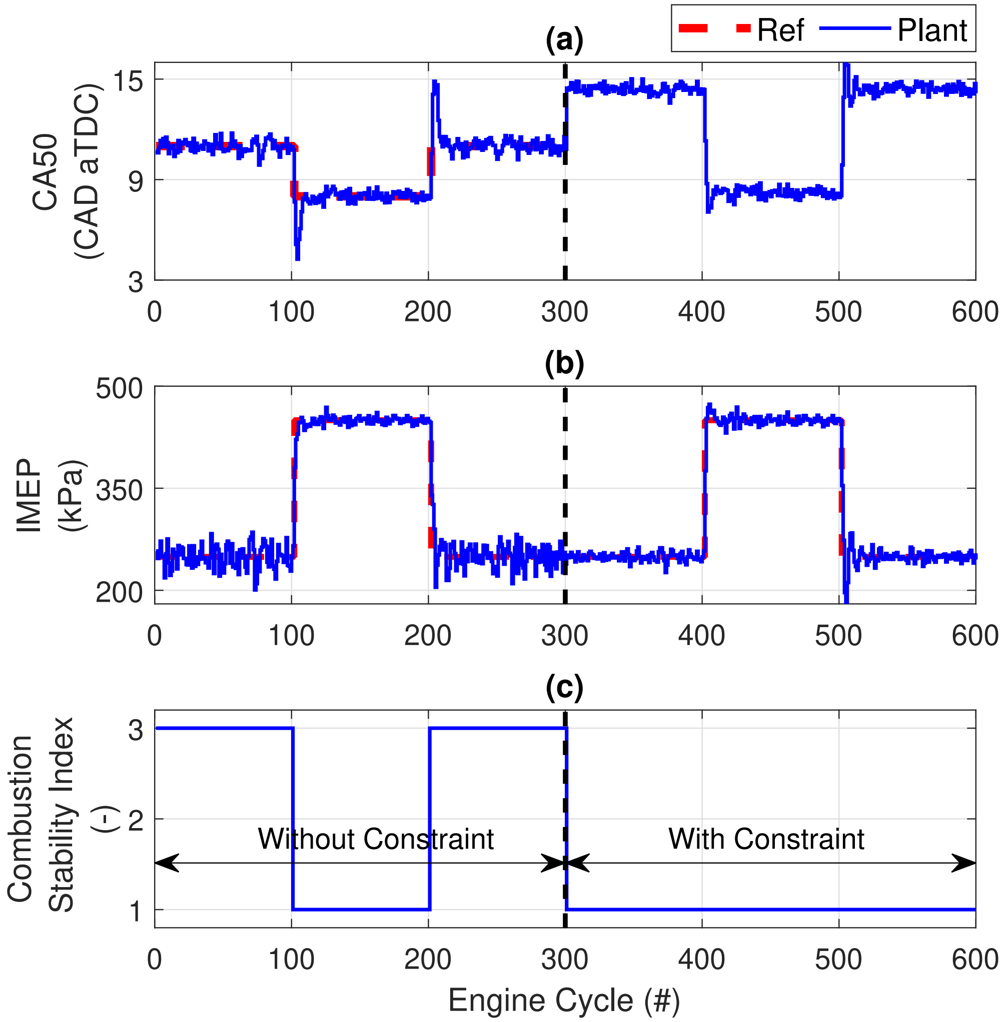

Figure 4.9: Simulation results for reference tracking of CA50 and IMEP with and without constraint on COV_{IMEP} for HCCI mode. Combustion stability index of 1, 2 and 3 indicates $COV_{IMEP} \leq 3\%$, $3 < COV_{IMEP} \leq 5\%$ and $COV_{IMEP} > 5\%$, respectively.

4.7 Conclusions

In this work, a data-driven predictive model of combustion stability classification is developed for the low temperature combustion (LTC) modes in a 2-liter 4-cylinder

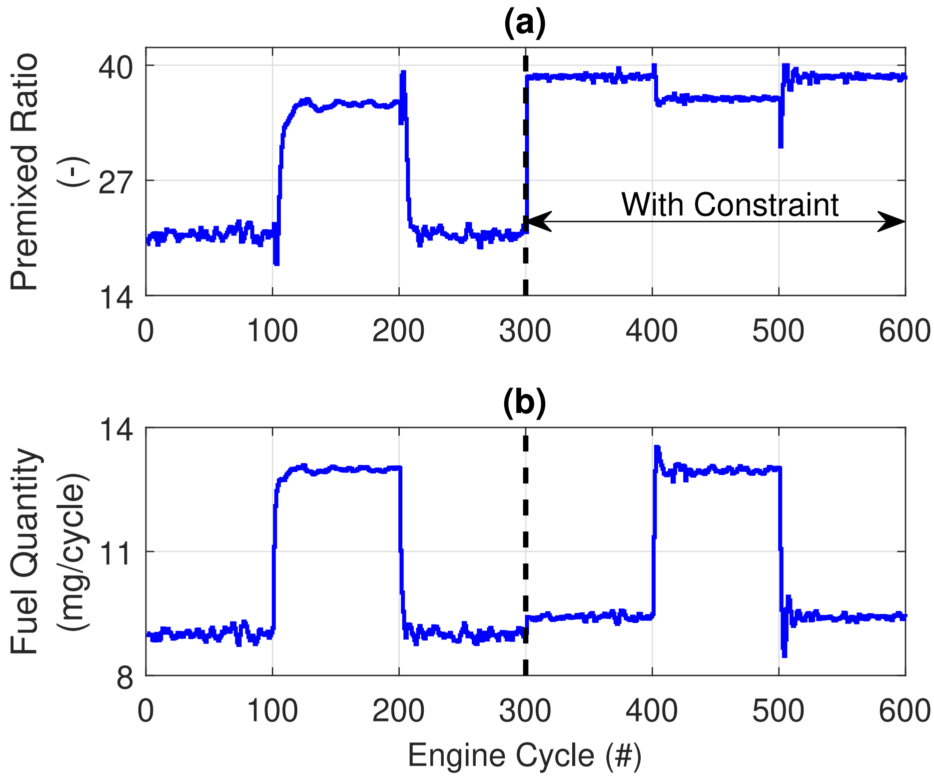

Figure 4.10: Control inputs of the NMPC for the results in Fig. 4.9

engine. The engine data at 510 operating conditions were used to develop and assess the model. Support vector machine (SVM) is used to classify COV_{IMEP} and create a predictive model of the engine combustion stability. CA50, IMEP, premixed ratio, fuel quantity, intake manifold temperature and start of injection (for RCCI only) are used as predictors to classify COV_{IMEP} into three different classes including class-I if $COV_{IMEP} \leq 3\%$, class-II if $3 < COV_{IMEP} \leq 5\%$ and class-III if $COV_{IMEP} > 5\%$. Experimental data with $COV_{IMEP} > 5\%$ mostly showed either partial burn or misfire. The developed combustion stability models for both LTC modes show more than 97% prediction accuracy.

Using the combustion stability models, closed-loop nonlinear model predictive controllers are designed for HCCI and RCCI combustion modes. The optimal control action is determined using SQP algorithm. The nonlinear MPC controller for HCCI is capable of tracking CA50 and IMEP in the absence of constraint on COV_{IMEP} and regulates CA50 whenever needed for keeping the combustion stable. For the RCCI mode, SOI and fuel quantity are used to control CA50 and IMEP. In the presence of active constraint on COV_{IMEP}, the designed controller adjusts premixed ratio to ensure stable combustion during engine load changes. These allow the multi-mode LTC engine to run stably in both HCCI and RCCI modes.

Chapter 5

Machine learning approaches for identification of heat release shapes in a low temperature combustion engine for control applications

5.1 Abstract

This paper presents application of machine learning classification algorithms to identify the type of heat release for combustion control in a low temperature combustion

engine for optimal engine operation. Low temperature combustion (LTC) is among advanced combustion technologies which produce low nitrogen oxides (NOx) and soot emissions compared to the conventional combustion engines and offers high thermal efficiency. LTC regimes are susceptible to high in-cylinder pressure rise rates which lie outside the engine safe zone. This limits the operating range of LTC engine. However, multi-regime controlled combustion can provide extended operating range of the high-efficiency LTC engine. Thus, it is imperative to understand and identify the different shapes of heat release traces to control these complex engines. This paper studies machine learning approaches for identification and classification of different heat release shapes for the engine operation with multiple combustion regimes. Experimental data from an LTC engine was collected and the in-cylinder pressure measurements were used to calculate heat release rate (HRR). The heat release rate traces for over six hundred engine operating conditions were analyzed and classified into three regimes based on the different shapes as a function of fractions of early and late heat release. Supervised (i.e., Decision Tree, K-Nearest Neighbors and Support Vector Machines) and unsupervised (i.e., Kmeans clustering) machine learning approaches were used to develop algorithms to segregate these regimes. Kmeans clustering was not successful in classifying the HRR types. Among different supervised machine learning techniques, Support Vector Machines was found as the best method with an overall classifier prediction accuracy of 92.4% for identifying the heat release shapes. Furthermore, three classifiers were also trained based on the combustion performance parameters which can be used as scheduling variables for developing predictive models of the multi-mode LTC engine for real-time control. The classifiers trained by using K-Nearest Neighbors algorithm showed 97% prediction accuracy. These classifiers are then used to achieve the simultaneous reference tracking of combustion phasing (CA50) and indicated mean effective pressure (IMEP) while constraining maximum pressure rise rate (MPRR) below 8 bar/CAD using LPV-MPC framework.

5.2 Introduction

Advanced combustion strategies including low temperature combustion (LTC) modes offer high thermal efficiency and low engine-out emissions. Light duty vehicles (LDVs) contribute to 52% of the fuel consumed in the transportation sector in the U.S. [45]. Moreover, the U.S. Energy Information Administration predicted that the new light duty vehicles running solely on internal combustion engines (ICEs) will still be contributing to 81% of the market share by 2050 [45]. Therefore, it is imperative to optimize the advanced ICE combustion strategies which would not only improve the fuel economy of LDVs but also help in meeting the stringent emission legislation. Because of the advantages over the conventional spark ignition (SI) and compression ignition (CI) engines, LTC strategies have been the focus of research for over the last two decades [145].

LTC modes offer thermal efficiency comparable to conventional diesel engines [107] while producing substantially lower NOx and particulate matter (PM) emissions [108]. The common LTC modes are homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), partially premixed charge compression ignition (PPCI), and reactivity controlled compression ignition (RCCI). Different strategies have been employed to realize LTC modes such as variable valve actuation [4, 111], variable compression ratio [5], preheating the intake air [69], fast thermal management [5], exhaust re-compression [146], exhaust gas recirculation (EGR) [69], dual fuels [107], and split fuel injection strategies [4, 117].

LTC modes encounter challenges of combustion timing control, high maximum pressure rise rate (MPRR) and high cyclic variations [61]. These challenges can be addressed by developing a model-based controller framework for the LTC modes to ensure safe engine operation. Model-based controllers require control-oriented models (COMs) for the LTC engine. LTC engine can be modeled as white-box models, black-box models or grey-box models. Physics-based mathematical models are categorized as white-box models. These dynamic engine models require separate calibrations for each LTC mode and are often computationally expensive for the real-time cycle-to-cycle engine combustion control. Black-box models are essentially data-driven models. The common black-box approaches used to model LTC modes found in the literature are system identification [25, 26] and machine learning (ML) algorithms [41, 44, 83, 147, 148]. These models do not require the detailed physics of the system inherent to the mathematical models. Therefore, they are simpler as compared to white-box models. System identification can either be based on output information only e.g., frequency domain decomposition, or includes input as well as output information of the system. e.g., eigensystem realization. However, using both input and output information provides better model accuracy. ML algorithms are data-driven regression or classification models. Grey-box modelling approach combines the white-box and black box models together to represent an engine model [83]. ML algorithms require sufficient and appropriate data and often high training time to develop the model. In addition, these models can only make accurate predictions within the training dataset range. A trained and validated model can readily be used for making new predictions and/or for control purposes. The trained models are computationally inexpensive and do not require any physical assumptions, initial or boundary conditions. Moreover, ML algorithms can easily handle multi-dimensional data which is not the case in most of the empirical models. Stochastic nature of combustion in ICEs, in-cylinder temperature gradients, turbulent air-fuel mixing, amount of residuals trapped from the previous engine cycles, and in-cylinder non-linear thermo-kinetic reactions are some of the physical phenomena which are difficult to predict and incorporate in the white-box models [148]. On the other hand, ML can predict the outputs of interest with significant accuracy without knowing the actual dynamics involved in the process. Here, ML is used in this study to develop a model for the automatic prediction and classification of the type of combustion event in the LTC engine operation to tackle the complex and multi-dimensional heat release rate data in multi-mode LTC engines.

ML can be used for regression which gives quantitative outputs, and classification which can make qualitative predictions [149]. These approaches can be categorized as supervised and unsupervised learning algorithms. A supervised learning algorithm is provided with the outputs together with the inputs. However, unsupervised learning approach is only provided with the input information and the algorithm detects the pattern in a principled way by clustering the data and generates the output labels [150]. Compared to supervised learning algorithms, the validity of the output inferences are hard to ascertain in unsupervised learning algorithms which do not offer direct measure of success [149]. ML regression and classification algorithms have been widely used in engine modeling [151, 152], control [153], optimization [43] and monitoring [154]. In [44], a control oriented model was developed using least square support vector machine (LS-SVM) algorithm to control combustion phasing (CA50) and indicated mean effective pressure (IMEP) while constraining MPRR below 6 bar/CAD with a model predictive controller (MPC) framework in an RCCI engine. In the study in reference [92], a supervised learning based classification algorithm was used to model the stochastic cyclic variations in HCCI and RCCI engine operations. Cyclic variations in the engine torque affect the smoothness in engine torque delivery and the noise, vibration and harshness (NVH) performance of vehicle [87]. These cyclic variations are often indicated by coefficient of variation of indicated mean effective pressure (COV_{IMEP}). A nonlinear MPC controller was designed in reference [92] to constrain the COV_{IMEP} below 3% while controlling CA50 and IMEP.

In LTC modes, high MPRR usually occurs due to advanced combustion. Delaying the rate of heat release helps in reducing high MPRR. One of the important parameters in the LTC engine operation is the optimal fuel injection timing which determines the level of fuel premixing. This affects not only the rate of heat release but also the HC and CO emissions [155]. In a dual fuel LTC operation, a homogeneous air-fuel mixture is formed due to the injection of low reactivity fuel during intake stroke. However, premixed ratio of dual fuels and injection timing of high reactivity fuel have paramount effects on the combustion event. Premixed ratio of fuels determines the level of reactivity gradient while start of injection timing of high reactivity fuel determines the level of mixture homogeneity and fuel stratification in the cylinder [134]. In addition, intake air temperature and equivalence ratio are also contributing towards different types of combustion events. Authors in [134] investigated the rate of heat release in a dual fuel operated LTC engine by providing a timing sweep of the directly injected fuel. Early injection timings (around -145 CAD aTDC) resulted in HCCI-like rapid combustion. Peak heat release rate was significantly reduced by retarding the injection timing to -50 CAD aTDC. While abrupt heat release in early stage with a tail near the end of heat release was observed when the injection timing was around -15 CAD aTDC [134]. In [123], an early injection timing in a low load RCCI operation resulted in fully premixed air-fuel mixtures. This provided the best efficiency with low emissions. It was observed that injection timings earlier than -70 CAD aTDC resulted in spray liner impingement. The study suggested that the cylinder liner impingement can be avoided by using double fuel injections at later injection timings which helped in reduction of CO and HC emissions and improved thermal efficiency [123]. A study conducted in reference [55] used decision tree, convolution neural network (CNN) and Kmeans clustering to classify the rate of heat release rate in five distinct groups. The prediction accuracy achieved from CNN and decision tree was 70% and 74.5% respectively. Another study classified the combustion events obtained from four different gasoline and diesel fuel blend ratios into three modes by analyzing different heat release shapes [156]. The start of injection of diesel fuel was varied between 6 to 46 CAD bTDC. Dual fuel mixture with 70% gasoline provided a prolonged ignition delay which resulted in reduced NOx emissions. Furthermore, fuel mixture with 70% gasoline resulted in increased indicated efficiency when compared with diesel combustion [156]. This study suggested that fuel injection timing and blend ratio of fuel can be the effective means of controlling the combustion event to the desired heat release rate while limiting MPRR and engine-out NOx and soot emissions [156].

To the best of authors' knowledge, this is the first study undertaken to investigate and classify heat release shapes into three types for extensive LTC operation for over 630 different operating conditions and to develop a model predictive control framework using the classification model to achieve a multi-mode LTC engine operation. This leads to a classification problem which can cluster the different HRR traces into different classes. ML based classification algorithms are used to distinguish between different types of HRR based on the shape and the attributes. This work is based on the comprehensive investigation of low temperature combustion events as a result of variation in the start of injection (SOI) timing of high reactivity fuel, premixed ratio of the two fuels (PR), intake air temperature (T_{man}), and fuel quantity (FQ). Based on the in-cylinder pressure data, the heat release rates are computed and characterized. The characterization is done on the basis of combustion metrics which includes start of combustion (CA10), combustion phasing (CA50), burn duration (BD), maximum pressure rise rate (MPRR), peak in-cylinder pressure (P_{max}), location of peak pressure (θ_{Pmax}), maximum in-cylinder temperature (T_{max}), and COV_{IMEP}. Furthermore, the engine operation can be optimized by implementing a supervisory controller to maximize the indicated thermal efficiency. Based on the demanded load and speed, the engine operation can be optimized by maximizing the indicated thermal efficiency while limiting MPRR and COV_{IMEP}.

The contributions of this work are as follows:

1. Rule-based classification of LTC heat release traces into three distinct classes based on the fraction of early and main heat release;
2. Characterization of different types of heat release rate based on the combustion

performance metrics corresponding to each class;

3. Development of supervised and unsupervised machine learning algorithms to identify the heat release rate shapes;

4. Designing of model predictive control framework based on the trained classification model to control the multi-regime engine operation.

The organization of this chapter is as follows: Section 2 comprehends the experimental setup, engine specifications and the range of experimental data used in this study. Data mining is used to analyze different combustion events based on the in-cylinder pressure data in Section 3. This section also includes the distinct combustion attributes corresponding to each heat release type evaluated on the basis of statistical parameters. In Section 4, supervised and unsupervised learning algorithms are used for the identification of heat release shapes and their classification into the respective group. Section 5 presents the results and discussions on the developed algorithms. Section 6 includes the model predictive control of LTC engine using the trained classification model. Section 7 summarizes the major findings of this work. Future work and applications of these algorithms are discussed in Section 8.

5.3 Experimental Setup

Low temperature combustion is achieved in a 2.0L GM EcoTec engine using dual fuels. The engine is coupled to a 460 hp AC dynamometer. The 4-cylinder gasoline direct injection (GDI) engine is modified by appending port fuel injection (PFI) systems as auxiliaries, as shown in Fig. 3.3. The naturally aspirated engine is run at wide open throttle (WOT) condition. A controlled electric heater is used to achieve the desired temperature of the intake air. In-cylinder gas pressure is measured at 1 CAD resolution using PCB piezoelectric pressure transducers. A dSPACE MicroAutoBox (MABX) serves as the engine control unit while the real-time combustion feedback control is achieved with Xilinx Spartan-6 field programmable gate array (FPGA).

Dual fuels of different reactivity are used to realize different LTC modes. The fuels used in this study are n-heptane (high reactivity) and iso-octane (low reactivity). The port fuel injectors are used for iso-octane injection during the intake stroke while direct injection system is used for the n-heptane. The engine is run at different operating conditions by varying total fuel quantity (FQ), intake air temperature (T_{man}), start of injection (SOI) timing of n-heptane and the dual fuel premixed ratio (PR). The premixed ratio of the two fuels is calculated using Eq. (5.1):

$$PR = \frac{m_{iso}\mathrm{LHV}_{\mathrm{iso}}}{m_{iso}\mathrm{LHV}_{\mathrm{iso}} + m_{nhep}\mathrm{LHV}_{\mathrm{nhep}}} \tag{5.1}$$

where m_{nhep} and $\mathrm{LHV_{nhep}}$ denotes the mass and the lower heating value of the injected n-heptane, respectively. While m_{iso} and $\mathrm{LHV_{iso}}$ are the mass and lower heating value of iso-octane, respectively.

Steady state engine data is recorded for 100 consecutive cycles for all operating conditions. Cycle-by-cycle combustion metrics are calculated. These include start of combustion (CA10), combustion phasing (CA50), burn duration (BD), indicated mean effective pressure (IMEP), maximum pressure rise rate (MPRR), and $\mathrm{COV_{IMEP}}$. $\mathrm{COV_{IMEP}}$ is calculated by:

$$COV_{IMEP}(\%) = \frac{\sigma_{IMEP}}{\mu_{IMEP}} \times 100. \tag{5.2}$$

where μ_{IMEP} and σ_{IMEP} are the mean and standard deviation of $IMEP$, respectively. The range of experimental data for the LTC engine used in this study is shown in Table 5.1.

Table 5.1
Range of operating conditions used for LTC engine operation

Parameters	**Range**
Intake temperature, $\mathrm{T_{man}}$ (°C)	40-100
Manifold pressure, $\mathrm{P_{man}}$ (kPa)	96
Engine speed, N (RPM)	800-2300
Premixed ratio, PR (-)	20-60
Start of injection, SOI (CAD bTDC)	15-100
Fuel quantity, FQ (mg/cyc)	9-40

5.4 Heat Release Rate Analysis of Low Temperature Combustion

Low temperature combustion results in different heat release rate (HRR) shapes as a consequence of variations in the engine operating conditions. These heat release rate traces can be classified into three distinct classes based on their shapes, as shown in Fig. 5.1.

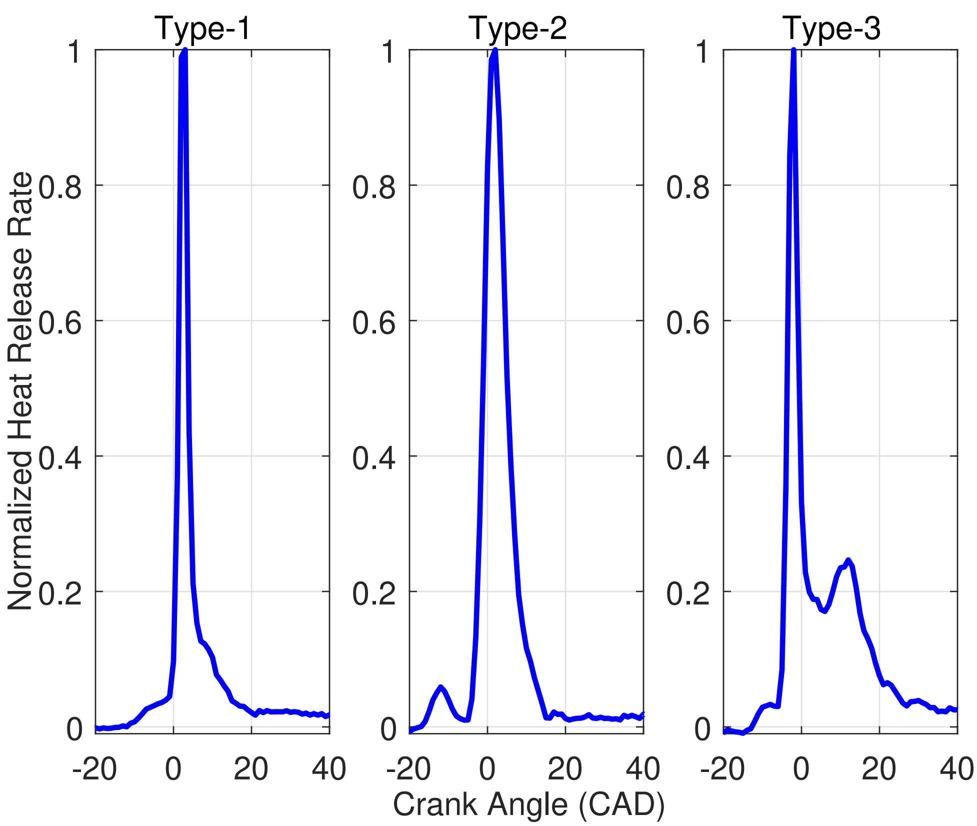

Figure 5.1: Three types of normalized heat release rates in LTC operation

5.4.1 Rule-based Classification

In-cylinder pressure data provides the information about the combustion event. Heat release rate and combustion performance metrics are computed from the in-cylinder pressure data. After visualizing the distinct shapes, a rule-based approach is adopted for classification. The three distinct HRR shapes showed single stage (type 1) and two stage combustion (type 2 and 3). The three distinct HRR shapes are shown in Fig. 5.1. The rule-based strategy is devised on the basis of start and end of the main stage HRR [157]. The crank angles for start and end of the main HRR are identified for individual traces and entered into the data files, as shown in Fig. 5.2. Fractions of early and late heat release are calculated on the basis of the crank angles of start and end of main heat release [157]. Fraction of early heat release (HR_{early}) is calculated as the percentage of total heat release which occurs before the main stage HR using Eq. 5.3.

$$HR_{early} = \frac{\int_{SOI}^{SOM} HR}{m_{iso}LHV_{iso} + m_{nhep}LHV_{nhep}} \times 100 \tag{5.3}$$

where SOM is the crank angle for the start of the main HR, and SOI is crank angle for start of injection of n-heptane.

The percentage of late heat release (HR_{late}) is determined as the ratio of amount of heat release during the end of main stage heat release and the crank angle where 90%

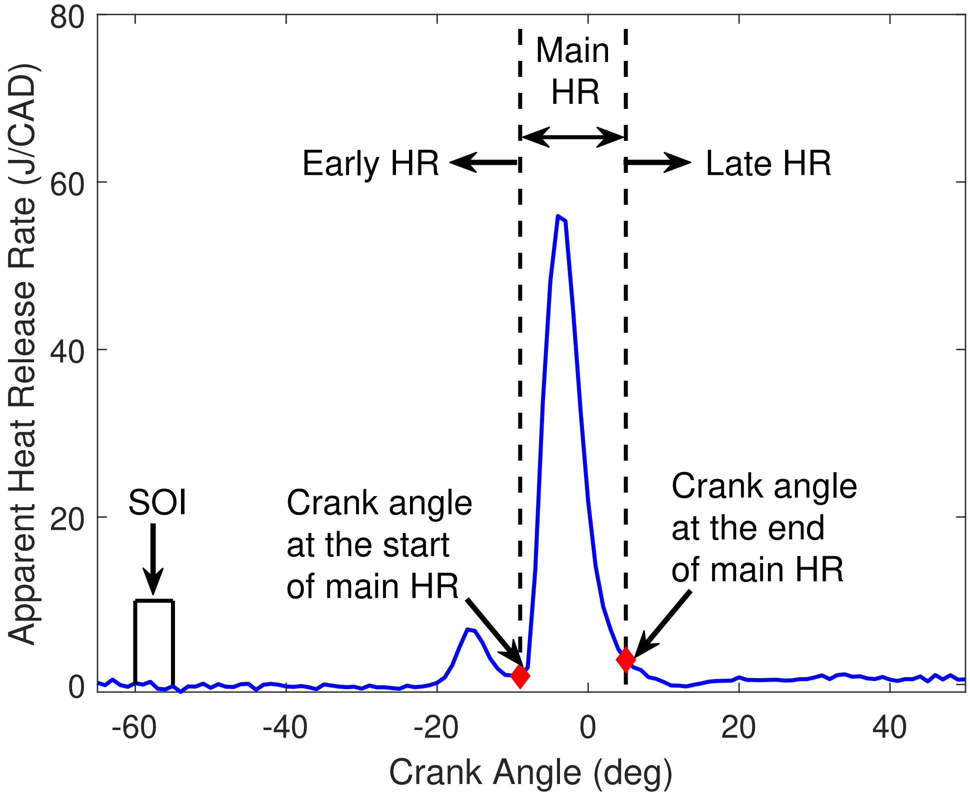

Figure 5.2: Crank angle identification of start and end of main HRR

of the total heat is released to the total energy content of the fuel. HR_{late} by using Eq. 5.4.

$$HR_{late} = \frac{\int_{EOM}^{CA90} HR}{m_{iso}LHV_{iso} + m_{nhep}LHV_{nhep}} \times 100 \tag{5.4}$$

where EOM is the crank angle for the end of main stage heat release.

Heat release rate provides most of the important attributes peculiar to a combustion event. Based on the experimental data, the values for the fractions of early (HR_{early}) and late HR (HR_{late}) are determined for different types of HRR. A rule-based approach is adopted to classify the HRR shapes into three distinct classes. This approach can

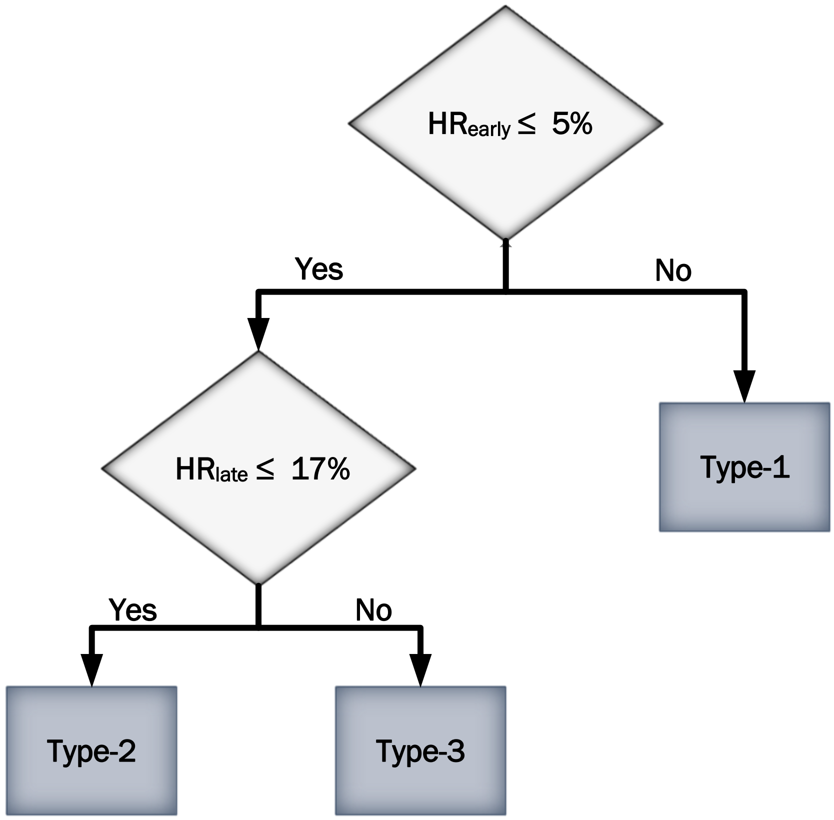

Figure 5.3: Rule based classification of HRR

be shown in the form of a simple decision tree, as shown in Fig. 5.3. The HRR traces are classified as follows:

- Type-1: $HR_{early} \leq 5\%$ and $HR_{late} \leq 17\%$
- Type-2: $HR_{early} > 5\%$.
- Type-3: $HR_{early} \leq 5\%$ and $HR_{late} > 17\%$.

HRR in type-1 occurred in single stage with shorter burn duration. This type of HRR does not show any significant low temperature reactions. Type 2 HRR has low temperature heat release followed by main stage combustion. Type-3 heat release shape has a main stage heat release followed by diffusion combustion. This type of HRR is similar to the heat release in the conventional diesel combustion.

To understand the HRR shapes, experimental data at 636 different engine operating conditions was analyzed. Iso-octane is injected during the intake stroke for all the operating conditions which homogeneously mixes with the air. The level of mixture homogeneity is dependent on the premixed ratio. For higher premixed ratios, majority of the fuel mass is injected during the intake stroke which has enough time to mix homogeneously with air. Type-1 HRR is observed when the SOI ranges between 35-60 (CAD bTDC). Type-1 heat release has relatively shorter burn duration, higher peak pressure and maximum pressure rise rate as compared to type-2 and type-3. Furthermore, 86% of the type-1 data have equivalence ratio (ϕ) $\geq$ 0.65. Injection of n-heptane during early compression stroke, (i.e., SOI $\geq$ 60 CAD bTDC) resulted in a premixed two-staged combustion. For higher PRs, majority of the fuel mixes with air homogeneously and early injection of n-heptane forms a premixed air-fuel mixture leading to low temperature heat release followed by high temperature heat release. 68% of the type-2 heat release traces can be associated to the SOI $\geq$ 60 (CAD bTDC). In addition, more lean air-fuel mixture resulted in type-2 combustion with advanced combustion onset compared to type-1 and type-3. Around 70% of data in type-2 category has $\phi < 0.65$. Late injection of n-heptane near TDC is responsible for diffusion type combustion. Unlike conventional diesel combustion, combustion in type-3 still offers finite amount of ignition delay.

5.4.2 Characterization of HRR Types

Based on the rule-based classification, HRR traces are divided into three distinct types. Heat release traces are characterized based on combustion performance parameters. Among 636 data points, HRR with type-1 consists of 131 data points, type-2 has 132, and type-3 has 373 data points. Table 5.2 summarizes the statistical analysis of HRR pertaining to start of combustion. Start of combustion (CA10) provides information about onset of combustion. It is defined as the crank angle at which 10% of the total amount of heat is released. An advanced CA10 is a result of an early heat release rate which can result in excessive pressure rates. That is why, it is important to control the heat release rate. Type-2 has the most advanced CA10 as compared with types 1 and 3, as shown in Fig. 5.4. The advanced combustion initiation is type-2 is because of the early injection of n-heptane which resulted in more premixed mixture. Type-1 and type-3 have retarded combustion initiation compared to that of type-2. CA10 distribution in type 1 HRR is fairly symmetrical. However, distribution of CA10 in type 2 and 3 are negatively skewed. Kurtosis value of a normal distribustion is 3. Based on kurtosis values of type 1 and 2, the distributions of CA10 are very close to a normal distribution. However, type 3 has excess kurtosis which makes it leptokurtic distribution with heavier tails as compared to the normal distribution.

Table 5.2
Analysis of HRR traces based on CA10 (CAD aTDC)

Parameters	Type 1	Type 2	Type 3
Median (CAD)	5	0	4
Mean (CAD)	4.6	-1.2	3.7
Std. Deviation (CAD)	5.5	5.2	2.0
Skewness (-)	-0.1	-0.6	-1.2
Kurtosis (-)	2.6	2.9	8.3

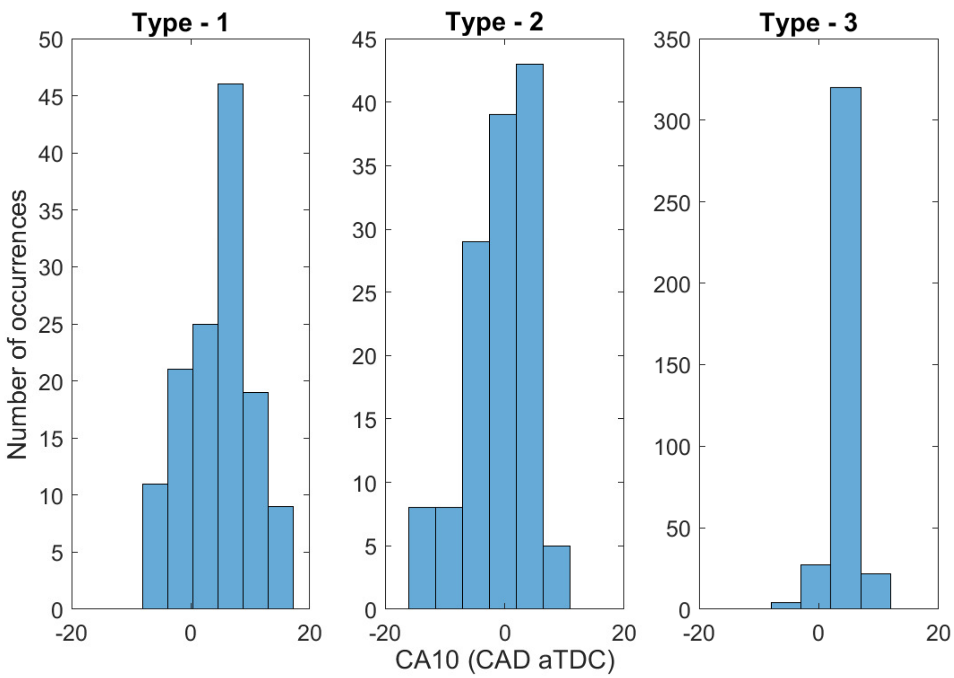

Figure 5.4: CA10 distribution

Combustion phasing (CA50) is defined as the crank angle where 50% of heat release occurs. CA50 is an important combustion parameter to avoid high pressure rise rates and to achieve maximum work output. The statistical analysis of HRR types based on CA50 is presented in Table 5.3. CA50 in type-2 is more advanced followed by

Table 5.3
Analysis of HRR traces based on CA50 (CAD aTDC)

Parameters	Type 1	Type 2	Type 3
Median (CAD)	8	6	7
Mean (CAD)	7.6	4.9	7.4
Std. Deviation (CAD)	6.5	4.8	2.3
Skewness (-)	0.0	-0.6	-0.7
Kurtosis (-)	2.7	3.2	8.2

type-3 and type-1, respectively, as shown in Fig. 5.5. This can be attributed to the higher premixed ratio of fuels in type-2 and type-3 as compared to type-1. Similar to CA10 distribution, type 1 shows symmetrical distribution of CA50 while type 2 and 3 are moderately skewed. The kurtosis value for type 1 and 2 show that the distribution tails are close to the normal distribution while distribution of type 3 has heavier tails as compared to the normal distribution.

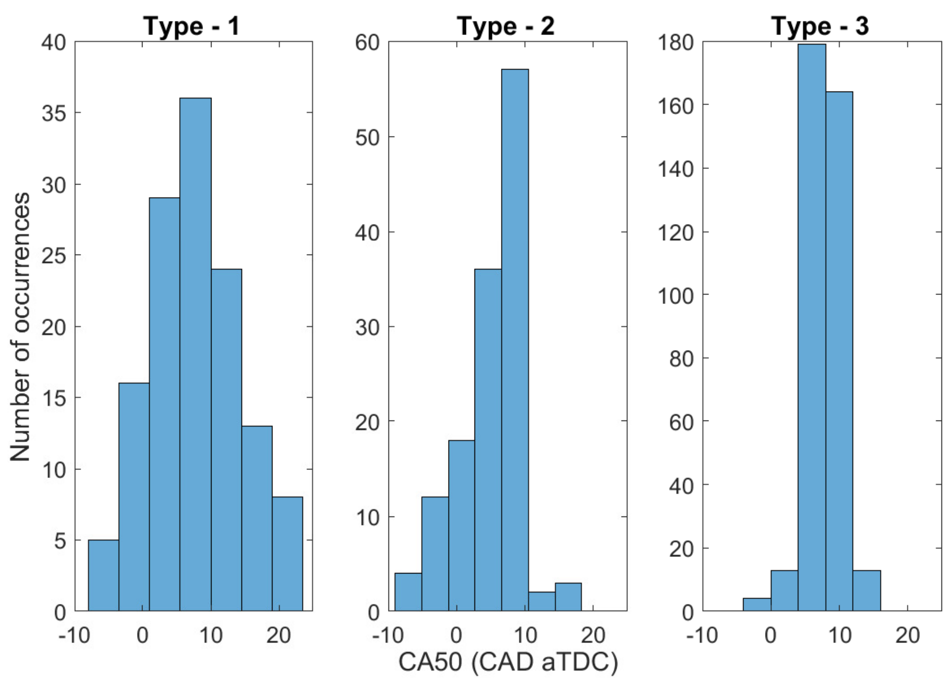

Figure 5.5: CA50 distribution

Table 5.4 shows the quantitative analysis of the burn duration in each combustion type. Type-1 has shorter burn duration compared to type-2 and type-3. That is why, the maximum pressure rise rate and peak in-cylinder pressure are higher in type-1 as compared to type-2 and type-3 combustion. The major factor contributing to type-1 HRR is the injection timing of n-heptane which creates fuel stratification; thus, the HRR resulted in a single stage combustion event. Burn duration in type-3 is the longest because of premixed and diffusion combustion, as can be seen in Fig. 5.6. The distribution of burn duration in type 1 and 3 are moderately skewed however type 2 shows normal distribution. The kurtosis value of type 1 is very close to that of normal distribution. However, type 2 has a kurtosis value of less than 3 which means that the distribution tails are lighter than that of a normal distribution while type 3 shows heavier tails as compared to that of a normal distribution.

Table 5.4
Analysis of HRR traces based on burn duration

Parameters	**Type 1**	**Type 2**	**Type 3**
Median (CAD)	11	18	22
Mean (CAD)	12	17	21
Std. Deviation (CAD)	4.9	7.1	3.3
Skewness (-)	0.7	-0.3	-1.0
Kurtosis (-)	3.2	2.0	4.1

Table 5.5 summarizes the statistical analysis of peak in-cylinder pressure corresponding to each HRR type. Type-1 shows the highest peak pressure among the three types with type-3 showing the lowest, as shown in Fig. 5.7. This can be explained by the fact the heat release in type-1 occurs in single stage as compared to type-2 and

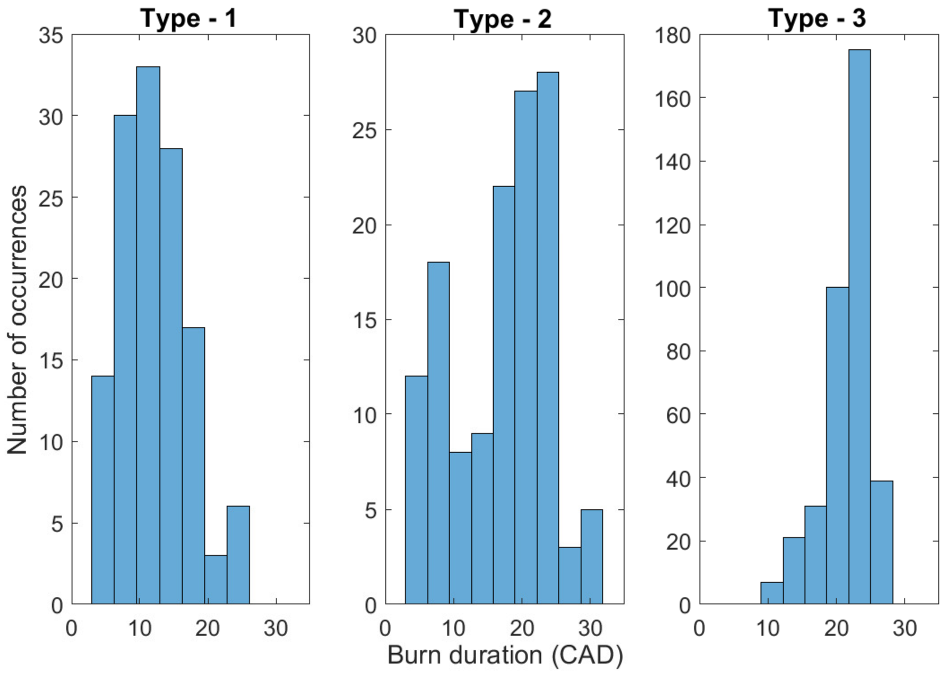

Figure 5.6: Burn duration distribution

type-3. Furthermore, the SOI timing of n-heptane in type-1 is mostly in the range of 35 to 60 CAD bTDC. This creates mixture stratification which results in local rich air-fuel mixture, promoting reaction initiation. This also explains the shorter burn duration in type-1 as compared with type-2 and type-3. A similar observation was made in [15] where start of injection of gasoline (RON 87) in the range of 35 to 50 CAD (bTDC) resulted in rapid combustion event due to mixture stratification. Type 1 and 3 show moderately skewed distributions while type 2 shows symmetrical distribution. All the three types have kurtosis values of less than 3 which means that the distribution tails are lighter than that of normal distribution. Table 5.6 shows the location of peak pressure ($\theta_{P_{max}}$) corresponding to each HRR type. The location of peak pressure in Type-2 is advanced followed by type-3 and type-1, respectively.

Table 5.5
Analysis of HRR traces based on peak cylinder pressure (P_{max})

Parameters	Type 1	Type 2	Type 3
Median (kPa)	4300	3800	3500
Mean (kPa)	4200	3900	3500
Skewness (-)	-0.7	0.3	0.3
Kurtosis (-)	2.7	2.1	2.7

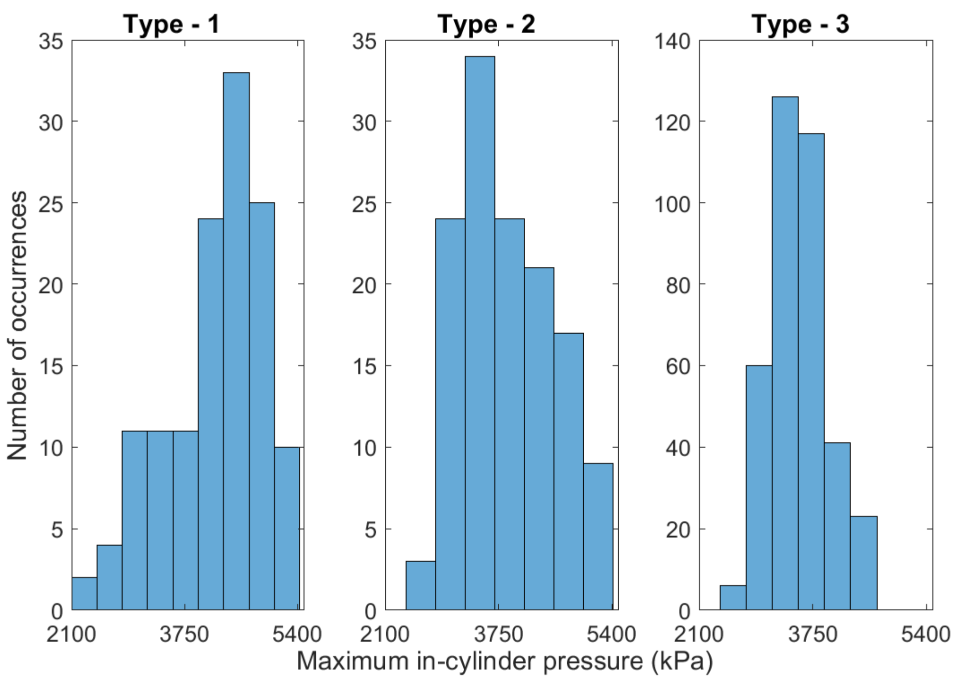

Figure 5.7: Peak pressure (P_{max}) distribution

Figure 5.9 shows the combustion temperature in the three types of HRR. The statistical analysis of maximum in-cylinder temperature is presented in Table 5.7. Type-1 resulted in the highest combustion temperature. This is because of the single stage combustion leading to high maximum in-cylinder pressure as compared to type-2 and type-3. Type-2 and type-3 offer much lower combustion temperatures which are favorable in avoiding NOx.

Table 5.6
Analysis of HRR traces based on location of peak cylinder pressure ($\theta_{P_{max}}$)

Parameters	Type 1	Type 2	Type 3
Median (CAD aTDC)	13	10	11
Mean (CAD aTDC)	12.4	9.5	11.6
Std. Deviation (CAD)	6.4	4.8	2.5
Skewness (-)	0.3	-0.3	3.5
Kurtosis (-)	2.6	3.5	4.4

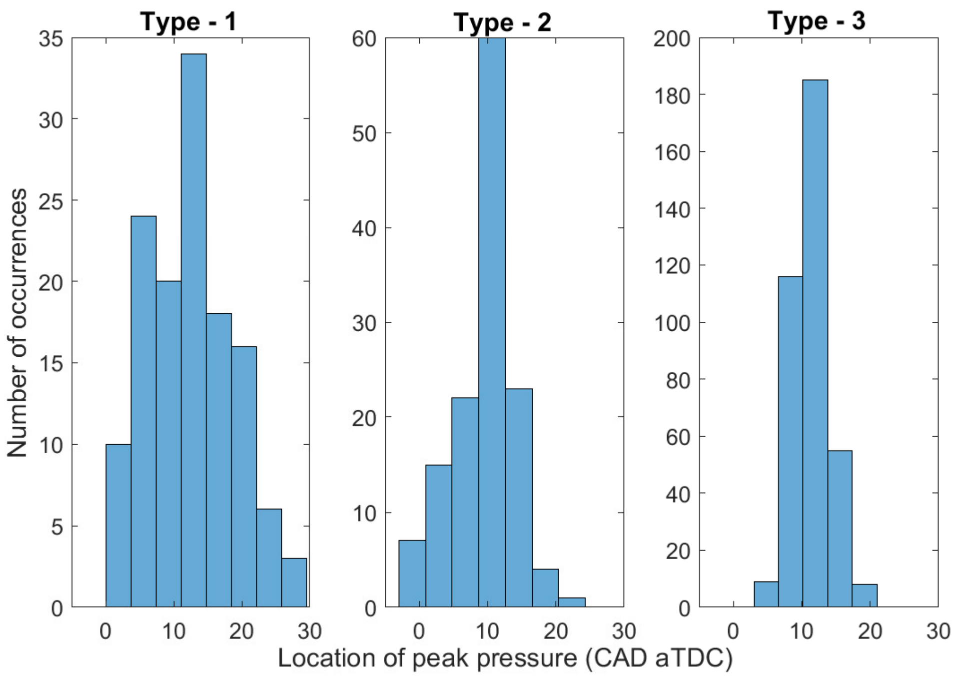

Figure 5.8: Location of peak pressure ($\theta_{P_{max}}$) distribution

Type-1 shows higher maximum pressure rise rate as compared to type-2 and type-3. However, type-2 shows typical premixed combustion with advanced combustion phasing but lower MPRR compared to type-1. This is because of the staged combustion in type-2. Heat release rate in type-1 is the highest. Combustion in type-1 happens in single stage with enhanced reaction rates and shorter burn duration. Type-3 shows the lowest average MPRR because of premixed and diffusion combustion. Table 5.8

Table 5.7
Analysis of HRR traces based on peak cylinder temperature (T_{max})

Parameters	Type 1	Type 2	Type 3
Median (K)	1800	1480	1500
Mean (K)	1700	1480	1550
Skewness (-)	-0.3	0.1	0.6
Kurtosis (-)	2.6	2.5	3.9

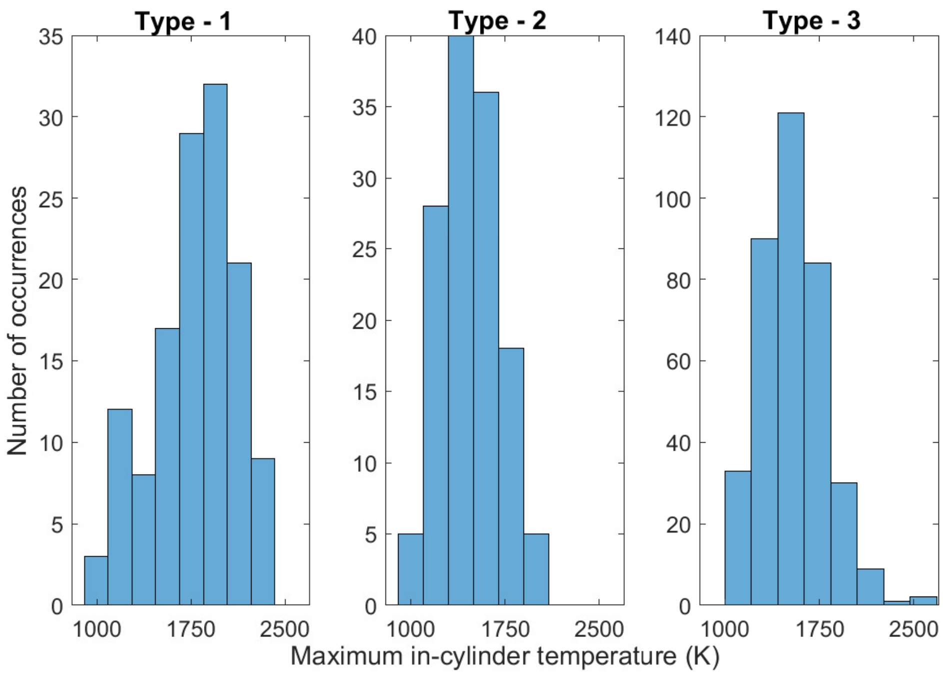

Figure 5.9: Peak in-cylinder temperature (T_{max}) distribution

provides an overview of statistical analysis of HRR types on the basis of variations in MPRR.

Coefficient of variation of indicated mean effective pressure (COV_{IMEP}) is a measure of cyclic variability and combustion stability. It is important to limit the COV_{IMEP} below 5% to reduce the load fluctuations. The engine $COV_{IMEP} > 5\%$ also affects the Noise, Vibration and Harshness (NVH) performance of vehicles. Majority of data

Table 5.8
Analysis of HRR traces based on maximum pressure rise (MPRR)

Parameters	Type 1	Type 2	Type 3
Median (bar/CAD)	5.8	3.8	3.9
Mean (bar/CAD)	5.6	4.8	4.0
Std. Deviation (bar/CAD)	2.4	2.6	1.1
Skewness (-)	0.3	0.9	0.5
Kurtosis (-)	2.4	2.7	3.1

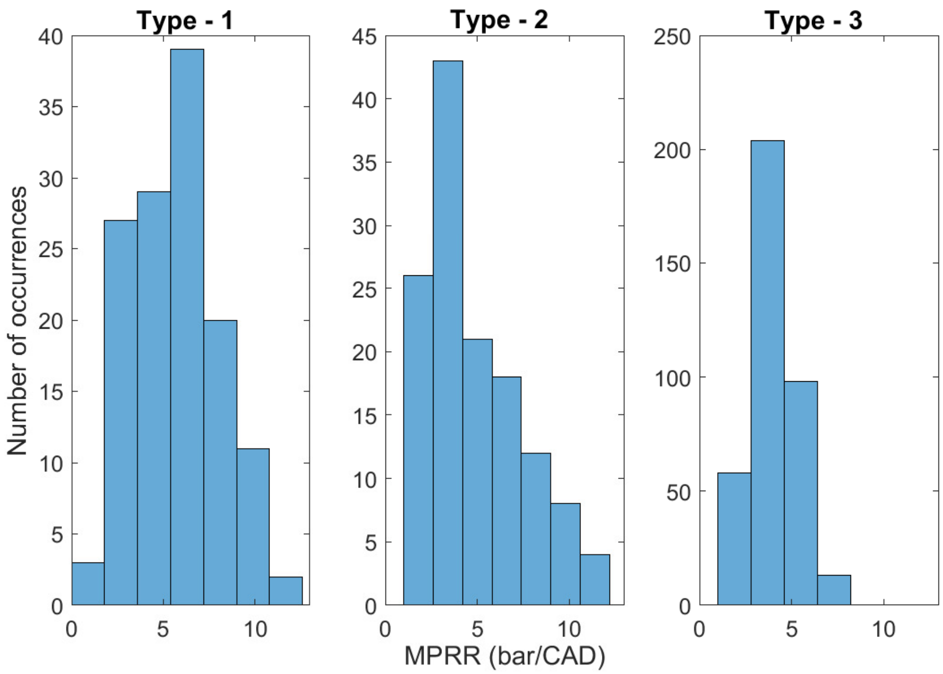

Figure 5.10: Maximum pressure rise rate (MPRR) distribution

points of LTC operation show COV_{IMEP} below 5% with type-1 showing the minimum variation in IMEP followed by types 3 and 2, respectively.

Table 5.9
Analysis of HRR traces based on COV_{IMEP}

Parameters	Type 1	Type 2	Type 3
Median (%)	2.2	4.3	3.9
Mean (%)	2.7	5.4	4.6
Std. Deviation (%)	1.7	2.9	2.5
Skewness (-)	1.7	1.4	1.4
Kurtosis (-)	6.1	5.9	6.5

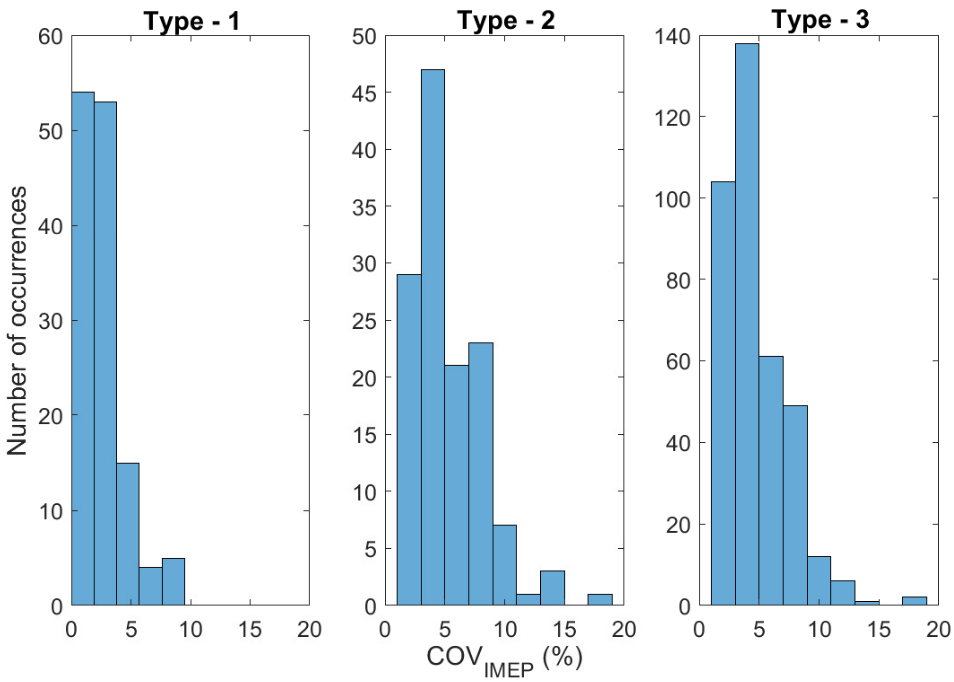

Figure 5.11: COV_{IMEP} distribution

5.4.3 Optimal Engine Operation

In order to optimize dual-fuel LTC engine operation, indicated thermal efficiency, maximum in-cylinder gas temperature, maximum pressure rise rate and COV_{IMEP} are selected as performance metrics. Majority of the operating conditions resulting

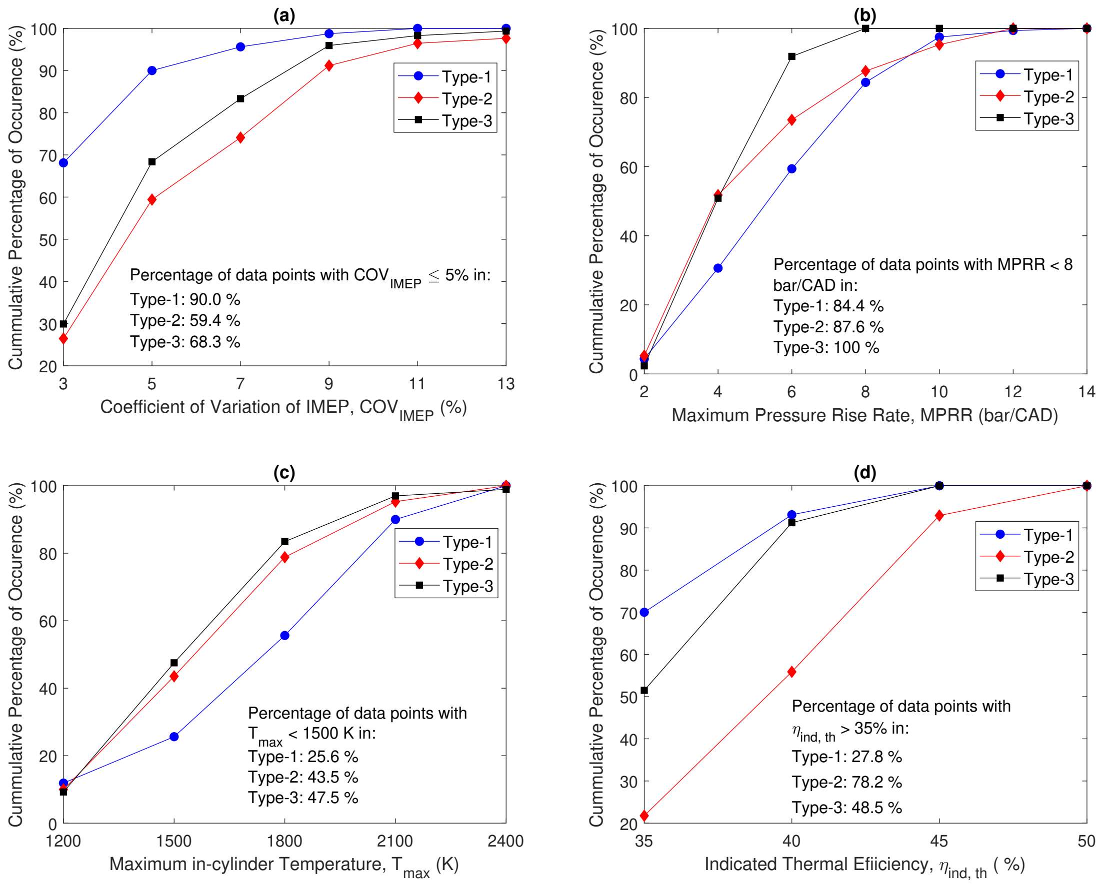

Figure 5.12: Cumulative percentage of occurrence of (a) COV_{IMEP}, (b) MPRR, (c) T_{max}, and (d) η_{th} for different HRR types

in type-2 HRR showed the maximum indicated thermal efficiency followed by type-3 and type-1 HRRs, respectively, as shown in Fig. 5.12. Formation of NOx can be prevented by avoiding very high in-cylinder gas temperatures [119]. 47.5% data points in type-3 and 43.5% data points in type-2 resulted in the maximum in-cylinder gas temperature below 1500 K. For the prevention of NOx formation, the desired HRR type can be selected based on the maximum in-cylinder temperatures. In addition, COV_{IMEP} below 5% is desired for smooth engine operation and reduced engine-out emissions [119]. 90% of the data points in Type-1 HRR resulted in COV_{IMEP} below

5%. Similarly, MPRR is another important parameter which is limited below 8 bar/-CAD to prevent engine knocking and combustion noise. All the operating conditions corresponding to type-3 combustion resulted in MPRR below 8 bar/CAD. Therefore, an optimal engine operation can be achieved by maximizing the indicated thermal efficiency subject to the constraints on COV_{IMEP} and MPRR.

5.5 Heat Release Rate Classification

Supervised and unsupervised machine learning methods can be used for the classification of data. Supervised machine learning approach is provided with the class labels together with the features to classify the data into specific classes. However, the unsupervised learning approach analyzes the data and clusters the data into different groups without any prior knowledge of class labels. In this study, both unsupervised and supervised classification algorithms are used for the classification of heat release rate shapes.

5.6 Unsupervised Learning - K-means Clustering

K-means clustering is a popular and heuristic unsupervised machine learning technique. This approach is provided with a data vector containing 'm' observations to classify the data into 'k' clusters [150]. The centroid/mean of each cluster is identified by averaging the data. Each observation is then given a class label of the nearest centroid/mean. In this study, heat release traces are provided as input to the algorithm. K-means clustering is an iterative process which starts with random initialization of the means (i.e., c_1,c_2,...c_k) for each cluster based on heat release rate data. Since, traces are intended to be segregated into three bins, k is initialized to 3. This algorithm adopts the following procedure:

1. After initializing the means for each cluster, the Euclidean distance between the observations and each mean is computed. Each data point is assigned to the nearest mean based on the minimum Euclidean distance.

$$argmin_{c_i \epsilon C}\ dist(x - c_i)^2 \tag{5.5}$$

   where C is the collection of means and the ith mean is represented by c_i. x corresponds to the data points assigned to the cluster based on Euclidean distance.

2. Each observation is then assigned a class label of the nearest mean based on the minimum Euclidean distance.

3. Once the cluster labeling is completed, mean for each cluster is recalculated and updated to iterate the algorithm until it converges. The set of data points

assigned to i^{th} cluster is S_i.

$$c_i = \frac{1}{|S_i|} * \Sigma_{x_i \epsilon S_i} x_i \tag{5.6}$$

The objective is to minimize the sum of Euclidean distance so that no data point switches among the clusters. This algorithm is, therefore, iterated to identify the means of different clusters for the heat release data. Instead of clustering the heat release traces on the basis of shape, this algorithm clustered the traces based on the magnitude of heat release. To address this issue, the heat release traces are normalized.

The result of k-mean clustering is shown in Fig. 5.13 for three different bins. K-means algorithm was unable to cluster the heat release traces based on the shape. The algorithm was able to cluster type-1 heat release traces together to some extent. However, there is no clear pattern distinction between the clustered type-2 and type-3 heat release traces. K-means clustering did not prove to be a promising approach for classification of heat release shapes based on the following observations. There was no apparent distinction among the three clustered heat release rate shapes. This can be referred to the fact that k-mean algorithm assumes the clusters to be spherical. This approach fails if the data clusters into different geometrical shapes rather than spherical. Furthermore, the data sizes are different for each type of heat release. This affects the performance of k-means algorithm because it gives more weight to the bigger cluster. It is difficult to justify the k-means clustered heat release shapes based on their unique characteristics. Therefore, it can be concluded that k-means approach can not cluster the heat release traces based on their shapes.

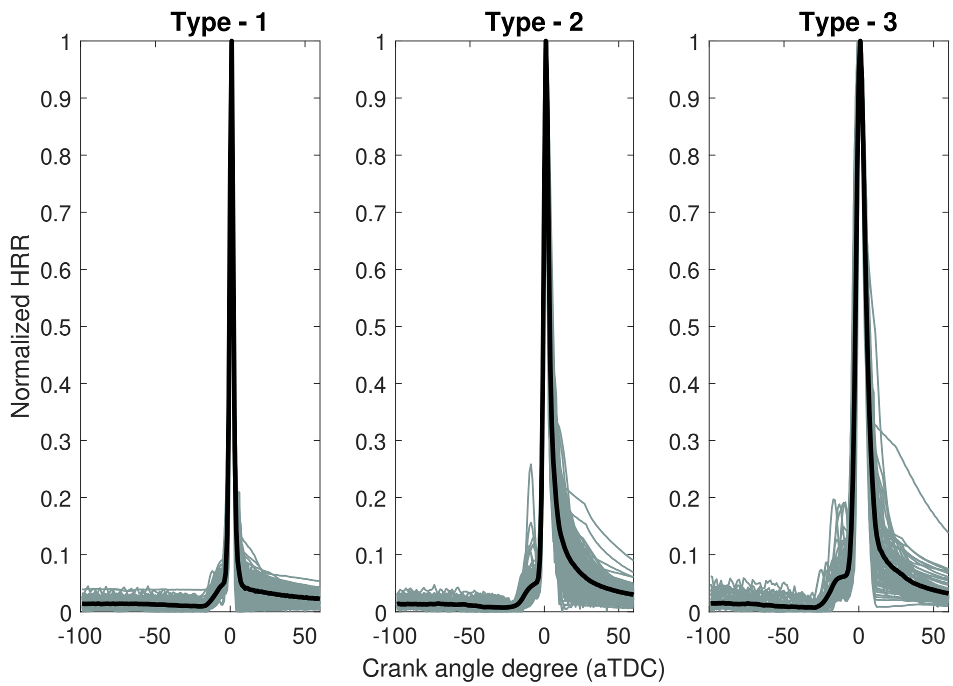

Figure 5.13: K-means classification of heat release rate traces

5.7 Supervised Learning

Classification is a supervised machine learning algorithm which categorizes the data into different classes. There are various algorithms which can be used for classification such as logistic regression, support vector machines (SVMs), neural networks (NN), Naive Bayes, K nearest neighbors (KNN), boosted decision trees and random decision forests. Decision tree and KNN are powerful classification tools which are easy to execute and are highly interpretable [150]. SVM is an efficient learning algorithm which can handle a high dimensional data frame [142]. Therefore, decision tree, KNN and SVM learning algorithms were investigated and their accuracies were compared for the classification of heat release rate shapes. Normalized heat release rates and their corresponding class labels are provided as input to train the models.

In addition to the classification based on normalized heat release traces, the study is extended to the development of predictive classifiers pertaining to three different heat release rate shapes which can be directly used for real-time control purposes. These classifiers can readily be used as scheduling parameters to develop linear parameter varying (LPV) control-oriented models (COMs) for LTC modes. Then, a multi-input multi-output (MIMO) adaptive model predictive controller can be developed based on LPV COMs [44]. A single MIMO adaptive model predictive controller (MPC) can be an effective framework in providing a broad range of control actions over the entire LTC operation. Multiple linear MPCs may be required to cover the dual fuel LTC engine operation for a range of premixed ratios because the COM is only accurate near the operating conditions around which it is linearized [8]. To this end, start of combustion (CA10), burn duration (BD), and control inputs i.e., dual fuel premixed ratio (PR), start of injection (SOI), fuel quantity (FQ) and intake manifold temperature (T_{man}) are chosen as the input features for the classification algorithms, as shown in Fig. 5.14. The required input feature data is available on cycle-to-cycle basis which makes the classification model favorable to be used for the real-time control purpose.

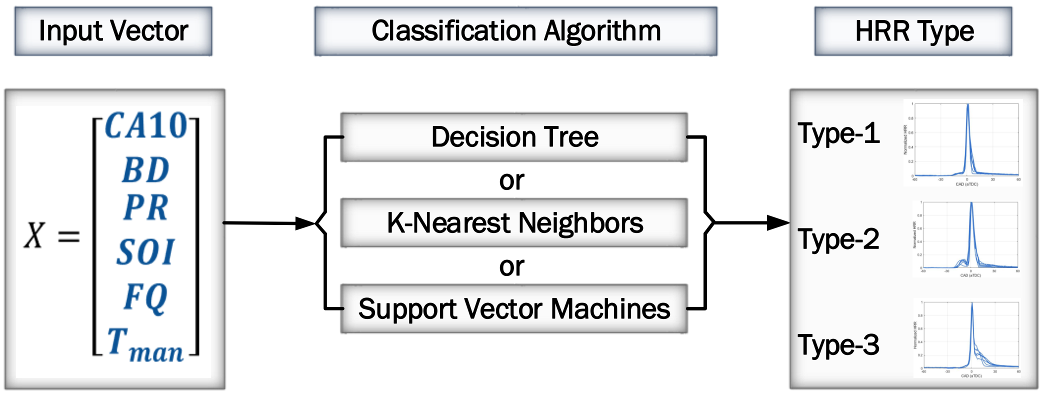

Figure 5.14: Schematic for the HRR classification using supervised learning algorithms

Type-1 has 133 data points, type-2 has 134 data points while type-3 has 373 data points. Due to imbalanced data set, synthetic minority oversampling technique (SMOTE) is used to oversample the data from the minority classes by finding k nearest neighbors to create synthetic data. 73% of the data is used for training the models and remaining 27% data is used to validate the model using test data.

5.7.1 Decision Tree

Decision tree is one of the powerful supervised learning algorithms which is not only highly interpretable but also provides extremely accurate results. Decision tree works in sequential hierarchy. A decision tree consists of nodes, edges/branches and leaf nodes. The nodes evaluate the conditions of the features and the outcome of one node is connected to the other via edges/branches. Leaf nodes receive the final outcome of the decision tree in the form of class labels. Decision tree used for classification of heat release rate traces employs recursive binary splitting at each node. The cost of split is calculated to evaluate the accuracy of split at each node. The goodness of split is determined by evaluating the cost function (G) which is given by the Eq. (5.7).

$$\mathrm{G} = 1 - \Sigma_k({p_k}^2) \tag{5.7}$$

where p_k is the proportion of class inputs of a specific group. The lower value of G corresponds to high level of purity which requires higher value of p_k. Decision tree evaluates the information gain at each split for its highest value. It is determined by using Eq. (5.8).

$$\mathrm{G}ain(S, A) = Entropy(S) - \Sigma_{Values(A)} \frac{|S_v|}{|S|} Entropy(S_v) \tag{5.8}$$

where S and A denote the set of occurrences and the features, respectively. The subset of S is denoted by S_v when a particular classification value becomes equal to A. The all the possible values of A in the training data are denoted by term *Values(A)*. The measure of uncertainty in the random variable and the impurity of the collection is determined by entropy. The decision tree method for HRR classification is implemented in MATLAB using binary recursive approach and two different models are trained. One model is trained for the HRR shape detection which is provided with the normalized heat release rate data. The second model is developed by using CA10, burn duration, premixed ratio, SOI, fuel quantity and intake manifold temperature as features to train the classifiers for different HRR types which can be used for control oriented modeling. Feature vector and class labels are provided as inputs to the model. The model is trained with 5-fold cross-validation. Decision tree often faces overfitting problem. A deep tree consisting of many leaves usually results in a highly accurate model with trained data set. However, this highly accurate model does not guarantee similar accuracy with test data set. Therefore, either pre-pruning or post-pruning is done. Pre-pruning limits the tree depth by tuning the hyperparameters. These hyperparameters include the maximum number of splits, the minimum parent and leaf sizes. The decision tree is then trained by using optimized hyperparameters. For post-pruning, the optimal pruning level is determined by minimizing the loss of cross validation. The trained model is then pruned to the optimal level. Post-pruning approach is adopted in this study. 73% of the data is used for training the model while remaining 27% is used to validate the trained model.

5.7.1.1 K-Nearest Neighbors

K-nearest neighbors (KNN) is a powerful supervised learning approach used for both classification and regression. KNN categorizes the data by computing their distance to the training data points. The data points lying in a closer proximity are grouped together. This approach does not require a model. It is a memory-based technique in which k training points (x_r), r=1,2,...,k, in the closest proximity of the query point (x_0) are identified. The query point is then classified based on the majority of k neighbors [149]. Euclidean distance (d_i) is determined by using Eq. (5.9) in the feature space:

$$d_i = ||x_i - x_0|| \tag{5.9}$$

KNN algorithm is run for different values of k. Increasing the value of k makes the predictions more stable because of the majority votes resulting in more accurate predictions. However, the increase in k after a certain limit results in an increased error. Therefore, the value of k is chosen such that it gives the minimum error while providing better prediction accuracy. k is usually selected to be an odd number for tie breaker. The input features are usually standardized. Here, 5-fold cross-validation is used and the KNN classification model is implemented in MATLAB. Exhaustive search algorithm is used in this approach. The main advantage of using KNN is its simplicity as it does not require optimization of hyperparameters. However, increased data volume makes this approach significantly slower. Normalized heat release rate traces and the class labels are input to the algorithm. The algorithm is trained with 73% of the data. Furthermore, three classifiers corresponding to each heat release class are also trained as scheduling variables.

5.7.2 Support Vector Machines

Support vector machine (SVM) is a supervised machine learning approach used for multi-class classification. This is a vector space based approach which maximizes the margin between two classes. Because of linearly inseparable data, the trained model is formulated as a non linear multi-class classification problem in which SVM maps the data from the input space (X) to a feature space F:

$$F = \{\phi(x) : x_i \in X\} \tag{5.10}$$

$$f(x) = \sum_{i=1}^{N} w_i \phi(x) + \beta_0 \tag{5.11}$$

where $x_i \in R^p$ is the data in the input space.

The linearly inseparable data in the input space (X) can be transformed into linearly separable data in the feature space (F) which provides better separation [143]. The classifier is represented by:

$$G(x) = sign(f(x)) \tag{5.12}$$

The dual optimization problem is solved by maximizing the following Langrange objective function using quadratic programming:

$$L_D = max \sum_{i=1}^{N} \alpha_i - \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} \alpha_i \alpha_j y_i y_j (\phi(x_i), \phi(x_j)) \tag{5.13}$$

Subject to:

$$\sum_j y_j \alpha_j = 0; \quad 0 \leq \alpha_j \leq C \tag{5.14}$$

Equation (5.15) represents the solution to the dual optimization problem [142].

$$f(x) = \sum_{i=1}^{N} \alpha_i y_i (\phi(x), \phi(x_i)) + \beta_0 \tag{5.15}$$

where α_i represents Lagrange multipliers, β_0 is the bias and y_i are the class labels. C is box constraint which limits the values of Lagrange multiplier. The best hyperplane separating the data points is given by Eq. 5.16.

$$y_i f(x_i) \geq 1 \tag{5.16}$$

where x_i is the support vector on the boundary for $y_i f(x_i) = 1$.

Kernel trick is adopted to avoid the transformation to feature space (F) and the computation of their corresponding inner product which can be very expensive. A kernel function is required for efficient computation which computes inner products in the feature space without any transformation. Kernel function (K) is of the form:

$$K(x_i, x_j) = (\phi(x_i), \phi(x_j)) \tag{5.17}$$

K is a symmetric positive semi definite function. The common nonlinear kernel functions are radial basis (Gaussian), sigmoid and polynomial. Among different kernel functions, polynomial function (Eq. 5.18) showed better accuracy.

$$K(x_i, x_j) = (1 + (x_i, x_j))^d \tag{5.18}$$

For the HRR shapes, a polynomial function of order two showed the better prediction accuracy as compared to other kernel functions. Three classifiers are trained by using CA10, burn duration, PR, SOI, fuel quantity and T_{man} as features. The trained classifiers using polynomial kernel function of cubic order provided the best prediction accuracy.

5.8 Results and Discussions

5.8.1 Classification Based on Normalized Heat Release Rates

The trained decision tree model showed an overall accuracy of 74% for the training data with 5-fold cross validation using normalized heat release rate traces. The accuracies for class-1, class-2 and class-3 were 73%, 80%, and 68%, respectively. The trained model is validated using test data set. The predictions of the model for each class are shown in the form of confusion chart as shown in Fig. 5.15a. The model showed 74% overall accuracy in predicting the classes. Class-1, class-2 and class-3 showed 79%, 76% and 67% prediction accuracies, respectively.

The trained KNN model showed an overall accuracy of 89.9% with 5-fold cross validation. Overall prediction accuracy of the model is calculated as the ratio of true positive predictions to the total number of predictions made. The overall prediction accuracy for model validation using test data is 88.2%. The validation results show the prediction accuracy of 100% for class-1, 79.4% for class-2 and 85.1% for class-3 using the test data set. The model prediction results are presented in the form of confusion chart as shown in Fig. 5.15b.

The trained SVM model showed an overall accuracy of 94% in predicting the HRR shapes using the normalized heat release rate data. Class-1 showed a prediction accuracy of 94.5%, class-2 showed 94.1% while class-3 showed 92.9% prediction accuracy for the training data set. The model is validated against the test data set. The results are shown in Fig. 5.15c. Class-1 showed two misclassified data points. Class-2 showed four misclassifications while class-3 showed five misclassified data points. However, the model showed overall prediction accuracy of 92.4% with the test data set. Among the three models used for classification of heat release shapes, support vector machines provided the best prediction accuracy. The trained model can successfully classify the heat release traces into three different types for the LTC engine with a prediction accuracy of 92.4%.

5.8.2 Classification Based on Combustion Performance Parameters and Control Inputs

In the previous section, classification algorithms are developed to segregate different types of heat release rate by simply providing the experimental data of the normalized heat release rates as input to the model. Instead of manually identifying the crank angles for start and end of main stage heat release and the corresponding calculations of the fractions of early and late heat release, the developed classification algorithm can readily identify the shape and type of heat release rates. This classification model can be used for offline data processing as well as an online updating

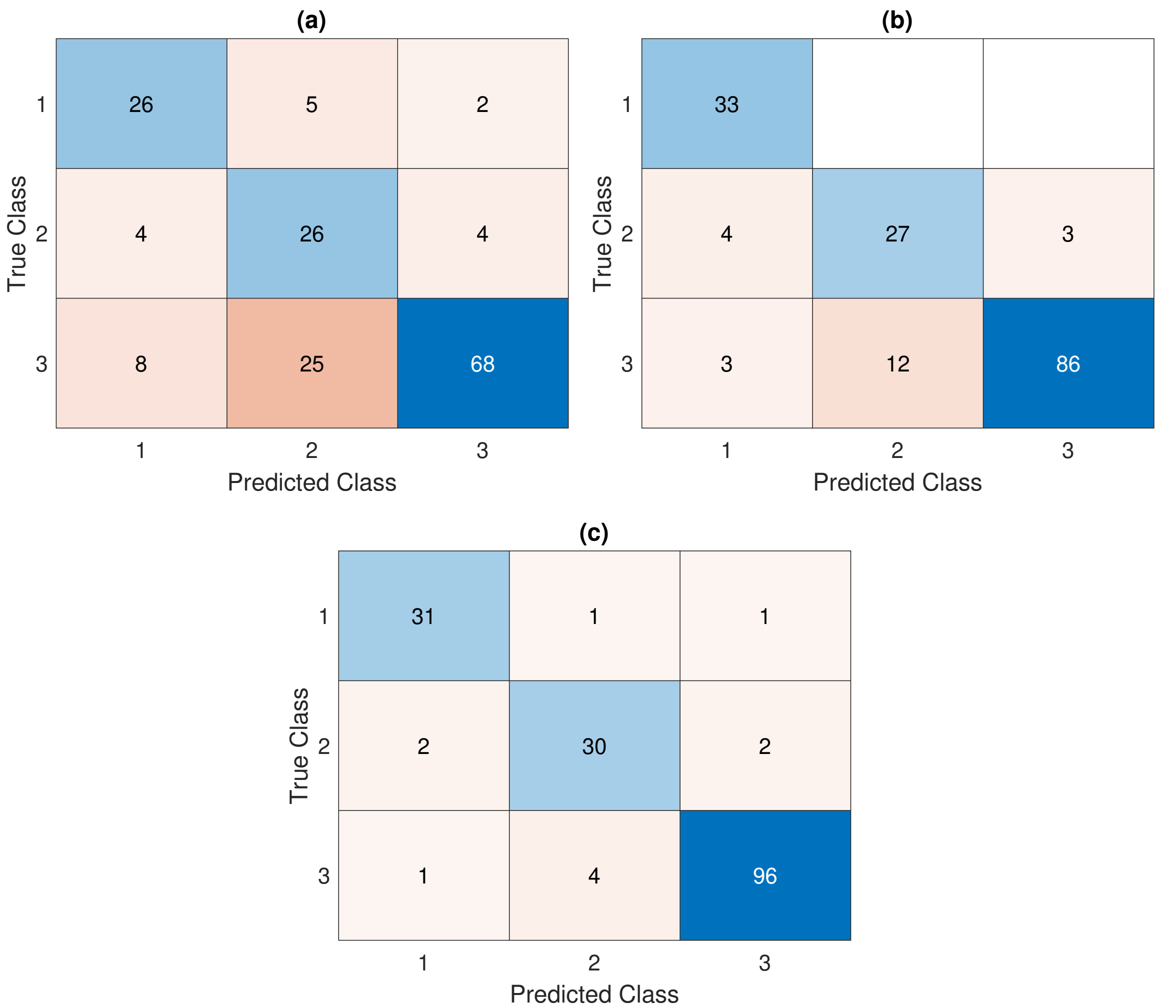

Figure 5.15: Confusion chart for classification of HRR shapes using (a) Decision tree, (b) KNN, and (c) Support vector machines algorithms

learning algorithm for control applications. Moreover, a classification algorithm as a function of the combustion performance parameters and control inputs is also developed. This classification approach can be used as a feedforward or supervisory controller to achieve the desired type of combustion event based on maximum indicated thermal efficiency, low MPRR and COV_{IMEP}. In addition to this, the developed classifiers can also serve as scheduling variables for control oriented modeling of LTC engine. Therefore, decision tree, K-nearest neighbors, and support vector machines algorithms are explored to develop the classification models.

Decision tree is used to model the three classifiers for each HR type using the input features. The validation of the decision tree model is represented in the form of a confusion chart as shown in Fig. 5.16a. The model shows an overall prediction accuracy of 79.6%. Class-1, class-2 and class-3 showed 82.2%, 69.6% and 87% prediction accuracy, respectively.

The trained KNN model showed an overall accuracy of 96.9% with 5-fold cross validation. The validation of the model is represented in Fig. 5.16b. Class-1 showed 100% prediction accuracy. Class-2 showed a prediction accuracy of 97% while class-3 showed 95% prediction accuracy. The overall prediction accuracy of the model is 97%.

SVM is also used to model the three classifiers, one corresponding to each class. One-vs-all classification approach is used for training. Hyperparameters are optimized to train the model. The trained model showed an overall accuracy of 96.6%. The model is validated using the test data and the results are shown in Fig. 5.16c. Class-1 showed one misclassified data point. Class-2 showed 2 misclassifications while class-3 showed seven misclassified data points. The overall prediction accuracy of the model with test data showed 94%. Among the three supervised machine learning approaches, KNN and SVM algorithms showed comparable accuracy for the trained data set.

However, KNN showed better prediction accuracy for the test data set compared to SVM. Decision tree model did not provide good accuracy.

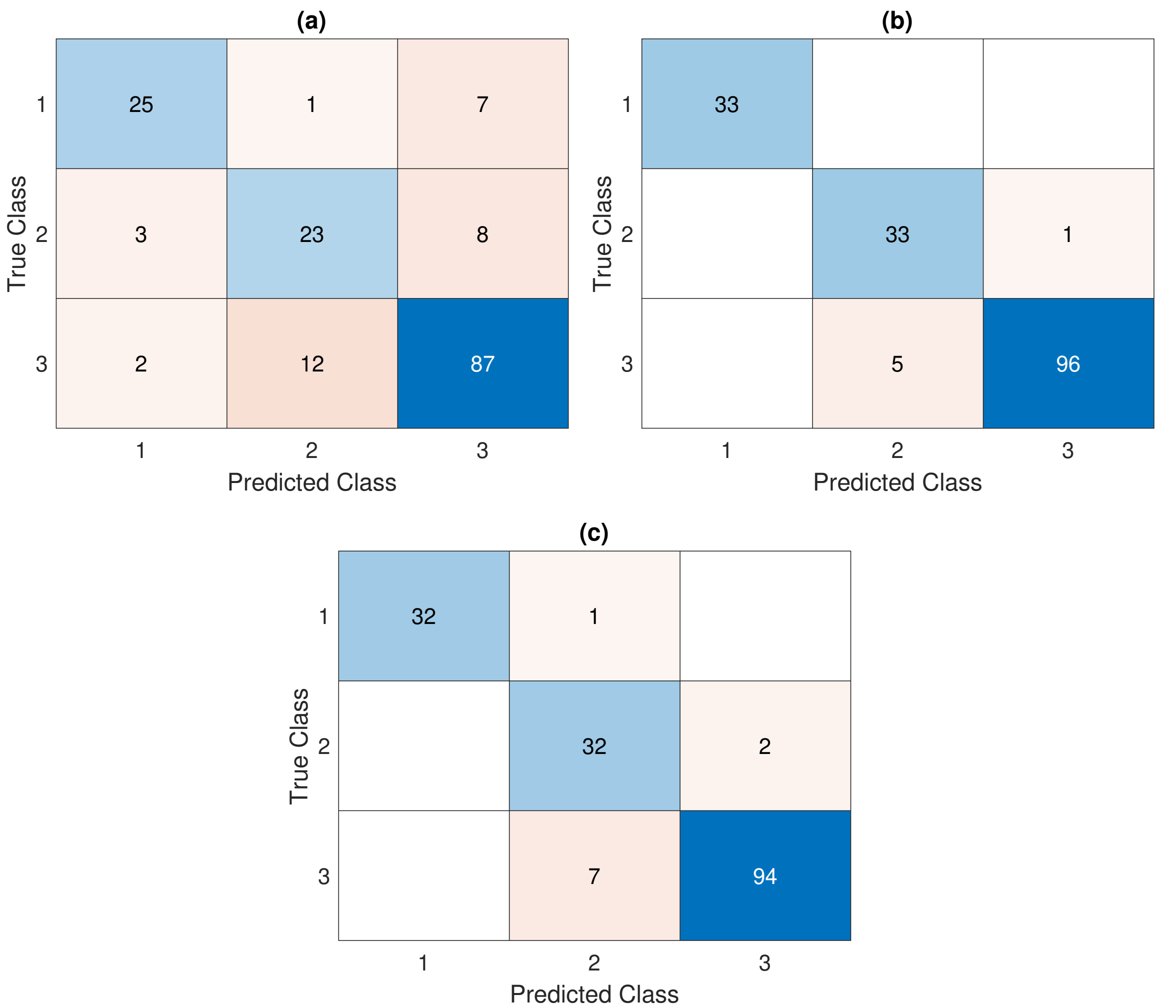

Figure 5.16: Confusion charts to characterize prediction accuracy of the trained classifiers for the HRR types using (a) Decision tree, (b) KNN, and (c) Support vector machines algorithms

5.9 Application of Classification Algorithm

Classification algorithm based on combustion performance parameters and control inputs is used to develop linear parameter varying (LPV) state space representation of the LTC engine. Based on the transient LTC data, least-square support vector machines (LS-SVM) is used to develop the state space control-oriented model [44]. The classification model obtained using SVM is used to compute the HR type. Using data-driven algorithm, transient engine data is used to obtain the LPV models as a function of the heat release rate type. The trained LPV models can be represented as follows:

$$X_{k+1} = A(p_k)X_k + B(p_k)U_k \tag{5.19}$$

$$Y_k = C(p_k)X_k + D(p_k)U_k \tag{5.20}$$

where X, U and Y represent the states, manipulated variables, and the outputs of the system. p is the heat release type which is used as a scheduling variable and k refers to the current engine cycle. The states, outputs, manipulated variables, and the scheduling parameter for the LTC engine model are:

$$X = \begin{bmatrix} CA50 & T_{soc} & P_{soc} & IMEP & MPRR \end{bmatrix}^T \tag{5.21}$$

$$Y = \begin{bmatrix} CA50 & IMEP & MPRR \end{bmatrix}^T \tag{5.22}$$

$$U = \begin{bmatrix} SOI & FQ & PR \end{bmatrix}^T \tag{5.23}$$

$$p_k = \begin{bmatrix} HR_{type} \end{bmatrix} \tag{5.24}$$

A model predictive control (MPC) framework is then developed to achieve the control of combustion phasing (CA50) and indicated mean effective pressure (IMEP) while limiting MPRR below 8 bar/CAD. MPC is an optimal control framework which provides the flexibility of handling the constraints. These constraints can be applied on output parameters, manipulated variables, and states of the system. Based on the desired reference trajectories of CA50 and IMEP, the controller computes the optimal manipulated variables using the LPV models.

A quadratic cost function is developed for the optimal control objective of tracking CA50 and IMEP subject to constraint on MPRR. Quadratic programming is used to obtain the control response. The cost function consists of three terms which are as follows:

$$J(k) = J_y(k) + J_{\Delta u}(k) + J_{\epsilon}(k) \tag{5.25}$$

where J_y is the cost function for the output reference tracking, $J_{\Delta u}$ is the cost function associated with the control actions, J_ϵ is the cost for constraint violation, and k is the current engine cycle.

The cost function associated with the output reference tracking is as follows.

$$J_y(k) = \sum_{j=1}^{N_y} \sum_{i=1}^{m} \left\{ \frac{Q_{i,j}^Y}{s_j^Y} \left[R_j(k+i|k) - Y_j(k+i|k) \right] \right\}^2 \tag{5.26}$$

In the equation, m represents the prediction horizon, N_y corresponds to the plant outputs.

$$U_k^T = \begin{bmatrix} u(k|k)^T & u(k+1|k)^T & u(k+m-1|k)^T & \epsilon_k \end{bmatrix} \tag{5.27}$$

$R_j(k+i|k)$ and $Y_j(k+i|k)$ refer to the j^{th} reference signal and plant output at the i^{th} time step. The variables to be controlled are scaled before tuning the controller by a factor s_j^y. $Q_{i,j}^y$ represents the tuning weights for each plant output at the i^{th} time step.

The cost function corresponding to the manipulated variables and their rate change is represented by Eq. 5.28.

$$J_{\Delta u}(k) = \sum_{j=1}^{N_u} \sum_{i=0}^{m-1} \left\{ \frac{R_{i,j}^{\Delta u}}{s_j^u} \left[u_j(k+i|k) - u_{j,target}(k+i|k)) \right] \right\}^2 \tag{5.28}$$

where N$_u$ refers to the number of manipulated variables. Manipulated variables are scaled by a factor of s_j^u, and $R_{i,j}^{\Delta u}$ is the tuning weight for the manipulated variables rate of change at the i^{th} time step.

J_ϵ is the cost to tackle the constraint violation.

$$J_\epsilon(k) = \rho_\epsilon \epsilon_k^2 \tag{5.29}$$

where ϵ is the slack variable at k time step and ρ represents the associated penalty weight. MPC is designed for a prediction horizon of 5 engine cycles and control horizon of 3 engine cycles.

To ensure knock free engine operation, constraint on MPRR is applied. In addition, the constraints are also applied on the manipulated variables.

$$MPRR \leq 8(bar/CAD) \tag{5.30}$$

$$25\ (CAD\ bTDC) \leq SOI \leq 60\ (CAD\ bTDC) \tag{5.31}$$

$$10\ (mg/cycle) \leq FQ \leq 35\ (mg/cycle) \tag{5.32}$$

$$10\ (-) \leq PR \leq 45\ (-) \tag{5.33}$$

Figures 5.17 and 5.18 show the tracking performance of MPC and the corresponding optimal control actions. The desired trajectories for CA50 and IMEP are provided with simultaneous step changes. CA50 can be controlled by manipulating SOI and PR. A simultaneous change in SOI and PR can be observed for a step change of CA50 and to keep MPRR below the set limit. SOI is retarded to track the CA50 from 8 CAD aTDC to 15 CAD aTDC. The reference tracking of IMEP is achieved by adjusting the fuel quantity. At 120^{th} engine cycle, when CA50 is advanced from 15 to 8 CAD aTDC, an increase in MPRR can be observed. PR is increased to keep the MPRR below 8 bar/CAD. The control actions are also within the set limits. The HRR type is computed based on the outputs which is used as scheduling variable for the LPV state space systems. The optimal control actions result in the HRR types 2 and 3 for the desired CA50 and IMEP. The controller is capable of tracking the reference trajectories of CA50 and IMEP with root mean square errors of 1.2 CAD and 9.3 kPa, respectively. The maximum value of MPRR observed is 6.5 bar/CAD.

Basina et. al. developed a MPC framework to control RCCI engine operation using premixed ratio (PR) as a scheduling variable [44]. The controller was tested for reference tracking of CA50 and IMEP while constraining MPRR below 5.8 bar/CAD [44]. The controller performance was limited to 650 kPa IMEP [44]. When the desired IMEP was increased beyond 650 kPa, the controller failed to track CA50 and IMEP effectively. In order to validate the performance of the controller designed in this work, step changes in CA50 and IMEP from 7 to 12 CAD (aTDC) and 500 to 720 kPa are provided, respectively. Figures 5.19 and 5.20 show the performance of MPCs, namely MPC-1 and MPC-2. MPC-1 is the framework designed in this work

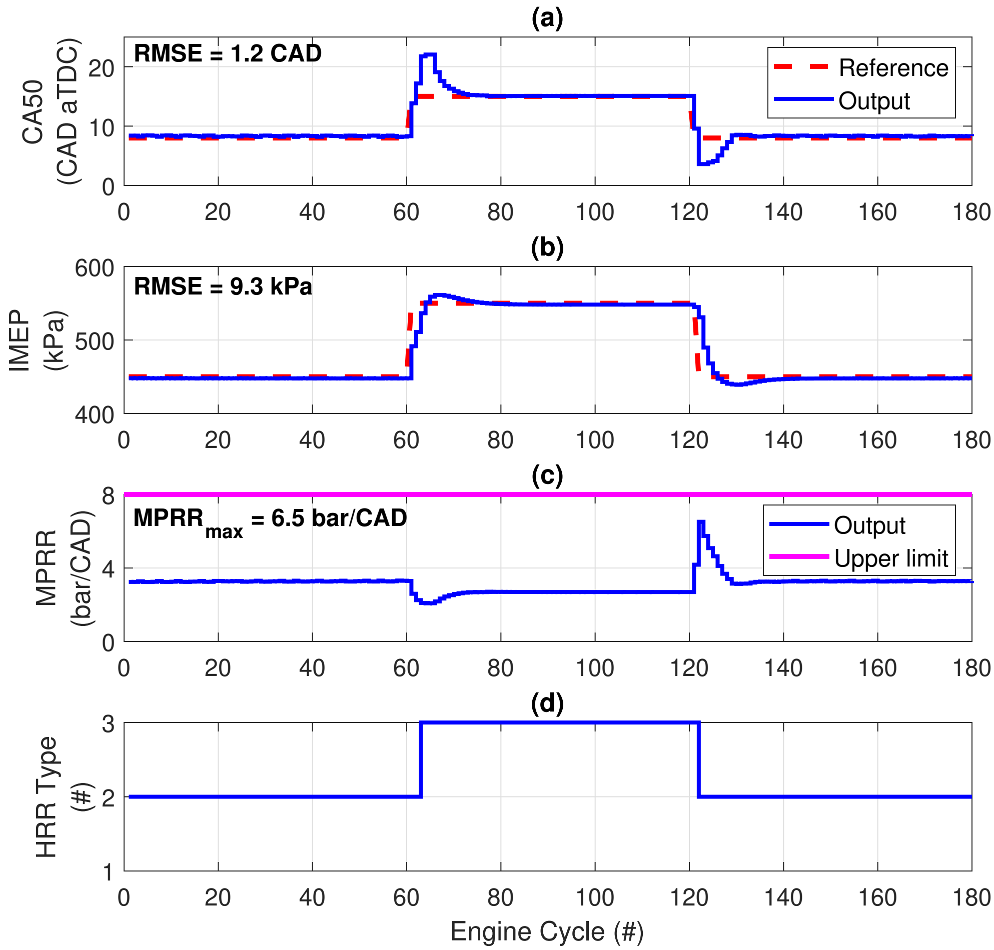

Figure 5.17: MPC performance for tracking CA50 and IMEP while constraining MPRR below 8 bar/CAD

and MPC-2 is the controller developed by Basina et. al. [44]. MPC-2 could not track both CA50 and IMEP when a step change in IMEP was provided. MPC-2 was not able to provide zero steady state errors for the desired IMEP of 720 kPa and the constraint on MPRR was also violated. However, MPC-1 successfully tracked the changes in the reference trajectories of CA50 and IMEP in one engine cycle with zero steady state errors. MPC-2 showed sluggish response as compared to MPC-1.

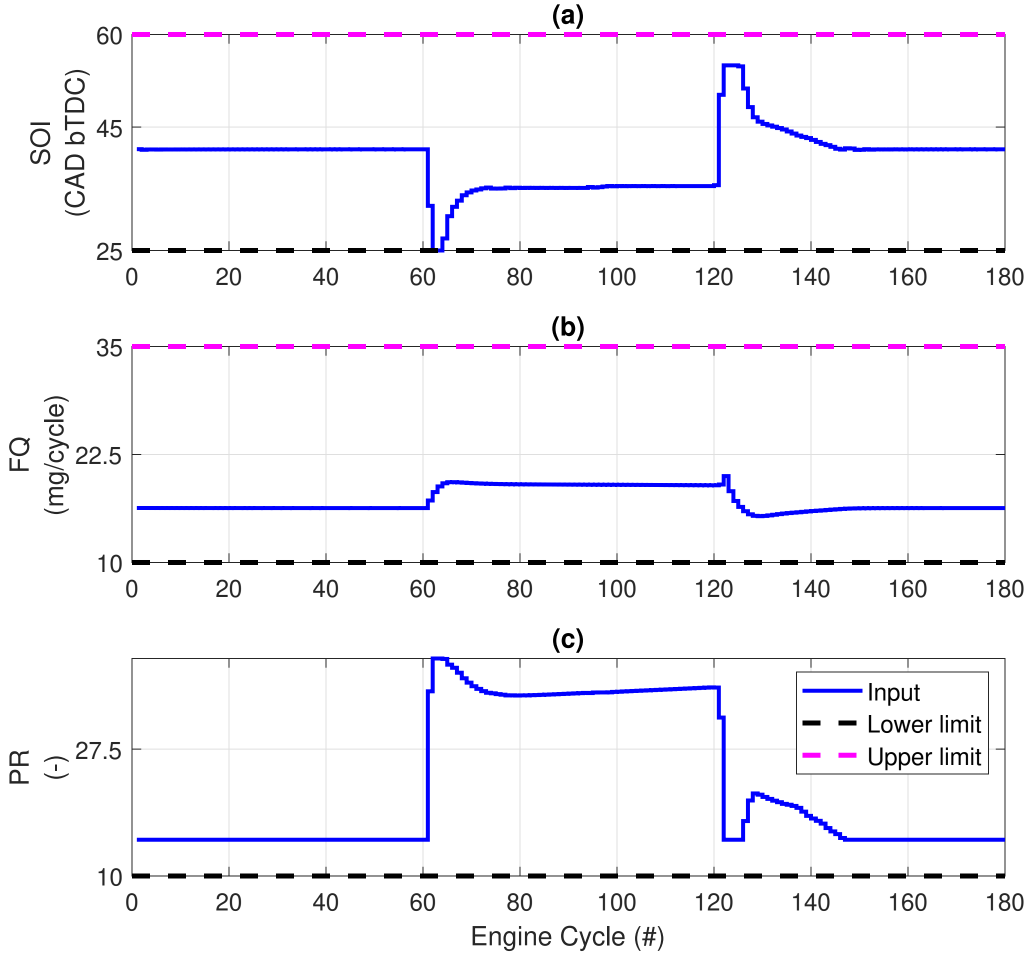

Figure 5.18: Optimal manipulated variables for the tracking of desired CA50 and IMEP while constraining MPRR below 8 bar/CAD

MPC-1 tracked CA50 and IMEP with root mean square errors of 0.4 CAD and 3.9 kPa, respectively. However, MPC-2 showed root mean square errors of 2.9 CAD and 40.3 kPa in tracking CA50 and IMEP, respectively. The maximum pressure rise rate observed in both cases was 6.5 bar/CAD. Based on the results, the controller MPC-1 designed with HRR type as scheduling variable showed better performance and a wider tracking range as compared to the MPC-2 [44].

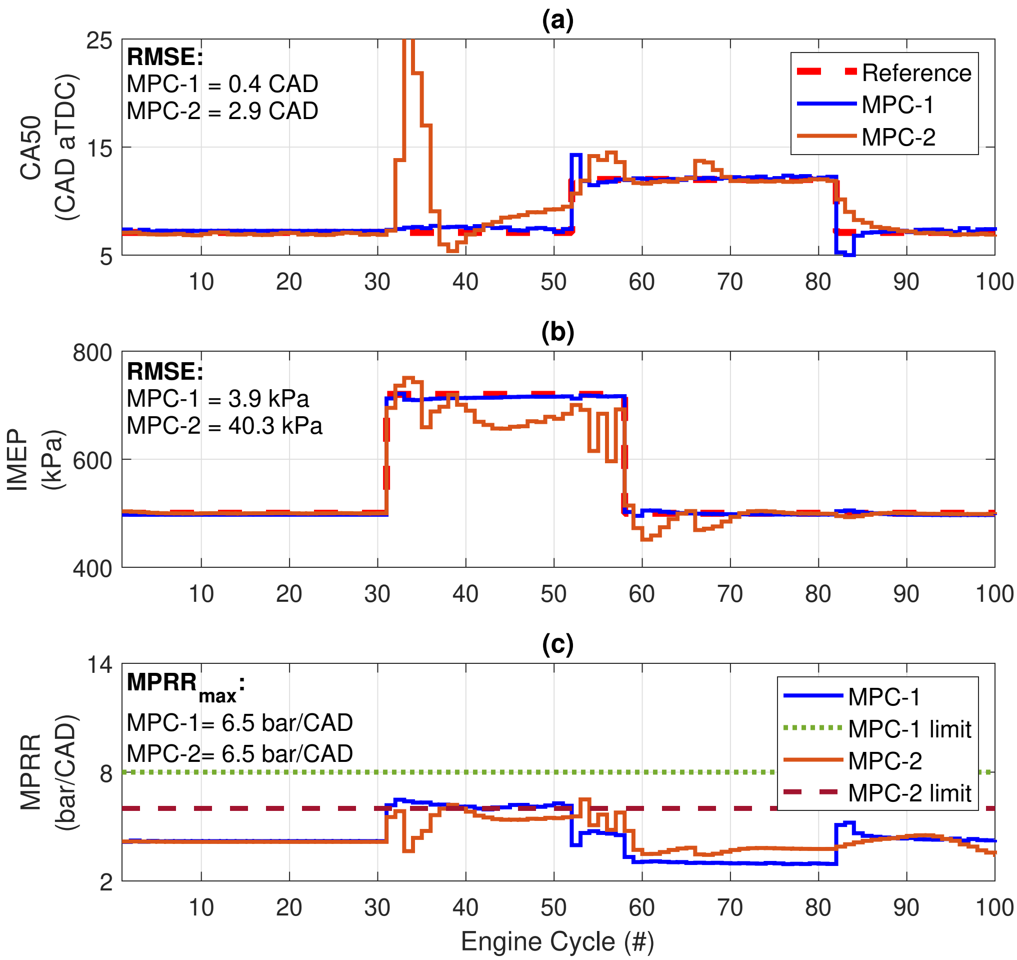

Figure 5.19: Performance comparison of model predictive controllers (MPC-1 and MPC-2) for tracking CA50 and IMEP while constraining MPRR. (MPC-1: Controller designed in this work; MPC-2: Controller designed in reference [44])

5.10 Summary and Conclusions

Heat release shapes of low temperature combustion (LTC) are investigated for over 600 different operating conditions from a 2.0 liter, 4-cylinder dual fuel LTC engine.

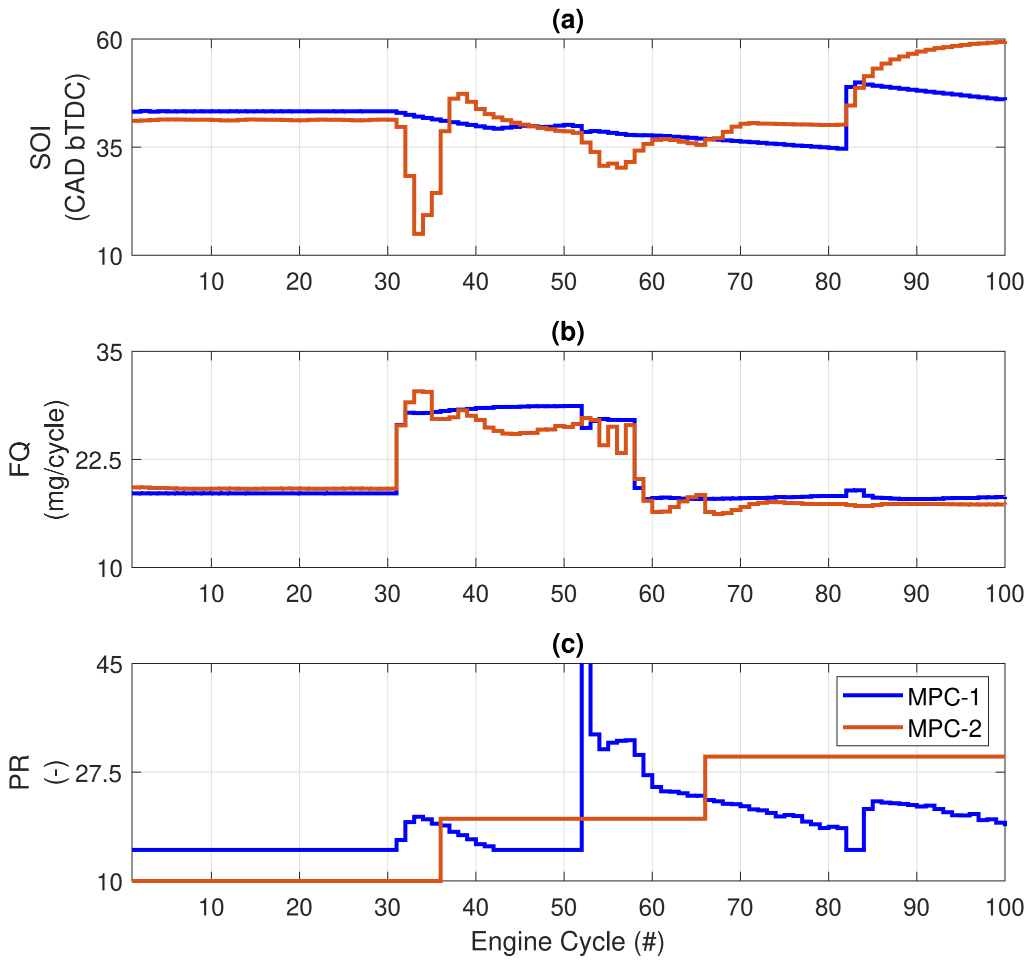

Figure 5.20: Comparison of the optimal control actions of MPC-1 and MPC-2 for the tracking of CA50 and IMEP while constraining MPRR. (MPC-1: Controller designed in this work; MPC-2: Controller designed in reference [44])

Premixed ratio, fuel quantity, start of injection timing of n-heptane and intake manifold temperature are varied. The resulting combustion events are analyzed based on the in-cylinder pressure data. Rule-based classification is used to categorize the heat release rate traces into three distinct types by computing the fractions of early and late heat release rates. Detailed statistical analysis on the heat release rate traces is carried out based on the combustion performance parameters. These combustion performance parameters include CA10, CA50, burn duration, maximum pressure rise rate, peak pressure, location of peak pressure, peak temperature and COV_{IMEP}. The main findings of this work are as follows:

- Three distinct types of heat release rate (HRR) shapes are identified in the LTC engine operation. These HRR types represent different combustion characteristics which can be classified as a function of fractions of early and late heat release.

- Type-1 HRR showed single stage heat release rate with shorter burn duration, higher peak in-cylinder pressure, and higher maximum pressure rise rate as compared to type-2 and type-3 HRRs. Furthermore, type-1 showed minimum COV_{IMEP} among the three types. Combustion in type-2 HRR occurred in two stages with advanced combustion phasing as compared to type-1 and type-3. Type-2 offered lower combustion temperature as compared to type-1 and type-3. Combustion in type-3 HRR showed main stage heat release together with diffusion type combustion tail.

- K-means clustering, an unsupervised approach, is used to group the heat release rate traces into three classes. The results showed that k-means algorithm can not classify the traces distinctly.

- Among supervised learning algorithms, decision tree, K-nearest neighbors and support vector machines are used to develop classification models for the HRR types using normalized heat release traces. SVM provided better accuracy compared to the other two supervised machine learning algorithms. The trained SVM model can predict the heat release rate type with a prediction accuracy of 92.4%.

- Three classification algorithms, decision tree, KNN and SVM are used to train the models. The classifiers are trained using start of combustion, burn duration, premixed ratio, start of injection, fuel quantity and manifold temperature as features. KNN and SVM showed better accuracy as compared to decision tree model. However, KNN is proved to be the best in predicting the heat release traces with an overall accuracy of 97%.

- An MPC framework is developed to demonstrate the application of classification algorithm for control applications. The output of SVM classification model is used to develop the LPV state space representation of RCCI. Based on the developed LPV system, a model predictive controller is designed to track CA50 and IMEP while constraining MPRR. The controller was capable of tracking CA50 and IMEP with root mean square error of 1.2 CAD and 9.3 kPa, respectively while limiting MPRR below 8 bar/CAD.

- The controller performance is compared with the one designed in the study [44] for the RCCI engine by providing same reference trajectories for CA50 and IMEP under same operating conditions. The controller designed in this work showed better overall tracking performance and wider operating range. It also showed faster response with zero steady state errors while satisfying the constraints on MPRR and actuators.

Chapter 6

Control Oriented Modeling of SI-RCCI-SI Mode Switching

This chapter explains the development of control oriented modeling for a multi-mode engine. This multi-mode engine operates in conventional spark ignition (SI) mode and reactivity controlled compression ignition (RCCI). RCCI offers higher thermal efficiency and lower NOx emissions as compared to the baseline SI engine. However, the major challenge associated to the RCCI mode is the limited operating range. Low load in RCCI mode is limited due to high cyclic variations while high load is restricted due to high maximum pressure rise rates (MPRR). Therefore, SI mode is required to run the engine where RCCI operation is not stable or ideal. To this end, an optimized engine map is developed based on the indicated specific fuel consumption and engine-out CO, THC and NOx emissions for SI and RCCI modes. The desired mode corresponding to the demanded net mean effective pressure (NMEP) is selected based on the optimized engine map. Therefore, a control-oriented multi-mode engine model is developed to achieve closed-loop control of the mode switching operation.

6.1 Optimal Engine Operation

Figures 6.1a and 6.1b show the comparison of baseline SI and RCCI modes, respectively. Iso-octane is used to operate the engine in SI mode while iso-octane and n-heptane are used to achieve RCCI operation. Iso-octane is injected via port fuel injectors and h-heptane is injected using direct injectors. For the same engine speed and load, RCCI mode offers lower specific fuel consumption as compared to SI mode over the load range of 300-700 kPa. Figures 6.2 and 6.3 show the CO (ppm), THC (ppm) and NOx (ppm) emissions in SI and RCCI modes, respectively. The emission data is collected by running the engine with NVO and by heating the intake air at 60° C. By comparing Fig. 6.2 and 6.3, we can observe that RCCI mode resulted in ultra-low NOx emissions as compared to SI mode. However, CO and THC emissions are lower in SI mode as compared to RCCI mode. Low combustion temperatures in LTC modes result in incomplete combustion, thus resulting in relatively higher CO and HC emissions. Emission data in RCCI mode is collected by providing sweeps of start of injection (SOI) timing of n-heptane and premixed ratio (PR) of the two fuels for different engine speeds. CO, THC and NOx emissions are lower with early SOI. However, CO and THC emissions increases when SOI is close to the TDC. B

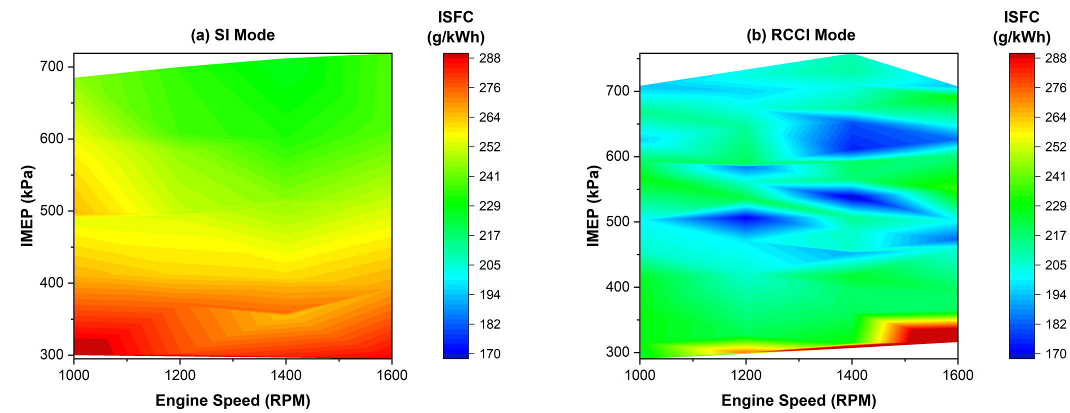

Figure 6.1: Comparison of SI and RCCI combustion modes in terms of specific fuel consumption

Based on optimal engine map based on ISFC and emission data, RCCI mode can provide safe operation in the range of 300-600 kPa. Above 600 kPa, RCCI mode results in high MPRR causing engine knock. RCCI operating range can be extended to high load by adding external exhaust gas recirculation (EGR) and/or using multiple fuel injections. In the current study, RCCI mode running at naturally aspirated conditions without EGR is coupled to the SI engine to provide a load range of 300-600 kPa.

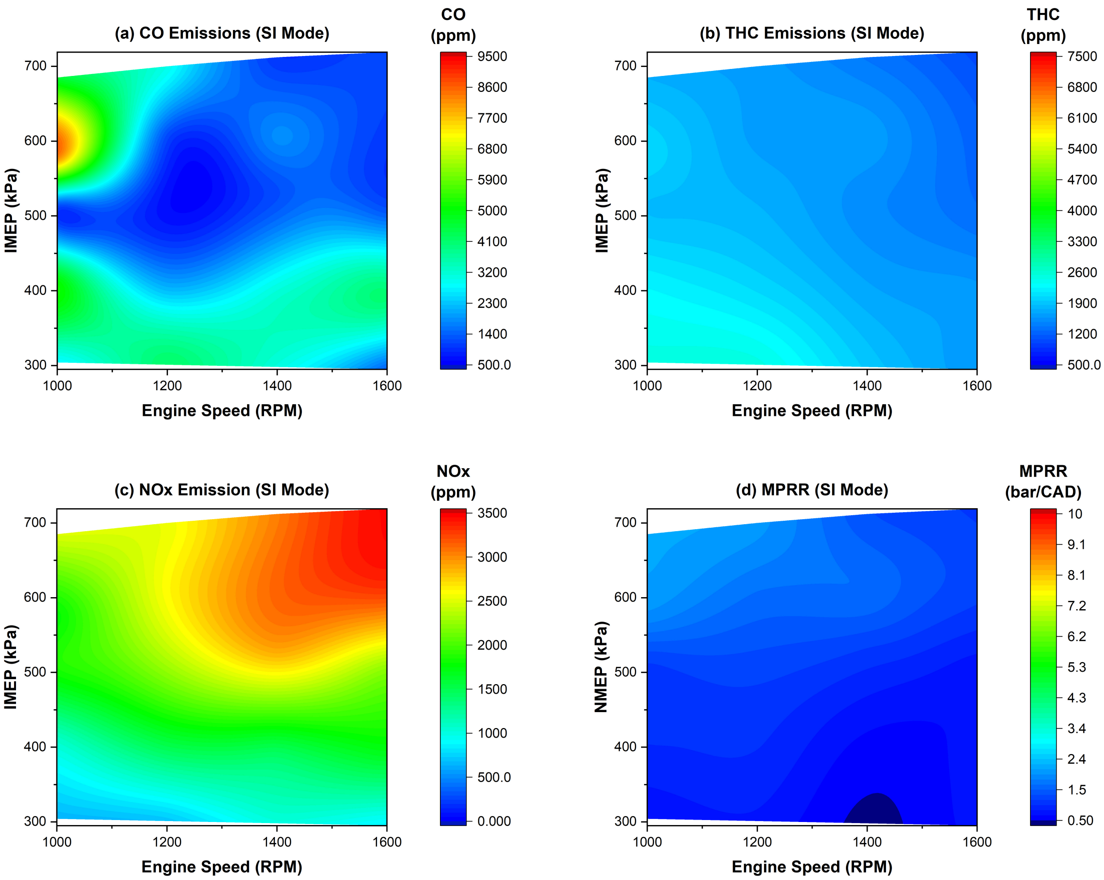

Figure 6.2: CO (ppm), THC (ppm) and NOx (ppm) emissions, and MPRR in SI mode

6.2 Engine Modeling Overview

The multi-mode engine platform is essentially a 2.0 liter 4 cylinder gasoline direct injection (GDI) engine equipped with two-additional sets of port fuel injectors for each cylinder and variable valve timing (VVT). There are four main actuators pertinent to SI mode, RCCI mode, and mode transition engine operation. These actuators include cam phasing, throttle, ignition coil and fuel injection systems. The response

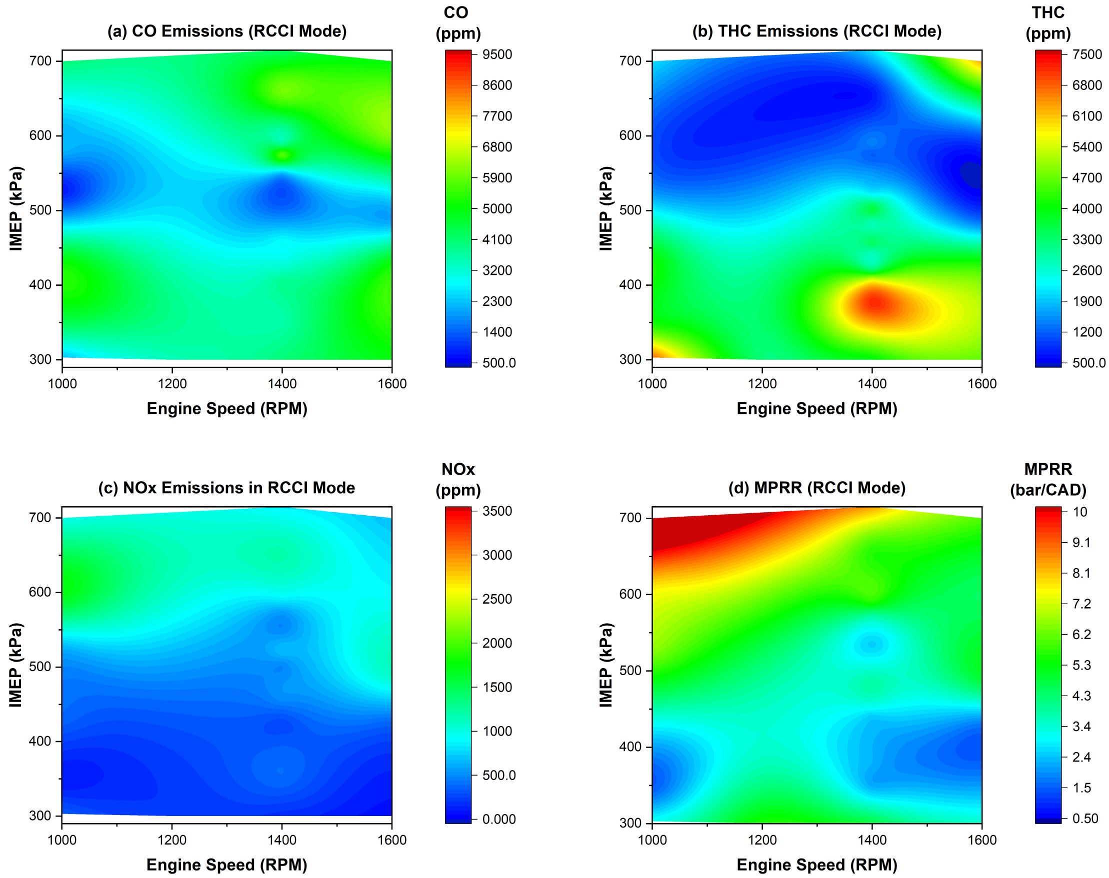

Figure 6.3: CO (ppm), THC (ppm) and NOx (ppm) emissions, and MPRR in RCCI mode

time of these actuators are shown in Fig. 6.4. Spark timing actuation is very fast and can effectively provide cycle-to-cycle control of combustion phasing. Direct injectors have also relatively fast response time. Injection timing is commonly used for cycle-to-cycle control of combustion phasing in LTC modes. VVT and throttle offer high response time which affect mode switching engine operation. To avoid the VVT dynamics during mode transition, the valve timings are changed from the typical SI mode to the phased RCCI mode before the mode switching. The typical and phased

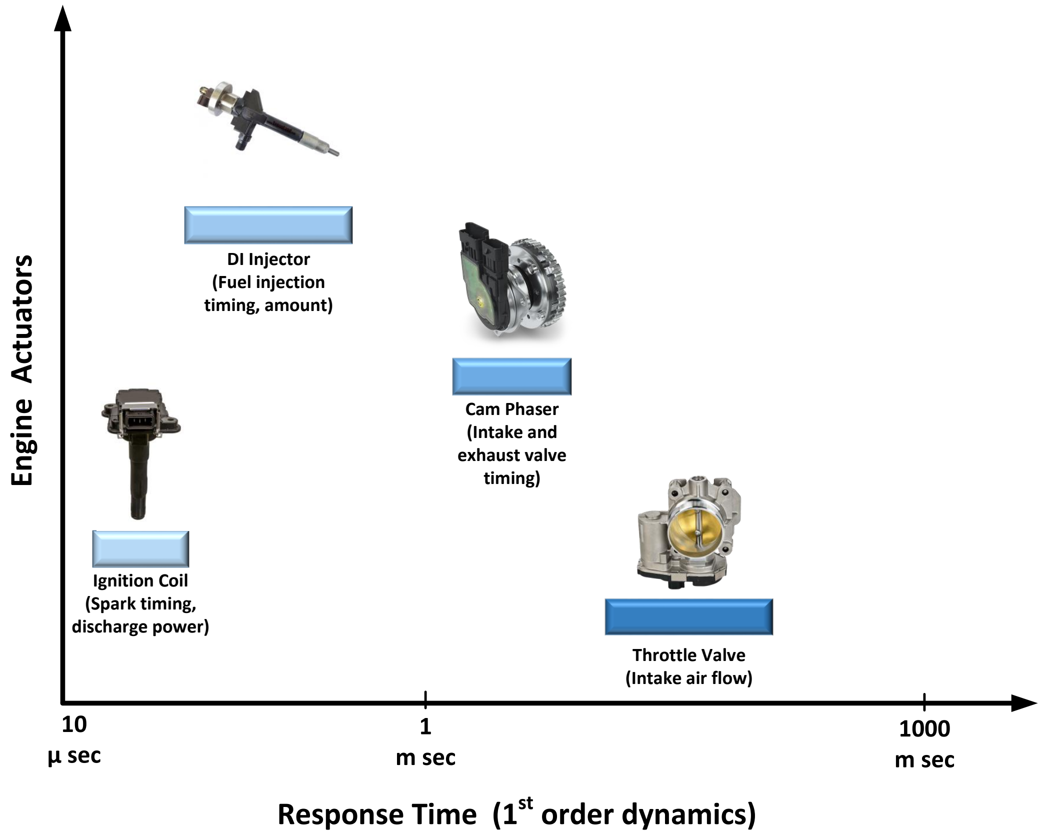

Figure 6.4: Response time of different actuators

valve timings are presented in Table 6.1. However, throttle dynamics is inevitable. Therefore, it is imperative to take throttle dynamics into account.

Table 6.1
Parked and Phased Valve Timings

Valve Timings	Parked	Phased
IVO (CAD bTDC)	-24.5	25.5
IVC (CAD bBDC)	-48	2
EVO (CAD bBDC)	-14	36
EVC (CAD bTDC)	-28	22
Valve Lift (mm)	10.3	10.3

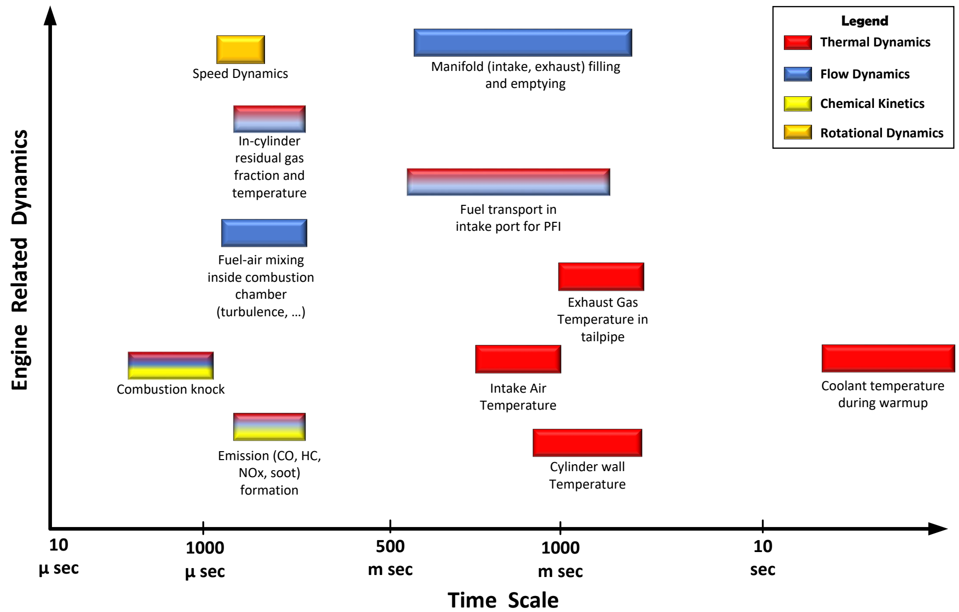

Figure 6.5: Engine dynamics pertinent to SI mode, RCCI mode, and mode switching operation

It is important to consider engine related dynamics into account during control-oriented modeling of mode switching engine operation. In addition, different engine related dynamics The common engine dynamics include thermal dynamics, chemical kinetics and flow dynamics. These engine related dynamics are function of time. Fig. 6.5 shows the prominent dynamics related to SI mode, RCCI mode and mode switching engine operations. Thermal dynamics are the slowest dynamics. Moreover, RCCI mode and SI-RCCI mode switching operation show high sensitivity towards thermal dynamics. Stable RCCI mode and SI-RCCI mode switching operations are achieved after engine warmup and by preheating the intake air. In addition, RCCI mode is achieved at negative valve overlap (NVO) to trap residual gases at the end of engine cycle. RCCI mode is sensitive to the thermodynamic states at IVC. Therefore, residual gas fraction and temperature play a vital role in SI-RCCI mode switching and RCCI mode operation. Hot residual gases from the SI mode often result in advanced combustion in RCCI mode during mode transition. This causes excessive pressure rise rate during mode switching. In addition, auto-ignition of air-fuel mixture in RCCI mode often result in engine knock. RCCI mode produce ultra-low NOx emissions. However, RCCI mode results in high CO and HC emissions. Low exhaust temperatures and lean air-fuel mixing in RCCI mode affect the performance of catalytic converter. In SI mode, high HC, CO and NOx emissions are produced. Intake manifold dynamics is substantial in SI mode and during RCCI-SI mode switching operation. Port fuel transport dynamics also significantly affect SI mode and RCCI to SI mode transitions. Therefore, it is imperative to take the engine dynamics into account during control-oriented modeling of a multi-mode engine.

6.2.1 Throttle Dynamics

In RCCI mode, lean air-fuel mixture is desired. That is why, RCCI mode requires wide open throttle (WOT). However, throttle dynamics plays a significant role during mode switching and it is an important actuator in SI mode to provide stoichiometric air-fuel ratio for the desired load. Throttle is essentially a spring loaded butterfly valve which is actuated with a DC motor via an H-bridge. Due to bidirectional mode switching, throttle response from SI to RCCI mode and from RCCI to SI mode is observed. It takes a few cycles to reach the steady state position from partial open to WOT and vice versa. Throttle dynamics does not significantly affect the transitioning from SI to RCCI mode. However, the throttle response from RCCI to SI mode switching is more critical as it can result in misfired cycles or unstable combustion. Whenever the mode is switched from RCCI to SI mode, throttle valve moves from WOT to the commanded throttle position. It takes at least 3 engine cycles at 1200 RPM to attain the desired throttle position. The first two cycles after mode switching result in a very lean air-fuel mixture; thus, causing misfire and partial burn. Therefore, it is imperative to take throttle dynamics into account

Throttle is modeled as a first order linear system.

$$G(s) = \frac{1}{\tau s + 1} \tag{6.1}$$

where $G(s)$ is the transfer function from input τ is the time constant. τ is defined as the response time to reach 63% of the targeted value. τ is equal to 84ms.

Figure 6.6 shows the throttle dynamics modeled as a first order system, measured throttle response and the commanded position.

In addition, whenever the change in throttle position is commanded from WOT to partial opening below 30%, it takes longer settling time to reach the desired position.

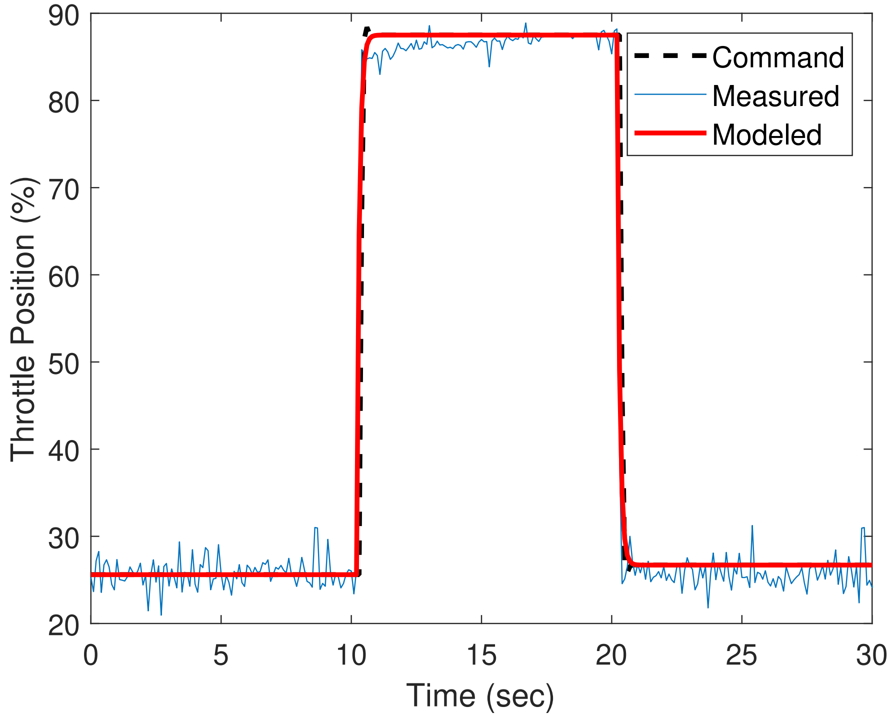

Figure 6.6: Comparison of measured and modeled throttle response

This increases cyclic variations in SI mode. The high idle position of the throttle valve is at 30% opening. Therefore, gain scheduling PI controller is designed to improve the settling time for the throttle valve position above and below 30%. The controller gains are made relatively aggressive for the throttle valve position range of 0-30%.

6.2.2 Fuel Transport Dynamics

Fuel transport dynamics is a significant phenomenon associated with the port fuel injection (PFI). In one cycle, a portion of the fuel injected via PFI vaporizes and enters the cylinder directly in one cycle. The remaining fuel makes a puddle on the surface of intake ports and intake valves. The fuel from the puddle then vaporizes slowly and enters the cylinder. Based on this assumption, the fuel transport dynamics can be represented as a state space $\tau - X$ model [135]. The rate at which fuel evaporates and leaves the puddle is assumed to be proportional to the puddle mass and the evaporation time constant (τ). It is represented as follows:

$$\dot{m}_p = -\frac{1}{\tau}m_p + X\dot{m}_{fi} \tag{6.2}$$

where $\dot{m}_p$ is rate of change of the puddle mass, τ is the evaporation time constant of the fuel, X is the fraction of injected fuel entering the puddle and $\dot{m}_{fi}$ is the rate of fuel injected from PFI. τ and X vary during engine warm up and during transient engine operating conditions. τ is a function of intake manifold pressure, intake manifold temperature and the engine speed. The fraction of fuel directly entering the cylinder is also a function of intake port temperature. The values of τ and X are determined to be 0.7s and 0.635, respectively.

The rate of the fuel entering the cylinders is the sum of rate of fuel entering the cylinder directly and the rate of the fuel leaving the puddle. It is denoted by $\dot{m}_{f,cyl}$.

$$\dot{m}_{f,cyl} = \frac{1}{\tau}m_p + (1 - X)\dot{m}_{fi} \tag{6.3}$$

The port fuel dynamics can be modeled as follows:

$$G(s) = \frac{\dot{m}_{f,cyl}}{\dot{m}_{fi}} = \frac{(1-X)s + \frac{1}{\tau}}{s + \frac{1}{\tau}} \tag{6.4}$$

6.2.3 Lambda Sensor Model

In order to maintain stoichiometric air-fuel ratio in SI mode and during RCCI-SI mode switching, it is important to consider the measurement dynamics and transport delay of the lambda sensor. Lambda sensor is mounted on the exhaust pipe after exhaust manifold. Exhaust gases take finite amount of time to reach the lambda sensor. The measurement dynamics and transport delay associated with the lambda sensor can be modeled as a first order dynamic system lag and exhaust gas transport time delay. The exhaust gas transport time delay is denoted by T_L while the sensor lag is represented by τ_m. Equation 6.5 shows the transfer function for lambda sensor model in Laplace domain.

$$G_L(s) = \frac{K_p e^{-sT_L}}{\tau_m s + 1} \tag{6.5}$$

where G_L is represents the lambda sensor model and K_p is the gain. The input to the model is the air-fuel ratio input to the cylinders and output of the model is the measured air-fuel ratio. The parameters T_L and τ_m depend on the engine speed and load. System identification is used to determine the parameters K_p, T_L and τ_m from

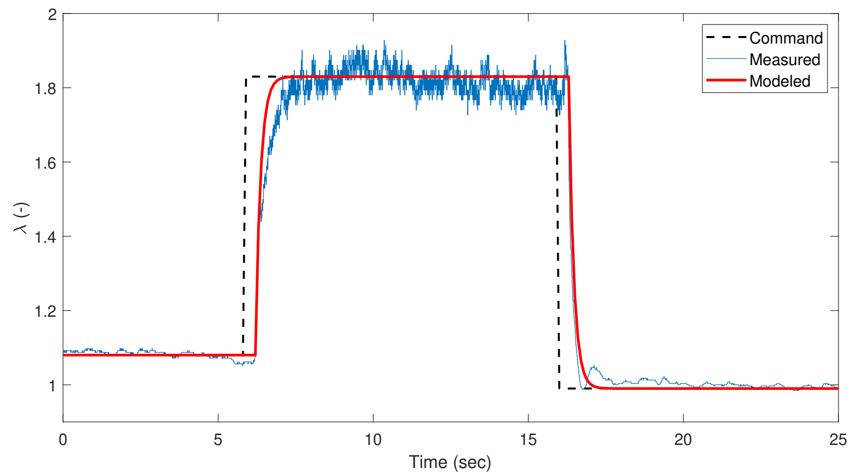

Figure 6.7: Comparison of Lambda sensor model response with the measured data

the measured data at engine speed of 1200 RPM. The model is parameterized by providing the input air-fuel ratio for SI-RCCI-SI mode switching. The values of K_p, T_L and τ_m are determined to be 1, 0.3s and 0.22s, respectively. Figure 6.7 shows the comparison of modeled lambda response to the actual lambda sensor measurements for different engine loads.

6.3 Dynamic Modeling of a Multi-Mode Engine

Dynamic model of the SI-RCCI-SI mode switching is developed for the entire engine cycle from intake valve opening (IVO) to exhaust valve closing (EVC) events. Based on the requested speed and load, the optimal mode is selected. This study is based on SI-RCCI-SI mode switching, that is why, the particular mode offering the lowest SFC is first selected from the engine map as shown in Fig. 6.1. Mode 1 and 2 represent SI and RCCI, respectively. After mode selection, the engine is run in the desired mode. Throttle dynamics and VVT dominantly affect the mode switching. Therefore, valve timings are adjusted in the SI mode prior to the mode switching to minimize the fluctuations in engine load. Combustion in SI mode is not significantly affected by cycle to cycle coupling of the residual gases trapped in the cylinder. However, RCCI mode is greatly affected by the cyclic coupling and the temperature and pressure at the IVC. Furthermore, the combustion temperatures are relatively higher in SI mode as compared to RCCI mode which results in higher temperature of the trapped residual gases and the cylinder wall at the end of SI cycle. This in turn increase the temperature of the mixture at the IVC and result in advanced combustion for the first few cycles after SI to RCCI mode switch. For RCCI to SI mode switching, SI mode is not much affected by lower exhaust gas temperature and lower cylinder wall temperature. However, throttle and intake manifold dynamics may cause misfire or partial burn cycles. In addition, the control actuators to control combustion phasing (CA50) are different in SI and RCCI modes. In SI mode, optimal combustion phasing (CA50) is achieved by adjusting the spark timing. However, start of injection (SOI) timing and premixed ratio of the dual fuels modulate CA50 and MPRR in RCCI mode. Similarly, throttle position is adjusted such that stoichiometric air-to-fuel ratio ($\lambda = 1$) is maintained in the SI mode. However, RCCI mode is achieved at WOT. Therefore, SI and RCCI models are developed to account for the cycle to cycle coupling, actuator dynamics and process dynamics in SI-RCCI-SI mode switching.

Before going into the details of dynamic modeling, following assumptions are made:

- The mixture is treated as an ideal gas.
- The rate of change of temperature in the intake manifold is negligible
- Cylinder to cylinder variations are ignored and average flows are considered.
- The specific heat of the air during intake and compression strokes are considered as that of atmospheric air. However, the specific heat of the mixture after combustion are determined by considering an appropriate combustion temperature.

6.3.1 SI Model

SI model includes the modeling of intake manifold dynamics and the entire engine cycle starting from intake valve opening (IVO) to exhaust valve closing (EVC).

6.3.1.1 Manifold Dynamics and Flow Restrictions

The air is assumed to be an ideal gas, therefore, it is described by the ideal gas law:

$$P_{man}V_i = m_i R T_{man} \tag{6.6}$$

where P_{man} is the intake manifold pressure, V_i is the intake manifold volume, m_i is the mass of air in the intake manifold, R is the gas constant, and T_{man} is the intake manifold temperature.

Assuming negligible change in the intake manifold temperature, the time derivative of the Eq. 6.6 can be written as:

$$\frac{dP_{man}}{dt} = \frac{RT_{man}}{V_i}\frac{dm_i}{dt} \tag{6.7}$$

The rate of change of mass of air in the intake manifold is the difference of air flow rate through the throttle and the air flow into the cylinder. It can be written as follows:

$$\frac{dm_i}{dt} = \dot{m}_{th} - \dot{m}_{cyl} \tag{6.8}$$

where $\dot{m}_{th}$ is the air flow rate (g/s) through the throttle and $\dot{m}_{cyl}$ is the air flow rate entering the cylinder (g/s) .

The air flow rate through the throttle is modeled using the modified orifice equation for compressible flow.

$$\dot{m}_{th} = A_{eff}\frac{P_{man}}{\sqrt{RT_{man}}}\phi \tag{6.9}$$

$$\phi = \begin{cases} \sqrt{\gamma(\frac{2}{\gamma+1})^{\frac{\gamma+1}{\gamma-1}}} & \frac{P_o}{P_i} < (\frac{2}{\gamma+1})^{\frac{\gamma}{\gamma-1}} \\ (\frac{P_o}{P_i})^{\frac{1}{\gamma}} \sqrt{\frac{2\gamma}{\gamma-1}(1-(\frac{P_o}{P_i})^{\frac{\gamma-1}{\gamma}})^{\frac{\gamma-1}{\gamma}}} & \frac{P_o}{P_i} \geq (\frac{2}{\gamma+1})^{\frac{\gamma}{\gamma-1}} \end{cases}$$

where γ is the specific heat ratio, P_o is outlet pressure, P_i is the inlet pressure, A_{eff} is the effective area with respect to the valve position. A_{eff} is estimated using the following correlation:

$$A_{eff} = (a_1 P_{man} + a_2 P_{man}^{a_3} + a_4 U_{th}/100 + a_5)a_6 \tag{6.10}$$

where U_{th} is the throttle valve position and P_{man} is the intake manifold pressure in bar.

The air flow rate entering the cylinder is given as:

$$\dot{m}_{cyl} = \frac{\eta \rho_i V_d N}{2} \tag{6.11}$$

where η is the volumetric efficiency of the engine, ρ_i is the density of air, V_d is the displacement volume, and N is the engine speed. Substituting Eq. 6.8 and 6.11 into Eq. 6.7:

$$\frac{dP_{man}}{dt} = -\frac{\eta V_d N}{2V_i} P_{man} + \frac{RT_{man}}{V_i} \dot{m}_{th} \tag{6.12}$$

Volumetric efficiency is given by:

$$\eta = \frac{2\dot{m}_{cyl}/N}{P_{man}V_d/(RT)} \tag{6.13}$$

Volumetric efficiency is a nonlinear function of intake manifold pressure, speed, valve area, lift, and timing [139]. This can be reduced to a simple function of the intake manifold pressure [158] and defined in terms of η_s:

$$\eta = \frac{P_{atm}}{P_{man}}\eta_s \tag{6.14}$$

where P_{atm} is the atmospheric air pressure.

$$\eta_s = aP_{man} + b \tag{6.15}$$

where a and b are the parameters to be determined. Substituting Eq. into Eq. 6.11

$$\dot{m}_{cyl} = \frac{P_{atm}}{P_{man}}\eta_s\frac{V_dN}{2RT}P_{man} \tag{6.16}$$

Simplifying Eq. gives the following:

$$\dot{m}_{cyl} = \frac{P_{atm}V_dN}{2RT}(aP_{man} + b) \tag{6.17}$$

Parameters a and b are determined using regression to estimate the air mass flow rate entering the cylinder.

Mass of intake air (m_{air}) is determined using the following:

$$m_{air} = \frac{120\dot{m}_{cyl}}{N_{cyl}N} \tag{6.18}$$

where N_{cyl} is the total number of cylinders.

6.3.1.2 Cylinder Charge Conditions at IVC

Pressure and temperature of the air-fuel mixture at IVC for both combustion modes are estimated using Eq. (6.19) and Eq. (6.20), respectively. To incorporate cycle to cycle coupling, the temperature at IVC is calculated by taking the residual gas fraction and the residual gas temperature into account.

$$P_{\text{ivc}} = \alpha P_{man} + \beta \tag{6.19}$$

$$T_{ivc} = (1 - X_{rg})T_{man} + X_{rg}T_{rg} \tag{6.20}$$

where N is engine speed, $\mathrm{P_{ivc}}$ is pressure at intake valve closing, $\mathrm{U_{th}}$ is the throttle position, $\mathrm{T_{man}}$ is the intake air temperature, $\mathrm{T_{rg}}$ is the residual gas temperature and

X_{rg} is the residual gas fraction. X_{rg} is estimated using Eq. (6.41), [116]:

$$X_{rg} = \overbrace{\sqrt{\frac{1}{C}.\frac{\pi\sqrt{2}}{360}.\frac{r_c-1}{r_c}.\frac{OF}{N}.\sqrt{\frac{RT_{man}|P_{exh}-P_m|}{P_{exh}}}.\quad(\frac{P_{exh}}{P_m})^{\frac{k_c+1}{k_c}}}}^{\alpha_1} + \overbrace{\frac{1}{C}.\frac{r_c-1}{r_c}.\phi_{tot}\frac{V_{ivo}}{V_d}.(\frac{P_{exh}}{P_m})^{\frac{1}{k_c}}}^{\alpha_2} \tag{6.21}$$

where OF is overlap factor, r_c is compression ratio, R is gas constant, and V_d is displaced volume. C is given by the following:

$$C = \left[1 + \frac{LHV}{c_v T_{man}\frac{m_t}{m_f}.r_c^{k_c-1}}\right]^{\frac{1}{k_c}} \tag{6.22}$$

where m_f is the mass of fuel injected and m_t is the sum of mass of air and mass of fuel. OF is the function of intake and exhaust valve diameters and lifts. The first term (α_1) in Eq. 6.41 accounts for the backflow of charge from the exhaust port into the cylinder during valve overlap period. The second term (α_2) accounts for the residual mass trapped in the cylinder at IVO [159]. In order to determine the OF, simulations are run in GT-POWER for different valve timings to obtain X_{rg}. OF is then determined from the Eq. 6.41 using the X_{rg} obtained from simulations for the valve timings of SI and RCCI operation.

6.3.1.3 Polytropic Compression and Start of Combustion

Ignition timing in homogeneous SI engine typically employs a map-based control algorithm strategy which needs substantial calibration efforts [160]. Heat release in SI mode can be divided into two stages. The first stage of heat release is the early flame development stage which is the time duration from ignition timing to the start of combustion (SOC). The second stage of heat release is the rapid burning stage which is duration from SOC to the time when the bulk of air-fuel charge is burned [160]. Different modeling approaches have been adopted to model combustion process in SI engine. These include 0-D combustion models, 3-D combustion models, physics-based combustion models and empirical combustion models. In this study, an empirical modeling approach is adopted to estimate SOC. SOC is defined as the crank angle where 10% of mass fraction is burned. SOC is given by the following empirical model:

$$SOC = a_1 + a_2 P_{man} + a_3 U_{th} + a_4 P_{man} U_{th} + a_5 \Delta U_{sp} \tag{6.23}$$

where a_1, a_2, a_3, a_4, and a_5 are parameters obtained by regression. U_{th} is the throttle valve position and ΔU_{sp} is the spark timing with respect to the spark timing of 40 CAD bTDC. a_1 is a function of engine speed given by Eq. (6.24):

$$a_1 = 30.35 - 0.16N + 5.8N^{0.56} \tag{6.24}$$

Temperature (T_{soc}) and pressure (P_{soc}) at SOC are determined using polytropic relationship, given by Eq. (6.25) and Eq. (6.26):

$$T_{soc} = T_{ivc}\left(\frac{V_{ivc}}{V_{soc}}\right)^{k_c-1} \tag{6.25}$$

$$P_{soc} = P_{ivc}\left(\frac{V_{ivc}}{V_{soc}}\right)^{k_c} \tag{6.26}$$

where $\mathrm{k_c}$ is the polytropic index of compression. $\mathrm{V_{ivc}}$ and $\mathrm{V_{soc}}$ are the volumes at intake valve closing and start of combustion, respectively.

6.3.1.4 Combustion Phasing

Combustion phasing (CA50) is defined as the crank angle by which 50% of the fuel mass is burned. Mass fraction burned rate can be represented by Wiebe function. It is essentially a function of crank angle, burn duration and start of combustion. Wiebe function is given by:

$$x_b\left(\theta\right) = 1 - exp\left(-a\left[\frac{\theta - \theta_{soc}}{\theta_d}\right]^n\right) \tag{6.27}$$

where a and n are the constants determined by parameterizing the Weibe function. θ_{soc} is the crank angle at start of combustion, θ_{d} is the burn duration. CA50 can be determined by parameterizing the Wiebe function. θ_{d} estimated by using the following correlation:

$$\theta_d = b_1 + b_2 P_{man} + b_3 T_{ivc} \tag{6.28}$$

CA50 can also be estimated from start of combustion and burn duration using Eq. 6.29.

$$CA50 = SOC + 0.5\theta_d \tag{6.29}$$

Temperature at the end of combustion is determined by adding T_{soc} and the temperature rise due to the combustion of air-fuel mixture, using Eq.(6.30).

$$T_{eoc} = T_{soc} + \Delta\ \mathrm{T_{comb}} \tag{6.30}$$

where ΔT_{comb} is the temperature increase due to the combustion of fuel.

$$\Delta T_{comb} = \frac{\eta_c LHV_f}{m_{total} c_v} \tag{6.31}$$

where LHV_f is the lower heating value of fuel, η_c is combustion efficiency, m_{total} is total mass of in-cylinder charge, and c_v is the specific heat at constant volume.

Pressure at the end of combustion is determined as follows:

$$P_{eoc} = m_{total} R_{comb} \frac{T_{eoc}}{V_{eoc}} \tag{6.32}$$

where R_{comb} is the gas constant and V_{eoc} is the volume at end of combustion. m_{total} is the mass of air (m_{air}), mass of fuel (m_f) and mass of residual gases in the cylinder. m_{total} is given by:

$$m_{total} = \frac{m_{air} + m_f}{(1 - X_{rg})} \tag{6.33}$$

6.3.1.5 Polytropic Expansion and End of Cycle Outputs

Pressure and temperature at the end of expansion stroke are calculated using polytropic relationship, as shown in Eq. (6.34) and Eq. (6.35), respectively.

$$P_{evo} = \ P_{eoc} \left(\frac{V_{eoc}}{V_{evo}} \right)^{k_e} \tag{6.34}$$

$$T_{evo} = \ T_{eoc} \left(\frac{V_{eoc}}{V_{evo}} \right)^{k_e - 1} \tag{6.35}$$

where k_e is the polytropic index of expansion, while V_{evo} and V_{evc} are the volumes at end of combustion (EOC) and exhaust valve opening (EVO), respectively. Temperature of the in-cylinder charge at exhaust valve closing (EVC) is calculated using Eq. (6.36):

$$T_{evc} = T_{evo} \left(\frac{V_{evo}}{V_{evc}} \right)^{k_e - 1} \tag{6.36}$$

where T_{evc} is the temperature at EVC, V_{evo} and V_{evc} in Eq. (6.58) are the volumes at EVO and EVC, respectively. *IMEP* is calculated using Eq. (6.37). m_t is the sum of mass of air, fuel and residual gases.

$$IMEP = m_t \frac{c_v}{V_{dis}} \left(T_{ivc} - T_{soc} \ + T_{eoc} - T_{evc}\right) \tag{6.37}$$

Net mean effective pressure (NMEP) is calculated by subtracting pumping mean effective pressure from gross indicated mean effective pressure, given by:

$$NMEP = IMEP - \left(P_{exh} - P_{man}\right) \tag{6.38}$$

where P_{exh} is the exhaust pressure.

6.3.2 RCCI Model

6.3.2.1 Cylinder Charge States at IVC

The dynamic model for RCCI mode includes the IVO to EVC events. Pressure and temperature of the air-fuel mixture at IVC for both combustion modes are estimated using Eq. (6.39) and Eq. (6.40), respectively. To incorporate cycle to cycle coupling, the temperature at IVC is calculated by taking the residual gas fraction and the residual gas temperature into account.

$$P_{\text{ivc}} = \alpha P_{man} + \beta \tag{6.39}$$

$$T_{ivc} = (1 - X_{rg})T_{man} + X_{rg}T_{rg} \tag{6.40}$$

where N is engine speed, P_{ivc} is pressure at intake valve closing, U_{th} is the throttle position, T_{man} is the intake air temperature, T_{rg} is the residual gas temperature and X_{rg} is the residual gas fraction. X_{rg} is estimated using Eq. (6.41), [116]:

$$X_{rg} = \overbrace{\sqrt{\frac{1}{C}.\frac{\pi\sqrt{2}}{360}.\frac{r_c - 1}{r_c}.\frac{OF}{N}.\sqrt{\frac{RT_{man}|P_{exh} - P_m|}{P_{exh}}}.\quad (\frac{P_{exh}}{P_m})^{\frac{k_c+1}{k_c}}}}^{\alpha_1} + \overbrace{\frac{1}{C}.\frac{r_c - 1}{r_c}.\phi_{tot}\frac{V_{ivo}}{V_d}.(\frac{P_{exh}}{P_m})^{\frac{1}{k_c}}}^{\alpha_2} \tag{6.41}$$

where OF is overlap factor, r_{c} is compression ratio, R is gas constant, and V_{d} is displaced volume. C is given by the following:

$$C = \left[1 + \frac{LHV}{c_v T_{man}\frac{m_t}{m_f}.r_c^{k_c - 1}}\right]^{\frac{1}{k_c}} \tag{6.42}$$

where m_f is the mass of fuel injected and m_t is the sum of mass of air and mass of fuel. OF is the function of intake and exhaust valve diameters and lifts.

6.3.2.2 Polytropic Compression and Start of Combustion

The air-fuel mixture undergoes auto-ignition in the LTC modes [134]. Start of combustion (SOC) is defined as crank angle where 10% of fuel mass is burned. SOC is estimated using a modified knock integral model. The integral of MKIM is divided into two parts to incorporate the effects of both PFI and DI as shown in Eq.(6.43) [21]. The first part (β_1) in Eq. (6.43) is the integration of MKIM from IVC to SOI incorporating the fuel injected via PFI during the stroke and the second part (β_2) in Eq. (6.43) integrates the fuel injected via DI into the model to determine SOC.

$$\overbrace{\int_{\theta_{ivc}}^{\theta_{soi}} \frac{d\theta}{B_1 \phi_{PFI}^{A_1} exp\left(\frac{C_1 \left(P_{ivc,k+1} v_c^k\right)^{D_1}}{T_{ivc} V_c^k c^{-1}}\right) N_k}}^{\beta_1} + \overbrace{\int_{\theta_{soi}}^{\theta_{soc}} \frac{d\theta}{B_2 (\phi_{PFI}^{A_2} + \phi_{DI}^{A_3}) exp\left(\frac{\left(P_{ivc,k+1} v_c^k\right)^{D_2}}{T_{ivc} V_c^k c^{-1}}\right) (\frac{C_2}{E_1 PR + E_2}) N_k}}^{\beta_2} = 1 \tag{6.43}$$

$$\phi_{DI} = (1 - PR)\phi \tag{6.44}$$

$$\phi_{PFI} = PR\phi \tag{6.45}$$

where A_1, A_2, A_3, B_1, B_2, C_1, C_2, D_1, D_2, E_1 and E_2 are the parameters estimated by calibrating the MKIM for the RCCI mode. ϕ_{PFI} and ϕ_{DI} are the equivalence ratios of iso-octane and n-heptane, respectively. ϕ_{PFI} and ϕ_{DI} are determined using Eq. 6.44 and Eq. 6.45. v_c is given by:

$$v_c = \frac{V_{ivc}}{V(\theta)} \tag{6.46}$$

where $V(\theta)$ is the volume of cylinder at crank angle (θ).

Pressure (P_{soc}) and temperature (T_{soc}) at start of combustion are calculated using a polytropic relationship, using Eq. (6.47) and Eq. (6.48).

$$P_{soc} = P_{ivc} \left(\frac{V_{ivc}}{V_{soc}} \right)^{k_c} \tag{6.47}$$

$$T_{soc} = T_{ivc} \left(\frac{V_{ivc}}{V_{soc}} \right)^{k_c - 1} \tag{6.48}$$

where k_c is the polytropic index of compression. V_{ivc} and V_{soc} are the volumes at intake valve closing and start of combustion, respectively.

6.3.2.3 Combsution Phasing

Weibe function is parameterized for the estimation of CA50, using Eq. (6.49). CA50 is defined as the crank angle by which 50% of the fuel mass is burned.

$$x_{b,RCCI}\left(\theta\right) = 1 - exp\left(-a\left[\frac{\theta - \theta_{soc}}{\theta_d}\right]^n\right) \tag{6.49}$$

where a and n are the constants determined by parameterizing the Weibe function. θ_{d} is the burn duration estimated by using Eq. (6.50).

$$\theta_d = f(T_{ivc}, PR, SOI, m_f) \tag{6.50}$$

The correlation in Eq. 6.50 is defined as follows:

$$f(T_{ivc}, PR, SOI, m_f) = z_1 T_{ivc} + z_2 PR + z_3 SOI + z_4 m_f + z_5 \tag{6.51}$$

where z_2 is the function of PR.

$$z_2 = \alpha_1 + \alpha_2 PR + \alpha_3 PR^{c_4} \tag{6.52}$$

Equations 6.43, 6.49 and 6.51 are parameterized over the engine speed range of 1000-1600 rpm.

Temperature at the end of combustion (T_{eoc}) is calculated from the temperature rise due to the fuel burned during combustion, using Eq.(6.53).

$$T_{eoc} = T_{soc} + \Delta\ \mathrm{T} \tag{6.53}$$

$$\Delta T_{comb} = \frac{LHV_f CoC}{m_{total} c_v} \tag{6.54}$$

$$P_{eoc} = \frac{P_{soc} V_{eoc}}{V_{eoc}} \frac{T_{eoc} R_{eoc}}{T_{soc} R_{soc}} \tag{6.55}$$

where CoC is the completeness of combustion.

6.3.2.4 Polytropic Expansion and End of Cycle Outputs

Pressure and temperature at the end of expansion stroke are calculated using polytropic relationship, as shown in Eq. (6.56) and Eq. (6.57), respectively.

$$P_{evo} = \ P_{eoc} \left(\frac{V_{eoc}}{V_{evo}} \right)^{k_e} \tag{6.56}$$

$$T_{evo} = \ T_{eoc} \left(\frac{V_{eoc}}{V_{evo}} \right)^{k_e - 1} \tag{6.57}$$

where k_e is the polytropic index of expansion, while V_{evo} and V_{evc} are the volumes at EOC and EVO, respectively. Temperature of the in-cylinder charge at exhaust valve closing (EVC) is calculated using Eq. (6.58):

$$T_{evc} = T_{evo}\left(\frac{V_{evo}}{V_{evc}}\right)^{k_e-1} \tag{6.58}$$

where T_{evc} is the temperature at EVC, V_{evo} and V_{evc} in Eq. (6.58) are the volumes at EVO and EVC, respectively. The mass of residual gases (m_{evc}) trapped in the cylinder at EVC is calculated using Eq. (6.59)

$$m_{evc} = \frac{P_{exh}V_{evc}}{R_{evc}T_{evc}} \tag{6.59}$$

where P_{exh} is the exhaust pressure, V_{evc}, T_{evc} and R_{evc} are the volume, temperature and gas constant at EVC, respectively. *IMEP* is calculated using Eq. (6.60) [83]. m_t is the sum of mass of air, fuel and residual gas fraction of the current cycle.

$$IMEP = m_t\frac{c_v}{V_{dis}}\left(T_{ivc} - T_{soc} + T_{eoc} - T_{evc}\right) \tag{6.60}$$

6.3.2.5 Maximum Pressure Rise Rate Modeling

Auto-ignition in low temperature combustion may result in abrupt heat release rate with short burn duration which leads to very high pressure rise rates. Therefore, it is important to regulate maximum pressure rise rate below safe limits to avoid engine knocking. Pressure rise rate is modeled using first law of thermodynamics given by

Eq. 6.61:

$$\frac{dQ_n}{d\theta} - P\frac{dV}{d\theta} = \frac{dU}{d\theta} \tag{6.61}$$

where P is in-cylinder pressure, V is the cylinder volume, and U is the internal energy. $dQ_n/d\theta$ is the net apparent heat release rate.

$$\frac{dU}{d\theta} = mc_v\frac{dT}{d\theta} \tag{6.62}$$

where m is the mass of working fluid in the cylinder, c_v is specific heat at constant volume, T is the temperature.

Applying the ideal gas law:

$$\frac{dP}{P} + \frac{dV}{dV} = mR\frac{dT}{T} \tag{6.63}$$

where R is specific gas constant. By substituting Eq. 6.62 and 6.63 into Eq. 6.61

$$\frac{dQ_n}{d\theta} = (1 + \frac{c_v}{R})P\frac{dV}{d\theta} + \frac{c_v}{R}V\frac{dP}{d\theta} \tag{6.64}$$

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma - 1}P\frac{dV}{d\theta} + \frac{1}{\gamma - 1}V\frac{dP}{d\theta} \tag{6.65}$$

where γ is the specific heat ratio.

Q_n is the difference between the energy content of the fuel (Q_{ch}) and heat transfer from the system (Q_{ht}).

$$\frac{dQ_n}{d\theta} = \frac{dQ_{ch}}{d\theta} - \frac{dQ_{ht}}{d\theta} \tag{6.66}$$

The normalized heat release rate can be determined from the mass fraction burn rate using Wiebe function. It is given by:

$$\frac{Q(\theta)}{Q_{total}} = \begin{cases} 0, & \text{for} \theta < \theta_{soc} \\ 1 - exp(-a(\frac{\theta - \theta_{soc}}{\theta_d})^{m+1}), & \text{for} \theta \geq \theta_{soc} \end{cases}$$

where Q_{total} is the total energy content of fuel. It is given by:

$$Q_{total} = \eta_c m_f LHV \tag{6.67}$$

where m_f is mass of fuel and LHV is the lower heating value of fuel. The heat transfer rate $dQ_{ht}/d\theta$ is given by:

$$\frac{dQ_{ht}}{d\theta} = \frac{h_c A}{60N}(T - T_w) \tag{6.68}$$

where, N is the engine speed, A is the area of combustion chamber, T_w is the cylinder wall temperature, and h_c the convective heat transfer coefficient. Woschni correlation is used to compute h_c:

$$h_c = 3.26B^{-0.2}P^{0.8}T^{-0.55}\omega^{0.8} \tag{6.69}$$

where, B is the cylinder bore and ω is the mean piston gas velocity.

$$\omega = C_1 S_p + C2\frac{V_d T_{soc}}{P_{soc}V_{soc}}(P - P_m) \tag{6.70}$$

where V_d is the displacement volume, P is the instantaneous in-cylinder pressure, P_m is the motoring pressure, P_{soc}, T_{soc} and V_{soc} are the pressure, temperature and volume at start of combustion, C_1 and C_2 are the constants associated to the engine strokes, and S_p is the mean piston speed.

Support vector machine (SVM) algorithm is also used to model MPRR in RCCI mode. SVM is used to mode MPRR due to the following reasons:

- Wiebe model is parameterized for different ranges of SOI which makes it difficult to use for control purposes

- MPRR prediction accuracy of the physics based model is relatively low.
- MPRR data for RCCI mode is available for over 700 different operating conditions.
- SVM provided better prediction accuracy. It is computationally inexpensive and easy to use for control purposes.

MPRR is an important parameter to be controlled in RCCI mode. Therefore, support vector machine algorithm is used to improve the prediction accuracy for better cycle-to-cycle control. SVM is a machine learning algorithm which can be used for regression and classification. The method is explained in detail in Section 5.7.2. SVM regression technique is used to model MPRR using CA50, SOI, PR and FQ as features. The model is trained using second order polynomial kernel function.

$$K(x_i, x_j) = (1 + (x_i, x_j))^2 \tag{6.71}$$

The hyperparameters are optimized for better accuracy using 5-fold cross validation. The model can predict MPRR with accuracy of 0.4 bar/CAD for SOI range of 30-80 CAD (bTDC), PR range of 10-40, and engine speed range of 1000-1600 RPM.

6.4 Model Validation

6.4.1 SI Model Validation

SI model is calibrated for different operating conditions for engine speed range of 1000-1600 RPM. The model is validated for 35 different steady state conditions. Figure 6.8 shows the prediction of start of combustion (SOC) for SI mode. The average error in predicting SOC is 0.9 CAD. Figure 6.9 shows the estimation of burn duration (θ_d) for SI model with an average error of 1 CAD. Figure 6.10 shows the prediction of CA50 for different operating conditions. The average error in predicting CA50 is 0.4 CAD. The net mean effective pressure (NMEP) model predictions are shown in Fig. 6.11. The average error in predicting NMEP is 10 kPa.

Figure 6.12 shows the comparison of maximum pressure rise rates observed in SI mode and the model response. The average error observed in predicting MPRR is 0.4 bar/CAD.

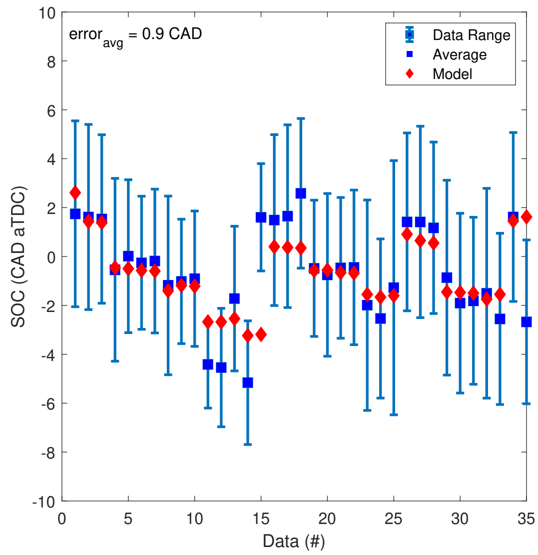

Figure 6.8: SOC model validation for different steady state conditions in SI mode

6.4.2 RCCI Model Validation

RCCI model is calibrated for different operating conditions for engine speed ranging from 1000-1600 RPM. The model is validated for 35 different steady state conditions for PR ranging between 10-40 (-) and SOI ranging between 30-80 (CAD bTDC). Figure 6.13 shows the prediction of start of combustion (SOC) using modified knock integral model. The error bars show the experimental data and the corresponding average SOC. The average error in predicting SOC is 1.8 CAD. Figure 6.14 shows the estimation of burn duration (θ_d) for RCCI model with an average error of 2.8 CAD. Figure 6.15 shows the prediction of CA50 using Wiebe function for different operating conditions. The average error in predicting CA50 is 1 CAD. The net mean

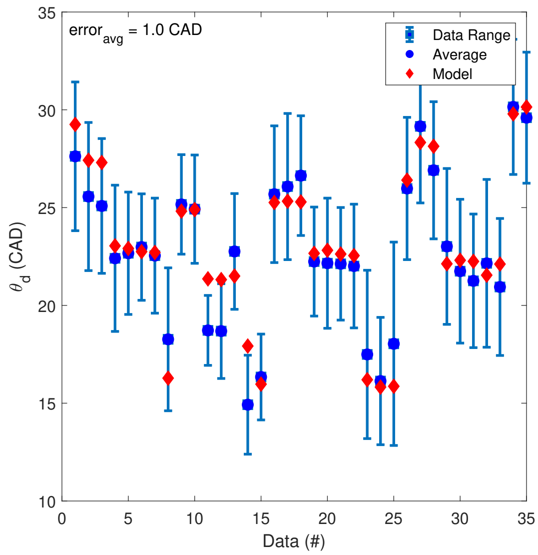

Figure 6.9: θ_d model validation for different steady state conditions in SI mode

effective pressure (NMEP) model predictions are shown in Fig. 6.16. The average error in predicting NMEP is 35 kPa.

Figure 6.17 shows the comparison of experimental data, MPRR model using Wiebe function and SVM model. The average error between measured MPRR and Wiebe model predictions is 1.6 bar/CAD. However, the average error for SVM model is 0.4 bar/CAD.

6.4.3 Model Validation for SI-RCCI-SI Mode Switching

SI and RCCI dynamic models are combined together to develop a control oriented model for mode switching. The SI-RCCI-SI mode switching model is validated against

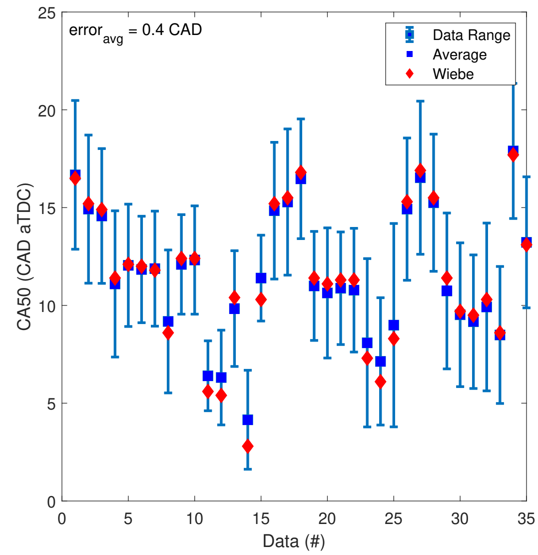

Figure 6.10: CA50 model validation for different steady state conditions in SI mode

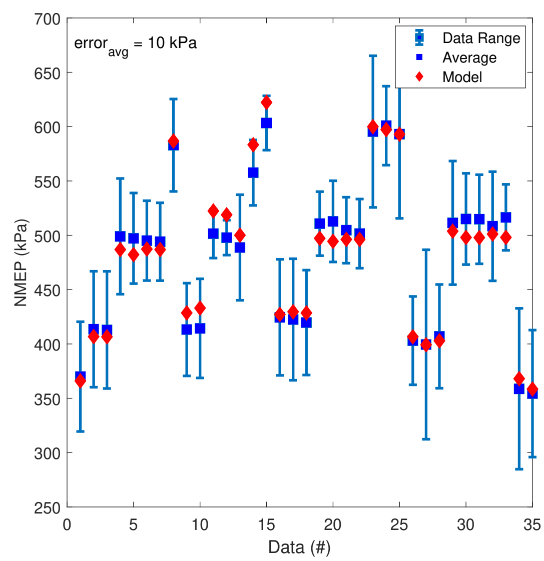

Figure 6.11: NMEP model validation for different steady state conditions in SI mode

the open-loop mode switching experimental data. Open-loop mode switching is carried out by presetting the fuel quantity, premixed ratio, SOI, throttle position and

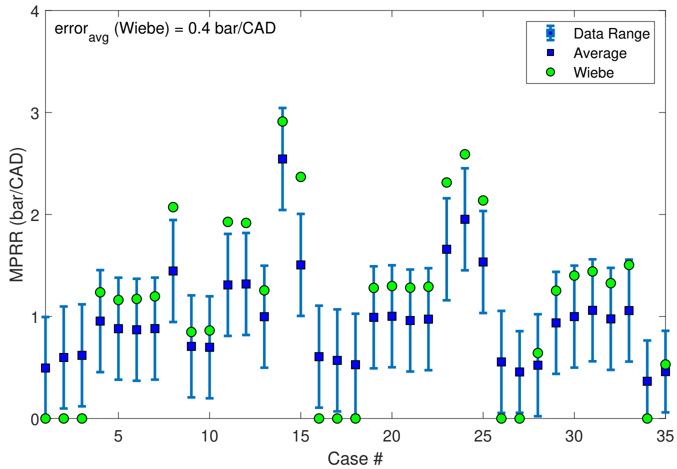

Figure 6.12: MPRR model validation for different steady state conditions in SI mode

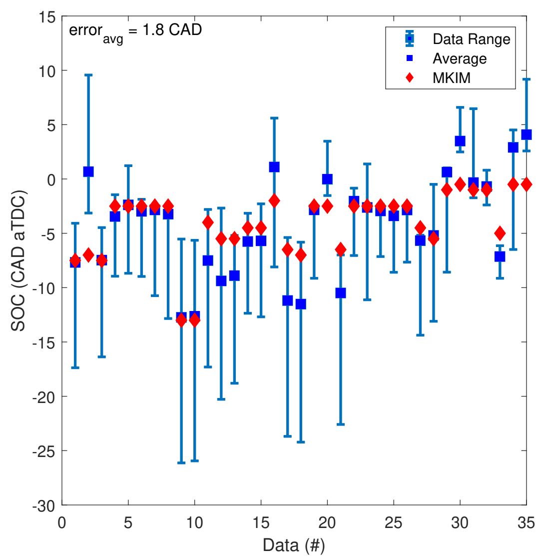

Figure 6.13: SOC model validation for different steady state conditions in RCCI mode

spark timing before commanding mode switch. The simulation of SI-RCCI-SI mode switching is carried out in Simulink. Figure 6.18 shows the model prediction for CA50 in SI and RCCI modes at 1200 RPM. The first two cycles after SI-RCCI mode switching showed advanced CA50. This can be explained by the fact that residual

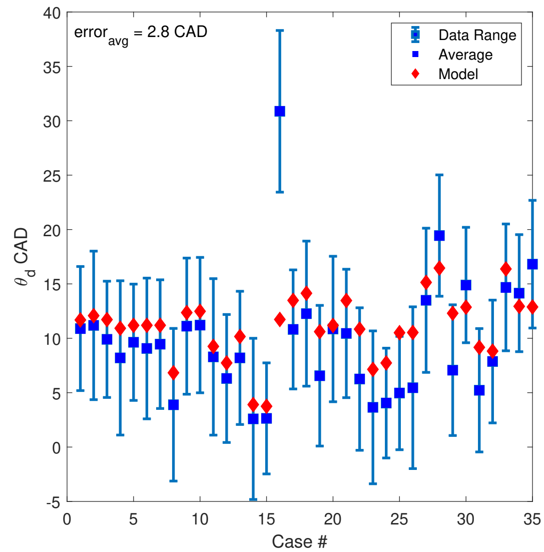

Figure 6.14: θ_d model validation for different steady state conditions in RCCI mode

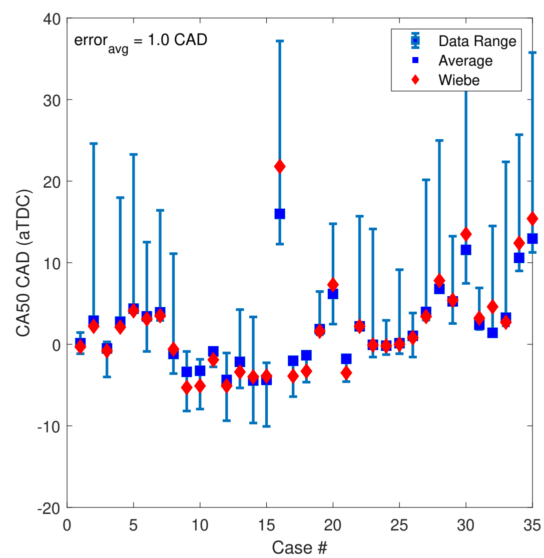

Figure 6.15: CA50 model validation for different steady state conditions in RCCI mode

gases at the end of SI cycle and cylinder wall temperatures are relatively higher as compared to the steady state RCCI engine operation. This results in advanced CA50

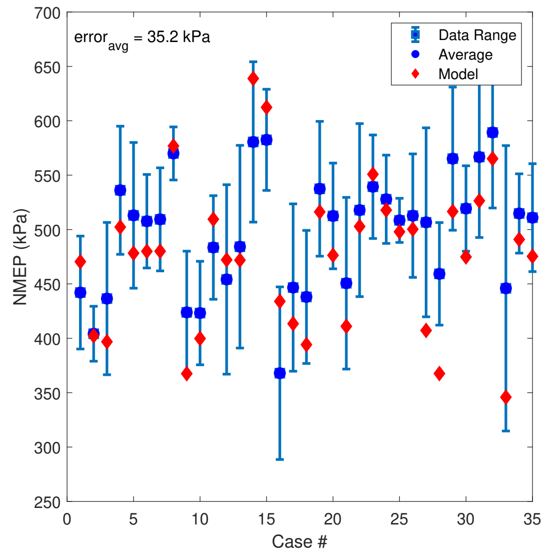

Figure 6.16: NMEP model validation for different steady state conditions in RCCI mode

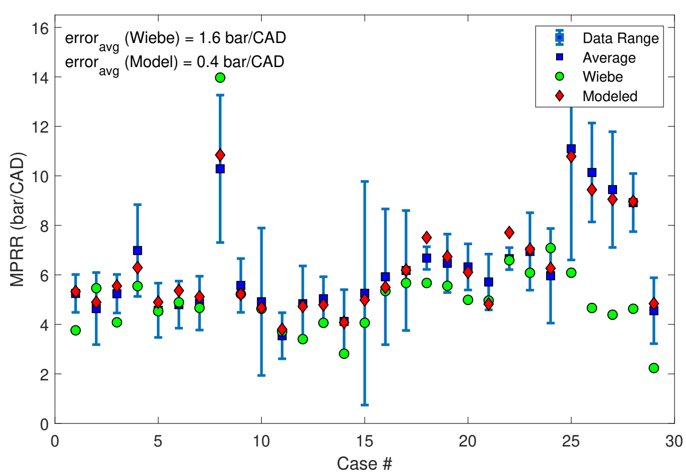

Figure 6.17: MPRR model validation for different steady state conditions in RCCI mode

for the first two cycles of RCCI mode. The average error in CA50 prediction is 2 CAD. The model is capable of predicting NMEP during SI-RCCI mode switching as shown in Fig. 6.19. However RCCI-SI mode switching resulted in one misfired cycle which can be associated to the intake manifold dynamics and throttle dynamics. The average error in predicting NMEP for both modes is 16.9 kPa. Figure 6.20 shows the λ prediction during mode switching. The model could not predict the misfired cycle during RCCI-SI mode switching and consequently λ prediction does not show it either. Figure 6.21 shows MPRR predictions. The experimental data showed an average MPRR of 5.7 bar/CAD in RCCI mode while the model predicted an average MPRR of 5.3 bar/CAD. The average error in MPRR prediction is 0.3 bar/CAD. Figure 6.22 shows the manifold pressure prediction with an average error of 0.4 kPa.

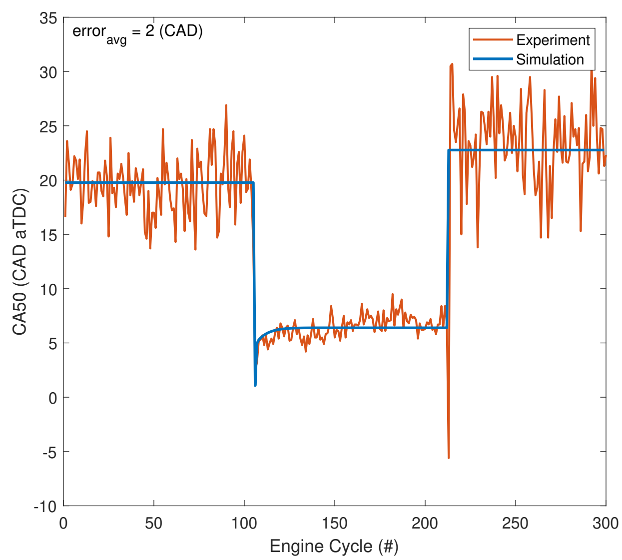

Figure 6.18: Model validation for CA50 during SI-RCCI-SI mode switching

Figure 6.23 shows the comparison of experimental data and model output for CA50 prediction. Figure 6.23 shows that the dynamic model is capable of capturing the

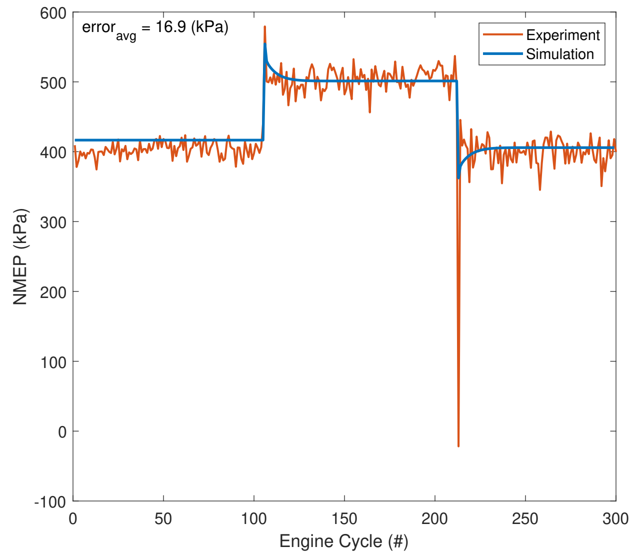

Figure 6.19: Model validation for NIMEP during SI-RCCI-SI mode switching

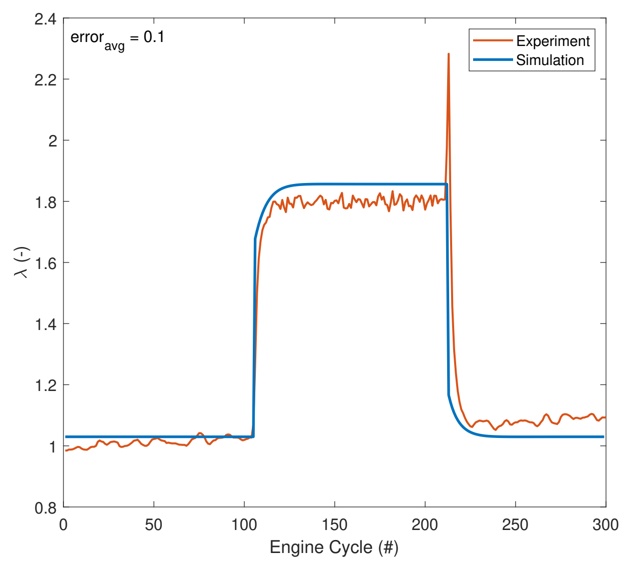

Figure 6.20: Model validation for λ during SI-RCCI-SI mode switching

advancement in CA50 from SI to RCCI mode switching. The average error for SI-RCCI-SI mode switching is 2 CAD. The model validation results for NMEP are shown in Fig. 6.24. The average error in predicting NMEP during mode switching is 12.5

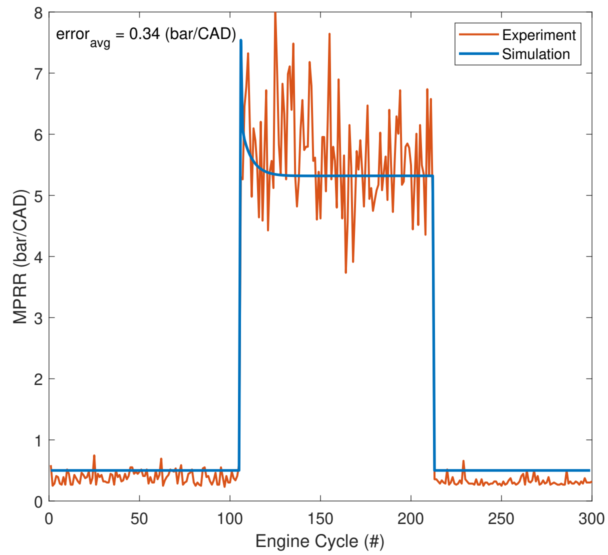

Figure 6.21: Model validation for MPRR during SI-RCCI-SI mode switching

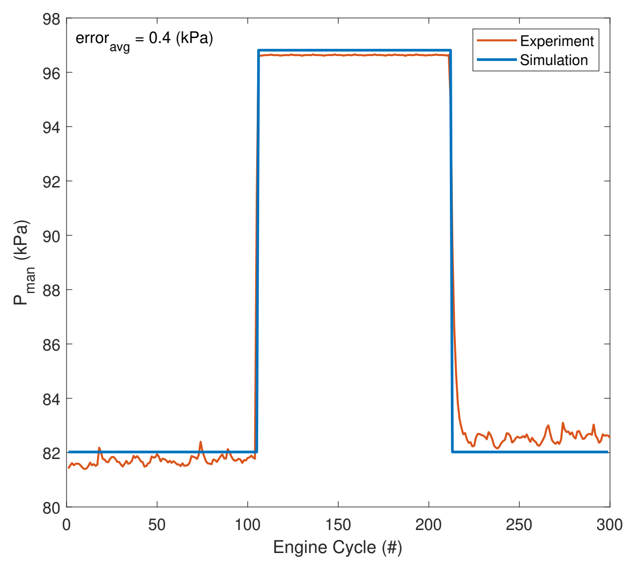

Figure 6.22: Model validation for P_{man} during SI-RCCI-SI mode switching

kPa. From SI to RCCI mode switching, extra fuel is injected for one cycle to avoid misfire or partial burn. That is why, the first SI cycle after mode switch shows high NMEP. Same amount of fuel is added in the simulation to validate the model response.

λ is important parameter in SI mode to maintain stoichiometeric air-fuel ratio. Fig. 6.25 shows the prediction of λ for SI and RCCI mode switching. The average error in estimating λ is 0.1. Fig. 6.26 shows the model response for predicting MPRR. MPRR is an important variable to consider during control development to avoid damage to the hardware. Fig. 6.27 shows the intake manifold pressure prediction for both SI and RCCI modes. The average error in predicting P_{man} is 0.3 kPa.

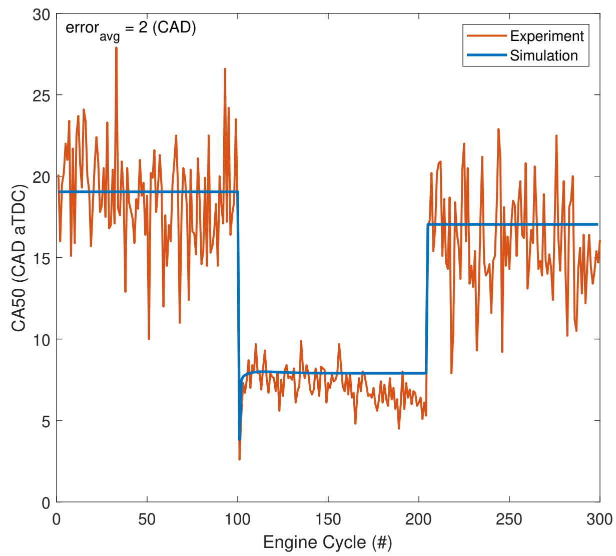

Figure 6.23: Model validation for CA50 during SI-RCCI-SI mode switching

The SI-RCCI-SI model shows good prediction accuracy for the parameters of interest. Therefore, the model is used to develop the closed-loop control framework for mode switching operation. The controller development is explained in the next chapter.

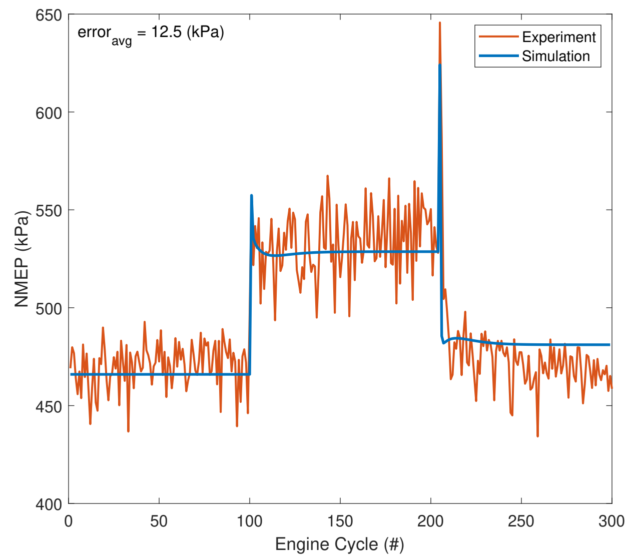

Figure 6.24: Model validation for NIMEP during SI-RCCI-SI mode switching

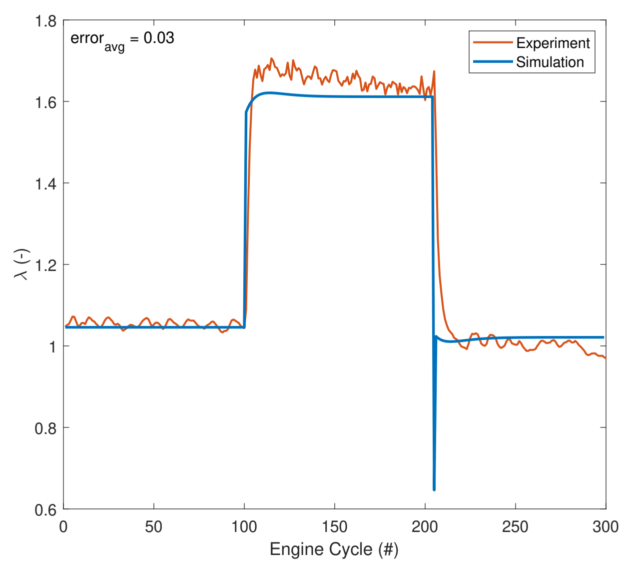

Figure 6.25: Model validation for λ during SI-RCCI-SI mode switching

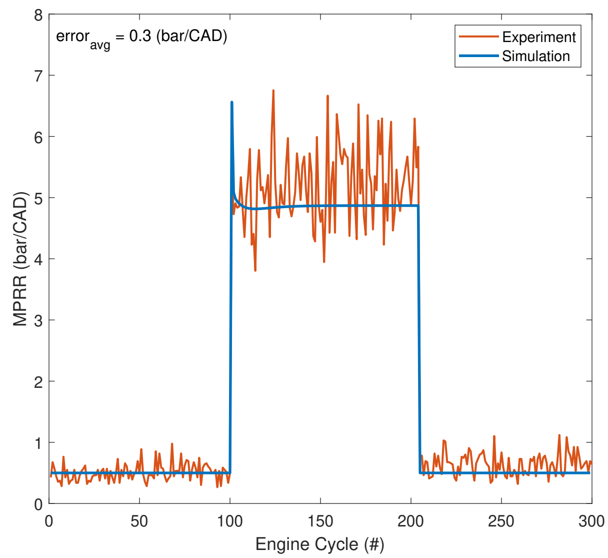

Figure 6.26: Model validation for MPRR during SI-RCCI-SI mode switching

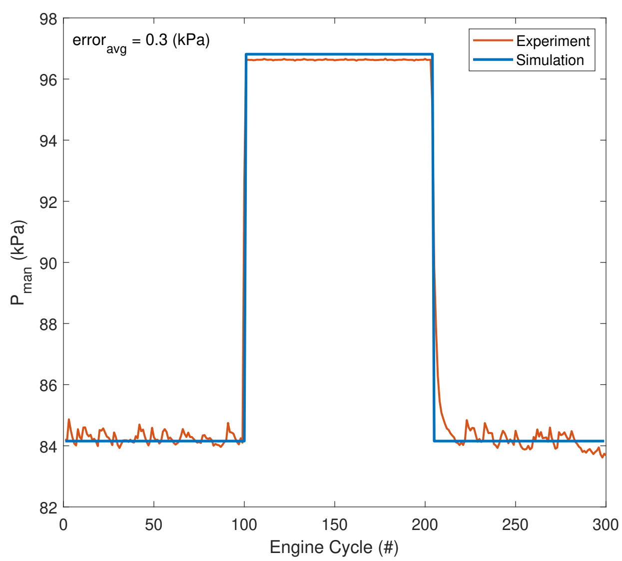

Figure 6.27: Model validation for P_{man} during SI-RCCI-SI mode switching

Chapter 7

Model Predictive Control of SI-RCCI-SI Mode Switching

This chapter focuses on the development of control framework for SI-RCCI-SI mode switching. The dynamic control oriented model developed in Chapter 6 is linearized at nominal operating conditions to develop state space representation. Here a model predictive controller is developed for mode switching operation to track the desired CA50 and NMEP while limiting λ in SI mode near stoichiometry and constraining MPRR below 8 bar/CAD in RCCI mode to avoid knocking.

7.1 State Space Representation

The aim of this work is to provide smooth SI-RCCI-SI mode switching operation. The states for SI and RCCI modes are selected based on the dynamics involved in the mode switching. The selected states of the system are as follows:

1. Combustion phasing ($CA50$)
2. Temperature at intake valve closing (T_{ivc})
3. Intake manifold pressure (P_{man})
4. Net mean effective pressure ($NMEP$)
5. Ratio of actual air-to-fuel ratio to the stoichiometric air-to-fuel ratio, λ
6. Maximum pressure rise rate ($MPRR$)

Combustion phasing ($CA50$) and net mean effective pressure ($NMEP$) are the parameters to be controlled in both SI and RCCI modes, and during mode switching. Intake manifold pressure (P_{man}) and temperature at intake valve closing (T_{ivc}) are the states common to both modes to incorporate the effects of the air-path dynamics and trapped residual gases at IVC. λ is the ratio of actual air to fuel ratio (AFR_{act}) to the stoichiometric air to fuel ratio (AFR_{st}). The SI mode requires λ =1. Therefore, λ is a parameter of interest in SI mode and during RCCI-SI mode switching.

Table 7.1
Nominal operating conditions for linearized COM of SI engine

Parameters	Value
CA50 (CAD aTDC)	11.6
T_{ivc} (°C)	367.6
P_{man} (kPa)	84.4
NMEP (kPa)	506.5
λ (-)	1.02
U_{sp} (CAD bTDC)	40
U_{th} (%)	25
FQ (mg/cyc)	18.9

It is constrained to avoid too lean or too rich air-fuel mixture in SI mode. The SI mode operation of the engine didn't show significant high $MPRR$, therefore, it is selected as a state to be constrained only in RCCI mode. The nonlinear COM can be represented in discrete time as follows:

$$x(k+1) = f(x(k), u(k)) \tag{7.1}$$

$$y(k) = f(x(k) \tag{7.2}$$

where, x represents the states of the system, u represents the control inputs, y are the output variables of the system, and $f(x, u)$ is the nonlinear function of states and control inputs.

The nonlinear COM is linearized for SI and RCCI modes at two different operating conditions, representative of each mode. The nominal operating conditions for SI and RCCI linearized models are presented in Tables 7.1 and 7.2.

Table 7.2
Nominal operating conditions for linearized COM of RCCI engine

Parameters	Value
CA50 (CAD aTDC)	1.5
P_{man} (kPa)	96
T_{ivc} (°C)	340.5
NMEP (kPa)	518.5
MPRR (bar/CAD)	7.5
SOI (CAD bTDC)	40
PR (-)	30
FQ (mg/cyc)	18.5

The linearized discrete state space model for SI and RCCI modes can be expressed as follows:

$$X(k+1) = AX(k) + BU(k) \tag{7.3}$$

$$Y(k) = CX(k) + DU(k) \tag{7.4}$$

where, X and U for SI mode are given by Eq. (7.5) and Eq. (7.6), respectively:

$$X = \begin{bmatrix} CA50 & T_{ivc} & P_{man} & IMEP & \lambda \end{bmatrix}^T \tag{7.5}$$

$$U = \begin{bmatrix} U_{sp} & U_{th} & FQ \end{bmatrix}^T \tag{7.6}$$

The plant matrices for SI mode are as follows:

$$A = \begin{bmatrix} 0.04 & 0.0033 & 0.0069 & -0.0042 & -1.15 \\ 0.0173 & 0.124 & 0.263 & -0.158 & -43.58 \\ -0.334 & -0.0024 & -0.051 & 0.0031 & 0.843 \\ -0.0019 & -0.0134 & -0.0285 & 0.17 & 4.72 \\ -0.013 & -9.37e05 & -0.00019 & 0.000119 & 0.329 \end{bmatrix} \tag{7.7}$$

$$B = \begin{bmatrix} -1.0 & -1.09 & -0.375 \\ 0 & 5.81 & -3.33 \\ 0 & -0.046 & 0.905 \\ 4.77 & 19.68 & 14.64 \\ 0 & -0.055 & 0.043 \end{bmatrix} \tag{7.8}$$

X and U for RCCI mode are given by Eq. (7.9) and Eq. (7.10), respectively:

$$X = \begin{bmatrix} CA50 & T_{ivc} & P_{man} & MPRR & IMEP \end{bmatrix}^T \tag{7.9}$$

$$U = \begin{bmatrix} SOI & PR & FQ \end{bmatrix}^T \tag{7.10}$$

$$Y = \begin{bmatrix} CA50 & IMEP & \lambda & MPRR \end{bmatrix}^T \tag{7.11}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{7.12}$$

$$D = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{7.13}$$

The plant matrices (A, B, C, D) for RCCI mode are as follows:

$$A = \begin{bmatrix} 0.185 & -0.025 & -0.0036 & 0.005 & 0.022 \\ -0.039 & 0.500 & 0.0077 & 0.0035 & -0.048 \\ 0.017 & -0.0023 & -0.032 & 0.0027 & 0.002 \\ -0.015 & 0.002 & 0.0288 & 0.0100 & -0.0018 \\ -0.0126 & 0.0171 & 0.0244 & 0.0033 & -0.0153 \end{bmatrix} \tag{7.14}$$

$$B = \begin{bmatrix} -0.51 & 0.157 & -1.002 \\ 0 & -0.00079 & 1.47 \\ 0 & 0.000003 & -0.047 \\ 0.016 & -0.061 & 0.47 \\ 0.00118 & -0.0136 & 18.83 \end{bmatrix} \tag{7.15}$$

Table 7.3
Open-loop system eigenvalues of linearized SI and RCCI modes in discrete-time

Modes	**Eigenvalues**
SI	0.41, 0.16, -0.039 0.039 + 0.048i 0.039 - 0.048i
RCCI	0.50, 0.18, -0.034 -0.012, 0.012

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{7.16}$$

$$D = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{7.17}$$

The open-loop stability for SI and RCCI modes are determined from the eigenvalues of the state space system in discrete time. Eigenvalues for SI and RCCI state space models are presented in Table 7.3. The roots of the characteristic equation lie within unit circle. This makes the systems open-loop stable.

7.2 Gain Scheduling Model Predictive Controller

Model predictive controller (MPC) is an optimal control algorithm which computes optimal control actions over the control horizon for a given trajectory in a prediction horizon. For controlled mode switching operation, CA50 and NMEP are the parameters to be controlled while constraining λ and MPRR in SI and RCCI modes, respectively. A gain scheduling MPC framework is developed to control CA50 and NMEP in SI and RCCI modes and during mode switching. A gain scheduled MPC helps in achieving a nonlinear control action using linear MPCs. In addition, following are the reasons behind choosing gain scheduling MPC framework:

- SI mode uses single fuel thus uses only port fuel injectors.
- RCCI mode uses port fuel injection and direct injection systems to achieve dual fuel engine operation. This requires optimal premixed ratio of the two fuels and start of injection timing in RCCI mode.
- SI mode runs at stoichiometric air-fuel ratio which requires throttle control. However, RCCI runs under lean conditions with WOT.

Figure 7.1 shows the schematic of the control architecture used in this study. A supervisory controller provides the mode switching signal for the optimal model based on the SI-RCCI engine maps. It decides the optimal mode of operation based on the

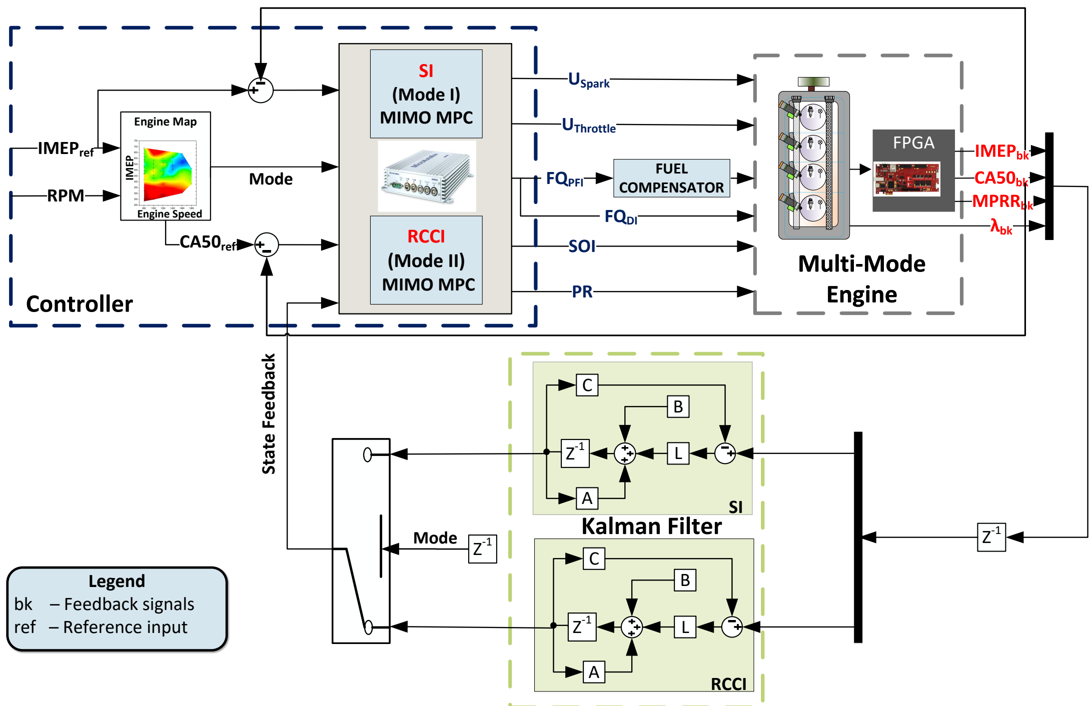

Figure 7.1: Schematic of supervisory controller, gain scheduled MPC and Kalman filter for State estimation for a multi-mode engine

desired engine load and speed. The output of supervisory controller goes into the gain scheduling MPC framework to activate the corresponding controller. Two MPC controllers are designed one for SI and one for RCCI mode. MPC uses receding prediction horizon algorithm which continuously solves the constrained optimization problem for the optimal control actions. The prediction and control horizons are selected based on the mode transition cycles. It usually takes 3 engine cycles to complete the SI-RCCI-SI mode transition. Thus, the prediction horizon is selected to be 5 engine cycles while control horizon is kept to be 3 engine cycles. The state space system for the prediction horizon (m) and control horizon (n) can be written as follows:

$$X_{k+1|k} = Ax(k) + B\Delta u(k) \tag{7.18}$$

$$X_{k+m|k} = A^m x(k) + A^{m-1} B\Delta u(k) + A^{m-2} B\Delta u(k+) ... + A^{m-n} B\Delta u(k+n-1) \tag{7.19}$$

$$\Delta U = \begin{bmatrix} \Delta u(k) & \Delta u(k+1) & ... & \Delta u(k+n-1) \end{bmatrix}^T \tag{7.20}$$

$$Y_k = \begin{bmatrix} y(k+1|k & y(k+2|k & y(k+3|k & y(k+4|k & y(k+5|k) \end{bmatrix}^T \tag{7.21}$$

$$Y_k = FX_k + \phi U_k \tag{7.22}$$

Eq. (7.23) and Eq. (7.24) are used to compute the matrices F and ϕ for prediction and control horizons of 5 and 3 engine cycles, respectively.

$$F = \begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ CA^4 \\ CA^5 \end{bmatrix} \tag{7.23}$$

$$\phi = \begin{bmatrix} CB & 0 & 0 & 0 & 0 \\ CAB & CB & 0 & 0 & 0 \\ CA^2B & CAB & CB & 0 & 0 \\ CA^3B & CA^2B & CAB & CB & 0 \\ CA^4B & CA^3B & CA^2B & CAB & CB \end{bmatrix} \tag{7.24}$$

The objective function of the controller is to minimize the tracking errors for CA50 and NMEP subject to constraints on λ, MPRR and the corresponding control signals. In SI mode, constraints are applied on λ, U_{th}, U_{sp}, and FQ. In RCCI mode, constraints are applied on MPRR, SOI, PR and FQ. A quadratic cost function developed for MPC consists of two main terms which are as follows:

$$J(k) = J_y(k) + J_{\Delta u}(k) \tag{7.25}$$

subject to the constraints

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \Delta U \leq \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{bmatrix} \tag{7.26}$$

where $J_y(k)$ is the cost function corresponding to the reference tracking of the desired output parameters at time k, the term $J_{\Delta u}(k)$ is associated with the cost of control actions at k^{th} engine cycle.

The cost function for the output reference tracking is as follows:

$$J_y(k) = \sum_{j=1}^{N_y} \sum_{i=1}^{m} \left\{ \frac{Q_{i,j}^y}{s_j^y} \left[R_j(k+i|k) - Y_j(k+i|k) \right] \right\}^2 \tag{7.27}$$

In the equation, m refers to the prediction horizon, N_y refers to the number of system outputs. $R_j(k+i|k)$ and $Y_j(k+i|k)$ refer to the j^{th} reference signal and the corresponding plant output at the i^{th} time step. s_j^y is the scaling factor for the variables to be controlled. $Q_{i,j}^y$ represents the tuning weights for each output at the i^{th} time step. .

The cost function corresponding to the manipulated variables and their rate change is represented by Eq. (7.28).

$$J_{\Delta u}(k) = \sum_{j=1}^{N_u} \sum_{i=0}^{m-1} \left\{ \frac{R_{i,j}^{\Delta u}}{s_j^u} \left[u_j(k+i|k) - u_{j,target}(k+i|k)) \right] \right\}^2 \tag{7.28}$$

where $R_{i,j}^{\Delta u}$ is the tuning weight associated with the rate of change of manipulated variables at the i^{th} time step. s_j^u is the scaling factor for the manipulated variables. N$_u$ is the total number of manipulated variables.

Constraints on the maximum and minimum limits and rate change of manipulated variables (ΔU) can also be imposed. The constraint on the rate change of manipulated variables can be expressed as follows:

$$\Delta U^{min} \leq \Delta U(k) \leq \Delta U^{max} \tag{7.29}$$

Eq. (7.29) can be written for all future control signals within the prediction horizon [161]. The inequality constraints on rate change of manipulated variables can be written as:

$$-\Delta U(k) \leq -\Delta U^{min} \tag{7.30}$$

$$\Delta U(k) \leq \Delta U^{max} \tag{7.31}$$

Similarly, constraints corresponding to minimum and maximum limits of control signals can be expressed as follows:

$$-(C_1 u(k-1) + C_2 \Delta U(k)) \leq -U^{min} \tag{7.32}$$

$$(C_1 u(k-1) + C_2 \Delta U(k)) \leq U^{max} \tag{7.33}$$

where, C_1 and C_2 are matrices associated to each control signal, U^{min} and U^{max} are the elements of a column vector consisting of N_c elements of upper and lower limit of corresponding control signal. Constraints applied on λ in SI mode and MPRR in

RCCI mode are expressed as follows:

$$Y^{min} \leq FX(k) + \Phi\Delta U \leq Y^{max} \tag{7.34}$$

Eq. (7.26) can be written for the constraints:

$$E_1 = \begin{bmatrix} -C_2 \\ C_2 \end{bmatrix}; E_2 = \begin{bmatrix} -I \\ I \end{bmatrix}; E_3 = \begin{bmatrix} -\Phi \\ \Phi \end{bmatrix} \tag{7.35}$$

$$\eta_1 = \begin{bmatrix} -U^{min} + C_1 u(k-1) \\ U^{max} - C_1 u(k-1) \end{bmatrix}; \eta_2 = \begin{bmatrix} -\Delta U^{min} \\ \Delta U^{max} \end{bmatrix}; \eta_3 = \begin{bmatrix} -Y^{min} + FX(k) \\ Y^{max} - FX(k) \end{bmatrix} \tag{7.36}$$

The following constraints are applied in SI mode:

$$0.95\ (-) \leq \lambda \leq 1.25\ (-) \tag{7.37}$$

$$60\ (\text{CAD bTDC}) \leq U_{sp} \leq 20\ (\text{CAD aTDC}) \tag{7.38}$$

$$12\ (\text{mg/cycle}) \leq FQ \leq 35\ (\text{mg/cycle}) \tag{7.39}$$

$$5\ (\%) \leq U_{th} \leq 45\ (\%) \tag{7.40}$$

To ensure knock free engine operation, constraint on MPRR is applied. In addition, the constraints are also applied on the manipulated variables.

$$MPRR \leq 8 \text{ (bar/CAD)} \tag{7.41}$$

$$25 \text{ (CAD bTDC)} \leq SOI \leq 60 \text{ (CAD bTDC)} \tag{7.42}$$

$$10 \text{ (\%)} \leq PR \leq 45 \text{ (}-\text{)} \tag{7.43}$$

$$11 \text{ (mg/cycle)} \leq FQ \leq 24 \text{ (mg/cycle)} \tag{7.44}$$

A quadratic cost function developed for the optimal control objective of tracking CA50 and IMEP subject to constraints respective to each combustion mode. Sequential quadratic programming (SQP) is used to obtain the optimal control response.

7.3 Kalman Filter Design

The system requires states to be either measured or estimated for feedback control. Not all the states can be measured on the system. Also, some measurements can be noisy. Therefore, an observer is designed to estimate the states to improve the noisy measurements [162]. In this work, the measured outputs of the system, i.e., CA50 and NMEP, are used to estimate the states of the system. Due to the noisy intake manifold pressure measurements, the estimated intake manifold pressure is used as state measurement. Similarly, transport delay is associated to λ sensor measurement. Therefore, estimated λ is used as state measurement. Kalman filter is an optimal state estimation algorithm which suppresses the measurement noise [162]. Kalman filter uses the state space model of the system which is given by:

$$X(k+1) = A(k)X(k) + B(k)U(k) + G_v(k)v_1(k) \tag{7.45}$$

The measurement equation is give by:

$$Y(k) = C(k)X(k) + v_2(k) \tag{7.46}$$

where $v_1(k)$ and $v_2(k)$ are the uncorrelated white noises with zero mean and covariances $V_1(k)$ and $V_2(k)$.

Kalman filter requires recursive estimations of the states at time k just before and after the measurement y(k). The estimate of the states at time k can be of the form:

$$\hat{X}(k)^+ = M(k)\hat{X}(k)^- + L(k)Y(k) \tag{7.47}$$

where $\hat{X}(k)^-$ and $\hat{X}(k)^+$ are the states before and after the measurement, respectively. M and L are the time varying gains to be determined for optimal estimates.

The filter error $e(k)^+$ after the measurement can be written as follows:

$$e(k)^+ = \hat{X}(k)^+ - X(k) \tag{7.48}$$

Substituting Eq. (7.46) and Eq. (7.47) into Eq. (7.48):

$$e(k)^+ = [M(k) + L(k)C(k) - I]X(k) + M(k)e(k)^- + L(k)v_2(k) \tag{7.49}$$

where $e(k)^-$ is the filter error before the measurement.

Given the expectation value of noise is zero. The expectation value of the errors is required to be zero. Taking the expectation value of Eq. (7.49):

$$M(k) = I - L(k)C(k) \tag{7.50}$$

Based on this requirement, the estimator equation becomes:

$$\hat{X}(k)^+ = \hat{X}(k)^- + L(k)Y(k) - C(k)\hat{X}(k)^- \tag{7.51}$$

The error covariance matrix is defined as:

$$Q(k)^+ = Ee(k)^+e^T(k)^+ \tag{7.52}$$

The error covariance measurement update equation is as follows:

$$Q(k)^{+} = [I - L(k)C(k)]Q(k)^{-}[I - L(k)C(k)]^{T} + L(k)V_2(k)L^{T}(k) \tag{7.53}$$

The noise covariance matrix is defined as:

$$V_2(k) = Ev_2(k)v_2^{T}(k) \tag{7.54}$$

The measurement error and noise are not correlated. Kalman gain $L(k)$ is obtained by minimizing the error covariance matrix. Optimal Kalman gain is given by:

$$L(k) = Q(k)^{-}C^{T}(k)[C(k)Q(k)^{-}C^{T}(k) + V_2(k)]^{-1} \tag{7.55}$$

Kalman filter is designed to estimate the states of the system for cycle-to-cycle control using the measured outputs. Actual engine setup is equipped with in-cylinder pressure transducer, intake manifold pressure sensor, and lambda sensor to measure the in-cylinder pressure, intake manifold pressure and λ, respectively. CA50, NMEP, and MPRR are obtained from in-cylinder pressure data on cycle to cycle basis. There is a transport delay associated to the λ measurement. To maintain λ near stoichiometric AFR on cycle-to-cycle basis, estimated λ is used. In addition, it is difficult to measure the temperature at IVC. Therefore, using CA50 and NMEP measurements, all the other states of the system are estimated using Kalman filter.

7.4 Simulation Results

Figure 7.2 shows the performance of MPC for step changes in CA50 and NMEP in the SI mode. These are the simulation results to validate the controller performance at 1200 RPM and intake air temperature of 60 °C. A step change in CA50 is provided from 9.5 to 12 CAD aTDC and a step change in NMEP is provided from 400 to 550 kPa. The controller is capable of tracking CA50 and NMEP with average error of 0.2 CAD and 9.9 kPa, respectively. The controller is capable of keeping the λ value closer to 1.05. The constraints are applied on λ to keep it between 0.95 and 1.25. The lower limit on λ is set to avoid too rich air-fuel mixture while the upper limit of λ is set to avoid too lean mixture which results in high COV_{NMEP}. The optimal control inputs of the MPC for SI mode are shown in the Fig. 7.9. Spark timing is retarded to track the change in CA50. Similarly, fuel quantity is adjusted to achieve the desired NMEP. In SI mode, fuel is injected via PFI. Thus, the optimal fuel quantity from MPC is input to the feedforward controller to incorporate the port fuel dynamics. The feedforward controller is essentially the inverse of the fuel transport dynamics. In order to maintain the stoichiometric λ value, a change in throttle position is commanded. Manipulated variables stayed within the set limits.

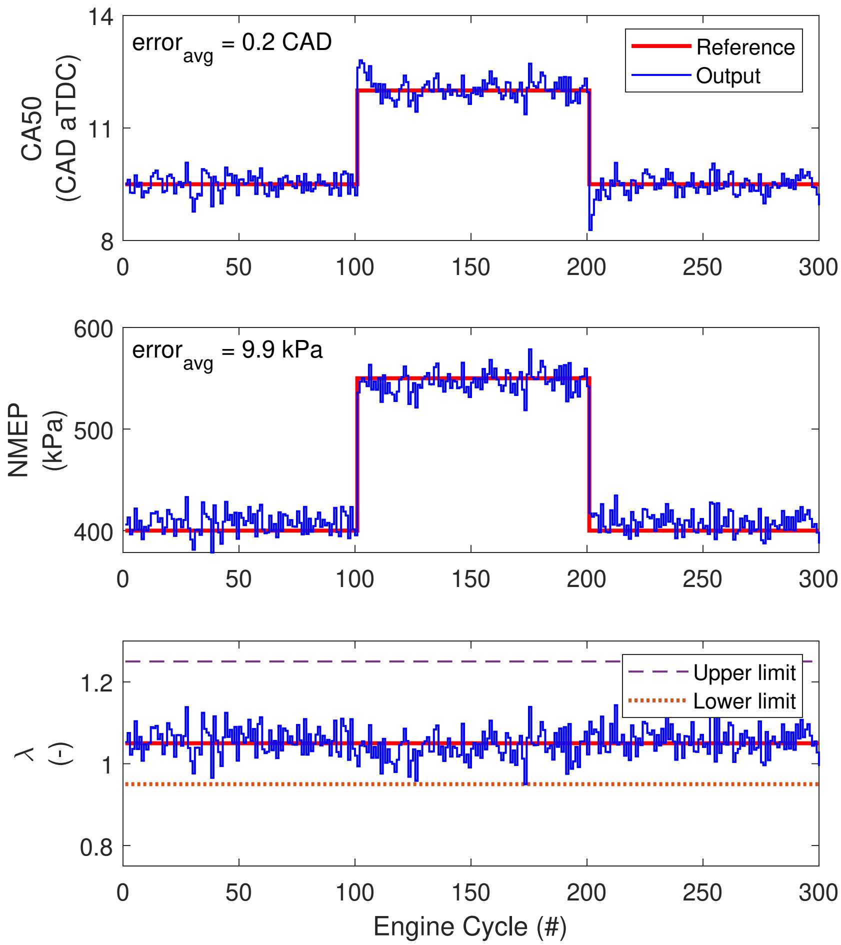

Figure 7.2: Simulation results for CA50, NMEP and λ control to validate MPC performance in SI mode

Figure 7.4 shows the comparison of the model outputs and the Kalman filter estimations. Process noise and sensor measurement noise are added to the model outputs based on the experimental data. The estimations of Kalman filter for CA50, NMEP, λ, and P_{man} are compared with the model outputs. The average error is calculated for the measured and estimated states. The average errors for the estimated CA50, NMEP, λ, and P_{man} are 0.3 CAD, 9.4 kPa, 0.03 and 0.3 kPa, respectively.

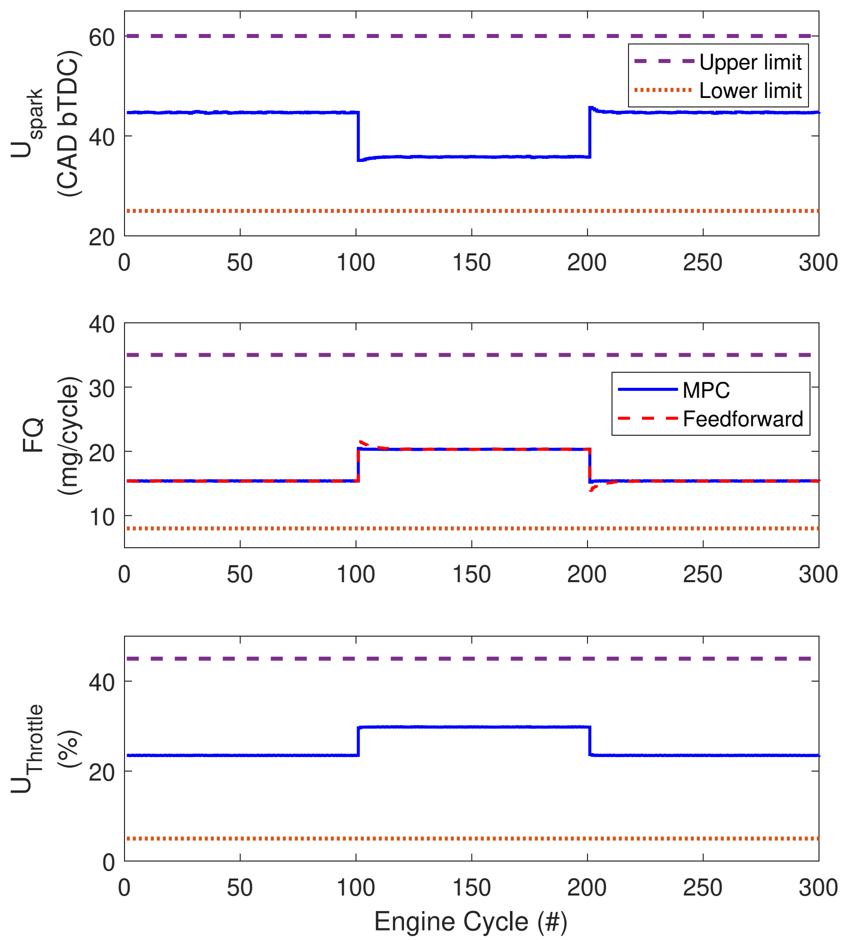

Figure 7.3: Manipulated variables of MPC for the results in Fig. 7.2

The performance of MPC for RCCI mode is also validated by providing simultaneous step changes in CA50 and NMEP. Figure 7.6 shows tracking performance of MPC. A step change in CA50 is provided form 4 to 7 CAD aTDC. The controller is capable of tracking CA50 with an average error of 0.1 CAD. At 100^{th} engine cycle, a step change NMEP is provided from 450 to 580 kPa. This leads to an advanced CA50 for the corresponding cycle due to relatively slow response of controller to vary SOI. This also resulted in increased MPRR. The constraints on rate change of manipulated variables

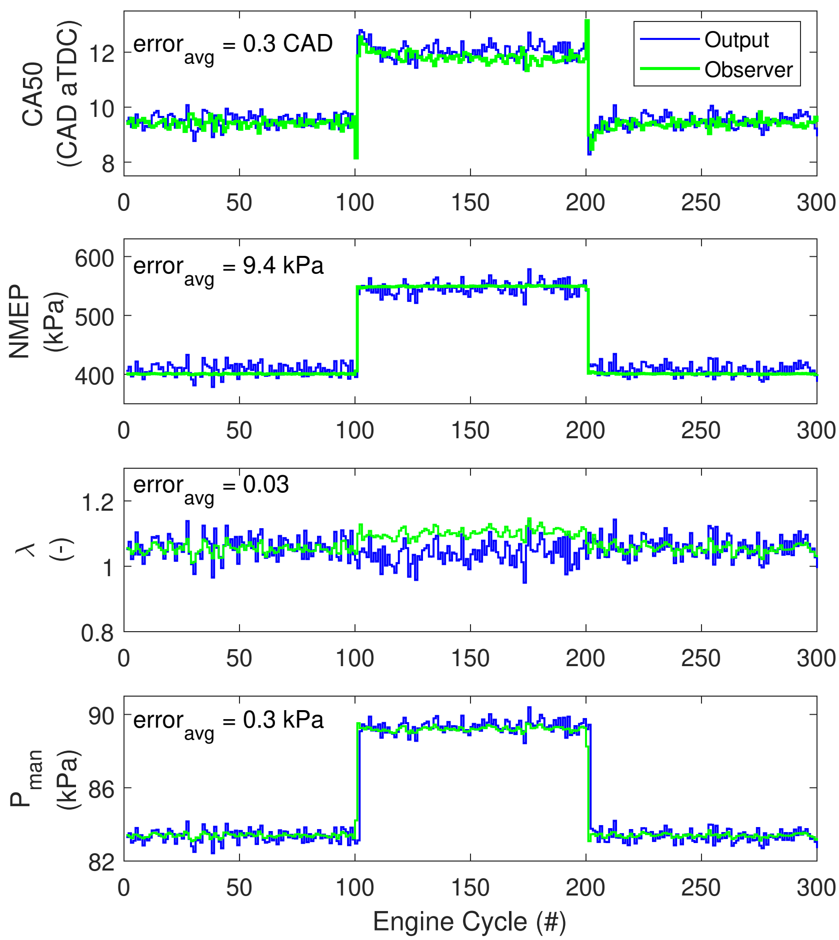

Figure 7.4: Comparison of plant model outputs and Kalman filter state estimations

are relaxed. The simultaneous adjustment of SOI and PR reduced the MPRR and controlled CA50 in the subsequent cycles as shown in Fig. 7.6. The average error in tracking NMEP is 10 kPa. The controller maintained MPRR below 8 bar/CAD. Figure 7.6 shows the variations in manipulated variables to control CA50 and NMEP and to constrain MPRR below the set limit. The controller response also shows that the control inputs stay well within the set limits.

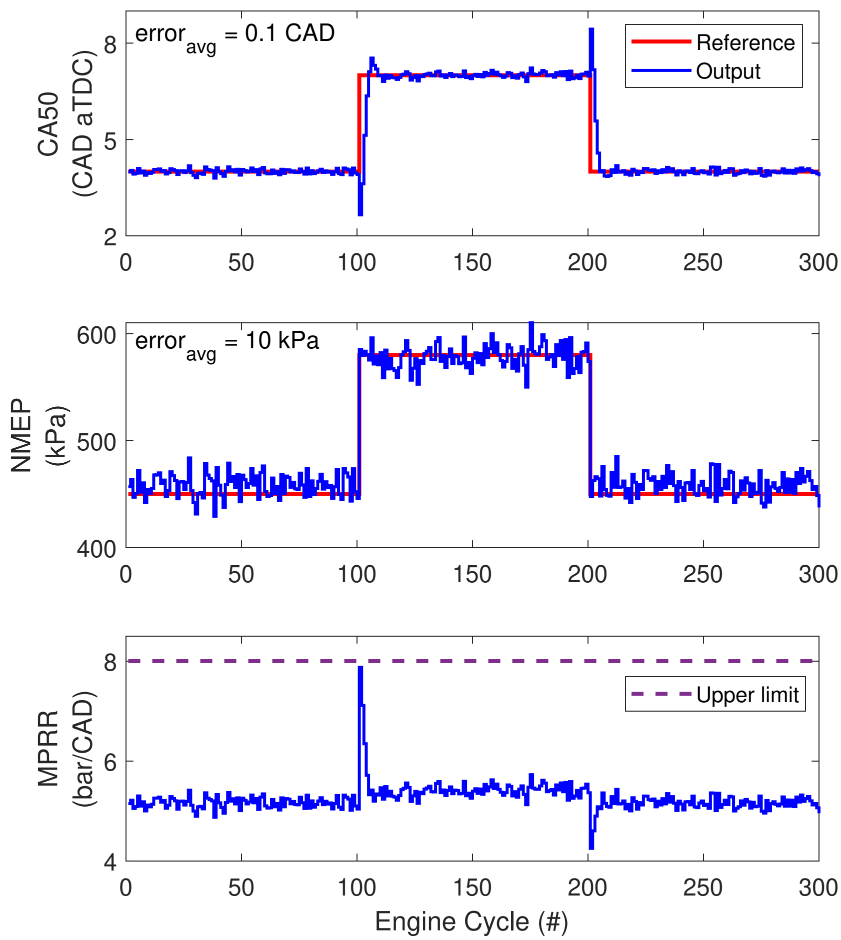

Figure 7.5: Simulation results for CA50, NMEP and MPRR control to validate MPC performance in RCCI mode

Figure 7.7 shows the performance of Kalman filter for state estimations. CA50, NMEP and MPRR are measured from the in-cylinder pressure measurements on cycle-to-cycle basis. Measurement noises are added to the model outputs based on the experimental data to design Kalman filter. Kalman filter takes process and measurement noises into account. Results show that the Kalman filter estimated the states to a great extent. The average error between the measured and estimated

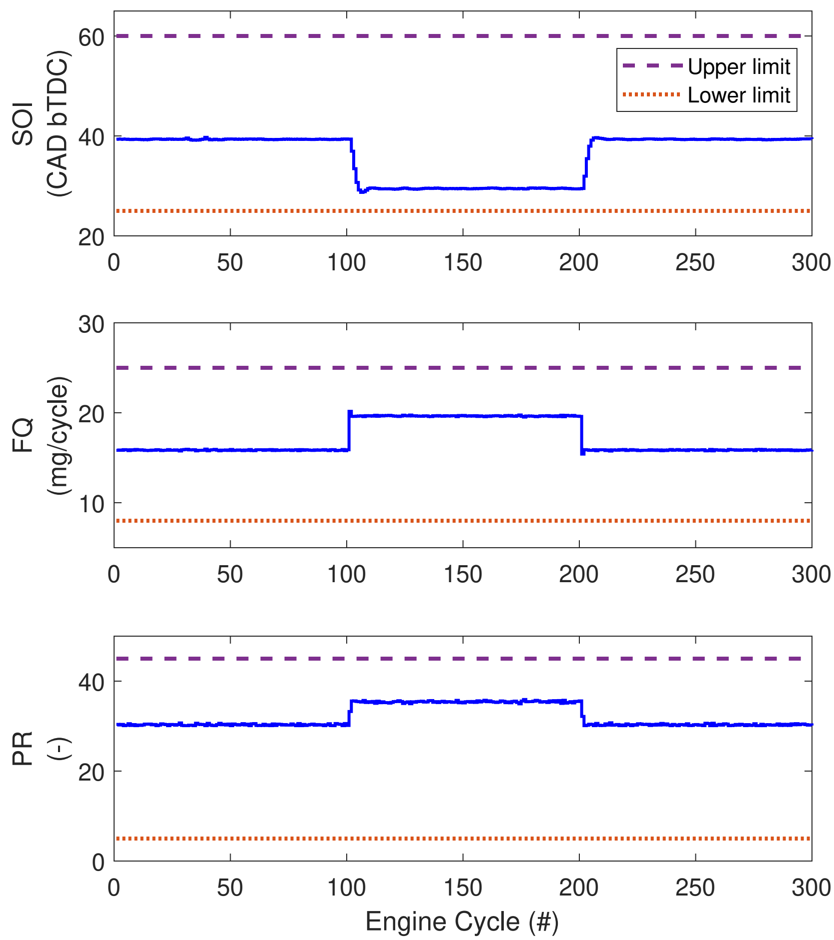

Figure 7.6: Manipulated variables of MPC for the results in Fig. 7.5

outputs is computed. The average error for CA50, NMEP and MPRR is 0.35 CAD, 9 kPa and 0.1 bar/CAD, respectively.

Figure 7.8 shows the controller performance for reference tracking of CA50 and NMEP while constraining λ in SI mode to stoichiometric value and limiting MPRR below 8 bar/CAD in RCCI mode. The controller performance is validated for engine speed of 1200 RPM. When the NMEP is switched from 275 kPa to 450 kPa, the mode

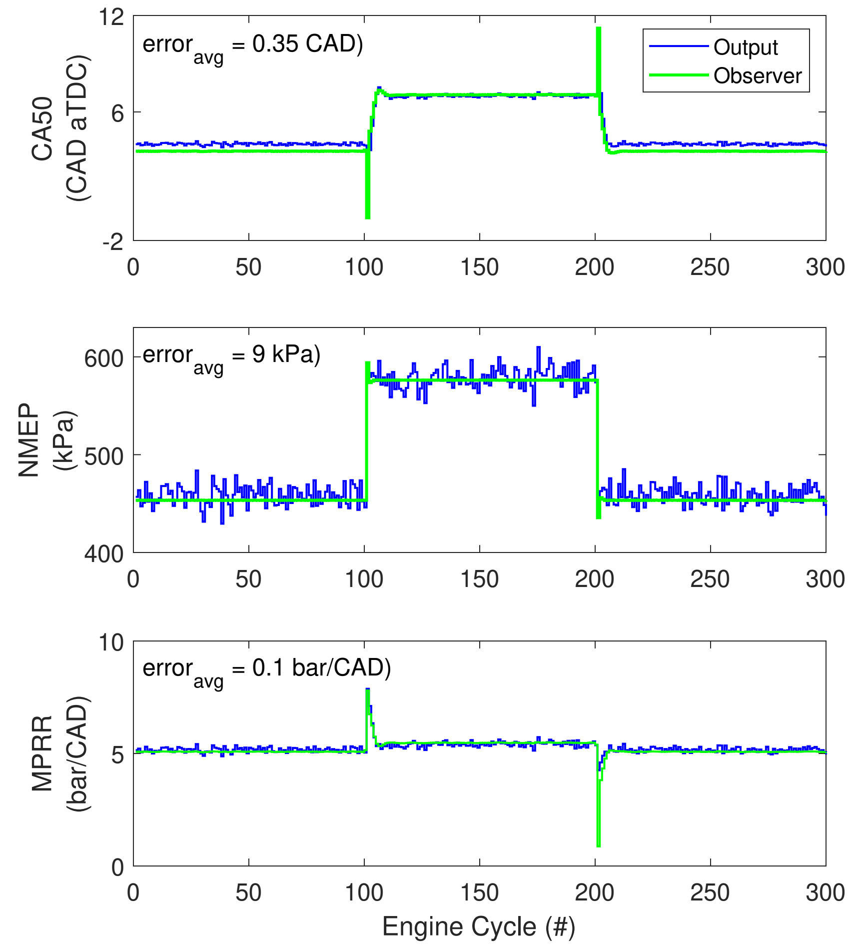

Figure 7.7: Comparison of plant model outputs and Kalman filter state estimations

is changed from SI to RCCI. The controller is gain scheduled MPC which provides the control action based on the actuators used in the respective modes. For the first 100 engine cycles, CA50 and NMEP are controlled in SI mode while the λ is maintained close to 1. Spark timing is adjusted to track CA50. Fuel quantity and throttle position are adjusted to track NMEP and maintain λ. When the mode is switched from SI to RCCI, the throttle position is changed to 90%. SOI and PR

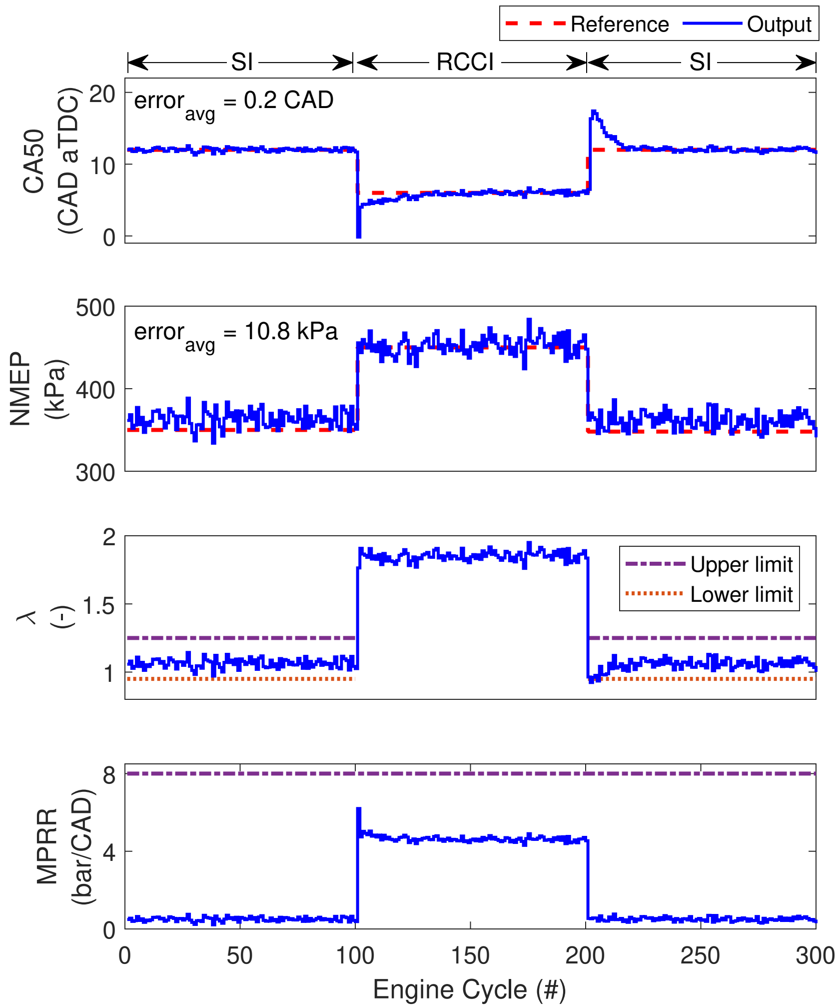

Figure 7.8: Simulation results to validate MPC performance for SI-RCCI-SI mode switching

are adjusted simultaneously to track CA50 and maintain MPRR below 8 bar/CAD. NMEP is controlled by modulating fuel quantity. The average error in tracking CA50 and NMEP is 0.2 CAD and 10.8 kPa, respectively.

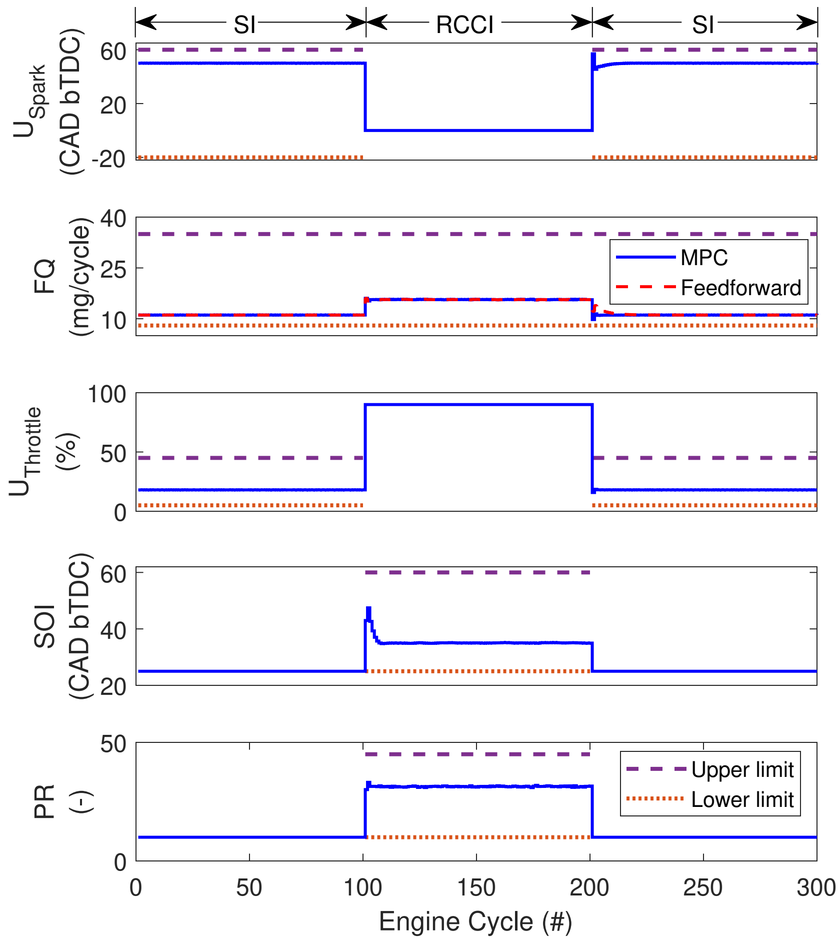

Figure 7.9: Manipulated variables of MPC for the results in Fig. 7.8

7.5 Experimental Results

7.5.1 Tracking Performance in RCCI Mode

Figure 7.10 shows experimental validation of the reference tracking performance of gain-scheduled MPC to control CA50 and NMEP in RCCI mode. A step change in

NMEP is provided from 540 to 620 kPa while maintaining constant CA50. Controller tracks CA50 and NMEP with an average error of 0.5 CAD and 9.9 kPa, respectively. The controller is also capable of limiting MPRR below 8 bar/CAD. COV_{NMEP} for the first 50 cycles of NMEP is 1.8%. From 51^{th} to 145^{th} engine cycles, the COV_{NMEP} of NMEP is 2.4%. COV_{NMEP} of NMEP is 2.5% for engine cycle between 146-200.

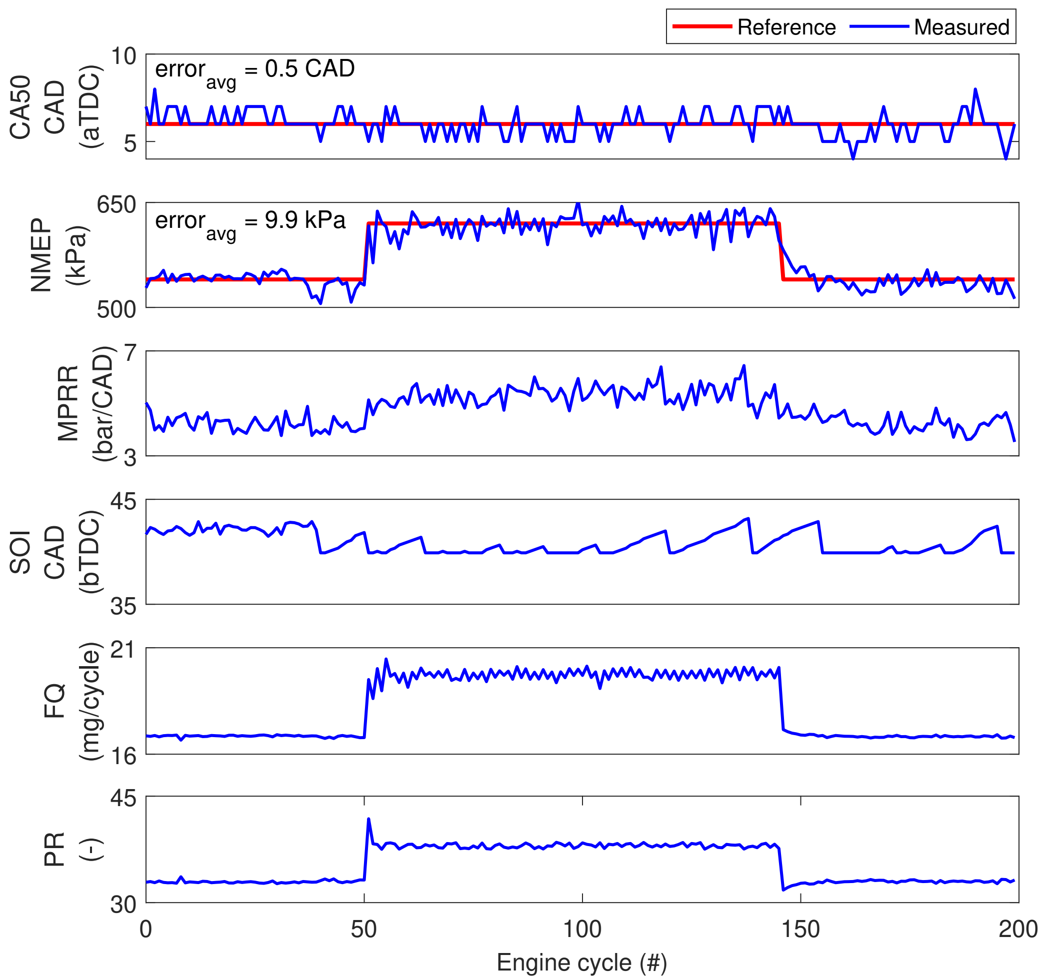

Figure 7.10: Experimental results for closed-loop control of CA50 and NMEP while constraining MPRR below 8 bar/CAD in RCCI mode

7.5.2 SI-RCCI-SI Mode Switching Results

SI-RCCI mode switching at constant NMEP is carried out while a step change in desired CA50 is provided. The measured outputs of the engine are shown in Fig. 7.11 and the corresponding controller response are presented in Fig. 7.12. The cyclic variations in CA50 during SI mode are observed to be high even with constant spark timing. These variations increase with an aggressive spark timing controller. Therefore, the weight on change in spark timing is adjusted for less aggressive control. Controller tracks CA50 in SI mode with an average error of 3.8 CAD. The mode switching MPC framework successfully tracks the changes in CA50 from 13 CAD (aTDC) in SI mode to 3 CAD (aTDC) in RCCI mode in 3 engine cycles. The average error in tracking CA50 is 0.5 CAD in RCCI mode. The first 3 engine cycles after the mode switching show a slight increase in NMEP but reaches the steady state value in the 4^{th} engine cycle. The average error in tracking NMEP is 8.7 kPa with COV_{NMEP} of 2.9% in SI mode. In RCCI mode, the average error in tracking NMEP and the corresponding COV_{NMEP} is 10.6 kPa and 3.0 %, respectively. The average error and COV_{NMEP} during RCCI mode are calculated from 160^{th} (the first mode switching) cycle to the 300^{th} engine cycle. COV_{NMEP} for both SI and RCCI modes is 3.25 %. λ is constrained between 0.95 - 1.25 (-). The results show that MPRR stays well below 8 bar/CAD during RCCI engine operation.

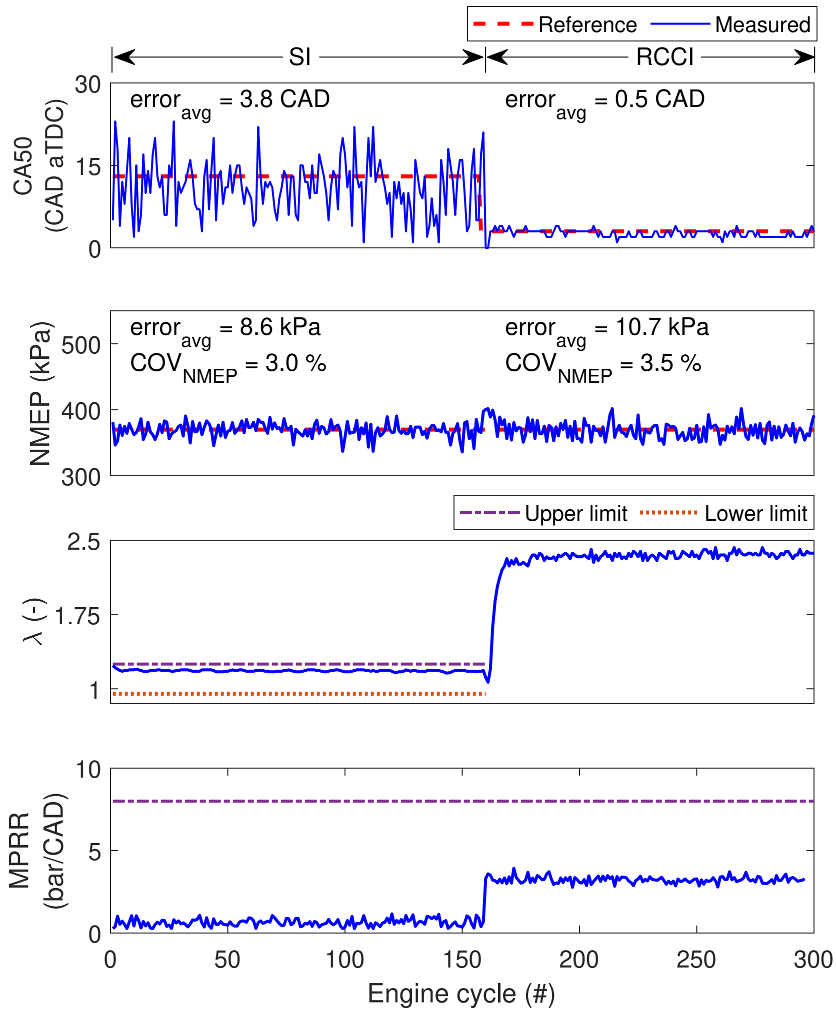

Figure 7.11: Experimental results for closed-loop control of CA50 and NMEP during SI-RCCI mode switching

An SI to RCCI and back to SI mode switching is carried out as shown in Fig. 7.13. A step change in NMEP is provided from relatively low NMEP of 350 kPa (SI mode) to medium NMEP of 450 kPa (RCCI mode) to high NMEP of 750 kPa (SI mode). A step change in CA50 is provided from 11 CAD (aTDC) to 7 CAD (aTDC). From SI to RCCI mode switching, CA50 and NMEP are changed simultaneously. As soon as mode is switched from SI to RCCI, throttle is commanded to open to 90 %. First few

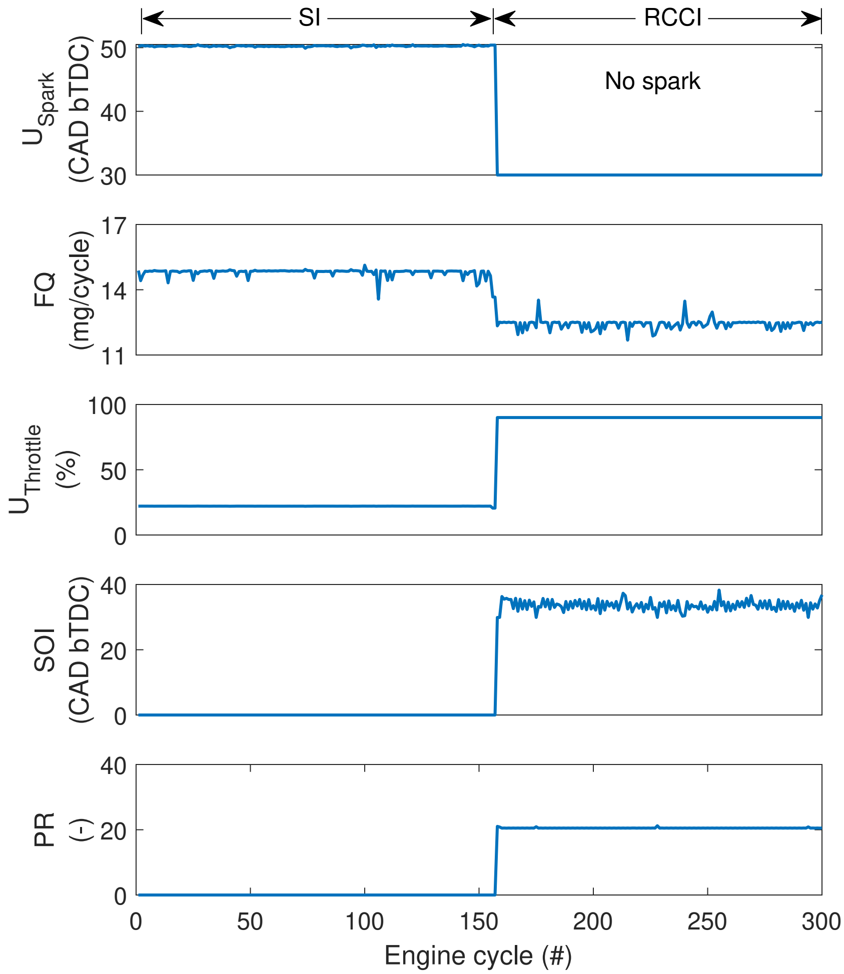

Figure 7.12: Control actions during SI-RCCI mode switching for the results in Fig. 7.11

cycles of mode switching showed an advanced CA50. This can be associated to the high cylinder wall temperature and high temperature of residual gases. As a response to advanced CA50, SOI is retarded for a few cycles to retard CA50. The average error in tacking CA50 in RCCI mode is 1 CAD. It reaches the desired NMEP in one engine cycle from SI to RCCI mode. Hot residual gases trapped at the end of SI cycle and high in-cylinder wall temperature make the SI to RCCI mode switching smooth.

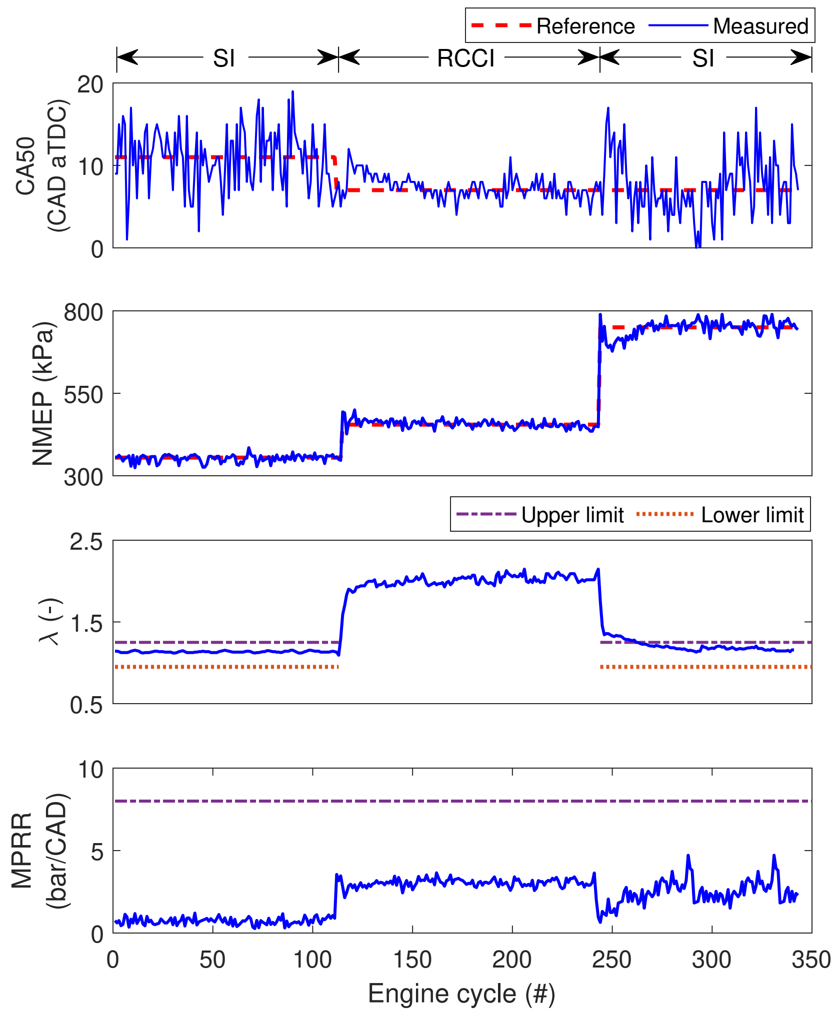

Figure 7.13: Experimental results for closed-loop control of CA50 and NMEP during SI-RCCI mode switching

The premixed ratio of the two fuels does not change much in the RCCI operation because the MPRR is below the set limit. The average MPRR in RCCI mode is 3 bar/CAD.

For RCCI to SI mode switching, a higher NMEP of 750 kPa is requested. Fuel quantity from the MPC passes through the inverse fuel dynamics. For the first cycle,

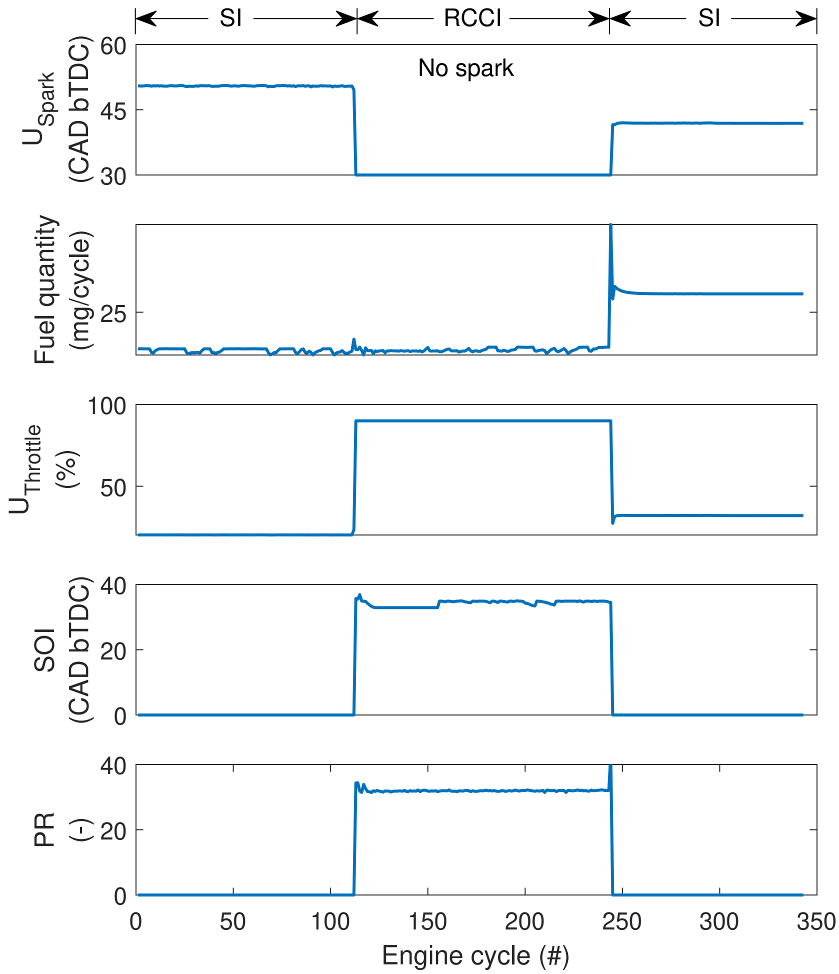

Figure 7.14: Control actions during SI-RCCI mode switching for the results in Fig. 7.13

NMEP reaches a maximum of 800 kPa. The controller reduces the fuel quantity in subsequent cycle to bring the NMEP to the desired value. However, due to port fuel transport dynamics the NMEP takes 14 engine cycles to reach the steady state. The port fuel transport dynamics are prominent even in the presence of a feedforward controller. This can be attributed to the variations in values of τ and X during transient engine operation. The first few cycles after RCCI to SI mode switching shows λ

Table 7.4
Average error in tracking CA50 and NMEP, and COV_{NMEP} during SI-RCCI-SI mode switching

Mode	**CA50**		**NMEP**		
	Mean (CAD)	$Error_{avg}$ (CAD)	**Mean** (kPa)	$Error_{avg}$ (kPa)	COV_{NMEP} (%)
SI	10.9	2.9	352.7	8.5	3.1
RCCI	7.2	1	454.3	9.5	2.7
SI	7.4	2.9	748.1	9.5	3.2

values greater than stoichiometric air-fuel ratio. The response of the controller can be improved by providing time varying $\tau - X$ model according to the engine operating conditions. Table 7.4 presents the summary of the results for CA50 and NMEP in SI and RCCI operations. The COV_{IMEP} for SI mode is 3.1%. The COV_{IMEP} of RCCI mode including the transient cycles of SI-RCCI mode transition is 2.7%. Similarly, COV_{IMEP} of SI operation after the RCCI-SI mode switching is 3.2% including the transient mode switching cycles.

SI-RCCI-SI mode switching is carried for medium NMEP range. Step changes in CA50 and NMEP are provided as reference signals during mode switching. The summary of the results are presented in Table 7.5. From SI to RCCI mode switching, CA50 is changed from 10 CAD (aTDC) to 7 CAD (aTDC) as shown in Fig. 7.15. During SI mode, controller modulates spark timing to achieve CA50 control. The average error for tracking CA50 is 2.6 CAD in SI mode. During SI to RCCI mode switching, the first cycle shows an advanced combustion phasing which is predominantly due to hot exhaust gases and high temperature of in-cylinder walls from SI mode. However, the subsequent cycles show retarded combustion phasing. The average error in tracking CA50 is 0.5 CAD including SI-RCCI mode switching cycles and steady state RCCI operation. The average error in reference tracking of NMEP in SI mode is 7.7 kPa. The high cyclic variations in CA50 do not affect NMEP in SI mode. The COV_{NMEP} is 1.8% in SI mode. During SI to RCCI mode transition, an increase in NMEP is observed during first few cycles. The possible reason can be the fuel flow from the intake manifold puddle formed by the PFI during SI mode. The average error in tracking NMEP is 11.2 kPa in RCCI mode including the mode transition cycles with COV_{NMEP} of 2.8 %. λ and MPRR are constrained in SI and RCCI modes, respectively. The results show that λ and MPRR satisfy the set limits.

Table 7.5
Average error in tracking CA50 and NMEP, and COV_{NMEP} during SI-RCCI-SI mode switching

Mode	**CA50**		**NMEP**		
	Mean (CAD)	$Error_{avg}$ (CAD)	**Mean** (kPa)	$Error_{avg}$ (kPa)	COV_{NMEP} (%)
SI	9.3	2.6	401.5	7.7	1.8
RCCI	7.0	0.5	500.7	11.2	2.8
SI	10.3	2.8	402.7	8.6	4.8

From RCCI to SI mode switching, intake manifold airflow dynamics, throttle airflow and actuator dynamics, and port fuel transport dynamics play a vital role. With feed-forward transient controller, port fuel transport dynamics can be overcome. However, addressing throttle response and intake manifold dynamics are challenging. When the controller switches the mode from RCCI to SI mode, the throttle changes position from 90% to the desired position to achieve stoichiometric AFR. However, the throttle takes at least three cycles to reach the steady state position even with aggressive control actions. In addition, manifold filling dynamics is faster due to high upstream pressure. However, the air is stored in the intake manifold with throttle valve position close to WOT. The stored air can only be discharged to the cylinder, thus creating higher intake pressure than desired in the SI mode [48]. For low to medium NMEP, combustion in SI mode is stable when λ is below 1.25. Thus, to account for more air pumped in the cylinders due to higher intake pressure, more fuel is required to avoid too lean air-fuel mixture. The designed MPC commands the throttle position between 5 and 45% in SI mode. The desired throttle position command from the MPC is input to the PID controller as discussed in Section 6.2.1. The PID controller then controls the throttle valve position. MPC only commands the desired throttle position. It does not have any control on how fast the throttle reaches the desired position. Throttle takes finite amount of time to reach the steady state. Thus, RCCI to SI mode switching undergoes one cycle of misfire/partial burn. In order to avoid misfired or partial burn cycle, additional amount of fuel is injected to compensate for the dynamics involved in the mode switching. The additional amount of fuel is calculated based on the desired NMEP and the lean limit of air-fuel mixture. This additional fuel mass results in high NMEP than the requested/desired NMEP. It takes a few engine cycles to reach the steady state λ and NMEP after RCCI to SI mode switching. This effect can also be observed in the CA50 tracking. The average

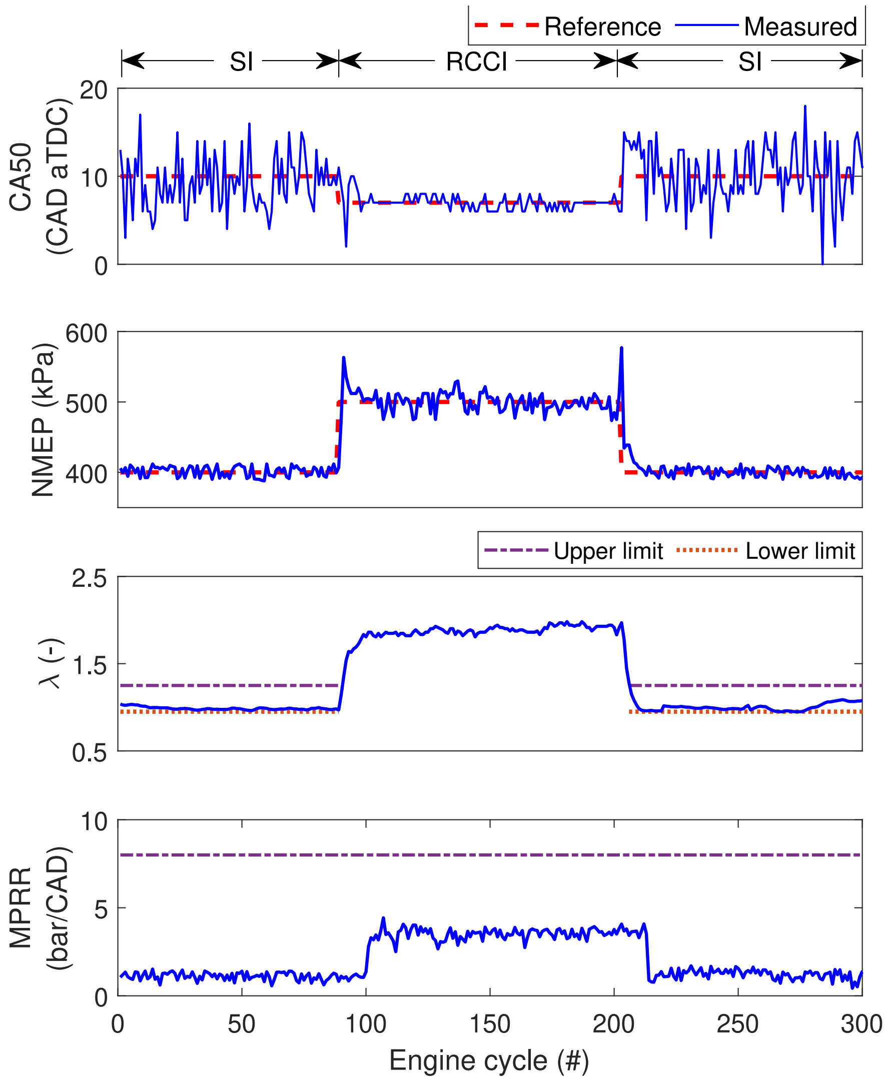

Figure 7.15: Experimental results for closed-loop control of CA50 and NMEP during SI-RCCI-SI mode switching

error in tracking CA50 and NMEP is 2.8 CAD and 8.6 kPa, respectively. COV_{NMEP} for SI operation during RCCI-SI mode switching is 4.8 % including the transient cycles. However, COV_{NMEP} for SI mode is 1.9 % if the first 3 engine cycles after mode switching are excluded.

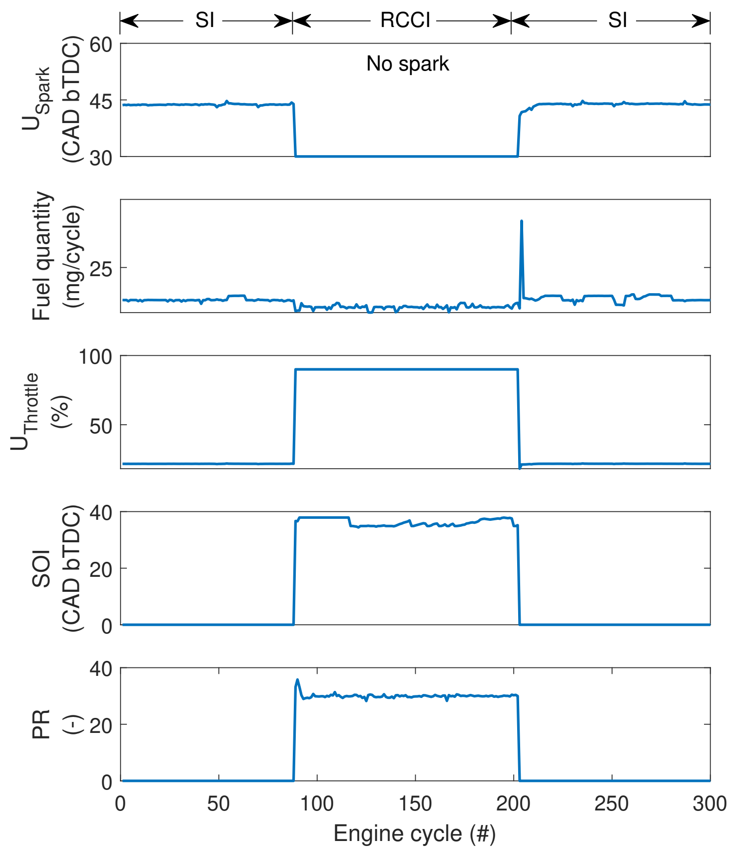

Figure 7.16: Control actions during SI-RCCI-SI mode switching for the results in Fig. 7.15

Chapter 8

RCCI-SI Mode Transition Control

In the previous chapter, the SI-RCCI-SI mode switching controller and observer design was discussed. Controller showed smooth mode transition from SI to RCCI mode with good tracking performance for CA50 and NMEP during transient and steady state engine operation. However, RCCI-SI mode transition either resulted in misfire or partial burn cycles. Extra fuel quantity was injected during the first cycle of RCCI-SI mode switching to avoid misfire or partial burn. Therefore, it is imperative to improve the RCCI-SI mode switching model and the MPC framework needs to be updated for better mode switching control.

The aim of this chapter is to model the dynamics involved in RCCI-SI mode switching and improve the performance and robustness of transient engine operation during mode transition. The main challenges observed during RCCI-SI mode transition are as follows:

- Port fuel injection leads to significant transport dynamics during RCCI-SI mode transition.
- Throttle valve needs finite amount of time to reach the final steady state position from initial position. This results in higher intake manifold pressure than the pressure required in SI mode during RCCI-SI mode transition.
- RCCI mode operates at wide open throttle position. This results in higher intake manifold pressure that increases the intake air flow. From RCCI to SI mode transition, the controller commands the throttle to close to the desired position. Throttle valve takes at least three engine cycle to attain the desired position. This results in more intake air flow during RCCI-SI mode transition. This requires extra fuel in the first few cycles of mode transition to maintain stoichiometric air-fuel ratio. Air stored in the intake manifold during RCCI operation due to WOT can only flow into the cylinders when RCCI-SI mode switch is commanded.
- Additional fuel quantity injected to compensate for the airflow during first few cycles of mode transition results in higher NMEP than desired.

8.1 Updated Model for RCCI-SI Mode Switching

Based on the above mentioned challenges, the model is appended with two more states to compensate for the process dynamics. Fuel transport dynamics due to PFI system is modeled as $\tau - X$ model which is explained in detail in Section 6.2.2. In Chapter 7, an additional feedforward controller was appended to the output of MPC framework to compensate for the port fuel transport dynamics. Therefore, a state is added to the existing system to embed the associated port fuel transport dynamics in the MPC framework. The intake manifold pressure model is updated to take into account the pressure changes during RCCI-SI mode switching. Mass of air entering the cylinder is added as a state to the system to take the throttle dynamics and intake manifold emptying dynamics into account during the RCCI-SI mode transition.

8.1.1 Port Fuel Transport Dynamics

A portion of fuel injected via PFI enters the cylinder and the remaining fuel forms a puddle in the intake manifold:

$$\dot{m}_p = \frac{-1}{\tau} m_p + X \dot{m}_{fi} \tag{8.1}$$

where $\dot{m}_p$ is rate of change of the puddle mass, m_p is mass of fuel forming the puddle, τ is the evaporation time constant of the fuel, X is the fraction of injected fuel entering the puddle and $\dot{m}_{fi}$ is the rate of fuel injected from PFI. Fuel flow in the cylinder $\dot{m}_{f,cyl}$ is given by:

$$\dot{m}_{f,cyl} = \frac{1}{\tau} m_p + (1 - X)\dot{m}_{fi} \tag{8.2}$$

Transfer function of the fuel dynamics is obtained by taking Laplace transform:

$$\frac{M_{f,cyl}(s)}{M_{fi}(s)} = \frac{(1 - X)s + \frac{1}{\tau}}{s + \frac{1}{\tau}} \tag{8.3}$$

$$\frac{M_{f,cyl}(s)}{M_{fi}(s)} = K + H(s) = 1 + \frac{\frac{X}{\tau(1-X)}}{s + \frac{1}{\tau}} \tag{8.4}$$

Therefore,

$$H(s) = \frac{Y(s)}{U(s)} = \frac{\frac{X}{\tau(1-X)}}{s + \frac{1}{\tau}} \tag{8.5}$$

By taking inverse Laplace transform of the Eq. 8.5,

$$\frac{dy}{dt} = -\frac{1}{\tau} y + \frac{X}{\tau(1 - X)} u(t) \tag{8.6}$$

The equation can be numerically solved as follows:

$$\frac{y(k + 1) - y(k)}{\Delta t} \approx \frac{dy}{dt} = -\frac{1}{\tau} y + \frac{X}{\tau(1 - X)} u \tag{8.7}$$

Equation 8.4 can be written in terms of injected fuel and the fuel flow inside the cylinder:

$$\dot{m}_{f,cyl}(k) = y(k) + \dot{m}_{fi}(k) \tag{8.8}$$

where:

$$y(k+1) = y(k) + \Delta t[-\frac{1}{\tau}y(k) + \frac{X}{\tau(1-X)}u(k)] \tag{8.9}$$

Eq. 8.9 gives the fuel flow entering the cylinder as a function of injected fuel.

8.1.2 Intake Manifold Dynamics

During RCCI-SI mode switching, the intake pressure does not change suddenly as shown in Fig. 8.1. When the change in throttle position is requested from 90% to the desired position in the SI mode, it takes at least 3 cycles to get within 5% of the steady state position. This means that the first two cycles after the mode switching require relatively high fuel quantity to avoid lean AFR. Table 8.1 presents the desired and actual throttle position and the corresponding change in the intake manifold pressure during RCCI to SI mode transition. $\text{Cycle}_{RCCI,last}$ represents the last RCCI cycle before mode switching. $\text{Cycle}_{SI,1}$ to $\text{cycle}_{SI,4}$ represent the first cycle and the subsequent engine cycles of SI mode after mode switching. An aggressive throttle valve control induces more transients which increase cyclic variations in the SI mode. Therefore, the pressure changes resulting from the slow throttle response

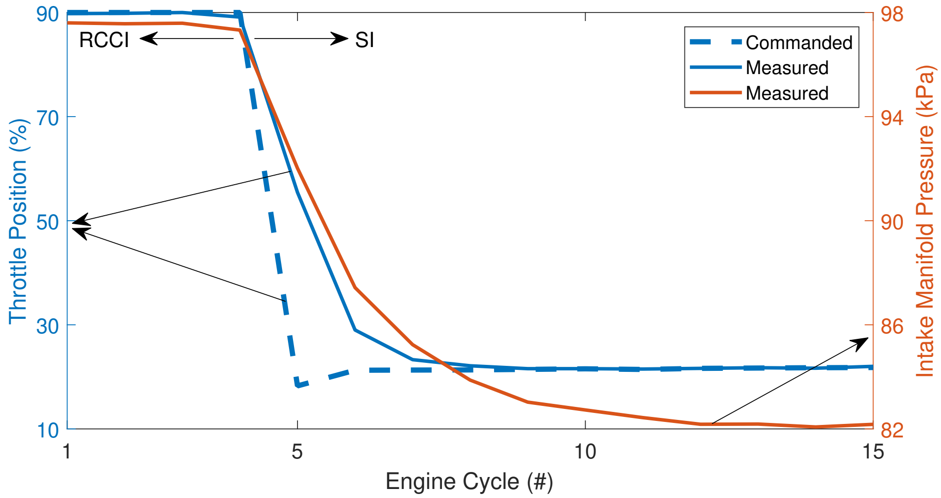

Figure 8.1: Throttle response vs. commanded position and corresponding variations in the intake manifold pressure

are incorporated. The intake manifold pressure is determined by empirical correlation by Eq. 8.10:

$$P_{man}(k+1) = P_{man}(k) - 0.36(P_{man}(k) - (\alpha U_{th}(k) + \beta(1)U_{th}(k)^{\beta(2)})) \qquad (8.10)$$

where α and β are given by:

$$\alpha = z(1) + z(2)U_{th}(k) + z(3)U_{th}(k)^{z(4)} \qquad (8.11)$$

$$z = \begin{bmatrix} 5.6 & 0.069 & 3.6 & -0.057 \end{bmatrix} \qquad (8.12)$$

$$\beta = \begin{bmatrix} -1.3 & 1.5 \end{bmatrix} \qquad (8.13)$$

Table 8.1
Desired and actual throttle position and the changes in the intake manifold pressure during RCCI-SI mode transition

Parameters	Engine Cycle (#)				
	RCCI-0	**SI-1**	**SI-2**	**SI-3**	**SI-4**
Desired throttle position (%)	22				
Actual throttle position (%)	90	55.4	29	23.3	22.1
Desired intake pressure (kPa)	82				
Actual intake pressure (kPa)	97.3	92	87.4	83.9	83

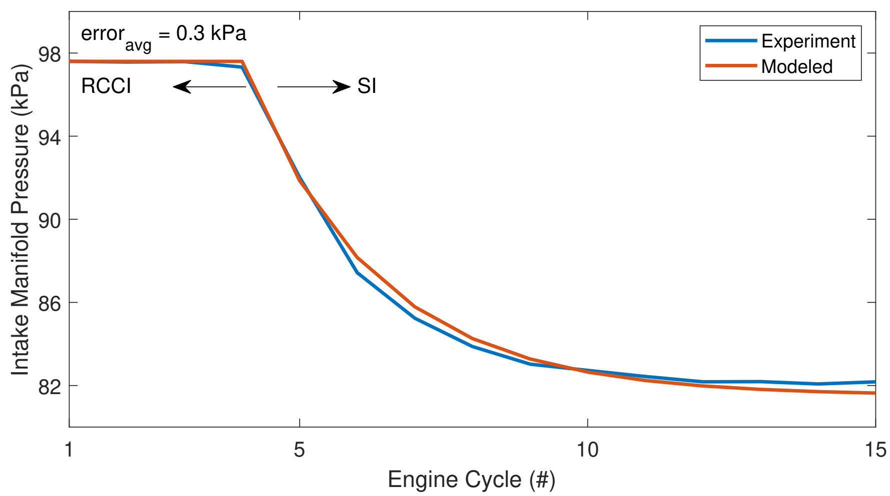

Figure 8.2: Comparison of the measured intake manifold pressure and model estimation

Figure 8.2 shows the comparison of modeled and experimental measurements for the change in the intake pressure during RCCI-SI mode switching for a change in throttle position from 90 to 22 %. The average error between measured and estimated intake manifold pressure is 0.3 kPa.

The controller developed in the Chapter 6 showed good performance under steady state RCCI and SI modes and during SI-RCCI mode switching. During the SI-RCCI mode transition, the throttle valve opens to 90%. The intake manifold fills faster because of the higher upstream pressure. For RCCI-SI mode switching, the air stored in the intake manifold during RCCI operation can only flow into the cylinder because of higher upstream pressure. This disturbs the transient operation from RCCI to SI mode transition. Therefore, another state is introduced to the system to account for the additional mass of air flow during emptying of the intake manifold from RCCI-SI mode transition. Rate of change of air Δm_{air} discharging from the intake manifold into the cylinder is modeled as a function of manifold pressure. Thus, the total mass of air flowing in the cylinder is given by:

$$m_{air,tot} = m_{cyl} + \Delta m_{air} \tag{8.14}$$

Δm_{air} is stored mass of air in the intake manifold which enters the cylinder during the RCCI-SI mode switching. Δm_{air} is assumed to be a percentage of mass of air (m_{th}) flowing through the throttle. Therefore, Δm_{air} is modeled by regressing the modified orifice Eq. 6.9.

$$\dot{m}_{air,total} = A_{eff}\frac{P_o}{\sqrt{RT_o}}\phi \tag{8.15}$$

where, ϕ is given by [139]:

$$\phi = (\frac{P_{man}}{P_o})^{\frac{1}{\gamma}}\sqrt{\frac{2\gamma}{\gamma-1}(1-(\frac{P_{man}}{P_o})^{\frac{\gamma-1}{\gamma}})^{\frac{\gamma-1}{\gamma}}} \tag{8.16}$$

where, γ is the specific heat ratio, P_o is upstream pressure, P_{man} is the downstream pressure. A_{eff} is the effective area which is modeled as a function of throttle valve position. However, A_{eff} is modeled as a function of intake pressure to estimate the mass of air stored in the intake manifold when the throttle valve is at 90%.

$$A_{eff} = a(1)P_{man} + a(2)P_{man}^{a(3)} + a(4) \tag{8.17}$$

where

$$a = \begin{bmatrix} -0.0018 & 0.0011 & 2.5761 & 0.0009 \end{bmatrix} \tag{8.18}$$

The air-fuel ratio (λ) is then determined as follows:

$$\lambda = \frac{\frac{m_{\dot{air},tot}}{\dot{m}_{f,cyl}}}{AFR_{st}} \tag{8.19}$$

Gorzelic et. al. developed a model-based HCCI to SI mode transition strategy in which an LQR controller was developed to control the throttle position to avoid throttle dynamics [48]. The study suggested that additional fuel in the first cycle of mode transition is inevitable due to the throttle dynamics and intake manifold dynamics [48]. The additional fuel injected in the cylinder to compensate for the additional intake air results in high NMEP. In order to maintain COV_{NMEP} below 5% during mode switching, CA50 is modulated to achieve the desired NMEP. To this end, a correlation developed by Ayala et. al. is used to determine the desired CA50 for the first two cycles of mode transition [163]. The correlation is given below:

$$\frac{NMEP}{NMEP_{MBT}} = 1 - 1.168[(1 + 4.443.10^{-3}(CA50 - CA50_{MBT})^2)^{0.5} - 1] \qquad (8.20)$$

The correlation is validated by simulating SI and RCCI mode in GT Power. For SI mode, the simulations are carried out by providing sweeps of CA50 and throttle valve position to compare the variation in NMEP due to change in CA50 for different engine loads at 1200 RPM and intake temperature of 333.1K. 75 simulations are carried out to compare the results with those obtained from the Eq. 8.20. NMEP obtained from the GT Power model is normalized w.r.t NMEP_{MBT}. Normalized NMEP from the simulations and the correlation are plotted against the retarded CA50 to compare the results for different operating conditions. Figure 8.3 shows that the correlation and the simulations provided very similar results with an average error of 0.004. Similarly, simulations are carried out for RCCI mode to compare the effect of CA50 on the NMEP. The simulations are run at WOT, 1200 RPM, and intake temperature of 333.1K. A sweep in CA50 is provided for different engine loads. A sweep in λ in the range of 1.4 - 2.2 is provided to achieve different NMEP. The results from the correlation and simulations are shown in Fig. 8.4. The correlation provides very similar results to those of the simulations with average error ranging from 0.002-0.008. Based on the simulation and the correlation results for SI and RCCI modes, it is assumed that the effect of combustion retard on NMEP in the transient engine operation would be similar to the results presented in Fig. 8.3 and 8.4. Therefore,

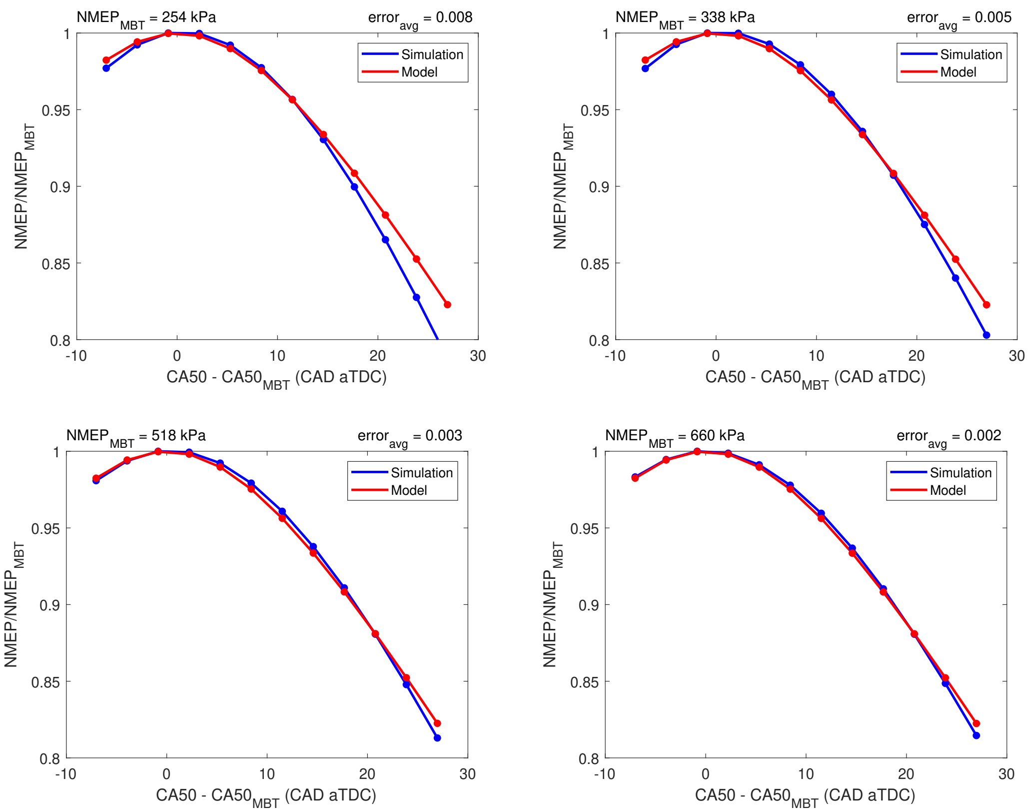

Figure 8.3: Variation in normalized NMEP w.r.t change in CA50 for λ = 1 and 1200 RPM in SI mode

the correlation 8.20 is used to determine the desired CA50 for the first two cycles after the RCCI to SI mode switching to avoid large variations in the desired NMEP.

8.2 State Space Representation of RCCI-SI Mode Switching

Based on the updated states, the model is compiled and linearized around the nominal operating conditions. The nominal operating conditions for linearized model are

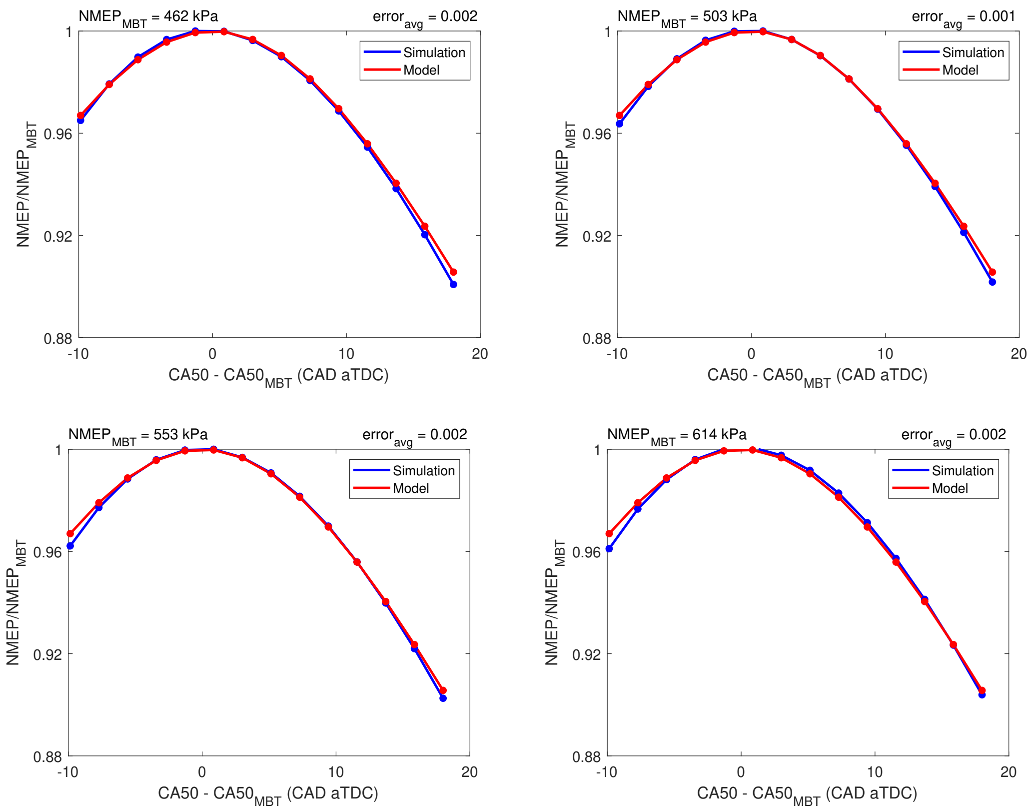

Figure 8.4: Variation in normalized NMEP w.r.t change in CA50 for T_{man} = 333.15 K and N = 1200 RPM in RCCI mode

Table 8.2
Nominal operating conditions for linearized COM

Parameters	**Value**
CA50 (CAD aTDC)	6.9
T_{ivc} (°C)	340
P_{man} (kPa)	97.6
NMEP (kPa)	500
MPRR (bar/CAD)	1.11
SOI (CAD bTDC)	37
PR (-)	30
FQ (mg/cyc)	17

presented in the Tables 8.2 and 8.3 for RCCI and SI modes, respectively.

Table 8.3
Nominal operating conditions for linearized COM

Parameters	Value
CA50 (CAD aTDC)	12
T_{ivc} (°C)	352.7
P_{man} (kPa)	85
NMEP (kPa)	497
λ (-)	1.11
U_{sp} (CAD bTDC)	40
U_{th} (%)	25
FQ (mg/cyc)	18.5

$$A = \begin{bmatrix} -0.195 & -0.029 & 0.196 & 0 & 0.0166 \\ -0.011 & 0.062 & -0.421 & 0 & -0.036 \\ 0.0002 & -0.0011 & 0.50 & 0 & 0.001 \\ 0.072 & 0.011 & -0.072 & 0.01 & -0.006 \\ -0.011 & 0.032 & 5.66 & 0 & 0.032 \end{bmatrix} \tag{8.21}$$

$$B = \begin{bmatrix} -0.358 & 0.157 & -0.903 \\ 0 & -0.0008 & 1.26 \\ 0 & 0 & -0.0163 \\ 0.152 & -0.089 & 0.961 \\ -0.010 & -0.0136 & 23.34 \end{bmatrix} \tag{8.22}$$

The linearized discrete state space model for SI modes can be expressed as follows:

$$X(k+1) = AX(k) + BU(k) \tag{8.23}$$

$$Y(k) = CX(k) + DU(k) \tag{8.24}$$

where X and U for SI mode are given by Eq. 8.25 and 8.26, respectively:

$$X = \begin{bmatrix} M_{f,cyl} & CA50 & T_{ivc} & P_{man} & \lambda & IMEP & \Delta m_{air} \end{bmatrix}^T \tag{8.25}$$

where, $M_{f,cyl}$ is the portion of the injected fuel that enters the cylinder and Δm_{air} is the mass of air that enters the cylinder during the filling/emptying of the intake manifold.

$$U = \begin{bmatrix} U_{sp} & U_{th} & FQ \end{bmatrix}^T \tag{8.26}$$

The plant matrices for SI mode are as follows:

$$A = \begin{bmatrix} 0.8187 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.0345 & 0.00499 & 0.0018 & -0.757 & -1.58 & -0.0022 & -0.388 \\ 0.038 & -0.0003 & 0.052 & 0.033 & -45.25 & -0.0634 & -0.214 \\ 0.01 & 0.0001 & 0 & 0.667 & 0 & 0 & 0 \\ -0.0022 & 0 & 0 & 0.038 & 0.001 & 0 & 0.0138 \\ 0.749 & -0.0197 & 0.011 & 2.015 & -9.15 & 0.0122 & -4.67 \\ 0 & 0 & 0 & 0.197 & 0 & 0 & 0.15 \end{bmatrix} \tag{8.27}$$

$$B = \begin{bmatrix} 0 & 0 & 1 \\ -1.00 & -0.041 & -0.76 \\ 0 & -0.156 & 0.839 \\ 0 & 0.446 & 0 \\ 0 & 0.025 & -0.0487 \\ 3.92 & 6.16 & 16.54 \\ 0 & 0 & 0 \end{bmatrix} \tag{8.28}$$

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{8.29}$$

$$D = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{8.30}$$

Using the updated state space models, a gain scheduled model predictive controller is developed as shown in Fig. 8.5. Two Kalman filters are designed for each mode. The details about the development of controller and Kalman filters can be found in Sections 7.2 and 7.3. The state estimations of Kalman filter are used to achieve the cyclic coupling of the states. The following constraints are applied in SI mode:

$$0.95\ (-) \leq \lambda \leq 1.25\ (-) \tag{8.31}$$

$$60\ (CADbTDC) \leq U_{sp} \leq 20\ (CADaTDC) \tag{8.32}$$

$$12\ (mg/cycle) \leq FQ \leq 55\ (mg/cycle) \tag{8.33}$$

$$5\ (\%) \leq U_{th} \leq 45\ (\%) \tag{8.34}$$

RCCI mode is subjected to the following constraints:

$$MPRR \leq 8\ (bar/CAD) \tag{8.35}$$

$$25\ (CAD\ bTDC) \leq SOI \leq 60\ (CAD\ bTDC) \tag{8.36}$$

$$10\ (\%) \leq PR \leq 45\ (-) \tag{8.37}$$

$$8\ (mg/cycle) \leq FQ \leq 24\ (mg/cycle) \tag{8.38}$$

8.3 Experimental Results

The developed controller and Kalman filters are first validated by simulating the system in Simulink using nonlinear control-oriented model as plant. The C code is

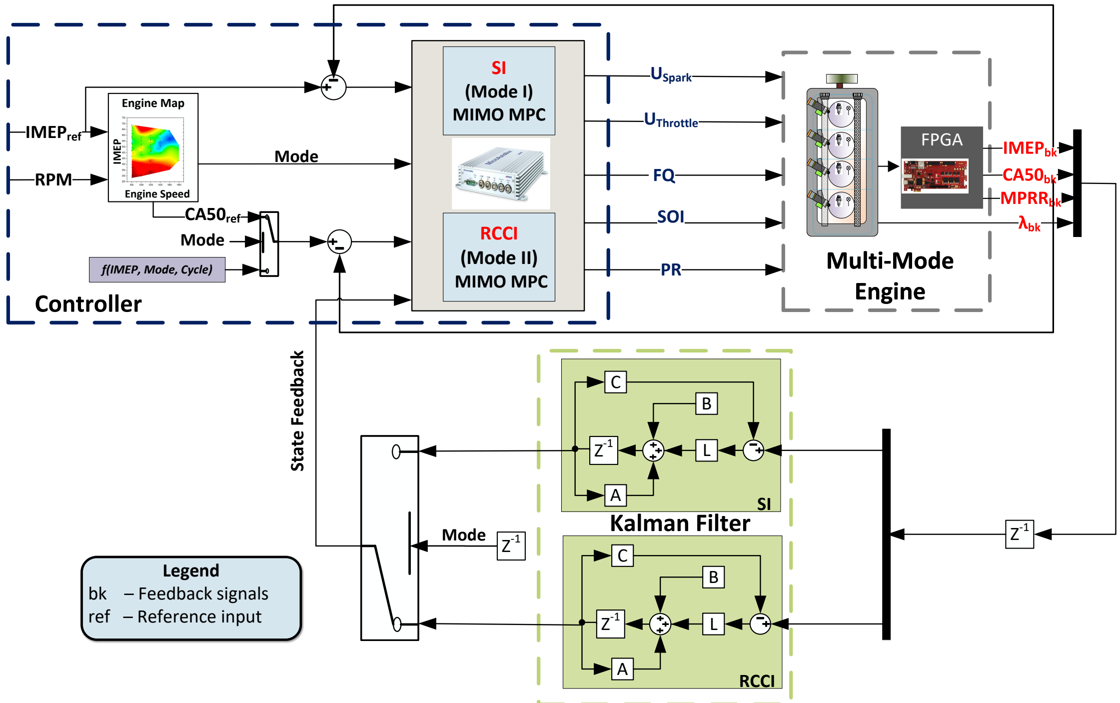

Figure 8.5: Schematic of supervisory controller, gain scheduled MPC and Kalman filter for State estimation for a multi-mode engine

then generated to implement the controller on the actual system. The optimal region for RCCI mode is identified between the NMEP range of 300-600 kPa. Therefore, supervisory controller selects the mode based on the requested NMEP. Step changes in NMEP and CA50 are simultaneously provided during mode switching, as shown in Fig. 8.6. A step change of NMEP from 285kPa to 520kPa is requested which indicates SI to RCCI mode switching. The change in CA50 is requested from 15 CAD (aTDC) in SI mode to 6 CAD (aTDC) in RCCI mode. The result shows good tracking of CA50 for both SI and RCCI modes. During SI-RCCI mode switching, the requested CA50 is advanced from 16 to 6 CAD, the controller modulated SOI and PR to achieve the desired CA50 while keeping MPRR below the set limit. The first

Table 8.4
Average error in tracking CA50 and NMEP, and COV_{NMEP} during SI-RCCI-SI mode switching

Mode	**CA50**		**NMEP**		
	Mean (CAD)	$Error_{avg}$ (CAD)	**Mean** (kPa)	$Error_{avg}$ (kPa)	COV_{NMEP} (%)
SI	14.6	1.8	292	10.6	3.5
RCCI	5.5	1.7	513	10.7	3.0
SI	14.7	2.0	288	7.9	3.6

cycle of mode switching showed an advanced CA50. However, the desired CA50 value is achieved in the subsequent cycles. The first cycle in RCCI mode resulted in higher NMEP than desired resulting in an overshoot of 6 %. Thus, the controller reduced the fuel quantity in the following cycles which can be observed in increased λ during those cycles. The steady state NMEP is achieved in the subsequent cycles. MPRR stayed below 8 bar/CAD for the entire mode switching operation. The summary of the results are presented in Table 8.4. The average errors for tracking CA50 and NMEP in SI mode are 1.8 CAD and 10.6 kPa, respectively. The COV_{NMEP} in SI mode is 3.5%. For RCCI mode, the average tracking errors for CA50 an NMEP are 1.7 CAD and 10.7 kPa. The COV_{NMEP} is 2.8 % excluding the first SI to RCCI mode switching cycle. The COV_{NMEP} including the first mode transition cycle is 4.3%.

RCCI to SI mode switching is carried out from higher to lower requested load. Simultaneous step changes in NMEP and CA50 are provided. As mentioned earlier, the first two cycles are majorly affected due to the intake manifold, throttle and port fuel transport dynamics. These dynamics are incorporated in the model states such as manifold pressure, change in mass of air flowing in the cylinder and fuel flowing into

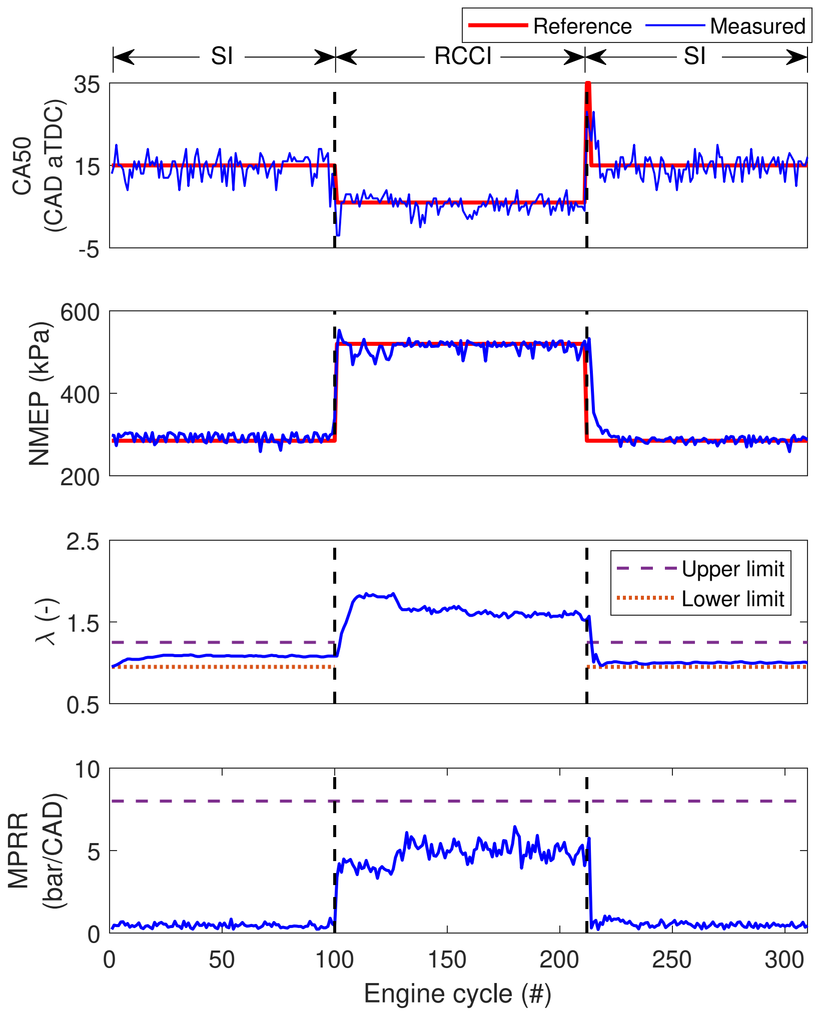

Figure 8.6: Experimental results for CA50 and NMEP control while constraining λ and MPRR to validate MPC performance in SI-RCCI-SI mode switching at 1200 RPM

the cylinder. To compensate for these dynamics, extra fuel is commanded to avoid misfire or partial burn which results in higher NMEP than desired. To ensure smooth mode switching with less fluctuations in the NMEP, the desired CA50 is regulated for the first two cycles of the mode switching. To this end, Eq. 8.20 is used to calculate the desired CA50 to maintain NMEP. The requested CA50 for the first two cycles is 35 CAD (aTDC). The controller adjusted spark timing to achieve the desired CA50.

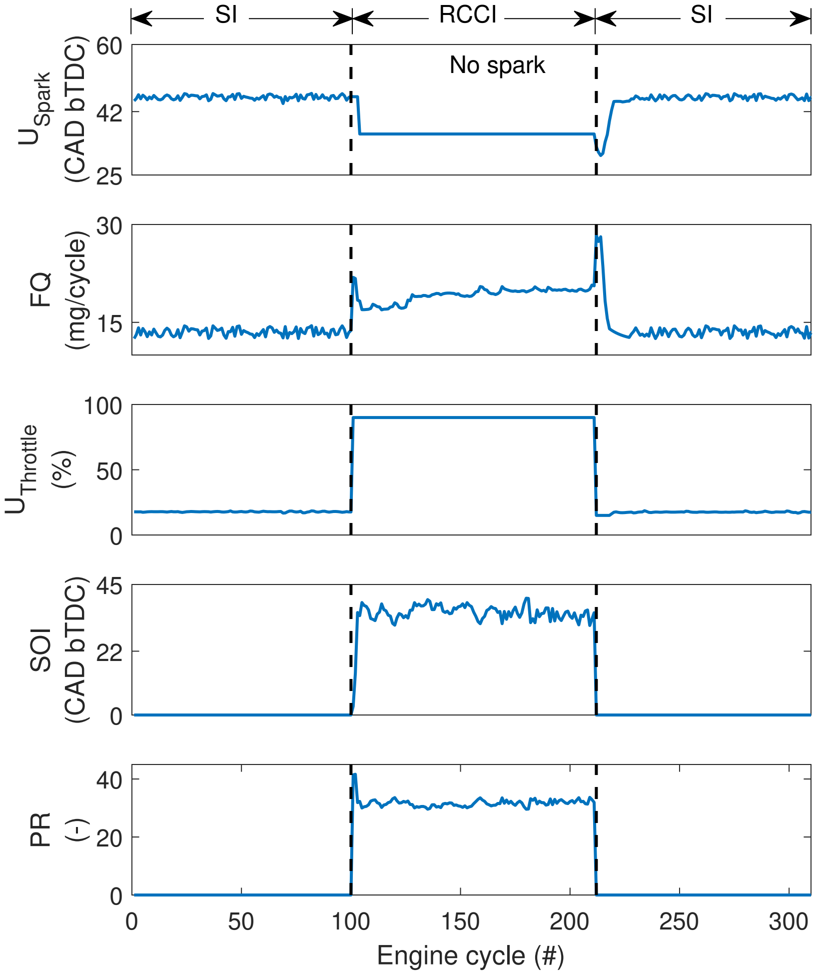

Figure 8.7: Manipulated variables of MPC for the results in Fig. 8.6

The resulting CA50 for the first two cycles was 28 and 21 CAD (aTDC), respectively. This discrepancy in the CA50 resulted in slightly higher NMEP but within the desired range. The controller is capable of providing steady state NMEP within 5 engine cycles of mode switching resulting in COV_{NMEP} of 3.6% excluding the first 5 engine cycles of mode transition.

The performance of the controller is also validated for a different load requirement

Table 8.5
Average error in tracking CA50 and NMEP, and COV_{NMEP} during SI-RCCI-SI mode switching

Mode	**CA50**		**NMEP**		
	Mean (CAD)	$Error_{avg}$ (CAD)	**Mean** (kPa)	$Error_{avg}$ (kPa)	COV_{NMEP} (%)
SI	16.1	2.3	288	7.4	3.0
RCCI	5.9	0.8	605.8	13.9	2.8
SI	14.9	2.0	717.4	13.0	2.3

mode switching operation. A step change of 285 kPa to 600 kPa is provided for SI to RCCI mode switching. A CA50 change of 16 CAD to 6 CAD is requested during SI to RCCI mode switching. The controller successfully tracks the changes in CA50 and NMEP from SI to RCCI mode as shown in Fig. 8.8. In SI mode, spark timing is adjusted to achieve the desired CA50 while throttle position and fuel quantity are simultaneously adjusted to achieve the desired NMEP while keeping air-fuel ratio close to stiochiometry. In RCCI mode, the throttle position is commanded to 90% while SOI and PR are simultaneously adjusted to track CA50 and maintain MPRR below 8 bar/CAD. NMEP in RCCI mode is achieved by regulating the fuel quantity. The average errors in tracking CA50 are 2.3 CAD and 0.8 CAD in SI and RCCI modes, respectively. The results of SI-RCCI-SI mode switching are presented in Table 8.5. The average errors in tracking NMEP are 7.4 kPa and 13.9 kPa in SI and RCCI modes, respectively.

For RCCI to SI mode switching from 600 kPa to 720 kPa NMEP, the controller takes into account the actuator and process dynamics into the account. The controller

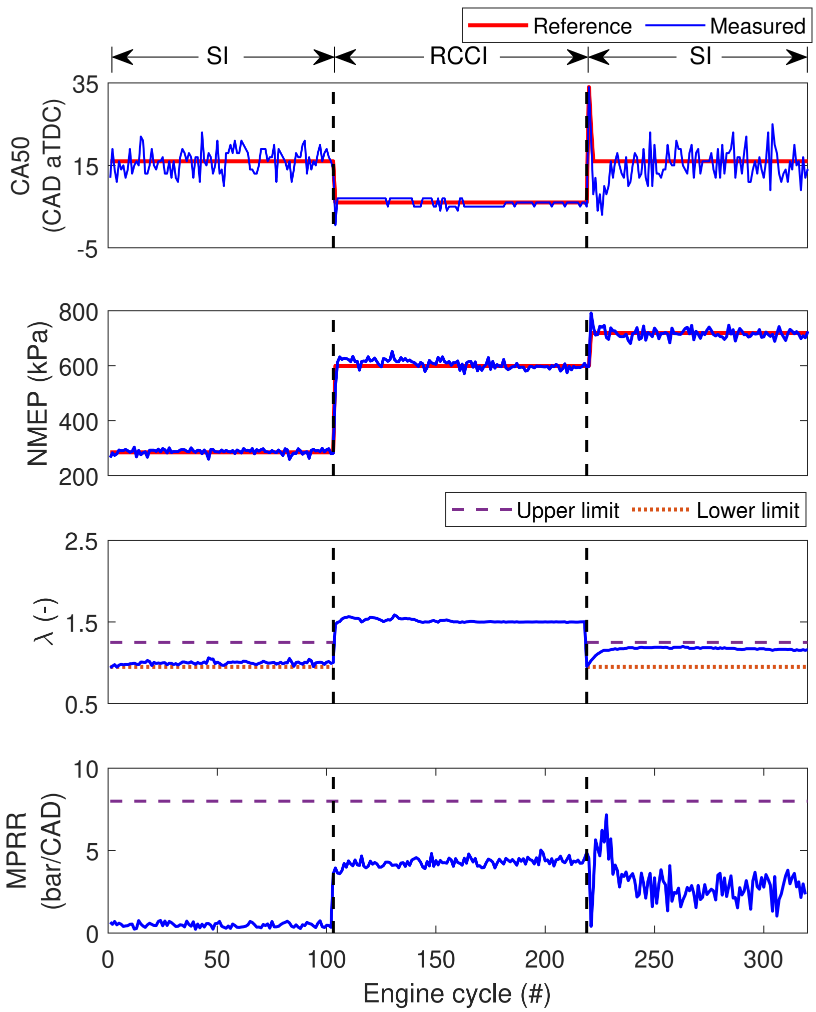

Figure 8.8: Simulation results for CA50 and NMEP control while constraining λ and MPRR to validate MPC performance in SI-RCCI-SI mode switching at 1200 RPM

commands extra fuel amount to achieve the desired NMEP. This resulted in relatively higher NMEP in the first cycle even when the CA50 is retarded. This can be mainly associated to the richer air-fuel mixture in the first few cycles. RCCI-SI mode switching at high load is dominantly affected by the slow fuel transport dynamics. That is why, the controller is designed to achieve minimum COV_{NMEP}. During the

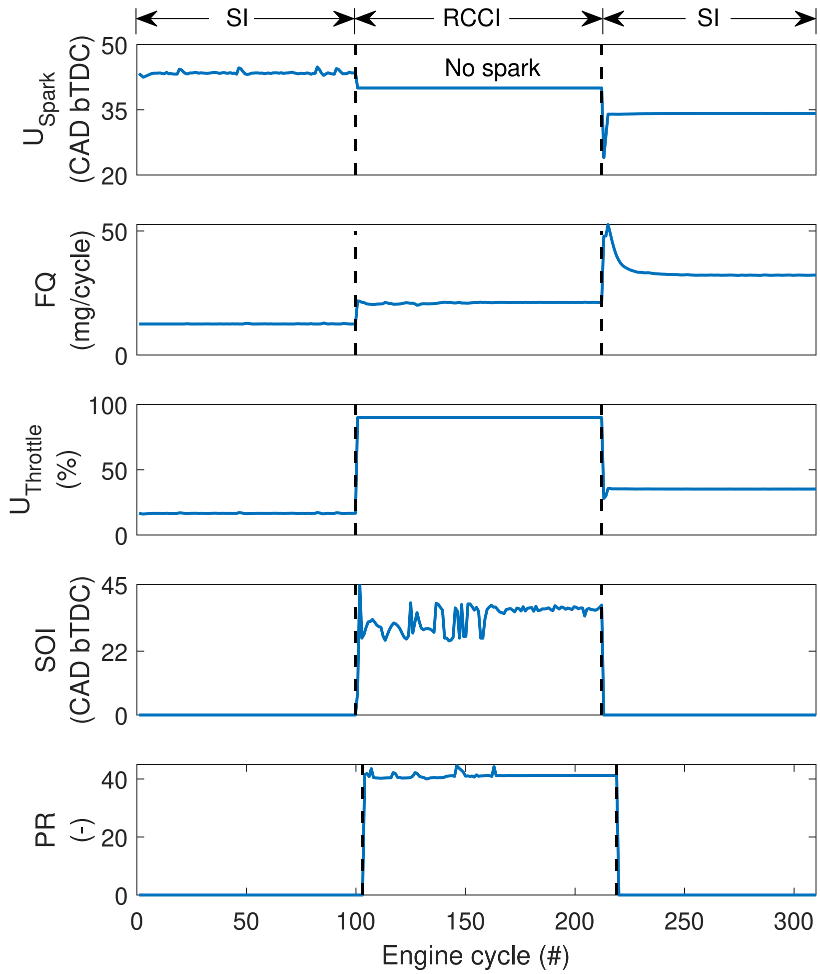

Figure 8.9: Manipulated variables of MPC for the results in Fig. 8.8

mode switching, first few cycles of SI mode resulted in advanced combustion causing higher MPRR than expected but overall MPRR stays below the knocking limit. MPRR reduces as the desired CA50 of 16 CAD is achieved in SI mode.

A constant low load sweep is provided for SI to RCCI mode switching at 1200 RPM. A step change in CA50 is provided from 8 CAD to 5 CAD from SI to RCCI mode as shown in Fig. 8.10. Spark timing is adjusted to achieve the desired CA50 in SI mode.

Table 8.6
Average error in tracking CA50 and NMEP, and COV_{NMEP} during SI-RCCI mode switching

Mode	**CA50**		**NMEP**		
	Mean (CAD)	$Error_{avg}$ (CAD)	**Mean** (kPa)	$Error_{avg}$ (kPa)	COV_{NMEP} (%)
SI	7.5	2.2	311	9.5	2.7
RCCI	5.2	0.9	323	7.8	2.9

While SOI is adjusted in RCCI mode to attain the desired CA50. The average errors in tracking CA50 for SI and RCCI modes are 2.2 CAD and 0.9 CAD, respectively. Mode switching for SI to RCCI mode is carried out at a constant low load of 320 kPa. Fuel quantity and throttle positions are modulated to track NMEP. In SI mode, λ is maintained near stoichiometric AFR. However, throttle is commanded to open to 90% for RCCI mode. In addition, MPRR is desired to be below 8 bar/CAD. The results show that MPRR stayed below the set limit for both SI and RCCI operations. The summary of the results is presented in Table 8.6. The average NMEP achieved in SI and RCCI modes is 311 and 323 kPa, respectively. The average error in tracking NMEP and COV_{NMEP} in SI mode are 9.5 kPa and 2.7%. In RCCI mode, the average error in tracking NMEP and COV_{NMEP} are 7.8 kPa and 2.9%.

Table 8.7
Average error in tracking CA50 and NMEP, and COV_{NMEP} during SI-RCCI mode switching

Mode	**CA50**		**NMEP**		
	Mean (CAD)	$Error_{avg}$ (CAD)	**Mean** (kPa)	$Error_{avg}$ (kPa)	COV_{NMEP} (%)
SI	7.2	2.0	313	16.2	3.3
RCCI	5.4	0.9	491.5	13.2	2.0

Figures 8.12 and 8.13 show SI to RCCI mode switching during simultaneous step

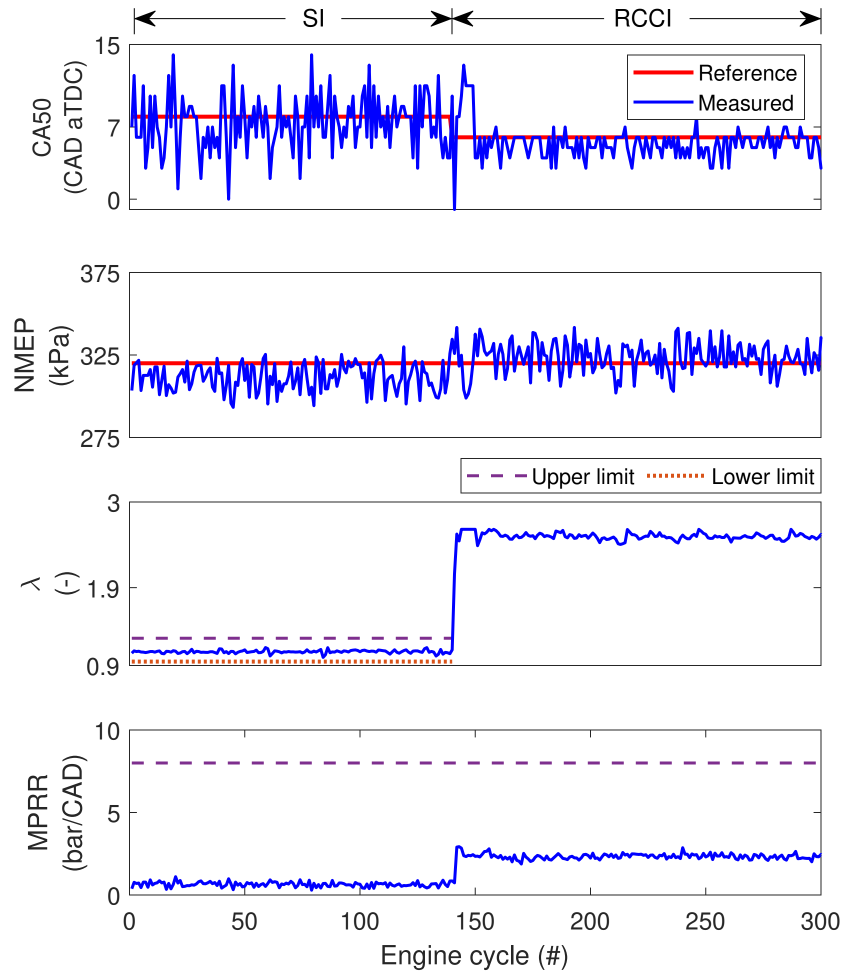

Figure 8.10: Simulation results for CA50 and NMEP control while constraining λ and MPRR to validate MPC performance during constant load SI-RCCI mode switching at 1200 RPM

changes in engine load and CA50. CA50 is changed from 8 CAD in SI mode to 5 CAD in RCCI mode while NMEP is changed from 300 kPa in SI mode to 500 kPa in RCCI mode. The controller successfully tracks the changes in CA50 and NMEP. The average errors of 2 CAD and 0.9 CAD are observed in tracking CA50 in SI and RCCI modes, respectively. The average error in NMEP and COV_{NMEP} in SI mode are 16.2 kPa and 3.3%, respectively. The results are provided in Tale 8.6. The average error in

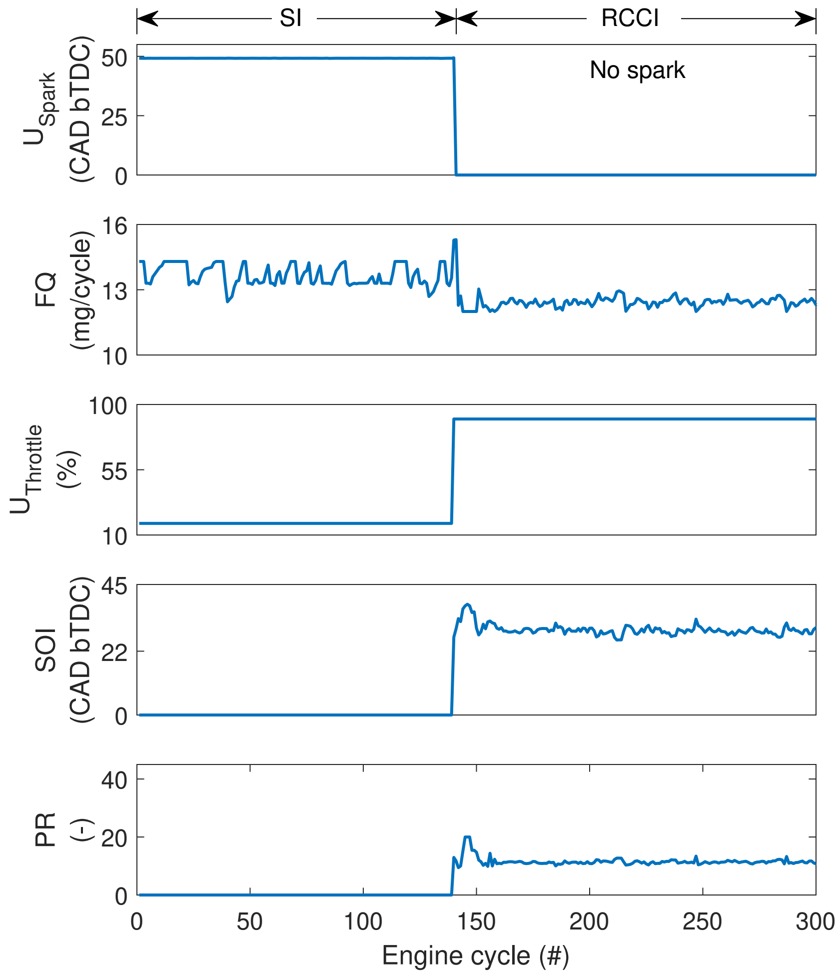

Figure 8.11: Manipulated variables of MPC for the results in Fig. 8.10

NMEP and COV_{NMEP} in RCCI mode are 13.2 kPa and 2%, respectively. Moreover, λ is kept near stoichiometric AFR during SI mode and MPRR is maintained below 8 bar/CAD in RCCI mode.

The controller performance is also validated for SI-RCCI-SI mode switching at 1600 RPM. Simultaneous step changes in CA50 and NMEP are provided during SI and RCCI mode switching as shown in Fig. 8.14. During SI to RCCI mode transition,

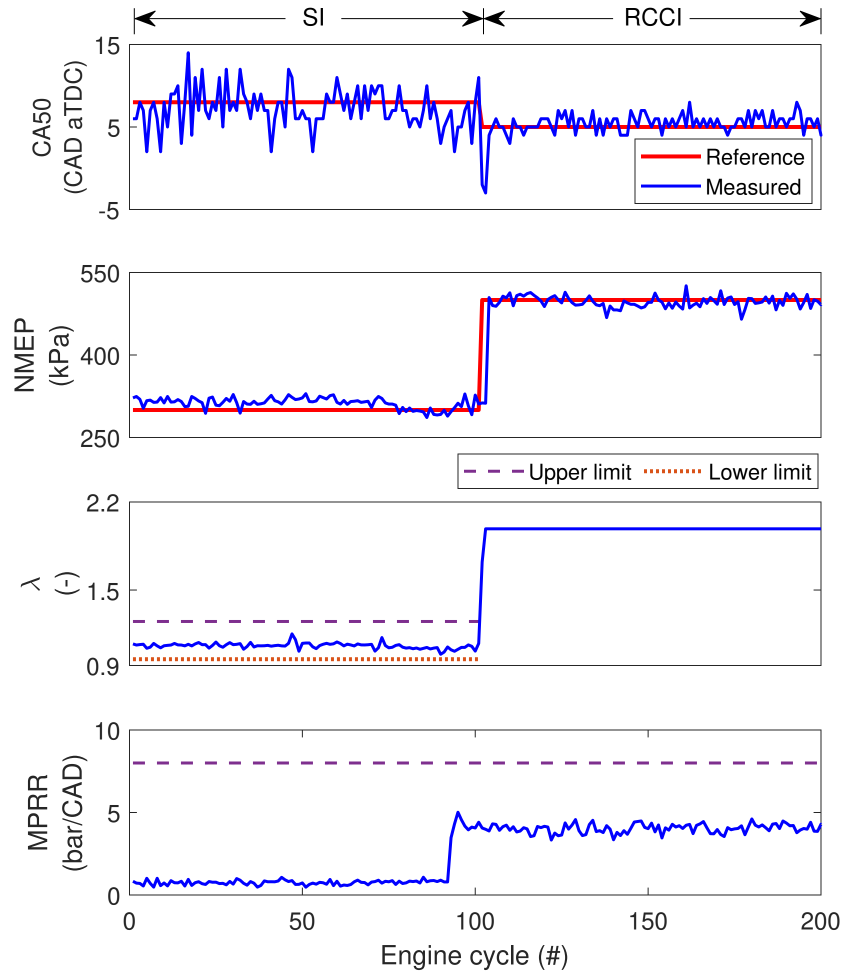

Figure 8.12: Experimental results for CA50 and NMEP control while constraining λ and MPRR to validate MPC performance in SI-RCCI mode switching at 1200 RPM

CA50 is varied form 8 CAD to 11 CAD and NMEP is changed from 300 kPa to 475 kPa. Spark timing is adjusted to achieve the desired CA50 in SI mode with an average error of 3.6 CAD. However, SOI is retarded to achieve the desired CA50 of 11 CAD in RCCI mode. The average error in tacking CA50 in RCCI mode is 0.4 CAD. Table 8.8 shows a summary of the results for tracking performance of the controller. The average errors in tracking NMEP in SI and RCCI modes are 13.4 kPa and 20.3

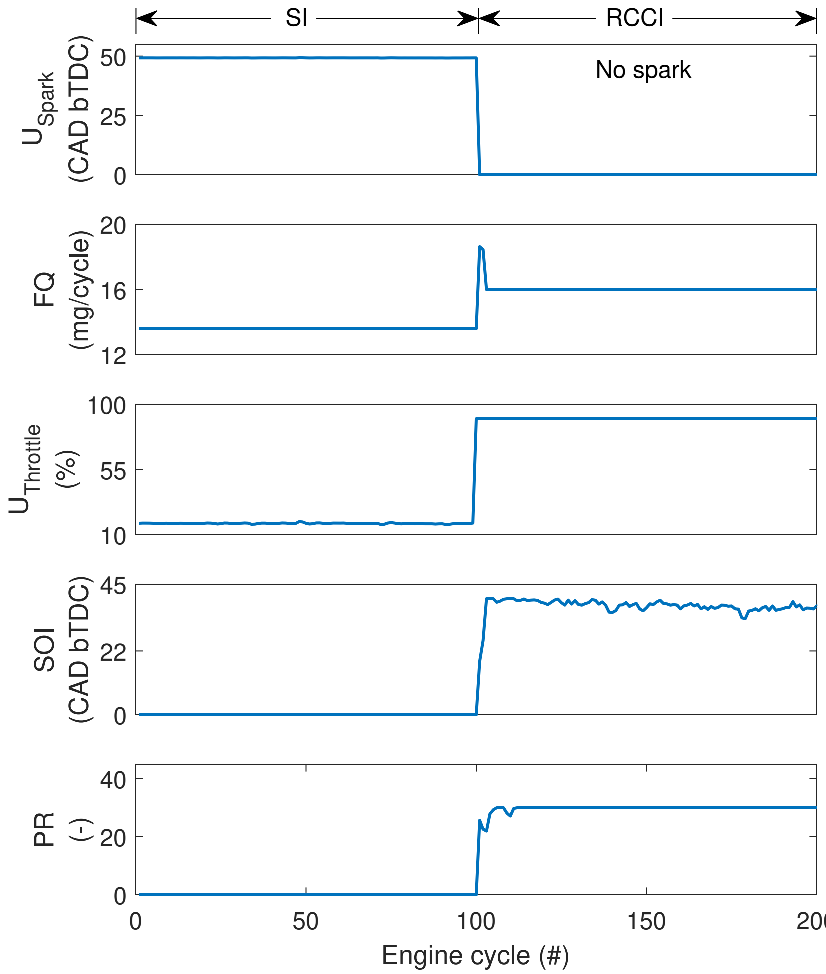

Figure 8.13: Manipulated variables of MPC for the results in Fig. 8.12

kPa, respectively. The COV_{NMEP} obtained in SI and RCCI modes are 3.5% and 3.8%, respectively. λ is maintained near stoichiometric AFR in SI mode and MPRR is limited below 8 bar/CAD by modulating premixed ratio of the two fuels in RCCI mode.

RCCI-SI mode switching is carried out from low to high load at 1600 RPM. The controller performance against the variations in CA50 and NMEP is validated. A

Table 8.8
Average error in tracking CA50 and NMEP, and COV_{NMEP} during SI-RCCI mode switching

Mode	**CA50**		**NMEP**		
	Mean (CAD)	$Error_{avg}$ (CAD)	**Mean** (kPa)	$Error_{avg}$ (kPa)	COV_{NMEP} (%)
SI	8.3	3.6	311	13.4	3.5
RCCI	10.7	0.4	460	20.3	3.8

Table 8.9
Average error in tracking CA50 and NMEP, and COV_{NMEP} during RCCI-SI mode switching

Mode	**CA50**		**NMEP**		
	Mean (CAD)	$Error_{avg}$ (CAD)	**Mean** (kPa)	$Error_{avg}$ (kPa)	COV_{NMEP} (%)
RCCI	4.9	1.7	454	13.8	3.6
SI	9.3	3.4	646	15.3	2.9

step change in CA50 is provided from 5 CAD in RCCI mode to 10 CAD in SI mode. Similarly, NMEP is varied from 450 kPa to 650 kPa for RCCI-SI mode switching. Controller modulates SOI mainly to track CA50. While PR is increased to 40 to keep the MPRR below 8 bar/CAD. The average values of CA50, NMEP and the corresponding average errors for both RCCI and SI modes are presented in Table 8.9. When mode is switched from RCCI to SI mode, throttle valve is commanded to 41% opening. However, throttle valve attains the position of 52%. This causes a leaner air fuel mixture resulting in the reduced NMEP without causing any overshoot. Though, a retarded value of CA50 was provided for the first two cycles of mode switch to the reduce the NMEP due to additional fuel injected. However, controller tracks CA50 and NMEP in SI mode with average errors of 3.4 CAD and 15.3 kPa. COV_{NMEP} observed in RCCI and SI modes are 3.6% and 2.9%, respectively.

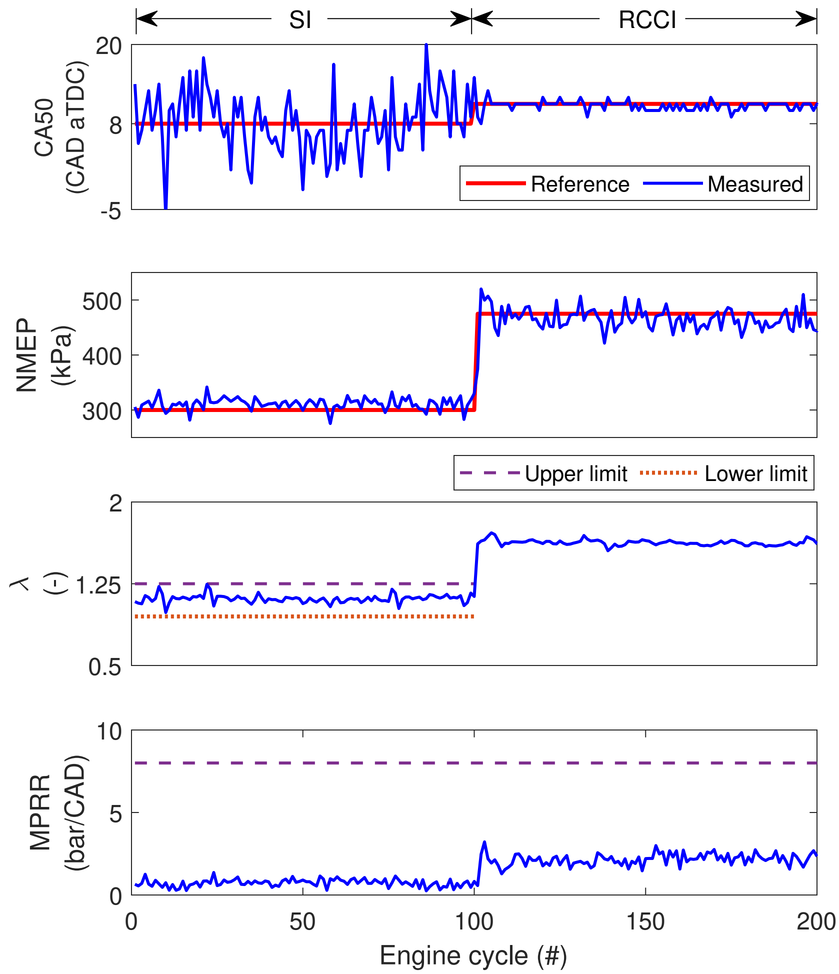

Figure 8.14: Experimental results for CA50 and NMEP control while constraining λ and MPRR to validate MPC performance in SI-RCCI mode switching at 1600 RPM

A constant load SI-RCCI mode switching is carried out at 1600 RPM while keeping CA50 constant at 7 CAD aTDC in both modes. Figure 8.18 shows the reference tracking of CA50 and NMEP while λ and MPRR are the constrained parameters. The corresponding control actions are shown in Fig. 8.19. The average CA50 and the corresponding average error obtained in SI mode are 6 CAD and 3.9 CAD, respectively. The average NMEP and the corresponding average error in SI mode are 308.9

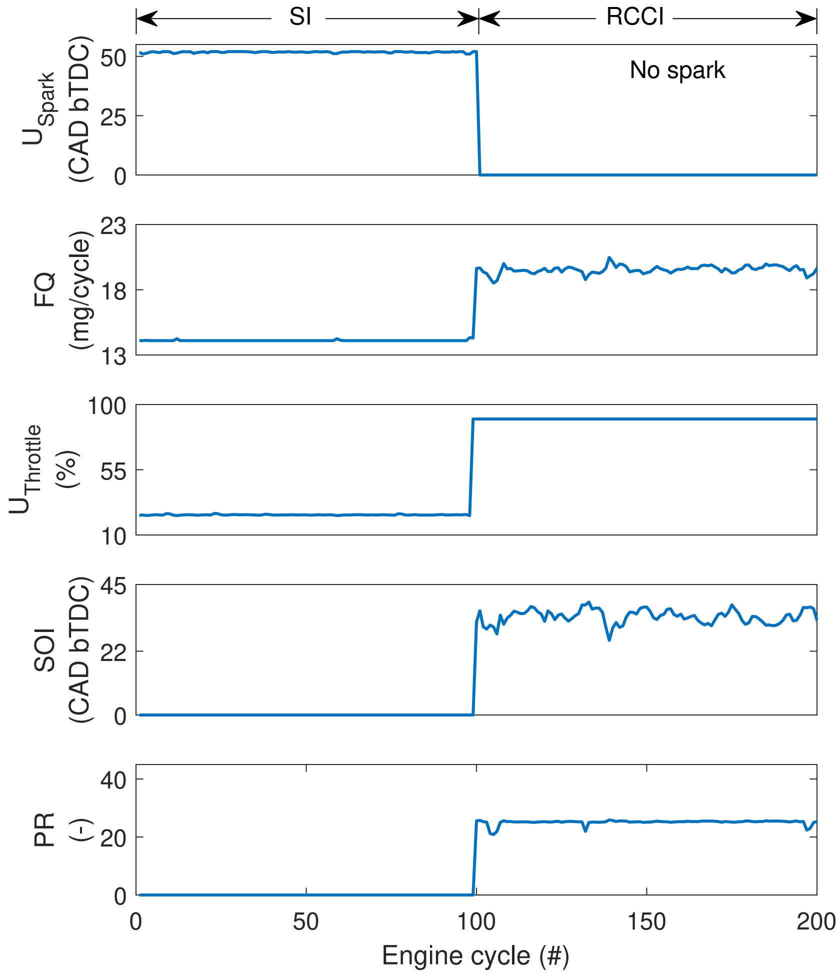

Figure 8.15: Manipulated variables of MPC for the results in Fig. 8.14

kPa and 11.6 kPa, respectively. The COV_{NMEP} in SI mode is 3.6%. The summary of the results are presented in Table 8.10. During mode SI-RCCI switching, the first cycle of RCCI mode resulted in higher NMEP. The controller commands a reduced NMEP which resulted in reduced NMEP for the subsequent cycle. However, RCCI mode reaches the steady state NMEP value in 4 engine cycles with average NMEP of 305.4 kPa and an average error of 11.4 kPa. The COV_{NMEP} in RCCI mode excluding the first 4 engine cycles of mode transition is 3.7%.

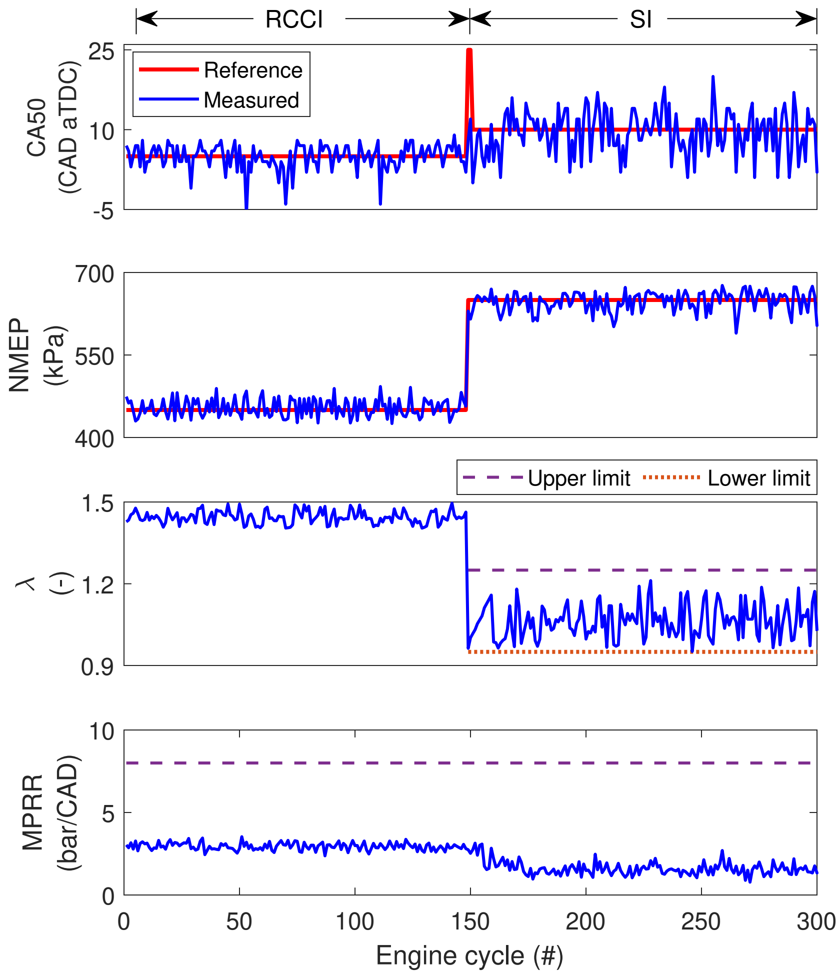

Figure 8.16: Experimental results for CA50 and NMEP control while constraining λ and MPRR to validate MPC performance in RCCI-SI mode switching at 1600 RPM

8.4 CA50 Variations in SI Mode

High cyclic variations were observed in SI mode even at constant spark timing. Engine load varies with CA50. Therefore, combustion stability in SI mode was evaluated by determining COV_{IMEP}. The maximum COV_{IMEP} of 5.5% was observed. COV_{IMEP}

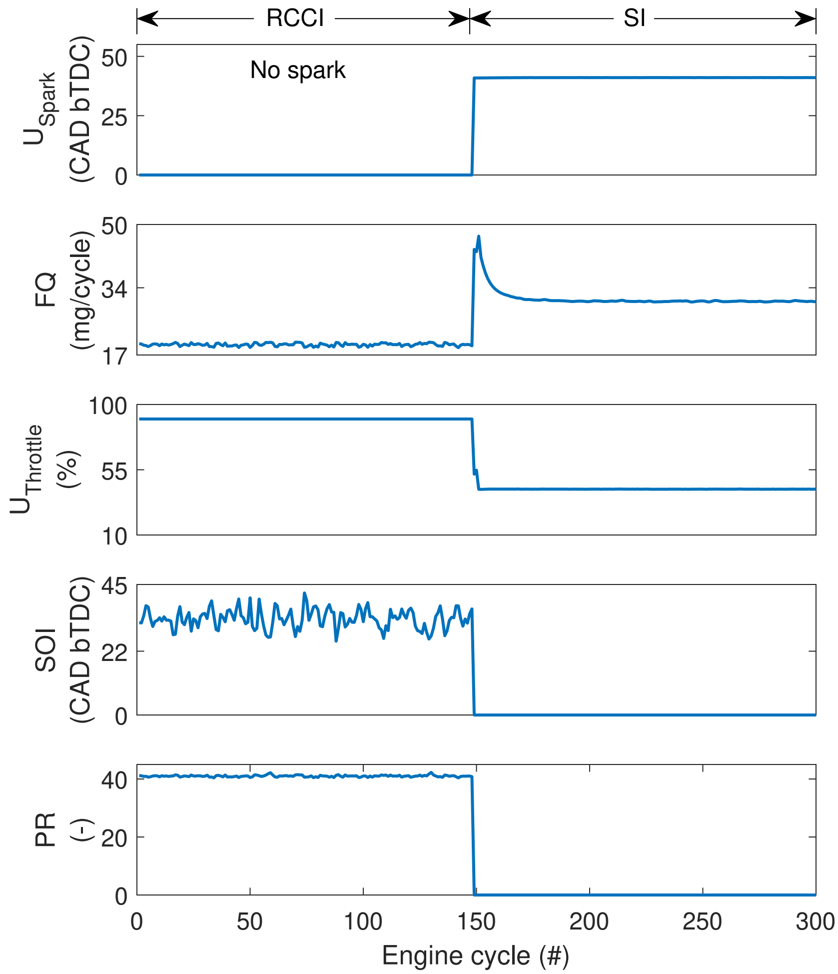

Figure 8.17: Manipulated variables of MPC for the results in Fig. 8.16

increased as CA50 was retarded, as shown in Fig. 8.20. COV_{IMEP} is also plotted against standard deviation of CA50 ($CA50_{std}$). Figure 8.20 showed a linear relationship between COV_{IMEP} and $CA50_{std}$. Increase in $CA50_{std}$ resulted in higher COV_{IMEP}. Variations in CA50 were also analyzed w.r.t the burn duration and standard deviation of burn duration (BD_{std}). Figure 8.20 showed that retarded CA50 resulted in longer burn duration. Moreover, BD_{std} is directly proportional to $CA50_{std}$. Combustion in SI mode starts with the help of spark. The flame propagates outwards after the start

Table 8.10
Average error in tracking CA50 and NMEP, and COV_{NMEP} during SI-RCCI mode switching

Mode	**CA50**		**NMEP**		
	Mean (CAD)	$Error_{avg}$ (CAD)	**Mean** (kPa)	$Error_{avg}$ (kPa)	COV_{NMEP} (%)
SI	5.9	3.9	308.9	11.6	3.6
RCCI	7.0	0.5	305.4	11.4	3.7

of combustion. Some of the factors affecting flame propagation include air-fuel ratio, engine speed, intake temperature and pressure, engine load, turbulence, and residual gas fraction. Small variations in local air-fuel ratio of a scale of millimeter at ignition point affect start of combustion and flame propagation. On the contrary, air-fuel mixture in LTC modes auto-ignite at multiple points resulting in faster burn rate and consistent CA50. That is why, variations in CA50 are very low in RCCI mode. In this study, 88.6% of the data points showed $COV_{IMEP} \leq 3\%$ in steady state SI engine operation. This ensures a stable engine operation in SI mode. Detailed analysis of combustion in SI mode is essential to identify the cause of variations in CA50 and to provide better control of CA50 to further reduce COV_{IMEP}.

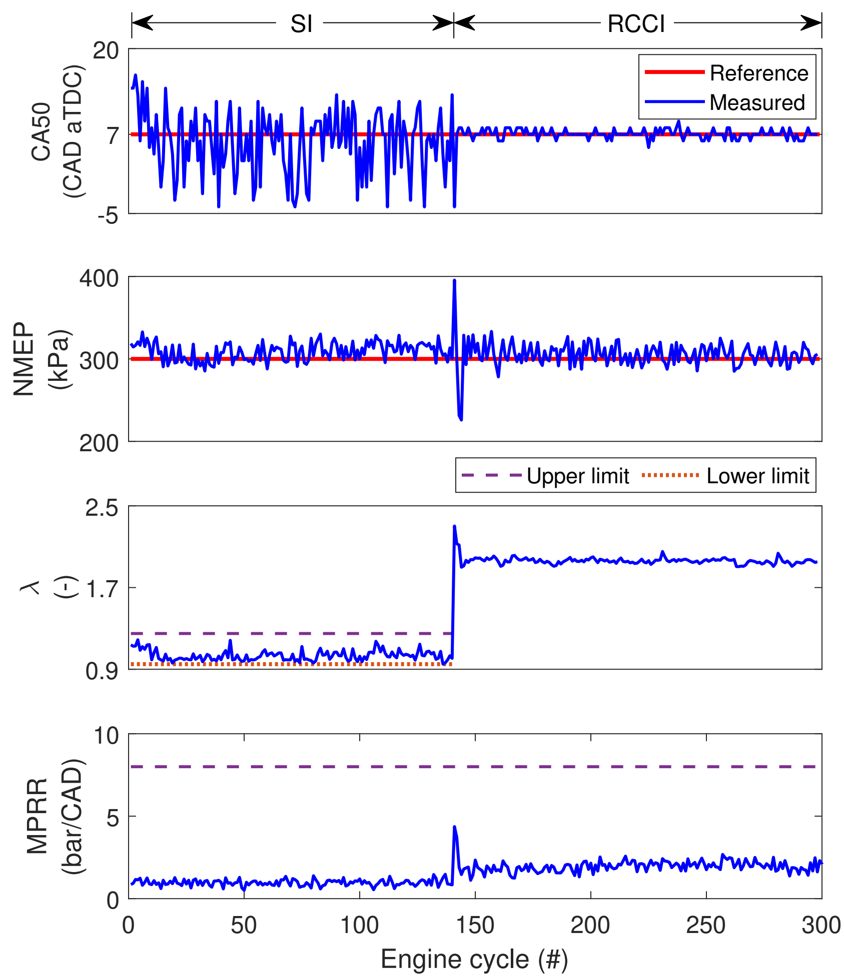

Figure 8.18: Experimental results for CA50 and NMEP control while constraining λ and MPRR to validate MPC performance for constant load SI-RCCI mode switching at 1600 RPM

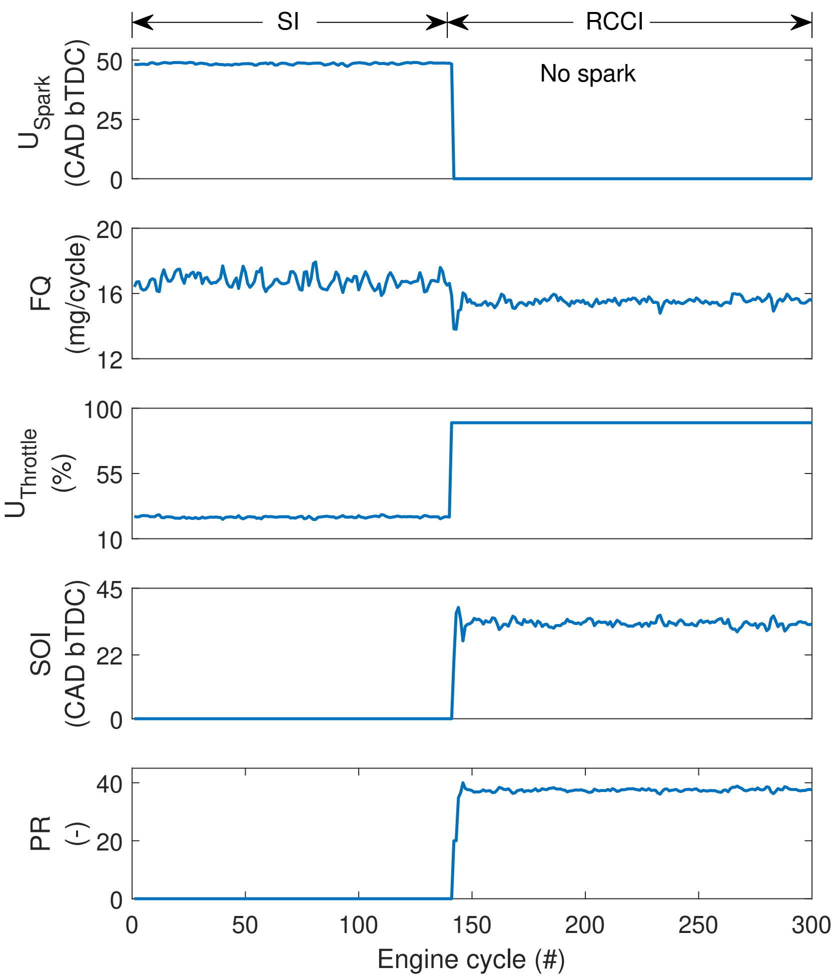

Figure 8.19: Manipulated variables of MPC for the results in Fig. 8.18

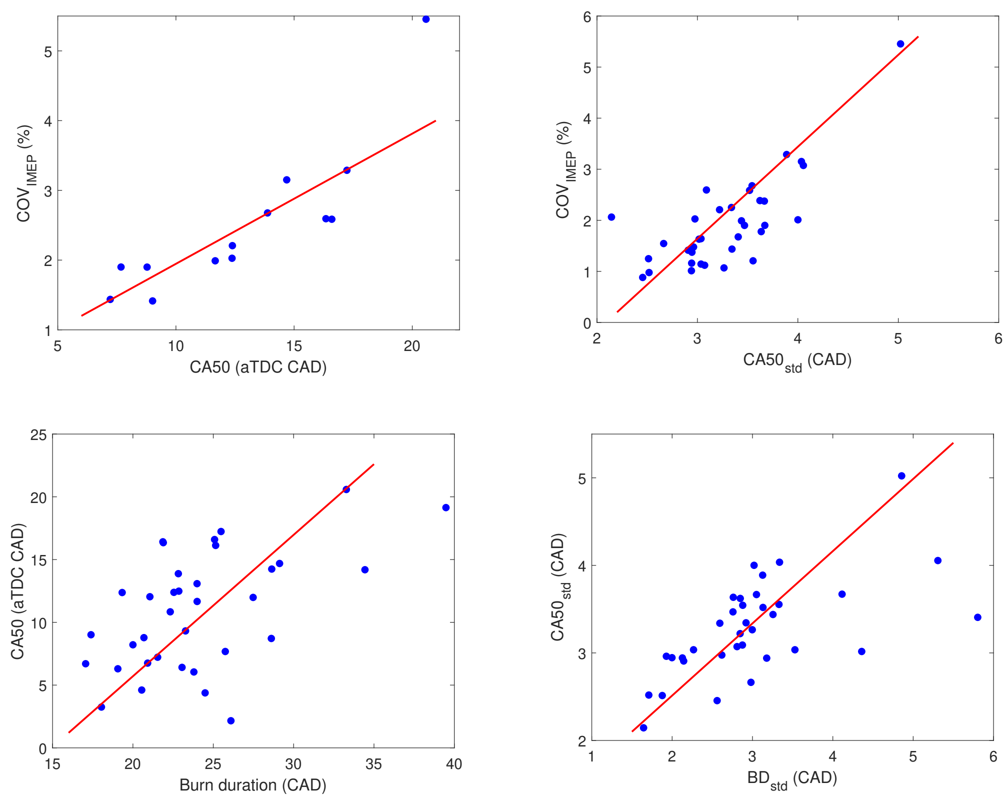

Figure 8.20: Variation in CA50 in SI mode

Chapter 9

Conclusions and Future Work

9.1 Research Summary

Low temperature combustion (LTC) modes offer significant improvement in thermal efficiency and reduced engine-out NOx and particulate matter (PM) emissions. Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Compression Ignition (PCCI), Partially Premixed Charge Compression Compression Ignition (PPCI) and Reactivity Controlled Compression Ignition (RCCI) are the common LTC modes. Combustion in HCCI mode is challenging to control because of the absence of a direct control knob to regulate the start of combustion which causes very high pressure rise rates. In this study, combustion control in HCCI mode is achieved by modulating the premixed ratio of two fuels. Unlike HCCI, PPCI and RCCI modes offer better combustion control where start of injection timing can be adjusted together with the premixed ratio of the fuels. Therefore, the feasible range of LTC modes can be extended with PPCI and RCCI modes as compared to HCCI mode.

The common challenges of the LTC modes are combustion control, high maximum pressure rise rate and cyclic variations. These challenges can be addressed by developing model-based control framework for the LTC modes. Even with the controlled engine operation, the feasible operating range of the LTC modes is a subset of the engine speed and load map of the conventional gasoline engines. Therefore, one or more LTC modes can be coupled with the conventional SI operation can be to achieve higher thermal efficiency and reduced emissions. This requires mode transitions in real-time. The common studies on mode switching include SI-HCCI-SI, CDC-RCCI, CDF-RCCI, HCCI-PPCI, and PPCI-CDC. Open-loop mode switching is the commonly used approach which uses look-up tables based on experimental calibrations for different operating conditions [10, 34, 49, 50]. Model-based closed-loop control studies commonly include SI-HCCI-SI mode switching [12, 13, 51, 52]. These control studies are commonly based on single fuel operated HCCI engine equipped with two-stage cams. Furthermore, most of the studies focused only on SI-HCCI direction of mode switching control.

This dissertation focused on the development of a closed-loop control framework for a multi-mode combustion engine. A unified model predictive control framework for HCCI, PPCI and RCCI modes was developed in Chapter 3 to control the combustion phasing (CA50) and engine load based on the optimal engine map. The average errors in tracking CA50 and IMEP in HCCI mode were 0.5 CAD and 7.6 kPa, respectively. The average tracking errors for CA50 and IMEP in PCCI mode are 0.1 CAD and 1.7 kPa, respectively. In RCCI mode, the adaptive MPC tracked CA50 and IMEP with average errors of 0.2 CAD and 5.2 kPa, respectively To improve the LTC engine performance, supervised machine learning classification algorithms were used to model cyclic variations in HCCI and RCCI modes. The developed classification models showed prediction accuracy of 97% for HCCI and RCCI modes. Nonlinear model predictive controllers were developed to track CA50 and IMEP while constraining cyclic variations below 3% in HCCI and RCCI modes. Chapter 5 included the development of classification algorithms to identify distinct shapes of heat release rates resulting in different types of combustion events in the LTC modes. An adaptive MPC controller was developed using the heat release type as scheduling variable to control CA50 and IMEP while restricting MPRR below 8 bar/CAD. Heat release type was modulated to constrain MPRR below 8 bar/CAD. The results showed average tracking errors of 1.2 CAD and 9.3 kPa in CA50 and IMEP, respectively. In addition, optimal engine map was developed based on indicated specific fuel consumption (ISFC) and engine-out CO, THC and NOx emissions to compare the performance of

SI and RCCI modes. RCCI mode showed lower ISFC and NOx emissions as compared to SI mode. However, SI mode resulted in lower CO and THC emissions as compared to RCCI mode. A supervisory controller was developed based on the optimized engine map to select the desired mode. A model predictive controller was then developed to carry out SI-RCCI-SI mode switching. The controller tracks the reference trajectories of combustion phasing (CA50) and net mean effective pressure (NMEP) while limiting λ within 0.95-1.25 range in SI mode for stable combustion and MPRR below 8 bar/CAD in RCCI mode.

9.1.1 Closed-loop Predictive Control of a Multi-Mode Engine

Model based control framework was development for three common low temperature combustion (LTC) modes namely, HCCI, PPCI and RCCI, using dual fuels. The supervisory controller selected the desired combustion mode based on the engine brake specific fuel consumption (BSFC) performance map. Independent controllers were developed for each mode which used linear parameter varying (LPV) models to capture the system dynamics for achieving the non-linear LTC engine control. Major findings from this work are as follows:

- Discrete time control-oriented models (COMs) were developed for HCCI, PPCI and RCCI modes. The developed control oriented models were validated for steady state and transient conditions. The results showed that the average errors in predicting CA50 and IMEP on cycle-to-cycle basis were less than 2 CAD and 37 kPa, respectively for each LTC mode. LPV systems for each mode were developed by linearizing the COM as a function of premixed ratio of the dual fuels.

- Adaptive model predictive controller (MPC) was developed to control CA50 and IMEP in HCCI mode. Dual fuel premixed ratio was modulated to control CA50 and fuel quantity was adjusted to control IMEP. The adaptive MPC showed good tracking performance of CA50 and IMEP with the LPV systems. The average errors in tracking CA50 and IMEP were 0.5 CAD and 7.6 kPa, respectively. The disturbance rejection performance of the controller was validated by varying the intake air temperature.

- For PPCI mode, adaptive MPC was developed to track CA50 and IMEP by adjusting premixed ratio and fuel quantity, respectively. The controller performance was validated in the presence of measured disturbance in the intake air temperature. The average tracking errors for CA50 and IMEP were 0.1 CAD and 1.7 kPa, respectively.

- In RCCI mode, CA50 and IMEP were controlled by modulating start of injection of DI and fuel quantity, respectively. Adpative MPC used remixed ratio as a scheduling variable for the LPV models. The adaptive MPC tracked CA50 and

IMEP with average errors of 0.2 CAD and 5.2 kPa, respectively.

- The MPC controllers developed for each mode show good tacking performance of combustion phasing with premixed ratio of fuels ranging between 0-50%. This showed that the LPV models captured the system dynamics, thus improved the performance of the controller.

Overall, developed MPC controllers show promising results for reference tracking of CA50 and IMEP for the dual fuel application in the HCCI, PPCI and RCCI modes.

9.1.2 Data-Driven Modeling of Cyclic Variability and NMPC Development

Cyclic variations in engine load affect the noise vibration and harshness (NVH) performance of a vehicle. Coefficient of variation of indicated mean effective pressure COV_{IMEP} is computed to determine the cyclic variations in IMEP. A 2-liter 4-cylinder engine was operated in HCCI and RCCI modes. Data-driven classification models for cyclic variations were developed for HCCI and RCCI modes. The COV_{IMEP} was classified into three different classes:

- Class-I: $COV_{IMEP} \leq 3\%$
- Class-II: $3 < COV_{IMEP} \leq 5\%$

- Class-III if $COV_{IMEP} > 5\%$

Experimental data with $COV_{IMEP} > 5\%$ mostly showed either partial burn or misfired cycle. CA50, IMEP, premixed ratio, fuel quantity, intake manifold temperature and start of injection (for RCCI only) were used as predictors to classify COV_{IMEP} into three different classes. The engine data for 510 different operating conditions were used to develop and validate the HCCI and RCCI models. The COV_{IMEP} classification algorithm provided a model for the engine combustion stability. The developed combustion stability models for HCCI and RCCI modes showed prediction accuracy of 97%.

Closed-loop nonlinear model predictive controllers for HCCI and RCCI modes were designed using the combustion stability models. Sequential quadratic programming (SQP) algorithm was used to determine the optimal control action. The nonlinear MPC controller for HCCI tracked CA50 and IMEP in the absence of constraint on COV_{IMEP}. However, the controller regulated CA50 to maintain COV_{IMEP} below 3% in the presence of constraint on COV_{IMEP} for stable combustion. For the RCCI mode, SOI and fuel quantity were used to control CA50 and IMEP. In the presence of active constraint on COV_{IMEP}, the designed controller adjusted premixed ratio to ensure stable combustion during engine load changes. These allow the multi-mode LTC engine to run stably in both HCCI and RCCI modes.

9.1.3 Machine Learning Models for Identification, Classification and Control of Heat Release Events in LTC Modes

Combustion events in low temperature combustion (LTC) were investigated using the heat release rates for over 600 different operating conditions for a 2.0 liter, 4-cylinder dual fuel LTC engine. Engine data was obtained by varying the fuel quantity, premixed ratio, start of injection timing, and intake manifold temperature. The in-cylinder pressure data was used to compute and analyze the resulting combustion events. Fractions of early and late heat release rates were calculated from the heat release rate data. A rule-based classification approach was developed to categorize the heat release rate traces into three distinct types on the basis of fractions of early and late heat release rates. Detailed statistical analysis on the heat release rate traces was carried out based on start of combustion, CA50, burn duration, maximum pressure rise rate, peak pressure, location of peak pressure, peak temperature and COV_{IMEP}. The main findings of this work are as follows:

- Three distinct heat release rate (HRR) shapes were identified in the LTC engine operation which showed different combustion characteristics. These HRR types can be classified as a function of fractions of early and late heat release.
- Type-1 HRR represented a single stage heat release rate. Type-I showed shorter

burn duration, higher peak in-cylinder pressure, and higher maximum pressure rise rate as compared to type-2 and type-3 HRRs. Furthermore, type-1 HRR showed minimum COV_{IMEP} among the three types. Combustion in type-2 HRR occurred in two stages with advanced combustion phasing as compared to type-1 and type-3. Combustion temperatures in Type-2 are lower than that of type-1 and type-3. Combustion in type-3 HRR showed main stage heat release together with diffusion type combustion tail.

- K-means clustering, an unsupervised approach, could not classify the traces distinctly.

- Three supervised learning algorithms namely, decision tree, K-nearest neighbors and support vector machines, were used to develop classification models for the HRR types using normalized heat release traces. SVM provided better accuracy compared to the other two supervised machine learning algorithms. The trained SVM model predicted the heat release rate type with a prediction accuracy of 92.4%.

- Three classification algorithms, decision tree, KNN and SVM were used to train the models using start of combustion, burn duration, premixed ratio, start of injection, fuel quantity and manifold temperature as features. KNN and SVM showed better accuracy as compared to decision tree model. However, KNN was proved to be the best in predicting the heat release traces with an overall accuracy of 97%.

- An MPC framework was developed to demonstrate the application of classification algorithm for control applications. KNN is a memory based algorithm which requires memory to make future predictions. Therefore, SVM classification algorithm was used to develop LPV models to achieve real-time control. The output of SVM classification model was used to develop the LPV state space representation of RCCI. Based on the developed LPV system, a model predictive controller was designed to track CA50 and IMEP while constraining MPRR. The controller was capable of tracking CA50 and IMEP with root mean square error of 1.2 CAD and 9.3 kPa, respectively while limiting MPRR below 8 bar/CAD.

- The controller performance was compared with the one designed in the study [44] for the RCCI engine by providing same reference trajectories for CA50 and IMEP under same operating conditions. The controller designed in this work showed better overall tracking performance and wider operating range. It also showed faster response with zero steady state errors while satisfying the constraints on MPRR and actuators.

9.1.4 Modeling and Control of SI-RCCI-SI Mode Switching

The engine maps for SI and RCCI were developed for speed range of 1000-1600 RPM and load range of 300-700 kPa. SI and RCCI modes were compared for the indicated specific fuel consumption and engine-out CO, THC and NOx emissions. Based on the comparison, a multi-mode engine proved to be a viable option which can provide lower fuel consumption and lower engine out NOx emissions as compared to conventional SI engine. Based on the comparison, open-loop SI-RCCI-SI mode switching studies were carried out to develop and validate the dynamic model. The dynamic mode switching model was validated for steady state and transient conditions. The model showed average errors of 0.4 CAD and 10 kPa in predicting CA50 and NMEP in SI mode, respectively. The average prediction errors in RCCI modes were 1 CAD and 35.2 kPa for CA50 and NMEP, respectively. Wiebe function was used to model MPRR in SI and RCCI modes. The model showed an average prediction error of 0.4 bar/CAD and 1.6 bar/CAD in SI and RCCI modes, respectively. To improve the accuracy of MPRR model in RCCI mode, support vector machines (SVM) was used to model MPRR. The average error in predicting MPRR for RCCI mode using SVM is 0.4 bar/CAD. Mode switching model was then linearized at two operating conditions corresponding to each mode.

A gain scheduled model predictive controller (MPC) was developed to achieve closed-loop SI-RCCI-SI mode switching. Kalman filter was designed to estimate the states of the system using measured outputs of the system. The in-cylinder pressure data was processed using FPGA in real-time for cycle-to-cycle control of CA50 and NMEP. The controller performance was first validated in Simulink. The MPC mode switching controller was then implemented on the hardware using dSPACE microautobox.

The performance of MPC mode switching controller was validated for different operating conditions. These operating conditions included constant load mode switching, and simultaneous step changes in the desired engine load and CA50. The controller objective was to minimize tracking errors in the desired CA50 and NMEP while constraining λ within a range of 0.95-1.25 and limit MPRR below 8 bar/CAD. The controller successfully tracked the desired CA50 and NMEP in both modes and during mode switching from SI to RCCI while constraining λ and MPRR within the set limits.

RCCI-SI mode switching proved to be challenging due to the intake manifold dynamics and throttle dynamics. Either one misfire or one partial burn was observed from RCCI to SI mode switching. This was mainly because of the air stored in the intake manifold which can only flow into the cylinder and the airflow because of the throttle response. In addition, SI mode can only result in stable combustion when the AFR is near stoichiometry. Therefore, extra fuel was injected in the first cycle of RCCI-SI mode switching. The amount of extra fuel was predetermined from the desired load request. This resulted in successful mode transition from RCCI to SI. However, the first cycle of mode switching resulted in higher NMEP than desired. Furthermore, fuel transport dynamics in SI mode was prominent at a higher load after mode switching. Therefore, two more states were added to the state space system of SI-RCCI-SI model. The appended states included fuel flowing into the cylinder and mass of air entering the cylinder during the emptying of intake manifold. In addition, the model for the rate change of intake manifold pressure was also improved to incorporate the pressure changes due to throttle response. The more airflow into the cylinder during the first few cycles of RCCI-SI mode switching required more fuel quantity, thus resulting in higher NMEP. Thus, CA50 was retarded for the first two cycles of mode switching which reduced the NMEP of the corresponding cycles. The desired retard in CA50 was estimated by using a correlation between the desired NMEP and $NMEP_{MBT}$ [163]. Based on the updated model, a gain scheduling MPC was developed and implemented on the system. Step changes in CA50 and NMEP were desired during SI-RCCI-SI mode switching. The performance of controller was validated for simultaneous step changes in CA50 and NMEP during SI-RCCI-SI mode switching. In addition, mode switching was carried out at different engine loads and speeds. The controller showed good tracking performance during mode switching while restricting λ and MPRR within the set limits.

9.2 Future Work

LTC modes offer a potential for real-time engine application with model-based control architecture. The current study includes the operating range of HCCI, PPCI and RCCI modes achieved with naturally aspirated engine and without external exhaust gas recirculation (EGR). For high load RCCI operation, the air-fuel mixture becomes relatively rich, thus resulting in abrupt heat release rate. Thus, RCCI operation is limited due to high MPRR that can cause damage to the hardware. The heat release rate can be controlled in the following possible ways to extend the RCCI load range while reducing MPRR.

- The first possible option is to use EGR which will help in reducing MPRR while helping in further reducing NOx emissions.
- Second possible way to reduce MPRR is using multiple fuel injections during the compression stroke.
- Using a boosted engine operation together with EGR can help in increased ignition delay, thus it can provide better control on the combustion [64].

In addition, RCCI phasing can be further improved by manipulating heat release rate for the maximum thermal efficiency. This can be done by modulating the start of injection timing using the classification algorithms developed in this study.

SI-RCCI mode switching is relatively simple. The high exhaust gas temperatures trapped at the end of SI mode resulted in smooth transition to RCCI mode. Furthermore, spark assistance in the first few cycles can help SI-RCCI mode transition. However, RCCI-SI mode transition is more challenging due to throttle response, intake manifold dynamics and fuel transport dynamics. In this study, valve timings were kept the same for SI and RCCI engine operation. In future, simultaneous changes in variable valve timing (VVT) and throttle position can be studied to improve the mode transition from RCCI to SI mode.

Future research can focus on RCCI-SI mode switching improvements. RCCI-SI mode switching strategy can be improved by implementing spark assisted compression ignition (SACI) to counter the dynamics during transition. This can be achieved with spark assistance and by delaying the change in fuel injection strategy from RCCI to SI for first three cycles of mode transition. In addition, control algorithm can be improved by adding SACI mode in the gain scheduled MPC for RCCI-SI transitions. In addition, the developed multi-mode engine model can be used in the vehicle model to simulate the drive cycles to access the emission reductions and improvements in the fuel economy of a light-duty vehicle. This study can provide information about mode switching frequency, residence time in each mode and the associated fuel penalty in the real-time drive cycles. This information can be incorporated into the supervisory controller to optimize the multi-mode engine operation.

References

[1] M. L. Wissink. *Direct Injection for Dual Fuel Stratification: Improving the Control of Heat Release in Advanced IC Engine Combustion Strategies*. PhD thesis, University of Wisconsin-Madison, 2015.

[2] Johansson R. Tuneståì P. Johansson B. Strandh P., Bengtsson J. "Variable Valve Actuation for Timing Control of a Homogeneous Charge Compression Ignition Engine". *SAE Tech. Pap. 2005-01-0147*, 2005.

[3] Morteza Fathi, Omid Jahanian, and Mahdi Shahbakhti. Modeling and controller design architecture for cycle-by-cycle combustion control of homogeneous charge compression ignition (HCCI) engines – a comprehensive review. *Energy Conversion and Management*, 139:1 – 19, 2017.

[4] N. Ravi, H. Liao, A. F. Jungkunz, Anders Widd, and et. al. Model predictive control of HCCI using variable valve actuation and fuel injection. *Cont. Engg. Prac.*, 20:421–430, 2012.

[5] Göran Haraldsson, Per Tunestål, Bengt Johansson, and Jari Hyvönen. HCCI closed-loop combustion control using fast thermal management. 2004.

[6] M. Bidaravatan. *"Physics-based modelling and control of powertrain systems integrated with low temperature combustion engines"*. PhD thesis, Michigan Technological University, 2015.

[7] Tianhao Yang, Lianhao Yin, Xiangyu Meng, Hua Tian, and et. al. Partially premixed combustion optimization using double injection strategy in transient operation. *App. Therm. Engg.*, 169:114963, 2020.

[8] A. Raut, M. Bidarvatan, and Shahbakhti M. Dynamic modeling and model predictive control of an rcci engine. *Control Engineering Practice*, 81:129–144, 2018.

[9] Halim Santoso, Jeff Matthews, and Wai K. Cheng. Managing SI/HCCI dual-mode engine operation. In *SAE 2005 World Congress Exhibition*. SAE International, apr 2005.

[10] Yan Zhang, Hui Xie, Nenghui Zhou, Tao Chen, and Hua Zhao. Study of SI-HCCI-SI transition on a port fuel injection engine equipped with 4vvas. In *SAE World Congress Exhibition*. SAE International, apr 2007.

[11] Guohong Tian, Zhi Wang, Qiangqing Ge, Jianxin Wang, and Shijin Shuai. Mode switch of SI-HCCI combustion on a GDI engine. In *SAE World Congress & Exhibition*. SAE International, Apr 2007.

[12] N. Collings S. Karagiorgis, K. Glover and A. Petridis. "hybrid modeling for switching between si and hcci combustion modes,". pages 62–69, 2007.

[13] A low-order adaptive engine model for si–hcci mode transition control applications with cam switching strategies. pages 451–468, 2016.

[14] Dongsheng Li, Zhi Wang, Hui Liu, and Jian-Xin Wang. Combustion mode switch by integrating stoichiometric ASSCI mode in a four-cylinder gasoline SI/HCCI engine. In *SAE 2014 World Congress & Exhibition*. SAE International, Apr 2014.

[15] Changle Li, Lianhao Yin, Sam Shamun, Martin Tuner, Bengt Johansson, Rickard Solsjo, and Xue-Song Bai. Transition from HCCI to PPC: the sensitivity of combustion phasing to the intake temperature and the injection timing with and without EGR. In *SAE 2016 World Congress and Exhibition*. SAE International, apr 2016.

[16] "Investigation of Cold Starting and Combustion Mode Switching as Methods to Improve Low Load RCCI Operation". *Proc. of the ASME 2015 Int. Comb. Eng. Div. Fall Tech. Conf.,Adv. Comb., USA*, 1, 2015.

[17] Bekdemir C. Feru E. Indrajuana, A. and F. Willems. Towards model-based control of RCCI-CDF mode-switching in dual fuel engines. *SAE Technical Paper 2018-01-0263*, 2018.

[18] J.K. Arora. Design of real-time combustion feedback system and experimental study of an RCCI engine for control. Master's thesis, Michigan Technological University, 2016.

[19] Changsheng Yao, Yaodong Hu, Tianyuan Zhou, Fuyuan Yang, Minggao Ouyang, and Haiyan Huang. Combustion stability control of dieseline PPCI based on in-cylinder pressure signals. *8th IFAC Symp. on Adv. in Auto. Cont. AAC*, 49(11):333 – 339, 2016.

[20] L. Yin, G. Turesson, P. Tunestål, and R. Johansson. Model predictive control of an advanced multiple cylinder engine with partially premixed combustion concept. *IEEE/ASME Trans. on Mechatronics*, 25(2):804–814, 2020.

[21] A. Raut, M. Bidarvatan, H. Borhan, and M. Shahbakhti. Model predictive control of an RCCI engine. In *2018 Annual Amer. Cont. Conf. (ACC)*, pages 1604–1609, 2018.

[22] Armando Indrajuana, Cemil Bekdemir, Xi Luo, and Frank Willems. Robust multivariable feedback control of natural gas-diesel RCCI combustion. *8th IFAC Symp. on Adv. in Auto. Cont. AAC*, 49(11):217 – 222, 2016.

[23] Hanson R. Wu, Y. and R. D. Reitz. Investigation of combustion phasing control strategy during reactivity controlled compression ignition (RCCI) multicylinder engine load transitions. *ASME. J. Eng. Gas Turb. Pow. 136(9): 091511.*, 2014.

[24] Jan-Ola Olsson, Per Tunestål, and Bengt Johansson. Closed-loop control of an HCCI engine. *SAE Technical Paper 2001-01-1031*, 2001.

[25] Petter Strandh, Johan Bengtsson, Rolf Johansson, Per Tunestål, and Bengt Johansson. Cycle-to-cycle control of a dual-fuel HCCI engine. In *SAE Technical Paper 2004-01-0941*, 2004.

[26] Johan Bengtsson, Petter Strandh, Rolf Johansson, Per Tunestål, and Bengt Johansson. Multi-output control of a heavy duty HCCI engine using variable valve actuation and model predictive control. In *SAE Technical Paper 2006-01-0873*, 2006.

[27] A. Widd, H. Liao, J. C. Gerdes, P. Tunestål, and R. Johansson. Control of exhaust recompression HCCI using hybrid model predictive control. In *Proc. of the 2011 Amer. Cont. Conf.*, pages 420–425, 2011.

[28] Gerdes J. C. Shaver, G. M. and M. J. Roelle. Physics-based modeling and control of residual-affected hcci engines. *ASME. J. Dyn. Sys., Meas., Control. 131(2).*, 2009.

[29] J. Kang and M. Druzhinina. HCCI engine control strategy with external EGR. In *Proc. of the 2010 Amer. Cont. Conf.*, pages 3783–3790, 2010.

[30] Khashayar Ebrahimi and Charles Koch. Model predictive control for combustion timing and load control in HCCI engines. In *SAE Technical Paper 2015-01-0822*, 2015.

[31] M. Bidarvatan, D. Kothari, and M. Shahbakhti. Integrated cycle-to-cycle control of exhaust gas temperature, load, and combustion phasing in an HCCI engine. In *2015 Amer. Cont. Conf. (ACC)*, pages 7–12, 2015.

[32] Gabriel Ingesson, Lianhao Yin, Rolf Johansson, and Per Tunestål. A double-injection control strategy for partially premixed combustion. *8th IFAC Symp. on Adv. in Auto. Cont. AAC*, 49(11):353 – 360, 2016.

[33] N. T. Kondipati. Experimental study, modelling and controller design for an RCCI engine. Master's thesis, Michigan Technological University, 2016.

[34] K. K. Sadabadi. Modelling and control of an RCCI engine. Master's thesis, Michigan Technological University, 2015.

[35] Varun Tandra and Nilabh Srivastava. Optimal peak pressure and exhaust temperature tracking control for a two-zone HCCI engine model with mean burn duration. In *SAE Technical Paper 2009-01-1130*. SAE International, 2009.

[36] Usman Asad, Ming Zheng, Jimi Tjong, and Meiping Wang. EC1-1 a control strategy analysis for clean and efficient combustion in compression ignition engines. *The Proc. of the Int. symp. on diag. and mod. of comb. in inter. comb. engines*, 2012.8:251–256, 2012.

[37] Usman Asad and Ming Zheng. Diesel pressure departure ratio algorithm for combustion feedback and control. *Int. J. of Engine Res.*, 15(1):101–111, 2014.

[38] E. Hellstrom, J. Larimore, S. Jade, A. G. Stefanopoulou, and L. Jiang. Reducing cyclic variability while regulating combustion phasing in a four-cylinder hcci engine. *IEEE Trans. on Cont. Sys. Tech.*, 22(3):1190–1197, 2014.

[39] C. Chiang, A. G. Stefanopoulou, and M. Jankovic. Nonlinear observer-based control of load transitions in homogeneous charge compression ignition engines. *IEEE Trans. on Cont. Sys. Tech.*, 15(3):438–448, 2007.

[40] Adrian Audet and Charles Robert Koch. Actuator comparison for closed loop control of HCCI combustion timing. In *SAE Technical Paper 2009-01-1135*. SAE International, 2009.

[41] B. K. Irdmousa, S. Z. Rizvi, J. M. Veini, J. D. Naber, and et. al. Data-driven modeling and predictive control of combustion phasing for rcci engines. In *2019 Amer. Cont. Conf. (ACC)*, pages 1617–1622, 2019.

[42] Lianhao Yin, Gabriel Ingesson, Rolf Johansson, Per Tunestål, and Bengt Johansson. Model-based partially premixed combustion (PPC) timing control. *8th IFAC Symp. on Adv. in Auto. Cont. AAC*, 49(11):340–346, 2016.

[43] Lu Xia, Bram de Jager, Tijs Donkers, and Frank Willems. Robust constrained optimization for RCCI engines using nested penalized particle swarm. *Cont. Engg. Prac.*, 99:104411, 2020.

[44] L. N. Aditya Basina, Behrouz K. Irdmousa, Javad Mohammadpour Velni, Hoseinali Borhan, and et. al. Data-driven modeling and predictive control of

maximum pressure rise rate in RCCI engines. In *2020 IEEE Conf. on Cont. Tech. and App. (CCTA)*, pages 94–99, 2020.

[45] Annual Energy Outlook 2020 with projections to 2050. U.S. Ener. Inf. Admin. Off. of Ener. Analysis, U.S. Dep. of Ener., 2020.

[46] Jari Hyvönen, Göran Haraldsson, and Bengt Johansson. Operating range in a multi cylinder HCCI engine using variable compression ratio. 2003.

[47] Jari Hyvönen, Göran Haraldsson, and Bengt Johansson. Operating conditions using spark assisted HCCI combustion during combustion mode transfer to si in a multi-cylinder VCR-HCCI engine. In *SAE 2005 World Congress Exhibition*. SAE International, Apr 2005.

[48] Patrick H. Gorzelic. *"Modeling and model-based control of multi-mode combustion engines for closed-loop SI/HCCI mode transitions with cam switching strategies"*. PhD thesis, University of Michigan, 2015.

[49] Haifeng Lu Stephan Schmitt Jun Deng Lidong Rao Yintong Liu, Liguang Li. SI/HCCI mode switching optimization in a gasoline direct injection engine employing dual univalve system. 2018.

[50] Nebojsa Milovanovic, Dave Blundell, Stephen Gedge, and Jamie Turner. SI-HCCI-SI mode transition at different engine operating conditions. In *SAE 2005 World Congress Exhibition*. SAE International, apr 2005.

[51] A. Fuerhapter, E. Unger, W. F. Piock, and G.K. Fraidl. The new AVL CSI engine - hcci operation on a multi cylinder gasoline engine. In *SAE 2004 World Congress Exhibition*. SAE International, mar 2004.

[52] Matthew J. Roelle, Gregory M. Shaver, and J. Christian Gerdes. Tackling the transition: A multi-mode combustion model of SI and HCCI for mode transition control. *ASME Int. Mech. Engg. Cong. and Expo., Dyn. Sys. and Cont., Parts A and B*, pages 329–336, 2004.

[53] Agarwal A. Singh A, Bajpai N. Combustion mode switching characteristics of a medium-duty engine operated in compression ignition/PCCI combustion modes. 2018.

[54] Nakayama S. Tanabe K., Komatsu F. A study on mode transition control between pci and conventional combustion in a diesel engine. pages 69–86, 2011.

[55] R. Sitaraman, S. Batool, H. Borhan, J. M. Velni, J. D. Naber, and M. Shahbakhti. "Machine Learning-based Classification of Combustion Events in an RCCI Engine Using Heat Release Rate Shapes". *IFAC Mod., Est. and Cont. Conf. (MECC)*, 2022.

[56] Bouter A. Melgar J. Ternel, C. Life cycle assessment of mid-range passenger cars powered by liquid and gaseous biofuels: Comparison with greenhouse gas emissions of electric vehicles and forecast to 2030. *Transp. Res. Part D Transp. Environ.*

[57] Ahmed N.A. Ogunkunle, O. Overview of biodiesel combustion in miti-gating the adverse impacts of engine emissions on the sustainable hu-man–environment scenario. *Sustain.*, (2021.

[58] Akhilendra Pratap Singh and Avinash Kumar Agarwal. Performance and emission characteristics of conventional diesel combustion/partially premixed charge compression ignition combustion mode switching of biodiesel-fueled engine. *International Journal of Engine Research*, 0(0):1468087419860311, 0.

[59] Adam Weall and Nick Collings. Highly homogeneous compression ignition in a direct injection diesel engine fuelled with diesel and biodiesel. In *JSAE/SAE International Fuels & Lubricants Meeting*. SAE International, jul 2007.

[60] Loeper P. Krieger R. Andrie M.J. Foster D.E. Adams, C.A. Effects of biodiesel-gasoline blends on gasoline direct-injection compression ig-nition (GCI) combustion. *Fuel.*, page 784–790, (2013).

[61] G. T. Kalghatgi and R. A. Head. "Combustion Limits and Efficiency in a HCCI Engine". *Int. J. of Eng. Res.*, 7(3):215–236, 2006.

[62] Kukwon Cho, Manbae Han, Robert M. Wagner, and C. Scott Sluder. Mixed-source egr for enabling high efficiency clean combustion modes in a light-duty diesel engine, apr 2008.

[63] Johansson B. Manente, V. and P. Tunestal. "partially premixed combustion at high load using gasoline and ethanol, a comparison with diesel,". 2009.

[64] Gautam T. Kalghatgi, Per Risberg, and Hans-Erik Ångström. Advantages of fuels with high resistance to auto-ignition in late-injection, low-temperature, compression ignition combustion. In *Powertrain & Fluid Systems Conference and Exhibition*. SAE International, oct 2006.

[65] Hu L. Nakazono T. Ohtsubo H. et al. Williams, S. ”oxidation catalysts for natural gas engine operating under hcci or si conditions,”.

[66] Subramanian Swami Nathan Ciatti, Stephen. An experimental investigation of low-octane gasoline in diesel engines. In *Journal of Engineering for Gas Turbines and Power*. ASME, 2011.

[67] Zander C. Johansson B. Tunestal P. et al. Manente, V. ”an advanced internal combustion engine concept for low emissions and high efficiency from idle to max load using gasoline partially premixed combustion,”. 2010.

[68] Paul M. Najt and David E. Foster. Compression-ignited homogeneous charge combustion. *SAE International Congress and Exposition*, Feb. 1983.

[69] R. H. Thring. Homogeneous-charge compression-ignition (HCCI) engines. *SAE Technical Paper 892068*, 1989.

[70] Lucien Koopmans, Hans Ström, Staffan Lundgren, Ove Backlund, and Ingemar Denbratt. Demonstrating a SI-HCCI-SI mode change on a volvo 5-cylinder electronic valve control engine. In *SAE 2003 World Congress Exhibition*. SAE International, mar 2003.

[71] G. M. Shaver, M. Roelle, and J. C. Gerdes. A two-input two-output control model of HCCI engines. In *2006 Amer. Cont. Conf.*, pages 6 pp.–, 2006.

[72] Hiromu Kakuya, Shiro Yamaoka, Kengo Kumano, and Shinya Sato. Investigation of a SI-HCCI combustion switching control method in a multi-cylinder gasoline engine. In *SAE World Congress Exhibition*. SAE International, apr 2008.

[73] S. H. Kim and C. Bae. "Strategy for Mode Transition between Low Temperature Combustion and Conventional Combustion in a Diesel Engine". *SAE Int. J. Eng.*, 6, (2013).

[74] Mack J. H Hedrick J. Dibble R. W. Souder, J. S. "microphones and knock sensors for feedback control of hcci engines,". (2004).

[75] Henein N.and Bryzik W. Taraza D. "determination of the gas pressure torque of a multicylinder engine from measurements of the crankshaft's speed variation,". (1998).

[76] Caton PA et al. Shaver GM, Roelle MJ. A physics-based approach to the control of homogeneous charge compression ignition engines with variable valve actuation. *International Journal of Engine Research.*, pages 361–375, 2005.

[77] Aziz A.A. Shahbakhti M. et al. Bahri, B. Analysis and modeling of exhaust gas temperature in an ethanol fuelled hcci engine. *J. Mech. Sci. Technol.*, page 3531–3539, (2013).

[78] Bahram Bahri, Mahdi Shahbakhti, Kaushik Kannan, and Azhar Abdul Aziz. Identification of ringing operation for low temperature combustion engines. *Applied Energy*, 171:142–152, 2016.

[79] Bahram Bahri, Mahdi Shahbakhti, and Azhar Abdul Aziz. Real-time modeling of ringing in hcci engines using artificial neural networks. *Energy*, 125:509–518, 2017.

[80] Ehsan Ansari, Tyler Menucci, Mahdi Shahbakhti, and Jeffrey Naber. Experimental investigation into effects of high reactive fuel on combustion and emission characteristics of the diesel - natural gas reactivity controlled compression ignition engine. *Applied Energy*, 239:948–956, 2019.

[81] G. Ingesson P. Tunestål R. Johansson T. Yang, L. Yin and W. Long. ”simultaneous control of soot emissions and pressure rise rate in gasoline ppc engine,”.

[82] Koch CR. Shahbakhti M, Ghazimirsaied A. Experimental study of exhaust temperature variation in a homogeneous charge compression ignition engine. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, pages 1177–1197, 2010.

[83] M. Bidarvatan, V. Thakkar, M. Shahbakhti, B. Bahri, and et. al. Grey-box modeling of HCCI engines. *App. Therm. Engg.*, 70(1):397 – 409, 2014.

[84] M. Bidarvatan and M. Shahbakhti. Gray-Box Modeling for Performance Control of an HCCI Engine With Blended Fuels. *Journal of Engineering for Gas Turbines and Power*, 136(10), 05 2014. 101510.

[85] M. Nazemi and M. Shahbakhti. Modeling and analysis of fuel injection parameters for combustion and performance of an rcci engine. *Applied Energy*, 165:135–150, 2016.

[86] Andrew Di Mauro, Hao Chen, and Volker Sick. "Neural network prediction of cycle-to-cycle power variability in a spark-ignited internal combustion engine". *Proceedings of the Combustion Institute*, 37(4):4937–4944, 2019.

[87] Zhu Qilun, Robert Prucka, Shu Wang, Michael Prucka, and Hussein Dourra. "Control Oriented Modelling of Engine IMEP Variation". ASME 2016 Internal Combustion Engine Division Fall Technical Conference, 10 2016.

[88] Lupul R. Audet A. Koch C. R. Shahbakhti, M. "experimental study of hcci cyclic variations for low-octane prf fuel blends,". *Proc. of Comb. Inst./Canad. Sect. (CI/CS) Spr. Tech. Conf.*

[89] M Shahbakhti and C R Koch. "Characterizing the cyclic variability of ignition timing in a homogeneous charge compression ignition engine fuelled with n-heptane/iso-octane blend fuels". *International Journal of Engine Research*, 9(5):361–397, 2008.

[90] Aziz A. A. Shahbakhti M. Muhamad Said M.F. Bahri, B. “under-standing and detecting misfire in an hcci engine fuelled with ethanol,”. *App. Ener.,*, pages 24–33, (2013).

[91] Ming Jia, Adam B Dempsey, Hu Wang, Yaopeng Li, and Rolf D Reitz. “Numerical simulation of cyclic variability in reactivity-controlled compression ignition combustion with a focus on the initial temperature at intake valve closing”. *International Journal of Engine Research*, 16(3):441–460, 2015.

[92] S. Batool, J. D. Naber, and M. Shahbakhti. Data-driven modeling and control of cyclic variability of an engine operating in low temperature combustion modes. *Mod., Est. and Cont. Conf. (MECC)*, 2021.

[93] Tuner M. Mello A. Tunestal P. et al. Borgqvist, P. ”the usefulness of negative valve overlap for gasoline partially premixed combustion, ppc,”. *SAE Technical Paper 2012-01-1578*, 2012.

[94] Risberg P. Kalghatgi, G. and H. Ångström. ”partially pre-mixed auto-ignition of gasoline to attain low smoke and low nox at high load in a compression ignition engine and comparison with a diesel fuel,”. *SAE Technical Paper 2007-01-0006*, 2007.

[95] Ickes A. Assanis D. N. Zhen H. Bohac S. V. Han, D.

[96] Mengqin Shen, Martin Tuner, Bengt Johansson, and William Cannella. Effects of EGR and intake pressure on PPC of conventional diesel, gasoline and ethanol

in a heavy duty diesel engine. In *SAE/KSAE 2013 International Powertrains, Fuels & Lubricants Meeting*. SAE International, oct 2013.

[97] M. Shahbakhti and C. R. Koch. Control oriented modeling of combustion phasing for an HCCI engine. In *2007 Amer. Cont. Conf.*, pages 3694–3699, 2007.

[98] Mahdi Shahbakhti, Robert Lupul, and Charles Robert Koch. Sensitivity analysis & modeling of HCCI auto-ignition timing. *5th IFAC Symp. on Adv. in Auto. Cont.*, 40(10):303 – 310, 2007.

[99] M. Bidarvatan N. N. T. Kondipati, J. K. Arora and M. Shahbakhti. "modeling, design and implementation of a closed-loop combustion controller for an rcci engine,". *2017 American Control Conference (ACC), Seattle, WA, USA*, pages 4747–4752, 2017.

[100] Derek Splitter, Martin Wissink, Dan DelVescovo, and Rolf D. Reitz. RCCI engine operation towards 60% thermal efficiency. In *SAE Technical Paper 2013-01-0279*, 2013.

[101] J. M. Velni H. Borhan J. D. Naber L. N. A. Basina, B. K. Irdmousa and M. Shahbakhti. "data-driven modeling and predictive control of maximum pressure rise rate in rcci engines,". *2020 IEEE Conference on Control Technology and Applications (CCTA), Montreal, QC, Canada*, pages 94–99, 2020.

[102] Alasdair Cairns and Hugh Blaxill. The effects of two-stage cam profile switching and external EGR on SI-CAI combustion transitions. *SAE Transactions*, 116:230–241, 2007.

[103] Tobias Nier, Andre Kulzer, and Roland Karrelmeyer. Analysis of the combustion mode switch between SI and gasoline HCCI. In *SAE 2012 World Congress Exhibition*. SAE International, apr 2012.

[104] Mengqin Shen, Sara Lonn, and Bengt Johansson. Transition from HCCI to PPC combustion by means of start of injection. In *JSAE/SAE 2015 International Powertrains, Fuels Lubricants Meeting*. SAE International, sep 2015.

[105] Choi S. B. Han S., Bae C. "Effects of operating parameters on mode transition between low-temperature combustion and conventional combustion in a light-duty diesel engine". *Int. J. of Eng. Res.*, 14, (2013).

[106] Shakiba-herfeh M. Solouk, A. and M. Shahbakhti. "Analysis and Control of a Torque Blended Hybrid Electric Powertrain with a Multi-Mode LTC-SI Engine". *SAE Int. J. of Alter. P/T*, 6, (2017).

[107] Xing-Cai Lü, Wei Chen, and Zhen Huang. A fundamental study on the control of the HCCI combustion and emissions by fuel design concept combined with controllable EGR. part 1. the basic characteristics of HCCI combustion. *Fuel*, 84(9):1074 – 1083, 2005.

[108] Tunestal P. Manente V, Johansson B. Characterization of partially premixed combustion with ethanol: EGR sweeps, low and maximum loads. *ASME. J. Eng. Gas Turbines Power*, 2010.

[109] Lianhao Yin, Gabriel Ingesson, Sam Shamun, and et. al. Tunestal. Sensitivity analysis of partially premixed combustion (PPC) for control purposes. In *SAE Technical Paper 2015-01-0884*, 2015.

[110] Joel Martinez-Frias, Salvador M. Aceves, Daniel Flowers, J. Ray Smith, and Robert Dibble. HCCI engine control by thermal management. In *SAE Technical Paper 2000-01-2869*, 2000.

[111] Gregory M. Shaver, Matthew Roelle, and J. Christian Gerdes. Modeling cycle-to-cycle coupling in HCCI engines utilizing variable valve actuation. *IFAC Symp. on Adv. in Auto. Cont.*, 37(22):227 – 232, 2004.

[112] Nikhil Ravi. "Modeling and Control of Exhaust Recompression HCCI using variable valve actuation and Fuel Injection". PhD thesis, Stanford University, 2010.

[113] Göran Haraldsson, Per Tunestål, Bengt Johansson, and Jari Hyvönen. HCCI combustion phasing in a multi cylinder engine using variable compression ratio. In *SAE Technical Paper 2002-01-2858*, 2002.

[114] Martin Wissink and Rolf D. Reitz. Direct dual fuel stratification, a path to

combine the benefits of RCCI and PPC. *SAE Int. J. Engines 8(2):878-889*, 2015.

[115] Junjun Ma, Xingcai Lü, Libin Ji, and Zhen Huang. An experimental study of HCCI-DI combustion and emissions in a diesel engine with dual fuel. *Int. J. of Therm. Sci.*, 47(9):1235 – 1242, 2008.

[116] Mahdi Shahbakhti and Charles Robert Koch. Physics based control oriented model for HCCI combustion timing. *J. of Dyn. Sys., Meas., and Cont.*, 132(2), 2010.

[117] Antonio Garcia Benajes Jesus, Bernardo Tormos and Javier Monsalve-Serrano. Impact of spark assistance and multiple injections on gasoline PPC light load. In *SAE Int. J. of Engines 7, no. 4, 1875-1887*, 2014.

[118] Christian Ibron, Mehdi Jangi, Sara Lonn, Alexios Matamis, and et. al. Effect of injection timing on the ignition and mode of combustion in a HD PPC engine running low load. In *SAE Technical Paper 2019-01-0211*, 2019.

[119] S. Batool, J. D. Naber, and M. Shahbakhti. “Multi-mode Low Temperature Combustion (LTC) and Mode Switching Control”. In Kalwar A. Valera H. (eds) In: Agarwal A.K., Martínez A.G., editor, *Advanced Combustion for Sustainable Transport. Energy, Environment, and Sustainability*, chapter 3, pages 43–93. Springer, Singapore, 2022.

[120] Adam B. Dempsey, N. Ryan Walker, Eric Gingrich, and Rolf D. Reitz. Comparison of low temperature combustion strategies for advanced compression ignition engines with a focus on controllability. *Comb. Sci. and Tech.*, 186(2):210–241, 2014.

[121] Asad U. Han X. Chen X. Divekar, P. and M.. Zheng. Study of cylinder charge control for enabling low temperature combustion in diesel engines. *ASME. J. Eng. Gas Turb. Pow.*, page 136(9): 091503., 2014.

[122] Christof Noehre, Magnus Andersson, Bengt Johansson, and Anders Hultqvist. Characterization of partially premixed combustion. In *SAE Technical Paper 2006-01-3412*, 10 2006.

[123] Derek Splitter, Reed Hanson, Sage Kokjohn, Martin Wissink, and et. al. Injection effects in low load RCCI dual-fuel combustion. In *SAE Technical Paper 2011-24-0047*, 2011.

[124] Reitz R. Eichmeier, J. and C. Rutland. A zero-dimensional phenomenological model for rcci combustion using reaction kinetics,.

[125] S. Zhang, G. Zhu, and Z. Sun. A control-oriented charge mixing and two-zone HCCI combustion model. *IEEE Trans. on Veh Tech.*, 63(3):1079–1090, 2014.

[126] Khashayar Ebrahimi, Charles Koch, and Alex Schramm. A control oriented model with variable valve timing for HCCI combustion timing control. In *SAE Technical Paper 2013-01-0588*, 2013.

[127] Khashayar Ebrahimi, Masoud Aliramezani, and Charles Robert Koch. An HCCI control oriented model that includes combustion efficiency. *8th IFAC Symp. on Adv. in Auto. Cont. AAC*, 49(11):327 – 332, 2016.

[128] Roelle MJ Jungkunz AF Gerdes JC. Ravi, N. A physically based two-state model for controlling exhaust recompression HCCI in gasoline engines. *Proc. of the ASME 2006 Int. Mech. Engg. Congress and Expo. Dyn. Sys. and Cont., Parts A and B.*, pages pp. 483–492, 2006.

[129] CM Hall, D. Van Alstine, L. Kocher, GM Shaver, and et. al. Combustion timing modeling and control framework for biodiesel/diesel blends during pre-mixed combustion. *Proc. of the ASME 2012 5th Annual Dyn. Sys. and Cont. Conf. joint with the JSME 2012 11th Mot. and Vib. Conf.*, pages 329–338., 2012.

[130] Per Tunestål and Magnus Lewander. *"Model Predictive Control of Partially Premixed Combustion"*, pages 171–181. Springer London, London, 2010.

[131] Anders Widd, Rolf Johansson, Patrick Borgqvist, Per Tunestal, and Bengt Johansson. Investigating mode switch from SI to HCCI using early intake valve closing and negative valve overlap. In *SAE International Powertrains, Fuels and Lubricants Meeting*. SAE International, aug 2011.

[132] Sandro Patrick Nuesch. *"Analysis and Control of Multimode Combustion Switching Sequence"*. PhD thesis, University of Michigan, 2015.

[133] K. Kannan. An experimental investigation of low temperature combustion regimes in a light duty engine. Master's thesis, Michigan Technological University, 2016.

[134] Splitter D. Kokjohn S., Reitz R. and M. Musculus. Investigation of fuel reactivity stratification for controlling pci heat-release rates using high-speed chemiluminescence imaging and fuel tracer fluorescence. 5(2):248–269, 2012.

[135] C.F. Aquino. Transient A/F control characteristics of the 5 liter central fuel injection engine. In *SAE Technical Paper 810494*, 1981.

[136] J. Davis Powell Gene F. Franklin and Abbas F. Emami-Naeini. *"Feedback Control of Dynamic Systems"*. 6th edition, Pearson, 2009.

[137] Yeliana. *"Parametric combustion modeling for ethanol-gasoline fuelled spark ignition engines"*. PhD thesis, Michigan Technological University, 2010.

[138] Lu Xingcai, Ji Libin, Ma Junjun, and Huang Zhen. "Experimental study on the cycle-by-cycle variations of homogeneous charge compression ignition combustion using primary reference fuels and their mixtures". *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 221(7):859–866, 2007.

[139] John B. Heywood. *"Internal combustion engine fundamentals"*. Mcgraw-hill New York, 1988.

[140] K. Pasupa and W. Sunhem. “A comparison between shallow and deep architecture classifiers on small dataset”. In *2016 8th International Conference on Information Technology and Electrical Engineering (ICITEE)*, pages 1–6, 2016.

[141] C. Cortes and V. Vapnik. “Support Vector Networks”. *Machine Learning*, 20:273–297, 1995.

[142] Shawe-Taylor J. Cristianini, N. “An Introduction to Support Vector Machines and Other Kernel-based Learning Methods.”, Cambridge: Cambridge University Press. 2000.

[143] Friedman J. Hastie T., Tibshirani R. “Support Vector Machines and Flexible Discriminants. In: The Elements of Statistical Learning. Springer Series in Statistics.”. 2009.

[144] E. S. Meadows. “Dynamic programming and model predictive control”. In *Proceedings of the 1997 American Control Conference (Cat. No.97CH36041)*, volume 3, pages 1635–1639, 1997.

[145] S. Batool, J. D. Naber, and M. Shahbakhti. “Closed-Loop Predictive Control of a Multi-Mode Engine Including Homogeneous Charge Compression Ignition, Partially Premixed Charge Compression Ignition and Reactivity Controlled Compression Ignition Modes”. *SAE Int. J. of Fuels and Lub.*, 2022.

[146] N. Ravi, M. J. Roelle, H. H. Liao, A. F. Jungkunz, C. F. Chang, S. Park, and

J. C. Gerdes. Model-based control of hcci engines using exhaust recompression. *IEEE Transactions on Control Systems Technology*, 18(6):1289–1302, 2010.

[147] Q. Tan, X. Chen, Y. Tan, and M. Zheng. "Model-Guided Data-Driven Optimization for Automotive Compression Ignition Engine Systems". *ASME. Mechanical Engineering*, 141(03):S16–S23, 2019.

[148] M. Aliriamezani, C. R. Koch, and M. Shahbakhti. "Modeling, diagnostics, optimization, and control of internal combustion engines via modern machine learning techniques: A review and future directions". *Prog. in Ener. and Comb. Sci.*, 88:100967, 2021.

[149] T. Hastie, R. Tibshirani, and J. Friedman. *"Prototype Methods and Nearest - Neighbors" in The Elements of Statistical Learning.* Springer Nature, 2009.

[150] S. L. Brunton and J. N. Kutz. *"Clustering and Classification" in Data-Driven Science and Engineering: Machine Learning, Dynamical Systems, and Control.* Cambridge University Press, 2019.

[151] A. S. Silitonga, H. H. Masjuki, H. C. Ong, A. H. Sebayang, S. Dharma, F. Kusumo, J. Siswantoro, J. Milano, K. Daud, T.M.I. Mahlia, W. H. Chen, and B. Sugiyanto. "Evaluation of the engine performance and exhaust emissions of biodiesel-bioethanol-diesel blends using kernel-based extreme learning machine". *Energy*, 159:1075 – 1087, 2018.

[152] S. Shin, Y. Lee, M. Kim, J. Park, S. Lee, and K. Min. Deep neural network model with bayesian hyperparameter optimization for prediction of nox at transient conditions in a diesel engine. *Engineering Applications of Artificial Intelligence*, 94:103761, 2020.

[153] A. Norouzi, D. Gordon, M. Aliramezani, and Koch C. R. "Machine Learning-based Diesel Engine-Out NOx Reduction Using a plug-in PD-type Iterative Learning Control". In *2020 IEEE Conference on Control Technology and Applications (CCTA)*, pages 450–455, 2020.

[154] A. Coraddu, L. Oneto, D. Ilardi, S. Stoumpos, and G. Theotokatos. Marine dual fuel engines monitoring in the wild through weakly supervised data analytics. *Engineering Applications of Artificial Intelligence*, 100:104179, 2021.

[155] Tomohiro Kanda, Takazo Hakozaki, Tatsuya Uchimoto, Jyunichi Hatano, Naoto Kitayama, and Hiroshi Sono. Pcci operation with early injection of conventional diesel fuel. In *SAE 2005 World Congress & Exhibition*. SAE International, apr 2005.

[156] J. Lee, S. Chu, J. Kang, K. Min, H. Jung, H. Kim, and Y. Chi. "The classification of gasoline/diesel dual-fuel combustion based on the heat release rate shapes and its application in a light-duty single-cylinder engine". *International Journal of Engine Research*, 20(1):69–79, 2019.

[157] R. Sitaraman, S. Batool, H. Borhan, J. M. Velni, J. D. Naber, and M. Shahbakhti. “Data-Driven Model Learning and Control of RCCI Engines based on Heat Release Rate”. *IFAC Mod., Est. and Cont. Conf. (MECC)*, 2022.

[158] E Hendricks, A Chevalier, M Jensen, S C Sorenson, D Trumpy, and J Asik. Modelling of the intake manifold filling dynamics. *SAE Transactions*, 105:122–146, 1996.

[159] Cheng W. Fox, J. and J. Heywood. “A Model for Predicting Residual Gas Fraction in Spark-Ignition Engines,”. *SAE Technical Paper 931025*, (1993).

[160] X. Wang. *A study of model-based control strategy for a gasoline turbocharged direct injection spark ignited engine*. PhD thesis, Michigan Technological University, 2020.

[161] Liuping Wang. *“Model Predictive Control System Design and Implementation Using MATLAB*. Springer London, 2009.

[162] Jannerup. O. Sorensen P. H. Hendricks, E. *“Linear Systems Control Deterministic and Stochastic Methods*. Springer Berlin, Heidelberg, 2008.

[163] Gerty M. Ayala, F. and J. Heywood. ”effects of combustion phasing, relative air-fuel ratio, compression ratio, and load on si engine efficiency,”. 2006.

[164] Inventory of U.S. greenhouse gas emissions and sinks 1990-2017. *United States E.P.A., EPA 430-R-19-001*, 2019.

[165] J.D. Naber and J.E. Johnson. 8 - internal combustion engine cycles and concepts. In Richard Folkson, editor, *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance*, pages 197 – 224. Woodhead Publishing, 2014.

[166] G. Fontana and E. Galloni. "Variable valve timing for fuel economy improvement in a small spark-ignition engine". *Applied Energy*, 86(1):96–105, 2009.

[167] Can Cinar, Özer Can, Fatih Sahin, and H. Serdar Yucesu. Effects of premixed diethyl ether (dee) on combustion and exhaust emissions in a hcci-di diesel engine. *Applied Thermal Engineering*, 30(4):360 – 365, 2010.

[168] K. Yoshida K. Yoshida H. Shoji K. Shimada K. Hamada, S. Niijima and K. Shibano. The effects of the compression ratio, equivalence ratio, and intake air temperature on ignition timing in an hcci engine using dme fuel. *SAE Technical Paper 2005–32–0002*, 2005.

[169] Kuang-Hung Tseng and Chih-Yu Hsu. *Control of HCCI by aid of Variable Valve Timings with Specialization in Usage of a Non-Linear Quasi-Static Compensation*. PhD thesis, 2006.

[170] Xing-Cai Lü, Wei Chen, and Zhen Huang. A fundamental study on the control of the hcci combustion and emissions by fuel design concept combined with controllable egr. part 2. effect of operating conditions and egr on hcci combustion. *Fuel*, 84(9):1084 – 1092, 2005.

[171] Xingcai Lu, Dong Han, and Zhen Huang. Fuel design and management for the control of advanced compression-ignition combustion modes. *Progress in Energy and Combustion Science*, 37(6):741 – 783, 2011.

[172] Junxing Hou, Xinqi Qiao, Zhen Wang, Wei Liu, and Zhen Huang. Characterization of knocking combustion in hcci dme engine using wavelet packet transform. *Applied Energy*, 87(4):1239 – 1246, 2010.

[173] Michael Boot, Erik Rijk, Carlo Luijten, Bart Somers, and Bogdan Albrecht. Spray impingement in the early direct injection premixed charge compression ignition regime. In *International Powertrains, Fuels & Lubricants Meeting*. SAE International, may 2010.

[174] Manbae Han, Dennis N. Assanis, and Stanislav V. Bohac. Sources of hydrocarbon emissions from low-temperature premixed compression ignition combustion from a common rail direct injection diesel engine. *Combustion Science and Technology*, 181(3):496–517, 2009.

[175] Girish E. Bhiogade, Neeraj Sunheriya, and J. G. Suryawanshi. Investigations on premixed charge compression ignition (pcci) engines: A review. In Debopam Saha, Arun K.and Das, Rajesh Srivastava, P. K. Panigrahi, and K. Muralidhar, editors, *Fluid Mechanics and Fluid Power – Contemporary Research*, pages 1455–1463, New Delhi, 2017. Springer India.

[176] Yong Sun and Rolf D. Reitz. Adaptive injection strategies (ais) for ultra-low emissions diesel engines. In *SAE World Congress & Exhibition*. SAE International, apr 2008.

[177] W. L. Hardy and Rolf D. Reitz. A study of the effects of high egr, high equivalence ratio, and mixing time on emissions levels in a heavy-duty diesel engine for pcci combustion. In *SAE 2006 World Congress & Exhibition*. SAE International, apr 2006.

[178] Fan Zhang, Hongming Xu, Soheil Zeraati Rezaei, Gautam Kalghatgi, and Shi-Jin Shuai. Combustion and emission characteristics of a ppci engine fuelled with dieseline. In *SAE 2012 World Congress & Exhibition*. SAE International, apr 2012.

[179] Jonathan Martin, Andre Boehman, Rutvik Topkar, Sumit Chopra, Uday Subramaniam, and Heng Chen. Intermediate combustion modes between conventional diesel and rcci, apr 2018.

[180] Magnus Sjöberg and John E. Dec. Smoothing hcci heat-release rates using partial fuel stratification with two-stage ignition fuels. In *SAE 2006 World Congress & Exhibition*. SAE International, apr 2006.

[181] Yi Yang, John E. Dec, Nicolas Dronniou, Magnus Sjöberg, and William Cannella. Partial fuel stratification to control hcci heat release rates: Fuel composition and other factors affecting pre-ignition reactions of two-stage ignition

fuels, apr 2011.

[182] Shuai S Wang Y Tian G An X. Wang Z, Wang J. Study of multimode combustion system with gasoline direct injection. *ASME. J. Eng. Gas Turbines Power*, 2006.

[183] G. Ingesson, L. Yin, R. Johansson, and P. Tunestål. Efficiency optimal, maximum-pressure control in compression-ignition engines. In *2017 American Control Conference (ACC)*, pages 4753–4759, May 2017.

[184] Zweigel R. Jochim B. Beeckmann J. Abel D. & Pitsch H. Korkmaz, M. Triple-injection strategy for model-based control of premixed charge compression ignition diesel engine combustion. international journal of engine research, 19(2), 230–240. 2018.

[185] Jinlin Han, Shuli Wang, and Bart Somers. Comparative study on the effects of inlet heating, inlet boosting, and double-injection strategy on partially premixed combustion. In *WCX SAE World Congress Experience*. SAE International, apr 2019.

[186] Anders Widd, Rolf Johansson, Patrick Borgqvist, Per Tunestal, and et. al. Investigating mode switch from SI to HCCI using early intake valve closing and negative valve overlap. In *SAE Technical Paper 2011-01-1775*. SAE International, 2011.

[187] Shukla Pravesh Shamun Sam Tuner Martin Deniz Cengiz Johansson Bengt Zincir, Burak. Investigation of effects of intake temperature on low load limitations of methanol partially premixed combustion. In *Journal of Eergy & Fuels*. American Chemical Society, 2019.

[188] Changle Li, Leilei Xu, Xue-Song Bai, Per Tunestal, and Martin Tuner. Effect of piston geometry on stratification formation in the transition from HCCI to PPC. In *International Powertrains, Fuels & Lubricants Meeting*. SAE International, sep 2018.

[189] Marcus Lundgren, Martin Tuner, Bengt Johansson, Simon Bjerkborn, Karin Frojd, Arne Andersson, Fabian Mauss, and Bincheng Jiang. Gasoline PPC: A parametric study of late cycle mixing conditions using a predictive two-zone SRM modeling tool. In *SAE/KSAE 2013 International Powertrains, Fuels & Lubricants Meeting*. SAE International, oct 2013.

[190] Antonio García, Javier Monsalve-Serrano, Rafael Sari, Nikolaos Dimitrakopoulos, Martin Tunér, and Per Tunestål. Performance and emissions of a series hybrid vehicle powered by a gasoline partially premixed combustion engine. *Applied Thermal Engineering*, 150:564 – 575, 2019.

[191] Amir Aziz, Changle Li, Sebastian Verhelst, and Martin Tuner. The relevance of different fuel indices to describe autoignition behaviour of gasoline in light

duty DICI engine under PPC mode. In *WCX SAE World Congress Experience*. SAE International, apr 2019.

[192] Mengqin Shen, Martin Tuner, Bengt Johansson, Per Tunestal, and Joakim Pagels. Influence of injection timing on exhaust particulate matter emissions of gasoline in HCCI and PPC. In *SAE 2016 International Powertrains, Fuels & Lubricants Meeting*. SAE International, oct 2016.

[193] Hans Aulin Per Tunestal Bengt Johansson William Cannella Martin Tuner, Thomas Johansson. Multi cylinder partially premixed combustion performance using commercial light-duty engine hardware. In *SAE 2014 International Powertrain, Fuels & Lubricants Meeting*. SAE International, oct 2014.

[194] G Tian, Z Wang, Q Ge, J Wang, and S Shuai. Control of a spark ignition homogeneous charge compression ignition mode transition on a gasoline direct injection engine. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 221(7):867–875, 2007.

[195] W. Fischer, R. Karrelmeyer, A. Löffler, A. Kulzer, and J.-P. Hathout. Closed-loop control of a multi-mode GDI engine with CAI. *IFAC Proceedings Volumes*, 40(10):479 – 486, 2007. 5th IFAC Symposium on Advances in Automotive Control.

[196] Richard Hutter, Severin Hänggi, Thivaharan Albin, and Christopher H. Onder.

Optimal transition control between combustion modes in a diesel-ignited gas engine. *Control Engineering Practice*, 97:104327, 2020.

[197] Awate S. Chowdhury A. et al. Lalwani, A. Conversion of a single-cylinder internal combustion engine to dual-mode homogeneous charge compression ignition engine. *Clean Techn Environ Policy 21, 23–37 (2019).*

[198] N Kalian, H Zhao, and J Qiao. Investigation of transition between spark ignition and controlled auto-ignition combustion in a v6 direct-injection engine with cam profile switching. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 222(10):1911–1926, 2008.

[199] S Batool, J Naber, and M Shahbakhti. Machine learning approaches for identification of heat release shapes in a low temperature combustion engine for control applications. *submitted to Control Engineering Practice.*

[200] Hao Wu, Nick Collings, Simon Regitz, Jonathan Etheridge, and Markus Kraft. Experimental investigation of a control method for SI-HCCI-SI transition in a multi-cylinder gasoline engine, Apr 2010.

[201] Praveen Kumar and Mark Sellnau. Evaluation of fast warm-up strategies for a light-duty gasoline compression ignition (GCI) engine. In *WCX SAE World Congress Experience*. SAE International, Apr 2020.

[202] Tom Tzanetakis, Mark Sellnau, Vincent Costanzo, Michael Traver, Tony Williams, Erol Kahraman, Jean Herve Petot, Guillaume Meissonnier, Aniket

Tekawade, Brandon Sforzo, and Christopher F. Powell. Durability study of a light-duty high pressure common rail fuel injection system using E10 gasoline. In *WCX SAE World Congress Experience*. SAE International, Apr 2020.

[203] Mark Sellnau, Matthew Foster, Wayne Moore, James Sinnamon, Kevin Hoyer, and William Klemm. Pathway to 50% brake thermal efficiency using gasoline direct injection compression ignition, Apr 2019.

[204] Mark Sellnau, James Sinnamon, Kevin Hoyer, and Harry Husted. Gasoline direct injection compression ignition (GDCI) - diesel-like efficiency with low co2 emissions. *SAE International Journal of Engines*, 4(1):2010–2022, 2011.

[205] Mark Sellnau, Matthew Foster, Wayne Moore, James Sinnamon, Kevin Hoyer, and William Klemm. Second generation GDCI multi-cylinder engine for high fuel efficiency and us tier 3 emissions, Apr 2016.

[206] Mark Sellnau, Matthew Foster, Kevin Hoyer, Wayne Moore, James Sinnamon, and Harry Husted. Development of a gasoline direct injection compression ignition (GDCI) engine, Apr 2014.

[207] Christopher P. Kolodziej, Mark Sellnau, Kukwon Cho, and David Cleary. Operation of a gasoline direct injection compression ignition engine on naphtha and E10 gasoline fuels, Apr 2016.

Appendix A

PhD Publications

A.1 Peer Reviewed Journal Papers

A.1.1 Published Journal Papers

1. S. Batool, J. Naber, and M. Shahbakhti, "Closed-Loop Predictive Control of a Multi-mode Engine Including Homogeneous Charge Compression Ignition, Partially Premixed Charge Compression Ignition, and Reactivity Controlled Compression Ignition Modes," SAE Int. J. Fuels Lubr. 16(1):15-36, 2023.

A.1.2 Submitted Journal Papers

1. S. Batool, J. Naber, and M. Shahbakhti,"Machine learning approaches for identification of heat release shapes in a low temperature combustion engine for control applications", submitted to Control Engineering Practice.

A.2 Book Chapter

1. S. Batool, J. Naber, and M. Shahbakhti, (2022). Multi-mode Low Temperature Combustion (LTC) and Mode Switching Control. In: Agarwal, A.K., Martínez, A.G., Kalwar, A., Valera, H. (eds) Advanced Combustion for Sustainable Transport. Energy, Environment, and Sustainability. Springer, Singapore

A.3 Peer Reviewed Conference Papers

1. S. Batool, J. Naber, and M. Shahbakhti,"Data-Driven Modeling and Control of Cyclic Variability of an Engine Operating in Low Temperature Combustion Modes", Modeling, Estimation and Control Conference (MECC), 54(20):834-839, 2021.

2. R. Sitaraman, S. Batool, J. Naber, and M. Shahbakhti,"Machine Learning-based Classification of Combustion Events in an RCCI Engine Using Heat Release Rate Shapes", Modeling, Estimation and Control Conference (MECC),55(37):601-607,2022.

3. R. Sitaraman, S. Batool, J. Naber, and M. Shahbakhti,"Data-Driven Model Learning and Control of RCCI Engines based on Heat Release Rate", Modeling, Estimation and Control Conference (MECC), 55(37):608-614, 2022.

A.4 Future Publications

A.4.1 Journal Publications

1. S. Batool, J. Naber, and M. Shahbakhti,"Model Predictive Control of a Multi-Mode Combustion Engine", Applied Thermal Engineering, 2023.

2. S. Batool, J. Naber, and M. Shahbakhti,"Dynamic Modeling of a Multi-Mode Engine", International Journal of Engine Research, 2023.

A.4.2 Conference Publications

1. S. Batool, J. Naber, and M. Shahbakhti,"Closed-loop Control of SI-RCCI-SI Transitions in a Multi-Mode Combustion Engine", Modeling, Estimation and Control Conference (MECC), 2023.

Appendix B

Summary of Program and Data Files

B.1 Chapter 2

Table B.1
Steady State Model Validations in 2

File Name	File Description
LTC-MultiModev2.pdf	Figure 2.1
LTC_Emissions.pdf	Figure 2.2
ModeSwitchSchematicV3.pdf	Figure 2.3
IVCvsCA50_St.pdf	Figure 2.4
NVO.pdf	Figure 2.5
PilotInj_R.pdf	Figure 2.6
FTM_1.pdf	Figure 2.7
DSM$_M$*T.pdf*	Figure 2.8
PPCI_MPC_paper93.pdf	Figure 2.9
RCCI_$_s$*ensitivity.pdf*	Figure 2.10
RCCI_Ak.pdf	Figure 2.11
MultiModeChallengesBlockDiagram_v3.pdf	Figure 2.12
MultiModeEmissions.pdf	Figure 2.13
LTC-MultiMode1.pdf	Figure 2.14
SI2HCCI_paper104.pdf	Figure 2.15
MFB_paper103.pdf	Figure 2.16
Two_Step_Strategy_paper43.pdf	Figure 2.17
SI2HCCI_paper43.pdf	Figure 2.18
SI2HCCI_paper139.pdf	Figure 2.19
SI_HCCI_paper107.pdf	Figure 2.20
SI_HCCI_paper44_1.pdf	Figure 2.21
Fig_paper76_1.pdf	Figure 2.22
LTC-MultiMode2.pdf	Figure 2.23
BMEP_RCCI2CDC_paper237_1.pdf	Figure 2.24
emissions_paper237.pdf	Figure 2.25
RCCI$_C$*DF_paper41.pdf*	Figure 2.26
RCCI_CDF_results_paper41.pdf	Figure 2.27
SchematicMultiMode_summary_v4.pdf	Figure 2.28

B.2 Chapter 3

Table B.2
Block Diagrams in 3

File Name	**File Description**
blockdiag_ControlStudies_v3_1.pdf	Figure 3.1
LTC_Engine_Setup_v3.pdf	Figure 3.2
Actual_Engine_Setup_4.pdf	Figure 3.3
DynamicModelSchematic_v4a.pdf	Figure 3.6
DynamicModelSchematic_v4a.vsdx	Figure 3.6
Schematic_LPVMPC_v6_2b.pdf	Figure 3.14
Schematic_LPVMPC_v6_2b.vsdx	Figure 3.14

Table B.3
Steady State Model Validations in 3

File Name	File Description
PowerSpeed.jpg	Figure 3.4a
BMEPvsSpeed_edit_v2.jpg	Figure 3.4b
HRR4_2.eps	Figure 3.5
SOCplotHCCI_new1.eps	Figure 3.7a
BDplotHCCI_new1.eps	Figure 3.7b
CA50plotHCCI_new1.eps	Figure 3.7c
imepplotHCCI_new1.eps	Figure 3.7d
SOCplotPPCI_new1.eps	Figure 3.8a
BDplotPPCI_new1.eps	Figure 3.8b
CA50plotPPCI_new1.eps	Figure 3.8c
imepplotPPCI_new1.eps	Figure 3.8d
SOCplotRCCI_new.eps	Figure 3.9a
BDplotRCCI_new.eps	Figure 3.9b
CA50plotRCCI_new.eps	Figure 3.9c
imepplotRCCI_new.eps	Figure 3.9d
HCCI_TranValid_PR_FQ_2.eps	Figure 3.10
RCCI_transValid_PR20_FQ23_stepSOI_2.eps	Figure 3.11
RCCI_transValid_PR20_SOI50_stepFQ_2.eps	Figure 3.12
RCCI_nyquistplot_CL_2.eps	Figure 3.13a
PPCI_nyquistplot_CL_2.eps	Figure 3.13b
RCCI_nyquistplot_CL_2.eps	Figure 3.13c
HCCInewv2.eps	Figure 3.15
HCCInewdv2.eps	Figure 3.16
PPCInewv2.eps	Figure 3.17
PPCInewdv2.eps	Figure 3.18
RCCInewv2.eps	Figure 3.19
RCCInewdv2.eps	Figure 3.20

Table B.4
MATLAB/Simulink Files 3

File Name	File Description
HCCI_dyn.m	HCCI Dynamic Model
MPC_HCCI_Adaptive_Final.slx	Simulink Model with MPC
HCCI_plots.m	M File
PPCI_dyn.m	HCCI Dynamic Model
MPC_PPCI_AdaptiveNew_v1.slx	Simulink Model with MPC
PPCI_plots.m	M File
RCCI_dyn.m	HCCI Dynamic Model
RCCI_adapMPC_LPVn_V3.slx	Simulink Model with MPC
RCCI_ploting.m	M File
DynamicModelSchematic_v4a.pdf	Figure 3.6
DynamicModelSchematic_v4a.vsdx	Figure 3.6
Schematic_LPVMPC_v6_2b.pdf	Figure 3.14
Schematic_LPVMPC_v6_2b.vsdx	Figure 3.14

Table B.5
MAT Files 3

File Name	File Description
mpc_LPV_hcci_tuned_final.mat	Tuned MPC and LPV systems
Results_HCCI.mat	HCCI tracking results
Results_HCCId.mat	HCCI disturbance rejection results
PPCI_data.mat	PPCI tracking results
PPCId_data.mat	PPCI disturbance rejection results
RCCI_Output_PRv.mat	RCCI tracking results
RCCI_Output_PRvd.mat	RCCI disturbance rejection results

B.3 Chapter 4

Table B.6
Figures in 4

File Name	File Description
InCylPressureHCCI_cov10.eps	Figure 4.1
InCylPressureHCCI_covMin.eps	Figure 4.2
InCylPressureHCCI_knock4v2.eps	Figure 4.3
ClassificationSchematic_v2b.pdf	Figure 4.4
ConfusionHCCItrain5.eps	Figure 4.5
ConfusionHCCItest5.eps	Figure 4.5
ConfusionRCCITrain5c.eps	Figure 4.5
ConfusionRCCITest5c.eps	Figure 4.5
Schematic_NMPC_v6e.pdf	Figure 4.6
RCCIOutputwC1v2e.eps	Figure 4.8
RCCIMVwC1v2ca.eps	Figure 4.9
HCCIOutputwC1v2d.eps	Figure 4.10
HCCIMVwC1v2ba.eps	Figure 4.11

Table B.7
MATLAB/Simulink Files in Chapter 4

File Name	File Description
HCCI_dyn.m	Dynamic HCCI Model
mycostfunctionHCCIv2C.m	Cost Function
covmodelHCCI.m	Constraint on COV_{IMEP}
HCCIModelv2C.m	NMPC for HCCI
NMPC_HCCIv1.slx	To simulate plant model with controller
RCCI_dyn.m	Dynamic RCCI Model
mycostfunctionRCCIv2d.m	Cost Function
mycostfunctionRCCIv2e.m	Cost Function with constraint
covmodel.m	Constraint on COV_{IMEP}
RCCIModelv2d.m	NMPC for RCCI
RCCIModelv2e.m	NMPC for RCCI with COV_{IMEP} model
NMPC_RCCIv2b.slx	To simulate plant model with controller
NMPC_RCCIv2e.slx	To simulate plant model with controller
RCCI_COV_plots.m	To plot the results for RCCI
HCCI_COV_plots.m	To plot the results for HCCI

Table B.8
Data Files in Chapter 4

File Name	File Description
RCCI_COV_Data.mat	Data for Fig. 4.7-4.8
HCCI_COV_Data.mat	Data for Fig. 4.9-4.10
Test_Data_HCCIall.mat	Data used for Modeling of HCCI
Combined_data_RCCI_NA.mat	Data used for Modeling of HCCI

B.4 Chapter 5

Table B.9
Figures in Chapter 5

File Name	File Description
HRR_types_plots_final_v2.eps	Figure 5.1
HRR_CAD_J.eps	Figure 5.2
DecisionTree_HRRv2b.pdf	Figure 5.3
CA10.eps	Figure 5.4
CA50.eps	Figure 5.5
BD.eps	Figure 5.6
Pmax.eps	Figure 5.7
Loc.eps	Figure 5.8
Tmax.eps	Figure 5.9
MPRR.eps	Figure 5.10
COV.eps	Figure 5.11
Cumulative_COV.eps	Figure 5.12
Cumulative_MPRR.eps	Figure 5.12
Cumulative_Tmax.eps	Figure 5.12
Cumulative_Indeff.eps	Figure 5.12
HRR_Kmeans_3_new.eps	Figure 5.13
ClassificationSchematic_HRR_v2.pdf	Figure 5.14
HRR_Decision_Tree_Pattern_2.eps	Figure 5.15
HRR_KNN_Pattern_2.eps	Figure 5.15
HRR_SVM_Pattern_2.eps	Figure 5.15
HRR_Decision_Tree_feature_2.eps	Figure 5.16
HRR_KNN_feature_2.eps	Figure 5.16
HRR_SVM_feature_2.eps	Figure 5.16
MPC_outputs2.eps	Figure 5.17
MPC_inputs2_2.eps	Figure 5.18
MPC_Outputs_Comparison_Combined2.eps	Figure 5.19
MPC_Inputs_Comparison_Combined2.eps	Figure 5.20

Table B.10
MATLAB/Simulink Files in Chapter 5

File Name	File Description
HRR_Types_Plots.m	To plot Fig. 6.1-6.3
MPC_RCCI_Classification_Results_Plots.m	To plot Fig. 6.4
RCCI_dyn_MPRR.m	RCCI dynamic model
LPV_MPC_RCCIClassification.slx	To simulate plant model with controller

Table B.11
Data Files in Chapter 5

File Name	File Description
RCCI_Parametricdata1.mat	Data for Fig. 5.1
trainedModelDtree.mat	Trained model to predict HRR shape
trainedModel_HRR_KNN _1.mat	Trained model to predict HRR shape
trainedModel_HRR_SVM _final.mat	Trained model to predict HRR shape
trainedModelDtree_HRR _feature.mat	Trained model to predict HRR type
trainedModelKNN_HRR _feature.mat	Trained model to predict HRR type
trainedModelSVM_HRR _feature.mat	Trained model to predict HRR type
MPC_Tuned.mat	MPC
LPV_System_Sadaf.mat	LPV system for RCCI
LPV_MPC_Controller _PR_MPRR_Controlled.mat	Aditya's LPV system and MPC for RCCI
MPC_HRR_Classification _Results.mat	Experimental data to plot Fig. 5.15
MPC_HRR_Classification _Results2.mat	Simulation data to plot Fig. 5.16
MPCTuned_final _comparison.mat	MPC
MPC_Results_Main _Paper.mat	Experimental data for Fig. 5.17 & 5.18
MPC_Results_Comparison _wo_Noise.mat	Experimental data for Fig. 5.19 & 5.20
Aditya_Results _wo_Noise.mat	Experimental data for Fig. 5.19 & 5.20

B.5 Chapter 6

Table B.12
Figures in Chapter 6

File Name	File Description
S5I_SFC.jpg	Figure 6.1
RCCI_SFC.jpg	Figure 6.1
SI_CO.jpg	Figure 6.2
SI_THC.jpg	Figure 6.2
SI_NOx.jpg	Figure 6.2
SI_MPRR.jpg	Figure 6.2
RCCI_CO.jpg	Figure 6.3
RCCI_THC.jpg	Figure 6.3
RCCI_NOx.jpg	Figure 6.3
RCCI_MPRR.jpg	Figure 6.3
EngineActTimeScales.pdf	Figure 6.4
EngineDyn_Time_Scale.pdf	Figure 6.5
Throttle_response_1.eps	Figure 6.6
Lambda_9.eps	Figure 6.7
SOC_SI.eps	Figure 6.8
BD_SI2.eps	Figure 6.9
CA50_SI.eps	Figure 6.10
NMEP_SI.eps	Figure 6.11
MPRR_SI.eps	Figure 6.12
SOC_RCCI.eps	Figure 6.13
BD_RCCI.eps	Figure 6.14
CA50_RCCI.eps	Figure 6.15
NMEP_RCCI.eps	Figure 6.16
MPRR_RCCI.eps	Figure 6.17
CA50_exp6.eps	Figure 6.18
NMEP_exp6.eps	Figure 6.19
Lambda_exp6.eps	Figure 6.20
MPRR_exp6.eps	Figure 6.21
Pman_exp6.eps	Figure 6.22
CA50_exp13.eps	Figure 6.23
NMEP_exp13.eps	Figure 6.24
Lambda_exp13.eps	Figure 6.25
MPRR_exp13.eps	Figure 6.26
Pman_exp13.eps	Figure 6.27

Table B.13
MATLAB Files in Chapter 6

File Name	File Description
SI_RCCI_SFC_modeSwitch.opju	To plot Fig. 6.1-6.3
Lambda_plots.m	To plot Fig. 6.4
SI_RCCI_MKIM_Weibe_Plots.m	To plot Fig. 6.6-6.25
MPRR_PhyBasedModel.m	Physics based MPRR model for SI and RCCI modes
trainedModelMPRR.mat	MPRR Model
Throttle.slx	Throttle Model

Table B.14
Data Files in Chapter 6

File Name	File Description
SI_RCCI_SFC_modeSwitch.opju	Data for Fig. 6.1-6.3
rec1_019	Experimental data for plot Fig. 6.4
Throttle_data	Simulation data for plot Fig. 6.4
rec1_009.mat	Experimental data for Fig. 6.5
lambda9.mat	Simulation data for Fig. 6.5
SI_RCCI_Sw2.mat	Experimental data for Fig. 6.6-6.15
SI_RCCI_Sw35.mat	Experimental data for Fig. 6.6-6.15
out_exp6.mat	Experimental data for Fig. 6.16-6.20
out_exp13	Experimental data for Fig. 6.21-6.25

B.6 Chapter 7

Table B.15
Figures in Chapter 7

File Name	File Description
MPC_Control_Mode_v1b.vsdx	Figure 7.1
MPC_Control_Mode_v1b.pdf	Figure 7.1
Outputs_SI.eps	Figure 7.2
MVs_SI.eps	Figure 7.3
Outputs_KF_SI2.eps	Figure 7.4
Outputs_RCCI.eps	Figure 7.5
MVs_RCCI.eps	Figure 7.6
Outputs_KF_RCCI.eps	Figure 7.7
Outputs_SI_RCCI2.eps	Figure 7.8
MVs_SI_RCCI2.eps	Figure 7.9
Outputs_MV.eps	Figure 7.10
Outputs_36_1.eps	Figure 7.11
MVs_36_1.eps	Figure 7.12
Outputs_4_1.eps	Figure 7.13
MVs_4_1.eps	Figure 7.14
Outputs_5_1.eps	Figure 7.15
MVs_5_1.eps	Figure 7.16

Table B.16
MATLAB and Simulink Files in Chapter 7

File Name	File Description
SI_RCCI_Switchdyn_Model.m	Dynamic Mode Switching Model
SI_RCCI_gMPCi.slx	Gain Scheduled MPC
SI_Plots.m	To plot Fig. 7.2, 7.3 & 7.4
RCCI_Plots.m	To plot Fig. 7.5, 7.6 & 7.7
SI_RCCI_plots.m	To plot Fig. 7.8 & 7.9
Test3_plots.m	To plot Fig. 7.10
Test36_plots.m	To plot Fig. 7.11 & 7.12
Test4_plots.m	To plot Fig. 7.13 & 7.14
Test5_plots.m	To plot Fig. 7.15 & 7.16

Table B.17

Experimental and Simulation Data Files in Chapter 7

File Name	File Description
Results_SI.mat	Simulation data for Fig. 7.2, 7.3 & 7.4
Results_RCCI.mat	Simulation data for Fig. 7.5, 7.6 & 7.7
Results_SIRCCI.mat	To plot Fig. 7.8 & 7.9
Test3	Experimental data for plot Fig. 7.10
Test36	Experimental data for Fig. 7.11 & 7.12
Test4	Experimental data for Fig. 7.13 & 7.14
Test5	Experimental data for Fig. 7.15 & 7.16

B.7 Chapter 8

Table B.18
Figures in Chapter 8

File Name	**File Description**
Throttle_Pman.eps	Figure 8.1
Pman_newModel.eps	Figure 8.2
NMEP1_norm.eps	Figure 8.3
NMEP2_norm.eps	Figure 8.3
NMEP3_norm.eps	Figure 8.3
NMEP4_norm.eps	Figure 8.3
NMEP5_normR.eps	Figure 8.4
NMEP4_normR.eps	Figure 8.4
NMEP3_normR.eps	Figure 8.4
NMEP2_normR.eps	Figure 8.4
MPC$_{C}ontrol_{M}ode2.pdf$	Figure 8.5
Outputs_30.eps	Figure 8.6
MVs_30.eps	Figure 8.7
Outputs_43.eps	Figure 8.8
MVs_43.eps	Figure 8.9
Outputs_17.eps	Figure 8.10
MVs_17.eps	Figure 8.11
Output_10.eps	Figure 8.12
MVs_10.eps	Figure 8.13
Output_72.eps	Figure 8.14
MVs_72.eps	Figure 8.15
Output_77.eps	Figure 8.16
MVs_77.eps	Figure 8.17
Output_80.eps	Figure 8.18
MVs_80.eps	Figure 8.19
CA50_COV1.eps	Figure 8.20
CA50std_COV1.eps	Figure 8.20
CA50_BD1.eps	Figure 8.20
CA50std_BDstd1.eps	Figure 8.20

Table B.19
MATLAB and Simulink Files in Chapter 8

File Name	File Description
SI_RCCI_Switchdyn_Modelv6Updated.m	Dynamic Mode Switching Model
SI_RCCI_gMPC_Updated.slx	Gain Scheduled MPC
Plots_GT_CA50_IMEP.m	To plot Fig. 8.3
Plots_GT_CA50_IMEP_R.m	To plot Fig. 8.4
Test30_plots.m	To plot Fig. 8.5 and 8.6
Test43_plots.m	To plot Fig. 8.7 and 8.8
Test_17_plots.m	To plot Fig. 8.9 and 8.10
Test_10_plots.m	To plot Fig. 8.11 and 8.12
Test_72_plots.m	To plot Fig. 8.13 and 8.14
Test_77_plots.m	To plot Fig. 8.15 and 8.16
Test_80_plots.m	To plot Fig. 8.17 and 8.18

Table B.20
Data Files in Chapter 8

File Name	Experimental Data
Test30	Data for Fig. 8.5 & 8.6
Test43	Data for Fig. 8.7 & 8.8
Test17	Data for Fig. 8.9 & 8.10
Test10	Data for Fig. 8.11 & 8.12
Test72	Data for Fig. 8.13 & 8.14
Test77	Data for Fig. 8.15 & 8.16
Test80	Data for Fig. 8.17 & 8.18

Table B.21
Data Files in Chapter 8

File Name	P_{man} Correlation Validation
Test_41	Test data
outputs_exp3_41	Simulation data
Test_84	Test data
outputs_exp1_84	Simulation data
Test_85	Test data
outputs_exp1_85	Simulation data

Table B.22
Data Files in Chapter 8

File Name	GTPower Model Simulation
DataSI.mat	SI simulation data
DataRCCI.mat	RCCI simulation data

Appendix C

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Best,

Martin

Martin Wissink, PhD

R&D Associate

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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.

Last updated October 2022

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Order Date	20-Mar-2023	**Type of Use**	Republish in a thesis/dissertation
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ISSN	1558-0865	**Publisher**	IEEE]
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LICENSED CONTENT

Publication Title	IEEE transactions on control systems technology	**Rightsholder**	The Institute of Electrical and Electronics Engineers, Incorporated (IEEE)
Article Title	Reference Governor for Load Control in a Multicylinder Recompression HCCI Engine	**Publication Type**	e-Journal
		Start Page	1408
		End Page	1421
		Issue	4
Author/Editor	IEEE Control Systems Society.	**Volume**	22
Date	01/01/2000		
Language	English		
Country	United States of America		

REQUEST DETAILS

Portion Type	Chart/graph/table/figure	**Distribution**	Worldwide
Number of Charts / Graphs / Tables / Figures Requested	1	**Translation**	Original language of publication
Format (select all that apply)	Electronic	**Copies for the Disabled?**	No
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Lifetime Unit Quantity	Up to 250,000	**Currency**	USD
Rights Requested	Main product		

NEW WORK DETAILS

Title	Dynamic Modeling and Predictive Control of a Multi-Mode Combustion Engine	**Institution Name**	Michigan Technological University
Instructor Name	Sadaf Batool	**Expected Presentation Date**	2023-03-20

ADDITIONAL DETAILS

Order Reference Number	Chapter-2_Fig2.5	**The Requesting Person/Organization to Appear on the License**	Sadaf Batool

REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Fig. 2 on Page 1410	**Title of the Article/Chapter the Portion Is From**	Reference Governor for Load Control in a Multicylinder Recompression HCCI Engine
Editor of Portion(s)	Jade, Shyam; Jade, Shyam; Hellstr??m, Erik; Hellstrom, Erik; Larimore, Jacob; Larimore, Jacob; Stefanopoulou, Anna G.; Stefanopoulou, Anna G.; Jiang, Li; Jiang, Li; IEEE Control Systems Society	**Author of Portion(s)**	Jade, Shyam; Jade, Shyam; Hellstr??m, Erik; Hellstrom, Erik; Larimore, Jacob; Larimore, Jacob; Stefanopoulou, Anna G.; Stefanopoulou, Anna G.; Jiang, Li; Jiang, Li; IEEE Control Systems Society
Volume of Serial or Monograph	22	**Issue, if Republishing an Article From a Serial**	4
Page or Page Range of Portion	1408-1421	**Publication Date of Portion**	2014-07-01

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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 unlawful, including without limitation if such use would violate applicable sanctions laws or regulations, would be defamatory, violate 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. Any unlawful use will render any licenses hereunder null and void. 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.

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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.

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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.

Last updated October 2022

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Order Date	20-Mar-2023	**Type of Use**	Republish in a thesis/dissertation
Order License ID	1336238-1		
ISSN	0196-8904	**Publisher**	PERGAMON
		Portion	Chart/graph/table/figure

LICENSED CONTENT

Publication Title	Energy conversion and management	**Rightsholder**	Elsevier Science & Technology Journals
Article Title	Modeling and controller design architecture for cycle-by-cycle combustion control of homogeneous charge compression ignition (HCCI) engines ? A comprehensive review	**Publication Type**	Journal
		Start Page	1
		End Page	19
		Volume	139
Date	01/01/1978		
Language	English, French, German		

Country	United Kingdom of Great Britain and Northern Ireland

REQUEST DETAILS

Portion Type	Chart/graph/table/figure	**Distribution**	Worldwide
Number of Charts / Graphs / Tables / Figures Requested	1	**Translation**	Original language of publication
Format (select all that apply)	Electronic	**Copies for the Disabled?**	No
Who Will Republish the Content?	Academic institution	**Minor Editing Privileges?**	No
Duration of Use	Life of current edition	**Incidental Promotional Use?**	No
Lifetime Unit Quantity	Up to 44,999	**Currency**	USD
Rights Requested	Main product		

NEW WORK DETAILS

Title	Dynamic Modeling and Predictive Control of a Multi-Mode Combustion Engine	**Institution Name**	Michigan Technological University
Instructor Name	Sadaf Batool	**Expected Presentation Date**	2023-03-20

ADDITIONAL DETAILS

Order Reference Number	Chapter-2_Fig_2.5	**The Requesting Person/Organization to Appear on the License**	Sadaf Batool

REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Fig. 4 on page 10
Editor of Portion(s)	Fathi, Morteza; Jahanian, Omid; Shahbakhti, Mahdi
Volume of Serial or Monograph	139
Page or Page Range of Portion	1-19
Title of the Article/Chapter the Portion Is From	Modeling and controller design architecture for cycle-by-cycle combustion control of homogeneous charge compression ignition (HCCI) engines ? A comprehensive review
Author of Portion(s)	Fathi, Morteza; Jahanian, Omid; Shahbakhti, Mahdi
Issue, if Republishing an Article From a Serial	N/A
Publication Date of Portion	2017-05-01

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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 unlawful, including without limitation if such use would violate applicable sanctions laws or regulations, would be defamatory, violate 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. Any unlawful use will render any licenses hereunder null and void. 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,
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- 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.

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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.

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LICENSED CONTENT

Publication Title	Control engineering practice	**Rightsholder**	Elsevier Science & Technology Journals
Article Title	Model predictive control of HCCI using variable valve actuation and fuel injection	**Publication Type**	Journal
		Start Page	421
		End Page	430
Author/Editor	INTERNATIONAL FEDERATION OF AUTOMATIC CONTROL.	**Issue**	4
		Volume	20
Date	01/01/1993		
Language	English		

Country	United Kingdom of Great Britain and Northern Ireland

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Portion Type	Chart/graph/table/figure	**Distribution**	Worldwide
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NEW WORK DETAILS

Title	Dynamic Modeling and Predictive Control of a Multi-Mode Combustion Engine	**Institution Name**	Michigan Technological University
Instructor Name	Sadaf Batool	**Expected Presentation Date**	2023-03-20

ADDITIONAL DETAILS

Order Reference Number	Chapter-2_Fig	**The Requesting Person/Organization to Appear on the License**	Sadaf Batool

REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Figure 3	**Title of the Article/Chapter the Portion Is From**	Model predictive control of HCCI using variable valve actuation and fuel injection
Editor of Portion(s)	Ravi, Nikhil; Liao, Hsien-Hsin; Jungkunz, Adam F.; Widd, Anders; Gerdes, J. Christian	**Author of Portion(s)**	Ravi, Nikhil; Liao, Hsien-Hsin; Jungkunz, Adam F.; Widd, Anders; Gerdes, J. Christian
Volume of Serial or Monograph	20	**Issue, if Republishing an Article From a Serial**	4
Page or Page Range of Portion	421-430	**Publication Date of Portion**	2012-04-01

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Last updated October 2022

Michigan Tech

Sadaf Batool <batool@mtu.edu>

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Mehran Bidarvatan <mbidarva@mtu.edu> Mon, Sep 27, 2021 at 2:50 AM
To: Sadaf Batool <batool@mtu.edu>

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Say hi to Dr. Shahbakhti, and good luck!

Mehran Bidarvatan, PhD

[Quoted text hidden]

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RE: Partially premixed combustion optimization using double injection strategy in transient operation, Applied Thermal Engineering, Volume 169, 2020, Yang et al, Figure 11

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Date: Wednesday, March 22, 2023 05:04 PM GMT

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Thank you for the information. I would really appreciate it if you could send me the permission letter.

Thank you
Regards,

Sadaf Batool
PhD Scholar
Department of Mechanical Engineering-Engineering Mechanics
Michigan Technological University
Houghton, MI, 49931

From: Roopa Lingayath
Date: Wednesday, March 22, 2023 05:00 PM GMT

[Quoted text hidden]

[Quoted text hidden]

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Order License ID	1336274-1		
ISSN	0967-0661	**Publisher**	PERGAMON
		Portion	Chart/graph/table/figure

LICENSED CONTENT

Publication Title	Control engineering practice	**Rightsholder**	Elsevier Science & Technology Journals
Article Title	Dynamic modeling and model predictive control of an RCCI engine	**Publication Type**	Journal
		Start Page	129
		End Page	144
Author/Editor	INTERNATIONAL FEDERATION OF AUTOMATIC CONTROL.	**Volume**	81
Date	01/01/1993		
Language	English		
Country	United Kingdom of Great Britain and Northern Ireland		

REQUEST DETAILS

Portion Type	Chart/graph/table/figure	**Distribution**	Worldwide
Number of Charts / Graphs / Tables / Figures Requested	2	**Translation**	Original language of publication
Format (select all that apply)	Electronic	**Copies for the Disabled?**	No
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Duration of Use	Life of current edition	**Incidental Promotional Use?**	No
Lifetime Unit Quantity	Up to 499	**Currency**	USD
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NEW WORK DETAILS

Title	Dynamic Modeling and Predictive Control of a Multi-Mode Combustion Engine	**Institution Name**	Michigan Technological University
Instructor Name	Sadaf Batool	**Expected Presentation Date**	2023-03-20

ADDITIONAL DETAILS

Order Reference Number	Chapter-2_Fig10_11	**The Requesting Person/Organization to Appear on the License**	Sadaf Batool

REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Figure 12 and Figure 13	**Title of the Article/Chapter the Portion Is From**	Dynamic modeling and model predictive control of an RCCI engine
Editor of Portion(s)	Irdmousa, B.K.; Raut, A.; Shahbakhti, M.	**Author of Portion(s)**	Irdmousa, B.K.; Raut, A.; Shahbakhti, M.
Volume of Serial or Monograph	81	**Issue, if Republishing an Article From a Serial**	N/A
Page or Page Range of Portion	129-144	**Publication Date of Portion**	2018-12-01

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Last updated October 2022

Marketplace

Order Date	21-Mar-2023	**Type of Use**	Republish in a thesis/dissertation
Order License ID	1336733-1		
ISSN	0148-7191	**Publisher**	SOCIETY OF AUTOMOTIVE ENGINEERS,
		Portion	Chart/graph/table/figure

LICENSED CONTENT

Publication Title	SAE technical paper series	**Language**	English
Article Title	Managing SI/HCCI Dual-Mode Engine Operation	**Country**	United States of America
		Rightsholder	SAE International
Author/Editor	SOCIETY OF AUTOMOTIVE ENGINEERS.	**Publication Type**	Monographic Series
Date	01/01/1970		

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Lifetime Unit Quantity	Up to 500,000	**Currency**	USD
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NEW WORK DETAILS

Title	Dynamic Modeling and Predictive Control of a Multi-Mode Combustion Engine	**Institution Name**	Michigan Technological University
Instructor Name	Sadaf Batool	**Expected Presentation Date**	2023-03-21

ADDITIONAL DETAILS

Order Reference Number	Chap2_Fig2.15	**The Requesting Person/Organization to Appear on the License**	Sadaf Batool

REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Figure 21	**Title of the Article/Chapter the Portion Is From**	Managing SI/HCCI Dual-Mode Engine Operation
Editor of Portion(s)	Santoso, Halim; Matthews, Jeff; Cheng, Wai K.	**Author of Portion(s)**	Santoso, Halim; Matthews, Jeff; Cheng, Wai K.
Volume of Serial or Monograph	N/A	**Issue, if Republishing an Article From a Serial**	N/A
Page or Page Range of Portion	10	**Publication Date of Portion**	2005-04-11

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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 unlawful, including without limitation if such use would violate applicable sanctions laws or regulations, would be defamatory, violate 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. Any unlawful use will render any licenses hereunder null and void. 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:

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- 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.

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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.

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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.

Last updated October 2022

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Order Date	21-Mar-2023	**Type of Use**	Republish in a thesis/dissertation
Order License ID	1336737-1		
System ID	2007-01-0199	**Publisher**	SAE International
		Portion	Chart/graph/table/figure

LICENSED CONTENT

Publication Title	Study of SI-HCCI-SI Transition on a Port Fuel Injection Engine Equipped with 4VVAS	**Country**	United States of America
		Rightsholder	SAE International
		Publication Type	Report
Author/Editor	Zhang, Yan		
Date	01/01/2007		

REQUEST DETAILS

Portion Type	Chart/graph/table/figure	**Distribution**	Worldwide
Number of Charts / Graphs / Tables / Figures Requested	1	**Translation**	Original language of publication

Format (select all that apply)	Electronic	**Copies for the Disabled?**	No
Who Will Republish the Content?	Academic institution	**Minor Editing Privileges?**	No
Duration of Use	Life of current edition	**Incidental Promotional Use?**	No
Lifetime Unit Quantity	Up to 250,000	**Currency**	USD
Rights Requested	Main product		

NEW WORK DETAILS

Title	Dynamic Modeling and Predictive Control of a Multi-Mode Combustion Engine	**Institution Name**	Michigan Technological University
Instructor Name	Sadaf Batool	**Expected Presentation Date**	2023-03-21

ADDITIONAL DETAILS

Order Reference Number	Chap2_Fig_2.16	**The Requesting Person/Organization to Appear on the License**	Sadaf Batool

REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Figure 11	**Title of the Article/Chapter the Portion Is From**	Study of SI-HCCI-SI Transition on a Port Fuel Injection Engine Equipped with 4VVAS
Editor of Portion(s)	N/A		

Volume of Serial or Monograph	N/A	**Author of Portion(s)**	Zhang, Yan
Page or Page Range of Portion	8	**Issue, if Republishing an Article From a Serial**	N/A
		Publication Date of Portion	2007-01-01

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"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.

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"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

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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. Any unlawful use will render any licenses hereunder null and void. 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.

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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

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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.

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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.

Last updated October 2022

CCC Marketplace

This is a License Agreement between Sadaf Batool ("User") and Copyright Clearance Center, Inc. ("CCC") on behalf of the Rightsholder identified in the order details below. The license consists of the order details, the Marketplace Permissions General Terms and Conditions below, and any Rightsholder Terms and Conditions which are included below.

All payments must be made in full to CCC in accordance with the Marketplace Permissions General Terms and Conditions below.

Order Date	21-Mar-2023	**Type of Use**	Republish in a thesis/dissertation
Order License ID	1336740-2	**Publisher**	SAE International
System ID	2007-01-0195	**Portion**	Chart/graph/table/figure

LICENSED CONTENT

Publication Title	Mode Switch of SI-HCCI Combustion on a GDI Engine	**Country**	United States of America
Author/Editor	Tian, Guohong	**Rightsholder**	SAE International
Date	01/01/2007	**Publication Type**	Report

REQUEST DETAILS

Portion Type	Chart/graph/table/figure	**Distribution**	Worldwide
Number of Charts / Graphs / Tables / Figures Requested	1	**Translation**	Original language of publication
		Copies for the Disabled?	No

Format (select all that apply)	Electronic	**Minor Editing Privileges?**	No
Who Will Republish the Content?	Academic institution	**Incidental Promotional Use?**	No
Duration of Use	Life of current edition	**Currency**	USD
Lifetime Unit Quantity	Up to 500,000		
Rights Requested	Main product		

NEW WORK DETAILS

Title	Dynamic Modeling and Predictive Control of a Multi-Mode Combustion Engine	**Institution Name**	Michigan Technological University
		Expected Presentation Date	2023-03-21
Instructor Name	Sadaf Batool		

ADDITIONAL DETAILS

Order Reference Number	Chap2_Fig_2.18	**The Requesting Person/Organization to Appear on the License**	Sadaf Batool

REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Figure 14	**Title of the Article/Chapter the Portion Is From**	Mode Switch of SI-HCCI Combustion on a GDI Engine
Editor of Portion(s)	N/A	**Author of Portion(s)**	Tian, Guohong

Volume of Serial or Monograph	N/A	**Issue, if Republishing an Article From a Serial**	N/A
Page or Page Range of Portion	9	**Publication Date of Portion**	2007-01-01

Marketplace Permissions 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 unlawful, including without limitation if such use would violate applicable sanctions laws or regulations, would be defamatory, violate 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. Any unlawful use will render any licenses hereunder null and void. 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
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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.

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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:

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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.

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"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.

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

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"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.

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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.

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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:

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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.

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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;

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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.

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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.

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Special Requests > Special Request Details

International journal of engine research

Article: A low-order adaptive engine model for SI?HCCI mode transition control applications with cam...

GENERAL INFORMATION

Request ID	Request Date
600116342	20 Mar 2023
Request Status	**Deny Reason**
Denied	Permission may not be needed for this request

ALL DETAILS

COMMENTS

Add Comment / Attachment

23 Mar 2023 2:20:31 PM, by Publisher Representative

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Order License ID	1339091-1	**Publisher**	ASME; AMERICAN SOCIETY OF MECHANICAL ENGINEERS
ISSN	1528-8919	**Portion**	Chart/graph/table/figure

LICENSED CONTENT

Publication Title	Journal of engineering for gas turbines and power	**Rightsholder**	American Society of Mechanical Engineers ASME
Article Title	Investigation of Cold Starting and Combustion Mode Switching as Methods to Improve Low Load RCCI Operation	**Publication Type**	e-Journal
		Start Page	092802
		Issue	9
Author/Editor	American Society of Mechanical Engineers.	**Volume**	138
Date	01/01/2000	**URL**	http://ojps.aip.org/ASMEJournals/GasTurbinesPower
Language	English		

Country	United States of America

REQUEST DETAILS

Portion Type	Chart/graph/table/figure	Distribution	Worldwide
Number of Charts / Graphs / Tables / Figures Requested	1	Translation	Original language of publication
Format (select all that apply)	Electronic	Copies for the Disabled?	No
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Duration of Use	Life of current edition	Incidental Promotional Use?	No
Lifetime Unit Quantity	Up to 499	Currency	USD
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NEW WORK DETAILS

Title	Dynamic Modeling and Predictive Control of a Multi-Mode Combustion Engine	Institution Name	Michigan Technological University
Instructor Name	Sadaf Batool	Expected Presentation Date	2023-03-20

ADDITIONAL DETAILS

Order Reference Number	Chapter-2_Fig_24

The Requesting Person/Organization to Appear on the License	Sadaf Batool

REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Figure # 10	**Title of the Article/Chapter the Portion Is From**	Investigation of Cold Starting and Combustion Mode Switching as Methods to Improve Low Load RCCI Operation
Editor of Portion(s)	Hanson, Reed; Reitz, Rolf	**Author of Portion(s)**	Hanson, Reed; Reitz, Rolf
Volume of Serial or Monograph	138	**Issue, if Republishing an Article From a Serial**	9
Page or Page Range of Portion	092802	**Publication Date of Portion**	2016-03-22

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ISSN	1528-8919	**Portion**	Chart/graph/table/figure

LICENSED CONTENT

Publication Title	Journal of engineering for gas turbines and power	**Rightsholder**	American Society of Mechanical Engineers ASME
Article Title	Investigation of Cold Starting and Combustion Mode Switching as Methods to Improve Low Load RCCI Operation	**Publication Type**	e-Journal
		Start Page	092802
		Issue	9
Author/Editor	American Society of Mechanical Engineers.	**Volume**	138
Date	01/01/2000	**URL**	http://ojps.aip.org/ASMEJournals/GasTurbinesPower
Language	English		

Country	United States of America

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NEW WORK DETAILS

Title	Dynamic Modeling and Predictive Modeling of a Multi-Mode Combustion Engine	Institution Name	Michigan Technological University
Instructor Name	Sadaf Batool	Expected Presentation Date	2023-03-21

ADDITIONAL DETAILS

Order Reference Number	Chap2_Fig_2.24

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REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Figure 9
Editor of Portion(s)	Hanson, Reed; Reitz, Rolf
Volume of Serial or Monograph	138
Page or Page Range of Portion	092802
Title of the Article/Chapter the Portion Is From	Investigation of Cold Starting and Combustion Mode Switching as Methods to Improve Low Load RCCI Operation
Author of Portion(s)	Hanson, Reed; Reitz, Rolf
Issue, if Republishing an Article From a Serial	9
Publication Date of Portion	2016-03-22

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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 unlawful, including without limitation if such use would violate applicable sanctions laws or regulations, would be defamatory, violate 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. Any unlawful use will render any licenses hereunder null and void. 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

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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.

Last updated October 2022

Marketplace

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Order Date	20-Mar-2023	**Type of Use**	Republish in a thesis/dissertation
Order License ID	1336247-1	**Publisher**	SOCIETY OF AUTOMOTIVE ENGINEERS,
ISSN	0148-7191	**Portion**	Chart/graph/table/figure

LICENSED CONTENT

Publication Title	SAE technical paper series	**Language**	English
Article Title	Towards Model-Based Control of RCCI-CDF Mode-Switching?in Dual Fuel Engines	**Country**	United States of America
		Rightsholder	SAE International
		Publication Type	Monographic Series
Author/Editor	SOCIETY OF AUTOMOTIVE ENGINEERS.		
Date	01/01/1970		

REQUEST DETAILS

Portion Type	Chart/graph/table/figure	**Distribution**	Worldwide

Number of Charts / Graphs / Tables / Figures Requested	1	**Translation**	Original language of publication
Format (select all that apply)	Electronic	**Copies for the Disabled?**	No
Who Will Republish the Content?	Academic institution	**Minor Editing Privileges?**	No
Duration of Use	Life of current edition	**Incidental Promotional Use?**	No
Lifetime Unit Quantity	Up to 499	**Currency**	USD
Rights Requested	Main product		

NEW WORK DETAILS

Title	Dynamic Modeling and Predictive Control of a Multi-Mode Combustion Engine	**Institution Name**	Michigan Technological University
Instructor Name	Sadaf Batool	**Expected Presentation Date**	2023-03-20

ADDITIONAL DETAILS

Order Reference Number	Chapter-2_Fig_25	**The Requesting Person/Organization to Appear on the License**	Sadaf Batool

REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Figure 11	**Title of the Article/Chapter the Portion Is From**	Towards Model-Based Control of RCCI-CDF Mode-Switching?in Dual Fuel Engines
Editor of Portion(s)	Indrajuana, Armando; Bekdemir, Cemil; Feru, Emanuel; Willems, Frank	**Author of Portion(s)**	Indrajuana, Armando; Bekdemir, Cemil; Feru, Emanuel; Willems, Frank
Volume of Serial or Monograph	N/A	**Issue, if Republishing an Article From a Serial**	N/A
Page or Page Range of Portion	7	**Publication Date of Portion**	2018-04-03

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"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.

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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.

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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.

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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.

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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.

Last updated October 2022

CCC Marketplace

This is a License Agreement between Sadaf Batool ("User") and Copyright Clearance Center, Inc. ("CCC") on behalf of the Rightsholder identified in the order details below. The license consists of the order details, the Marketplace Permissions General Terms and Conditions below, and any Rightsholder Terms and Conditions which are included below.

All payments must be made in full to CCC in accordance with the Marketplace Permissions General Terms and Conditions below.

Order Date	20-Mar-2023	Type of Use	Republish in a thesis/dissertation
Order License ID	1336225-2		
ISSN	1946-3952	Publisher	SAE International
		Portion	Chapter/article

LICENSED CONTENT

Publication Title	SAE International journal of fuels and lubricants	Rightsholder	SAE International
		Publication Type	Journal
Article Title	Closed-Loop Predictive Control of a Multi-mode Engine Including Homogeneous Charge Compression Ignition, Partially Premixed Charge Compression Ignition, and Reactivity Controlled Compression Ignition Modes	Start Page	15
		End Page	36
		Issue	1
		Volume	16
Author/Editor	Society of Automotive Engineers.		

Date	01/01/2009
Language	English
Country	United States of America

REQUEST DETAILS

Portion Type	Chapter/article	**Rights Requested**	Main product
Page Range(s)	15-36	**Distribution**	Worldwide
Total Number of Pages	22	**Translation**	Original language of publication
Format (select all that apply)	Print, Electronic	**Copies for the Disabled?**	No
Who Will Republish the Content?	Academic institution	**Minor Editing Privileges?**	No
Duration of Use	Life of current edition	**Incidental Promotional Use?**	No
Lifetime Unit Quantity	More than 2,000,000	**Currency**	USD

NEW WORK DETAILS

Title	Dynamic Modeling and Predictive Control of a Multi-Mode Combustion Engine	**Institution Name**	Michigan Technological University
Instructor Name	Sadaf Batool	**Expected Presentation Date**	2023-03-20

ADDITIONAL DETAILS

Order Reference Number	Chapter-3

The Requesting Person/Organization to Appear on the License	Sadaf Batool

REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Closed-Loop Predictive Control of a Multi-mode Engine Including Homogeneous Charge Compression Ignition, Partially Premixed Charge Compression Ignition, and Reactivity Controlled Compression Ignition Modes	**Title of the Article/Chapter the Portion Is From**	Closed-Loop Predictive Control of a Multi-mode Engine Including Homogeneous Charge Compression Ignition, Partially Premixed Charge Compression Ignition, and Reactivity Controlled Compression Ignition Modes
Editor of Portion(s)	Batool, Sadaf; Naber, Jeffrey; Shahbakhti, Mahdi	**Author of Portion(s)**	Batool, Sadaf; Naber, Jeffrey; Shahbakhti, Mahdi
Volume of Serial or Monograph	16	**Issue, if Republishing an Article From a Serial**	1
Page or Page Range of Portion	15-36	**Publication Date of Portion**	2022-10-20

Marketplace Permissions 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 unlawful, including without limitation if such use would violate applicable sanctions laws or regulations, would be defamatory, violate 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. Any unlawful use will render any licenses hereunder null and void. 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:

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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:

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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).

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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;

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Last updated October 2022

Michigan Tech

Sadaf Batool <batool@mtu.edu>

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