

# **Reactivity controlled compression ignition engine: pathways towards commercial viability**

Amin Paykani<sup>1</sup>, Antonio Garcia<sup>2</sup>, Mahdi Shahbakhti<sup>3</sup>, Pourya Rahnama<sup>4</sup>, Rolf D. Reitz<sup>5</sup>

<sup>1</sup>*School of Physics, Engineering and Computer Science, University of Hertfordshire, Hatfield, UK*

<sup>2</sup>*CMT – Motores Térmicos, Universitat Politècnica de València, Camino de Vera s/n, 46022  
Valencia, Spain*

<sup>3</sup>*Mechanical Engineering Department, University of Alberta, Edmonton, T6G 1H9, Canada*

<sup>4</sup>*Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven,  
Netherlands*

<sup>5</sup>*Engine Research Center, University of Wisconsin-Madison, Madison, WI, USA*

## **Abstract**

Reactivity-controlled compression ignition (RCCI) is a promising energy conversion strategy to increase fuel efficiency and reduce nitrogen oxide (NO<sub>x</sub>) and soot emissions through improved in-cylinder combustion process. Considering the significant amount of conducted research and development on RCCI concept, the majority of the work has been performed under steady-state conditions. However, most thermal propulsion systems in transportation applications require operation under transient conditions. In the RCCI concept, it is crucial to investigate transient behavior over entire load conditions in order to minimize the engine-out emissions and meet new real driving emissions (RDE) legislation. This would help further close the gap between steady-state and transient operation in order to implement the RCCI concept into mass production. This work provides a comprehensive review of the performance and emissions analyses of the RCCI engines with the consideration of transient effects and vehicular applications. For this purpose, various simulation and experimental studies have been reviewed implementing different control strategies like control-oriented models particularly in dual-mode operating conditions. In addition, the application of the RCCI strategy in hybrid electric vehicle platforms using renewable fuels is also discussed. The discussion of the present review paper provides important insights for future research on the RCCI concept as a commercially viable energy conversion strategy for automotive applications.

**Keywords:** Reactivity controlled compression ignition (RCCI); control; performance; emissions; transient behavior; hybrid vehicles

## Nomenclature

AHRR	Apparent heat release rate
ATDC	After top dead center
BMEP	Brake mean effective pressure
BTE	Brake thermal efficiency
BEV	Battery electric vehicle
CAD	Crank angle degree
CDC	Conventional diesel combustion
CDF	Conventional dual fuel
CFD	Computational fluid dynamics
CI	Compression ignition
CL	Close loop
CNG	Compressed natural gas
CO	Carbon monoxide
COM	Control-oriented model
COV	Coefficient of variation
CPBC	Cylinder pressure-based control
DF	Dual fuel
DI	Direct injection
DISI	Direct injection spark ignition
DMDF	Dual mode dual fuel
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EGR	Exhaust gas recirculation
EHN	Ethylhexyl nitrate
EPA	Environmental protection agency
ERC	Engine research center
FPGA	Field programmable gate arrays
GDI	Gasoline direct injecton
GHG	Greenhouse gas emissions
GIE	Gross indicated efficiency
HCCI	Homogenous charge compression ignition
HD	Heavy-duty
HEV	Hybrid electric vehicle
HWFET	Highway fuel economy test
HRR	Heat release rate
ICE	Internal combustion engine
IMEP	Indicated mean effective pressure

ITE	Indicated thermal efficiency
IVC	Inlet valve closing
LCA	Life cycle analysis
LQI	Linear quadratic integral
LTC	Low temperature combustion
LD	Light duty
MHEV	Mild hybrid electric vehicle
MIMO	Multiple input multiple output
MPC	Model predictive control
MTU	Michigan technological university
NG	Natural gas
NO <sub>x</sub>	Nitrogen oxides
NMOG	Non-methane organic gases
OL	Open loop
OEM	Original equipment manufacturer
PFI	Port fuel injection
PFR	Premixed fuel ratio
PHEV	Plug-in hybrid electric vehicle
PID	Proportional integral derivative
PM	Particulate matter
PRR	Pressure rise rate
RCCI	Reactivity controlled compression ignition
RDE	Real driving emissions
SAE	Society of Automotive Engineers
SCR	Selective catalytic reaction
SI	Spark ignition
SOC	Start of combustion
SOI	Start of injection
UDDS	Urban dynamometer driving schedule
UHC	Unburned hydrocarbons
ULSD	Ultra-low sulfur diesel
WHTC	World harmonized transient cycle
WTW	Well-to-wheel

## 1. Introduction

Concerns on greenhouse gas emissions (GHGs), combustion generated pollutant emissions and energy security are having a considerable impact on the future development of internal combustion (IC) engines, and have led to investigations of advanced combustion strategies as well as alternative hybrid propulsion systems for automotive applications [1, 2]. Low temperature combustion (LTC) strategies such as homogeneous charge compression ignition (HCCI) [3] and reactivity controlled compression ignition (RCCI) [4] have the potential to achieve simultaneously low emissions of both nitrogen oxides (NO<sub>x</sub>) and particulate matter (PM), while maintaining high thermal efficiencies [5, 6]. RCCI combustion has been introduced to address the drawbacks of the HCCI strategy in terms of limited operating range, low combustion control and excessive unburned products [7, 8]. In RCCI combustion, a low reactivity fuel like gasoline was premixed through port and a high reactivity fuel like diesel is directly injected into the cylinder; thus, it is possible to achieve more efficient control of ignition timing and combustion rate by changing the ratio of the two fuels with different reactivities [9, 10]. Therefore, RCCI is a fuel-flexible combustion strategy and has the potential to use various combinations of gasoline and diesel-like fuels particularly produced from renewable resources with low carbon footprint [11, 12].

Regardless of the benefits of RCCI strategy, its operation is restricted to engine medium loads [13, 14], due to the high carbon monoxide (CO) and unburned hydrocarbons (UHC) emissions at low engine load operation, and high pressure rise rates (PRR) at high loads which still need to be addressed [15]. Thus, to extend the operating range, solutions have been proposed such as mode-switching to utilize RCCI concept in practical applications [16]. By operating conventional dual fuel engines in RCCI mode, the thermal efficiency of the engine can be further increased while at the same time pollutant emissions can be reduced. On the other hand, RCCI combustion with lower gas temperatures compared to conventional diesel

combustion (CDC), results in lower heat losses and higher fuel conversion efficiencies, and due to the sensitivity of reactions to thermal and chemical composition of air-fuel mixtures, combustion control of RCCI engines is a major challenge during transient operations.

The literature has shown that engine performance under steady-state conditions is not generally a true indicator of transient emissions [17, 18], since significant amount of the total emissions are produced during the short periods when rapid speed/load changes happen [11, 15]. Considering the significant amount of conducted research and development of RCCI combustion, the majority of the work has been performed under steady-state conditions [19, 20]. However, for transportation applications, RCCI concept requires operation under transient conditions, since robust performance for a wide variety of operating conditions is key to real-world application.

Unlike HCCI combustion, combustion phasing (indicated by CA50, i.e., crank angle of 50% cumulative heat release) and indicated mean effective pressure (IMEP) can be controlled in RCCI strategy [21]. An overview of different RCCI control studies is given in [22], and the following challenges have been determined on the control side associated with RCCI combustion:

- **Stable and safe combustion:** At low load, misfire must be avoided, while at high loads peak pressure and peak pressure rise rate limits must be mitigated. RCCI combustion has high sensitivity to parameters controlling the mixing of low- and high-reactive fuels. Output work, peak pressure and engine-out emissions can also change due to variations in the EGR ratio, or variations in injection parameters due to wear of the components. Individual cylinder control of fueling parameters is therefore used to cope with these effects and achieve optimal efficiency for all cylinders. Cylinder balance can be realized by controlling all individual cylinders in parallel [23]. The intra-cycle

differences as well as the inter-cylinder differences can be significantly decreased with feedback control, resulting in an improved load operating range.

- **Precise air-fuel path control:** In order to achieve the required dynamic in-cylinder conditions, highly dynamic fuel path control with robust stability and precise air path control are necessary. This control of coordinated air-fuel path also benefits integrated engine-aftertreatment control in order to achieve potential targets for HC and CO emissions, for mode switching and optimum thermal management [24-26].
- **Handling alternative fuel combinations:** RCCI combustion has the potential to be flexi-fuel and various fuels can be used. A prerequisite for this is the use of two fuels with quite different auto-ignition properties. Fueling is adjusted with feedback control to influence the auto-ignition cycle and compensate for fuel auto-ignition properties that diverge from requirements due to changes in fuel composition at various conditions. This must eventually be endorsed for a wide variety of fuels; so-called fuel flexibility [22, 27].

While initial RCCI studies were encouraging, further improvements have been undertaken to assess its ability to achieve future emissions reduction and assess its commercialization in automotive, stationary and marine applications (using natural gas-diesel for mid-speed marine engines) [28, 29]. These developments are supported by new, single-fuel operation [30-32], optimized combustion system [33], variable valve timing [34], and new aftertreatment technologies [35, 36]. RCCI combustion engines not only are useful in mobile applications but also they can be used in stationary applications such as power generator, particularly in hybrid configuration combined with fuel cells [37] and electric motors [38].

Although, there are several published review papers on RCCI combustion in the literature [15, 19, 39], they have paid less attention to cover the transient behavior, thus there is still need

for a dedicated review paper to bridge the gap and address combustion control for commercialization of this concept in future thermal propulsion systems. Additionally, there have been quite considerable amount of published work in the literature addressing the combustion control and transient behavior of RCCI strategy taking into account main RCCI state operating constraints like in-cylinder PRR limit, peak in-cylinder pressure limit, maximum allowed engine-out emission limits, and combustion stability limit ( $COV_{IMEP}$ ). The objective of the present paper is to provide a comprehensive review on performance and emissions of the RCCI combustion with consideration of transient effects, as well as its vehicular applications particularly in hybrid electric vehicle (HEV) configurations. For this purpose, various experimental and simulation studies for RCCI combustion control, combustion mode-switching to extend operating range, the effects of alternative fuels in transient operation, and RCCI engine in hybrid electric configurations have been reviewed. Concluding remarks with promising future research directions for commercial viability of RCCI combustion are provided.

## **2. RCCI transient operation**

While majority of vehicles operate under transient conditions, most of the engine research work has been carried out under steady-state conditions, since transient testing needs specialized and often costly equipment [40, 41]. There are also significant variations in emissions of the engines reported in the literature for various test cycles under transient operation. Swain et al. [18], for example, reported that 60% of the under-predicted HC and PM emissions could occur during transient diesel engine operation. These findings are crucial, because the RCCI strategy has also been developed with most of the data in the steady-state operating conditions, and for on-road applications, robust performance has to be guaranteed under real-world conditions, including engine speed-load transients, varying fuel quality and varying ambient conditions.

A comprehensive study was conducted by Glewen et al. [42] in a light duty diesel engine to investigate transient behavior of LTC and CDC strategies. It was noticed that there are significant differences for all load transitions between transient and steady-state emissions and combustion noise. The results of the transient tests were compared with measurements conducted at the same speed and fuel rate during steady-state operation to identify variations in control parameters and subsequent engine efficiency between transient and steady-state operation. Eventually, it was found that the thermal inertia of the engine components can influence the transient emissions as the volumetric efficiency, NO<sub>x</sub> and HC emissions can be changed when working at different temperatures from the steady-state conditions.

Compared to very early injection strategies associated with HCCI, controllability of the combustion process is significantly improved in RCCI, but still requires attention to phase correctly. Due to controllability challenge, RCCI concept drove the research community to develop advanced control strategies. The techniques adopted for controlling combustion in RCCI engines play a key role in addressing current and future automotive industry requirements for propulsion systems. The conventional open-loop (OL) control technique attempts to achieve a desired combustion behavior by controlling the system boundary conditions, indirectly, with the goal of achieving an optimal trade-off between engine emissions, combustion noise, drivability performance, etc. In order to gain accurate control over engine with great margins of safety, close-loop (CL) combustion control, primarily based on in-cylinder pressure signals have been introduced [43]. CL control of the ignition delay is key, since this LTC concept is significantly affected by inevitable differences in temperature or EGR variations between cylinders. So far, OL control systems based on calibration maps designed for a specific set of operating conditions have been frequently used to date, rather than CL control strategies. The cost and complexity of these calibration maps, however, are rapidly becoming unacceptable, and CL control systems also seem crucial for further increases

in fuel conversion efficiency [44]. First fundamental studies on RCCI transient performance comparing OL and CL phasing control methods were carried out by Hanson [45] in a light duty diesel engine at engine research center (ERC) of University of Wisconsin-Madison. Fig. 1 illustrates the test engine schematically.

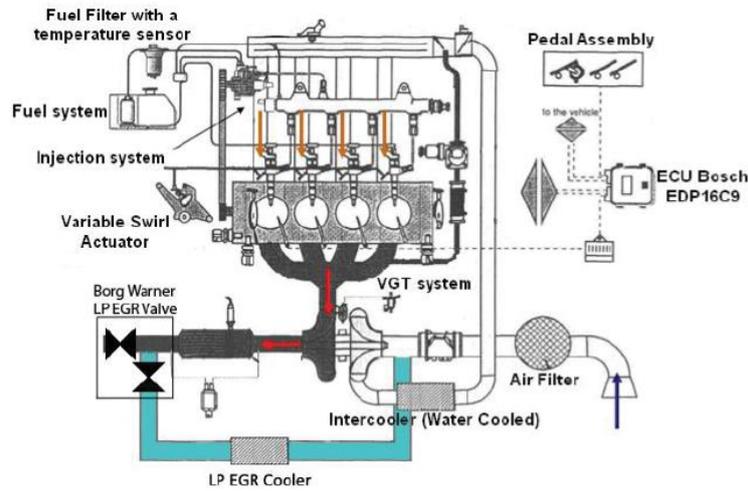


Fig. 1. RCCI engine test setup configuration (Reprinted from [45] with the permission of Author)

OL and CL phasing control methods for engine combustion were utilized for RCCI whereas CDC was only controlled in OL. The controller worked with 2D torque-based tables to control the EGR, intake pressure and fuel injection parameters. The controller had tables loaded with CDC values reflecting the OEM 2005 EURO IV calibration in steady-state condition. Additional tables were included for RCCI operation to control the gasoline port fuel injection (PFI) system. Then, these tables were recalibrated at a steady-state with appropriate RCCI values to provide the optimal combustion phasing and emissions. A simulated pedal accelerator was provided to the controller to run the engine. From this current engine speed and pedal position command, the interpolated table value was utilized for the correct engine control parameter, such as duration of the PFI or target pressure of the intake manifold.

The same torque-based controller was used for CL RCCI operation, with additional code to control the cycle-by-cycle combustion phasing. A proportional integral derivative (PID) controller was used for CL operation to control phasing of the combustion. The PID method was first used by Olsson et al. [21] for CL control of an HCCI engine, and discussed in detail in Refs. [46-48]. In the RCCI tests, CA50 was determined from the cylinder #2 pressure trace of each cycle using CL control and was compared to a target value from a 2D table. The RCCI CL controller changes the PFI ratio on a cycle-by-cycle basis by changing the duration commands for gasoline PFI and diesel direct injection (DI) to advance or delay CA50 as necessary to meet the target value.

The RCCI combustion controlled by OL and CL was compared with the OL CDC in a 1-4 bar brake mean effective pressure (BMEP) change of load at 1500 rpm [46]. Both combustion modes used similar intake conditions but the RCCI experiments did not use EGR. The CDC mode used a calibration of the EURO IV method of fuel injection, while the RCCI mode was calibrated using best practices from previous experiments on steady-state operation. Fig. 2 illustrates the BMEP as an engine cycle function for three specific transient modes of testing. It can be observed that load increase from 1 to 4 bar BMEP with RCCI taking roughly 80 cycles to close 4 bar. It was due to either low wall temperatures while operating at low loads and then transitioning to high loads, or to a lack of PFI enrichment during the transient operation. Fig. 3 depicts comparison of RCCI OL and CL and CDC emission performance; As can be predicted from a CDC engine, and also based on Glewen et al.'s [42] observations, HC emissions are small and PM and NO are relatively high. By having lower NO and PM with higher HC, RCCI emissions are distinct from the CDC performance. It is also obvious here that the CL controller operated and improved engine performance. The reason of the HC spike was not completely clear, but it was attributed to the cooler cylinder walls from running at low load or lack of PFI

enrichment. From OL to CL, NO and PM emissions were very similar as the charge is well-mixed and the small shift in CA50 did not affect them as much as it did for the HC emissions.

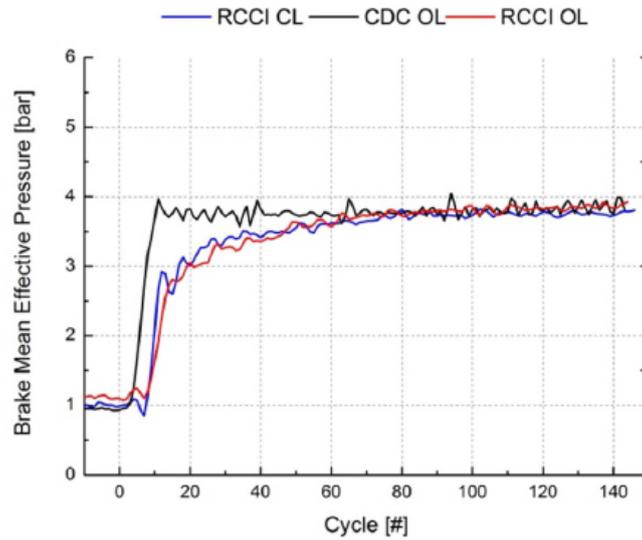


Fig. 2. RCCI OL and CL control and CDC BMEP over the step load transient (Reprinted from [46] with the permission of SAE)

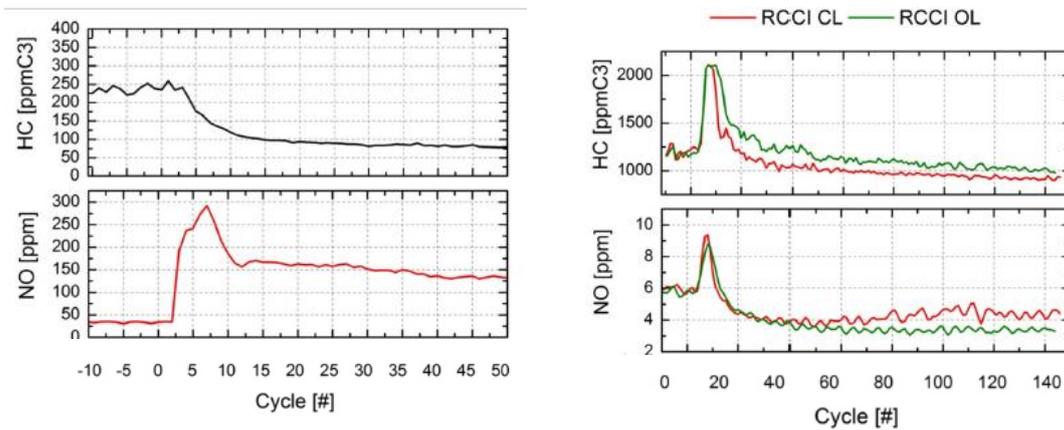


Fig. 3. CDC OL and RCCI OL and CL emissions performance (Reprinted from [46] with the permission of SAE)

Hanson and Reitz [46] also noticed that the engine was capable of operating with RCCI combustion with lower PM and NO emissions, but higher HC and CO emissions than CDC over the defined transient engine operating conditions using either OL or CL combustion

phasing feedback control. Later, they carried out the transient combustion of RCCI and CDC with the effects of emissions over an speed variation from 1000 to 2000 rpm [49] and from 2000 to 1000 rpm at constant BMEP load of 2.0 bar. It was shown that the engine can be controlled using RCCI combustion under transient engine speed operation. Overall conclusion was that transient RCCI operation of the engine speed was possible with either an OL or a CL controller. In addition, RCCI was able to operate with EGR, airflow rate, intake temperature, engine speed, intake pressure and pedal position in a wide range of operating conditions.

From the findings reviewed in this section, it was noticed that it is possible to operate the engine in the RCCI mode over a transient load step change without significant issues, and RCCI operation with a quite simple OL steady-state controller was possible over transient conditions. The addition of a CL controller can lower the HC emissions seen during the RCCI transient event.

### **3. RCCI combustion Control**

A lot of research work has been conducted over the last two decades on engine combustion control. These studies usually concentrate on a single combustion concept and use cylinder pressure as the primary feedback variable [43, 50]. Precise control of combustion in RCCI engines can have significant results on the performance and thermal efficiency of the engine. Prior works on RCCI combustion controller design fall into two categories based on the platform for controller implementation and testing. The first category includes RCCI controllers using high fidelity RCCI models such as control-oriented models to verify controller performance, while the second category included controllers validated on a real RCCI engine as shown in Fig. 4.

Among simulation studies, Wu et al. [51] used an experimentally validated GT-Power model to establish a technique for combustion phasing control during load transitions of a multi-cylinder RCCI engine. The engine was given a step change in the pedal command and

worked to accomplish the load changes without any CL feedback. The load transition period was 50 cycles, and it involved a transient load-up and load-down of 1 bar to 4 bar BMEP at 1500 rpm. Six load-up cycles and seven load-down cycles were chosen to reflect the entire transition phase. The PFI ratio was used as a control parameter for raising the CA50 differences caused by the pressure lag of the intake manifold. By changing the PFI ratio, the CA50 can be predicted at various PFI ratios for each cycle, as illustrated in Fig. 5. The horizontal lines in the indicate the optimal CA50 for load-up and load-down transitions, accordingly. The cumulative amount of fuel from cycle 2 to cycle 50 is nearly doubled compared with the quantity of steady-state fuel at cycle 0. The cycles from cycle 0 to cycle 30 have identical IVC temperatures for the 4 bar to 1 bar BMEP transition, while the IVC temperature at cycle 50 is about 30 degrees lower, and the overall fuel quantity from cycle 2 to cycle 50 is around half the steady-state fuel quantity at cycle 0. The combustion phasing is retarded during the load-down process, while the fuel quantity falls from 12.6 mg/cycle at cycle 0 to 6.54 mg/cycle at cycle 2.

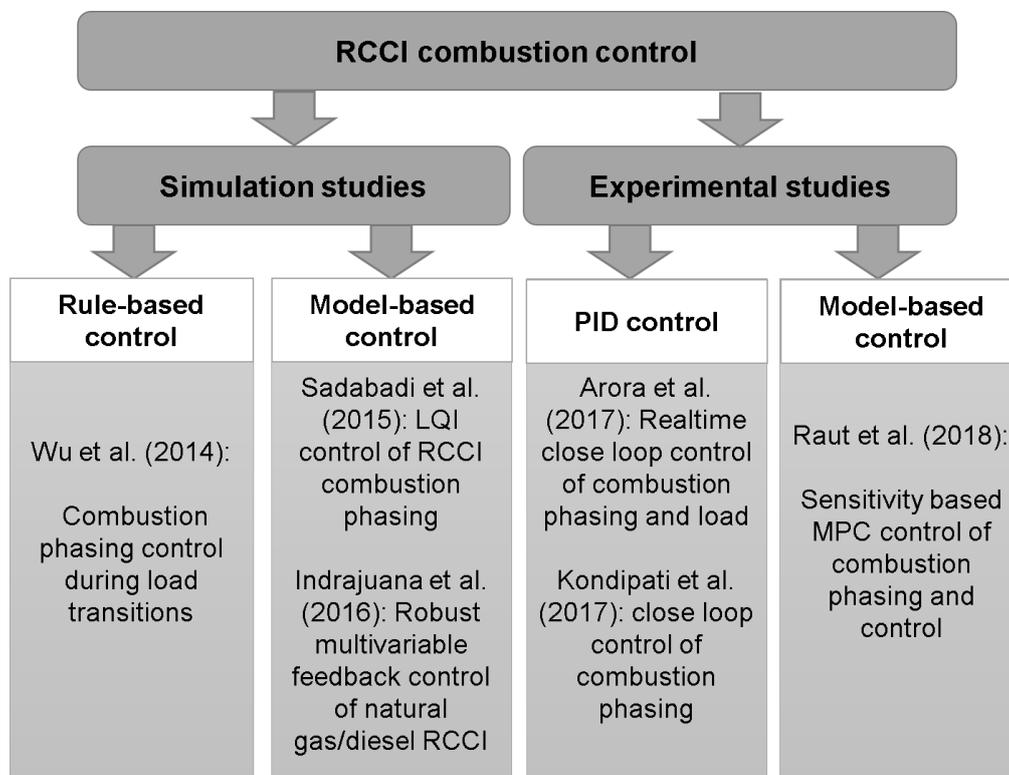


Fig. 4. Overview of previous RCCI combustion control studies [47, 48, 51-54].

It can be seen in Fig. 5 that during the load-up transition from cycle 0 to cycle 44 has similar CA50 at the same PFI ratio while the overall fuel quantity at cycle 0 is half the value of next cycles. The additional modeling results indicated that CA50 was retarded by 7 to 15 degrees during the transition for the load-up phase if the pre-calibrated steady-state PFI table was employed the lower intake pressure compared with the fuel system's rapid response. The findings implied that the proposed control strategy can be used for CL control during engine transient operating conditions.

Combustion phasing and heat release control are crucial for advanced combustion strategies such as RCCI to guarantee reliable and safe operation. Additionally, CL control of the ignition delay is also important, as RCCI combustion is strongly influenced by temperature or EGR variations between cylinders. Therefore, RCCI would need additional controls to suit the CDC load output including model-based control to compensate for the temperature of the combustion chamber wall and transient effects of PFI fueling.

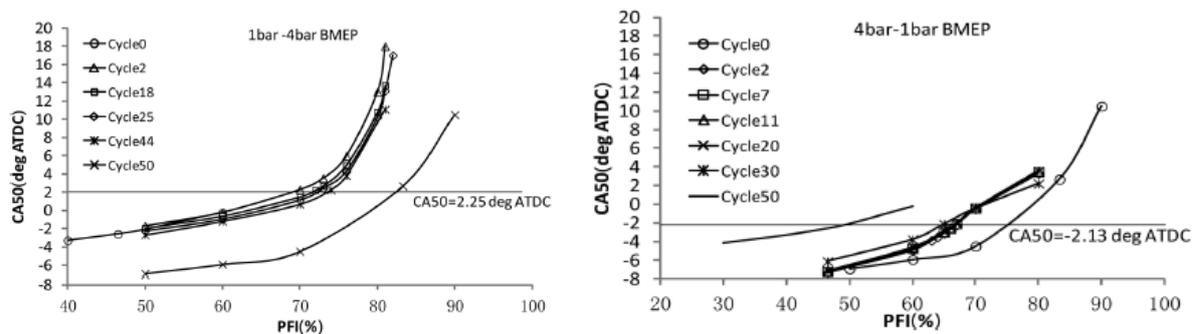


Fig. 5. Simulation results of CA50 during the engine transient at various PFI ratios for each cycle (Reprinted from [51] with the permission of ASME)

Researchers at Michigan Technological University (MTU) developed the first validated physics-based control-oriented model (COM) for RCCI combustion considering transient engine operation [52, 55]. A mean value COM of RCCI was built by integrating an auto-ignition model, a burn duration model, and a Wiebe function to predict the combustion phasing.

The COM was parameterized and validated using simulation data from an experimentally validated, comprehensive CFD combustion model developed in KIVA-3V code. The findings indicated that the COM can estimate the SOC, burn duration and CA50 with an average error of less than 2 crank angle degrees. In addition, a dynamic mean value COM was developed for modelling RCCI engine operation on a cycle-to-cycle basis. This model was then simplified and linearized around a stable operating point of the engine. A Linear Quadratic Integral (LQI) was designed to control the combustion phasing of the RCCI engine by modulating the premixed fuel ratio (PFR). The linearized COM is then used to design an observer based LQI controller to track a desired CA50 trajectory. The state-feedback controller regulates the CA50 at its desired value, while the integral component of the controller removes the steady-state error in the tracking process. It also assists in rejecting any disturbances in engine operation, including temperature and fueling variations ( $\varphi$ ). The structure of the observer-based LQI controller is shown in Fig. 6.

The quantitative metrics corresponding to the controller performance are given in Table 1. Due to the model mismatch between the linearized COM and the physical model of the engine, some level of steady state error ( $e_{ss}$ ) was noticed. However, as the model was augmented and its order was increased by the addition of the integral controller, this  $e_{ss}$  was successfully reduced to zero, thus significantly improving the controller performance. Other characteristics of the controller such as settling time ( $t_s$ ), rise time ( $t_r$ ), and maximum overshoot demonstrated fast and accurate controller performance. Moreover, a state observer was developed to estimate the states of the engine, as they are not measurable during the operation of the engine. Furthermore, the performance of the observer was examined during the transient operation of the engine, which exhibited accurate estimation of the states.

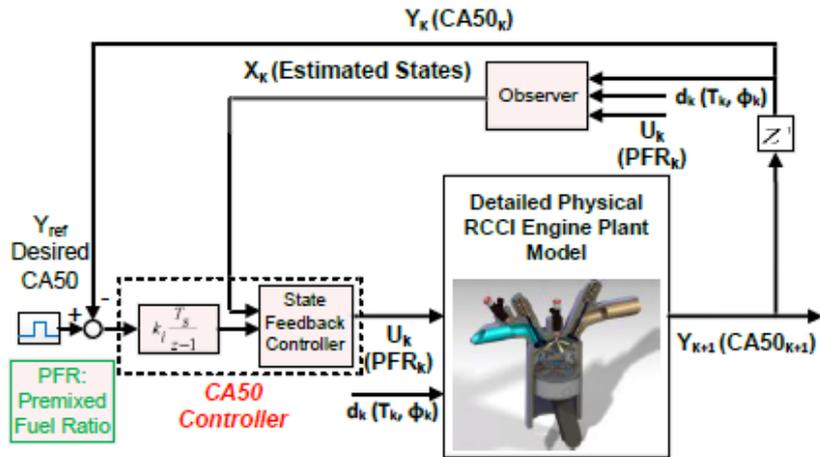


Fig. 6. Schematic of designed RCCI combustion phasing controller at MTU (Reprinted from [52] with the permission of ASME)

Table 1. Tracking performance of the controller (Reprinted from [52] with the permission of ASME)

Controller performance metric	value
Maximum overshoot	0.4 CAD
Rise time ( $t_r$ )	3 Cycles
Settling time ( $t_s$ )	6 Cycles
Steady state error ( $e_{ss}$ )	0 CAD

Later, Indrajuna et al. [53] proposed a multiple input multiple output (MIMO) feedback control strategy using a combination of control parameters including ignition delay, IMEP and premixed ratio on a multi-zone model for natural gas/diesel RCCI combustion (see Fig. 7). The cycle-to-cycle monitoring technique utilizes diesel injection timing, quantity of diesel and natural gas fuels to monitor the desired engine load, ignition delay, and mixture ratio. They showed that the robust and stable performance of the proposed control strategy for simulated disturbance rejection and reference monitoring situations, although it has the potential to reduce interaction between the controlled variables.

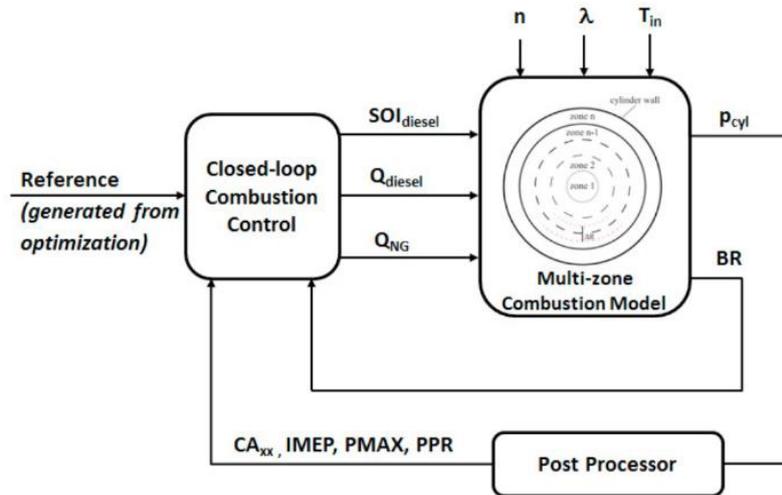


Fig. 7. Combustion control with CL for multi-zone combustion model (Reprinted from [53]

with the permission of Elsevier)

A COM-based model was developed by Guardiola et al. [56] based on physical equations, which aimed to predict the SOC and the CA50 in RCCI combustion using a modified knock integral model taking into account the fuel blending ratio of both fuels. The model was optimized and validated using experimental data from a heavy-duty engine that showed good results in transient operation. Fig. 8 Shows the results obtained for the calculation of SOC and CA50 of many cycles from various operating conditions. The model showed good results in the CA50 estimation with an average error of  $\pm 0.43$  CAD.

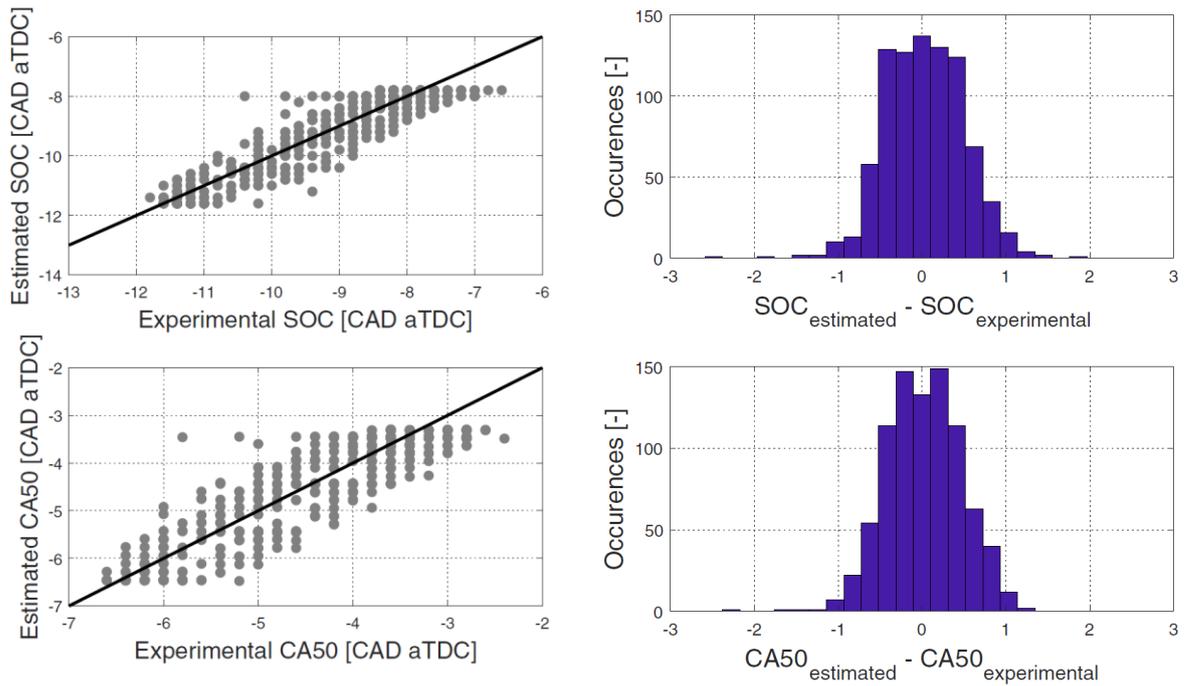


Fig. 8. SOC and CA50 estimation and error distribution from the COM against experimental values from tests used for calibration (Reprinted from [56] with the permission of Elsevier)

The reviewed papers here show that the proposed models provide a fast and reliable route to identify an RCCI engine model, and to design a model predictive controller to control CA50 for varying engine conditions. The experimental results also demonstrated that the designed controllers can follow the desired CA50. The availability of in-cylinder pressure sensors started a new era in engine control. With these sensors, more detailed information of the in-cylinder process became available. A literature study [57] shows that cylinder pressure-based control (CPBC) is a key enabler for principles of ultra-high performance and clean combustion in RCCI strategy. In addition, CPBC has shown to minimize the calibration effort and increase the robustness of operation for all combustion principles. We also need to have better understanding of self-learning control capabilities and coordinated air-fuel path control for in-cycle control of the HRR shape to fully leverage the CPBC potential.

Second category of RCCI combustion controllers design includes studies with RCCI controller implementation on an experimental engine setup. Real-time RCCI control during engine load and transient speed operation is difficult, since RCCI combustion phasing depends on nonlinear thermo-kinetic reactions controlled by reactivity gradients of the fuels. There are multiple control variables (e.g., PR, SOI, DI fuel split ratio) that can be used to control combustion phasing. The model-based control of RCCI combustion phasing is a great tool for real-time control during transient operation of the engine, which requires a computationally efficient combustion model that encompasses factors such as, injection timings, fuel blend composition and reactivity.

Bekdemir et al. [58] initially proposed a multi-zone model in a heavy-duty natural gas/diesel RCCI engine to explain the auto-ignition process and predict the in-cylinder pressure. After validation, the model was used to create a real-time, map-based control which was then applied in a CL controller, based on PID behavior on the amounts of gas and diesel injected, but also on the timing of diesel injection. The resulting 5-dimensional map describes the dependency of engine outputs (NO<sub>x</sub> emissions, IMEP, CA50, P<sub>MAX</sub>, and PPR) on control inputs (SOI, diesel mass flow, and NG mass flow). Furthermore, the effect of disturbances in intake conditions, such as intake manifold pressure and temperature, on combustion and engine performance can be examined. This combustion model was capable to be embedded in the existing air path model, as illustrated in Fig. 9.

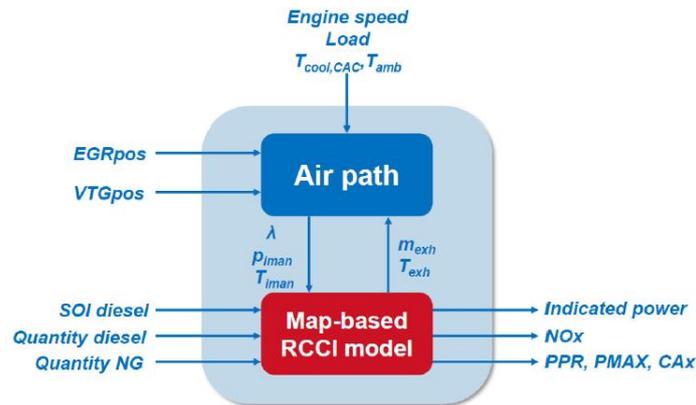


Fig. 9. Control-oriented NG-diesel RCCI model (Reprinted from [58] with the permission of SAE).

RCCI combustion strategy enhances the demands on feedback combustion control, and economic considerations impose the use of low-end control hardware limiting implementation options. Significant development has been carried out within the field of Field Programmable Gate Arrays (FPGAs) in recent years, since they are a type of flexible devices in performance and cost sensitive applications. Arora and Shahbakhti [47] developed new algorithms for combustion phasing calculations and real-time in-cylinder pressure analysis and implemented a FPGA to measure cycle-by-cycle RCCI combustion and efficiency metrics. Such cycle-by-cycle data is then utilized as a feedback to the controller for combustion, which is applied on a real-time processor. The designed RCCI controller changes CA50 and IMEP at the same time during transient engine operations. To control CA50, either start of injection (SOI) timing of high reactive fuel or premixed ratio (PR) was used. The results showed that the designed RCCI controller can maintain desired CA50 during engine load transients and also reach to a desired IMEP within 2-4 engine cycles. As is evident from Fig. 10, for the lower load area (i.e., IMEP = 450 kPa), SOI differs for controlling CA50 in that operating range. Likewise, PR is used to control CA50 for the higher load, where higher PR and advanced SOI are needed. For the test run 2 which takes place at 1300 rpm a similar approach was used. Both experimental runs indicate that the controller is particularly able to retain the optimum CA50 particularly during

the load switch. It takes about 2-4 engine cycles for IMEP monitoring to achieve the desired value. This lag is largely due to the transient fueling response of the low pressure PFI rail. Finally, the results of the experimental validation indicated that the built RCCI controller can sustain required CA50 during transient engine load and also achieve a desired IMEP within 2-4 engine cycles. In another study, Kondipati et al. [48] developed a new PI controller for an RCCI engine and used a physics-based model to tune the PI controller. Their experimental results proved controller capability to reach desired CA50 in 2–3 engine cycles with an average tracking error of 1 CAD.

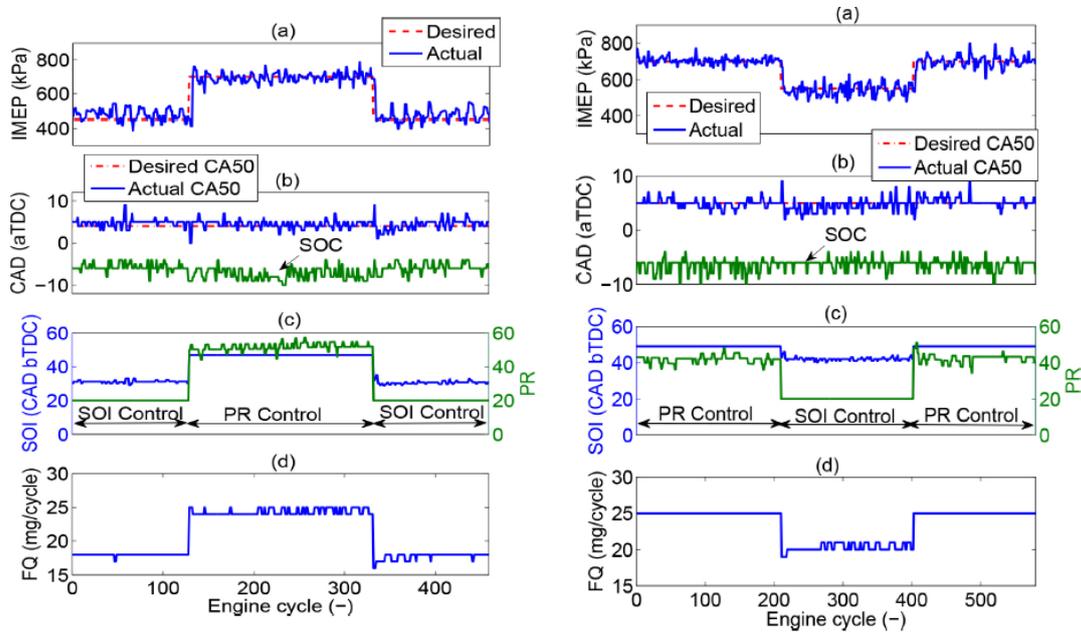


Fig. 10. Test results for controller at intake air temperature: 60°C and pressure: 95 kPa; left: Run 1. n: 1000 rpm, target CA50: 4 CAD ATDC; right: Run 2. n: 1300 rpm, target CA50 : 5 CAD ATDC (Reprinted from [47] with the permission of SAE)

Apart from PID method to control combustion [47, 48], COM is another strategy to model combustion of the engine, which consists of determining the combustion physical process while maintaining a fast computational time, making it suitable for real-time control applications [59-61]. To adjust the combustion phasing of an RCCI engine, COM approaches and model

predictive controller have been recently developed [62]. Raut et al. [54, 63] employed a model-based approach for dynamic modelling and predictive model control of an RCCI combustion system. A Xilinx Spartan-6 FPGA, with a clock speed of 80MHz and a memory of 4824 kB, was designed for real-time simulations of combustion metrics such as CA50, IMEP, HRR and SOC to allow cycle-to-cycle combustion control. The combustion metrics were then inserted into the MABX's real-time processor board, where the controller was embedded. There were two categories of experiments, including steady-state and transient. Results were recorded for 300 engine cycles for the transient tests, which included PR changes (defined as the ratio of isoctane energy to total fuel energy) and SOI. The transient experiments were used to determine the RCCI model for CA50 and IMEP predictions. Data for 100 engine cycles were also recorded for a steady-state data point analysis of the combustion. The experiments were performed at a constant speed of 1000 rpm and a constant intake temperature of 60<sup>0</sup> C. A fuel quantity (FQ) sweep was performed for various combinations of PR and SOI. Combustion stability is defined using a common parameter which is widely used in the literature, i.e., coefficient of variation of IMEP ( $COV_{IMEP}$ ) and calculated by:

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{\mu_{IMEP}} \quad (1)$$

Where  $\sigma_{IMEP}$  and  $\mu_{IMEP}$  are the standard deviation and mean of  $IMEP$ , respectively. In this analysis  $COV_{IMEP}$  was measured for steady-state tests over 50 engine cycles and it was calculated over 10 engine cycles for transient operation. Fig. 11 depicts the proposed RCCI combustion controller structure at MTU. The running constraints of the RCCI engine included the maximum permissible PRR ( $\leq 8$  bar/CAD), permissible peak in-cylinder pressure ( $\leq 65$  bar) and combustion stability ( $COV_{IMEP} \leq 5\%$ ) were all considered during the creation of the engine map that is part of the designed controller structure. The engine map gives feedforward values of PR, SOI and CA50 based on the required load and current engine speed. Either SOI or PR

control was applied on the basis of the sensitivity values. Next, switched MPC controllers change CA50 and IMEP to the desired values. Additionally, in the control structure, a fuel compensator was designed and implemented to account for the dynamics of fuel transport due to PFI injections, especially when the PR changes. The CA50 and IMEP were the only measurable system states. The built MPC requires complete state feedback; therefore, an observer was designed. The observer predicts the current state of the system ( $X_k$ ) based on the existing output ( $Y_k$ ) and system input ( $U_k$ ) measurements. The important point about this work was that the MPC controller incorporated engine-out emissions constraints as part of the calibrated engine map. The experimental results showed that the designed multi-MPC is successfully able to maintain the desired CA50 and reach the required IMEP for a range of PR values. In addition, the developed model can predict cycle-to-cycle CA50 and IMEP with average errors of 1.8 CAD and 36 kPa, respectively.

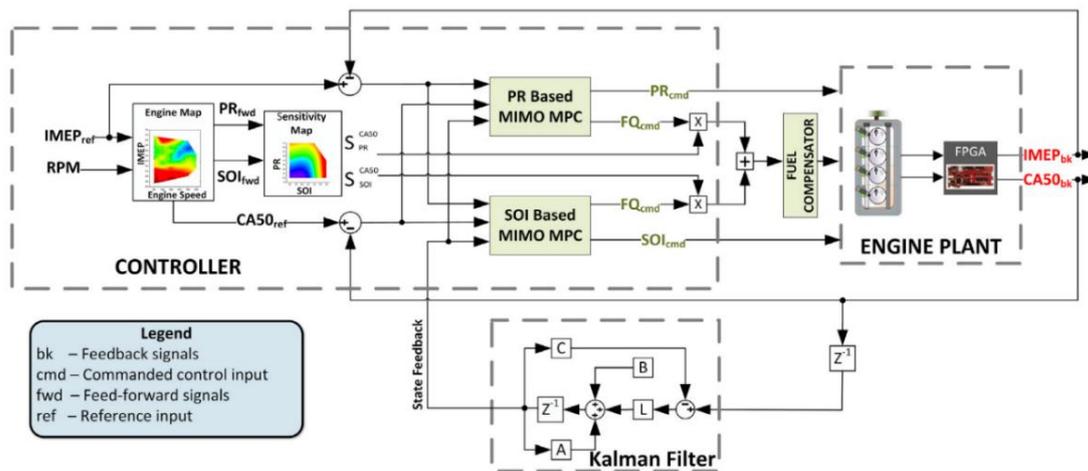


Fig. 11. Proposed control system for RCCI engine load and combustion phase adjustment

(Reprinted from [54] with the permission of Elsevier)

Overall, the use of real-time RCCI combustion controller for transient engine load operations can be very effective tool. The designed controllers showed an accurate tracking performance of the desired combustion phasing and successfully rejects external disturbances

in engine operating conditions. While the physics-based approach is powerful, it requires accurate, COMs which are hard and time consuming to develop. An alternative approach is to utilize data-driven modeling (DDM) to develop RCCI models adapting support vector machines (SVM) to adjust MPRR, while controlling IMEP and CA50 [64, 65].

#### **4. Combustion mode-switching strategies**

In RCCI concept, under certain low-load conditions the dual-fuel mode is not feasible, such that the engine inherently requires two combustion modes: At low loads, the engine can be operated in Diesel-only mode, while at medium and high loads both fuels are injected and engine can run in dual-fuel RCCI mode [66]. Consequently, mode-switching enables operation over the full engine envelope [67], despite of being challenging task as various actuator settings, from both the fuel and the air paths, change significantly during the transition. It requires a smooth transition between different operating conditions, such as lambda ( $\lambda$ ), EGR rate, intake temperature and blend ratio, without compromising combustion stability, engine safety and drivability. This transition has to be guaranteed for all operating conditions, including engine speed-load transients, varying fuel quality and varying ambient conditions.

The operation of RCCI engine using combustion mode-switching offers the benefit of higher thermal efficiency compared to single-mode operation. For various fuel combinations, the engine research community has shown that running dual fuel engines in RCCI mode, is a feasible way to further improve thermal efficiency compared to Conventional Dual Fuel (CDF) operation of the same engine.

In 2016, RCCI real-world operating conditions was explored by Hanson et al. [68] through a series of simulations using low coolant temperatures and combustion mode switching to improve RCCI combustion at low load operation. The first set of experiments investigated RCCI operation during cold start conditions, and the next set of tests investigated combustion mode switching between RCCI and CDC. A combination of OL and CL controls enabled RCCI

to operate at a 1500 rpm, 1.0 bar BMEP operating point over this range of coolant temperatures. At 1500 rpm, 2 bar BMEP operating condition, the engine was instantaneously switched between CDC and RCCI combustion using the same OL and CL controls as the cold start testing. During the mode switch tests, emissions and performance were measured with high-speed sampling equipment. The tests revealed that it was possible to operate RCCI down to 48 °C with simple OL and CL controls with emissions and efficiency similar to the warm steady-state values. In addition, the mode switching tests were successful in switching combustion modes with minimal deviations in emissions and performance in either mode at steady state.

The dual-mode RCCI/CDC concept was also extensively investigated at CMT-Motores Térmicos. Universitat Politècnica de València (UPV) as a technique for completing an engine map region in which RCCI operations become crucial for either excessive HC and CO emissions (low load) or MPRR (high load). Generally, this concept is based on covering all the engine map switching between the RCCI and the CDC operating modes [69, 70]. The results obtained indicated that RCCI combustion can be utilized between 25% and 35% load, and it can provide up to 2% increase in GIE than CDC but led to lower efficiency at low engine speeds. In addition, it was demonstrated that the regeneration periods of the DPF during dual-mode operation can be reduced more than twice, which entails a great reduction of the diesel fuel amount injected in the exhaust line. From a technical point of view, the modifications required to incorporate the dual-mode RCCI/CDC on the engine configuration can only be justified if the aftertreatment needs are minimized and the fuel economy is improved compared to CDC. To accomplish this, it is important to optimize the operating range covered by RCCI in the engine map.

To further investigate the application of RCCI concept in automotive engines, and mitigate these shortcomings of RCCI/CDC, the dual-mode dual-fuel (DMDF) concept,

combining RCCI and diffusive dual-fuel diesel-gasoline combustion, was developed [16, 35, 71-73]. The combustion strategy of the DMDF concept is modified as the engine load is increased. Hence, during the low load operation, the concept uses a fully premixed RCCI strategy. From medium load, the concept switches to highly premixed RCCI and dual-fuel diffusive strategy up to full load operation. The stability and control of combustion in each of the strategies depend mainly on the low reactivity/high reactivity fuel ratio, the injection settings and the EGR rate [74]. It has been shown that an appropriate EGR strategy in the DMDF concept is not only important to ensure the correct operation of each strategy involved in this concept, but also that it has a substantial impact on pollutants emission. Particularly, during the RCCI strategy the increase in low pressure EGR rate provided a reduction in NO<sub>x</sub> emissions [75]. They also evaluated emissions and efficiency of two dual-mode RCCI combustion strategies (i.e., DMDF and RCCI/CDC) under the World Harmonized Transient Cycle (WHTC) test suggested by the EURO VI Heavy Duty Engine Emissions Regulation [35]. A 1-D model of a Volvo FL240 truck was built with GT-Suite for this purpose. Experimental emissions and fuel consumption data on the real medium-duty engine used in the FL240 truck were collected experimentally. Table 2 provides a comparison of the raw simulated values for the two dual-mode concepts. One of the main benefits of using DMDF is the reduction in NO<sub>x</sub> emissions. This mode, on the other hand, provides higher values for CO and HC emissions, which demonstrates the need for an aftertreatment system to meet the emissions legislation levels. Despite the better CO and HC emission values, the RCCI/CDC strategy requires more than 3 g/km of urea to minimize NO<sub>x</sub> to EURO VI rates (in WHVC driving cycle conditions) and thus requires a different aftertreatment system.

Table 2. Comparison of emissions and fuel consumption between the two dual-mode concepts. EURO VI limits are given as reference (Reprinted from [35] with the permission of Elsevier)

	<b>EURO VI</b>	<b>RCCI/CDC</b>	<b>DMDF</b>
BS <sub>CO</sub> [g/kWh]	4.00	3.64	33.67
BS <sub>HC</sub> [g/kWh]	0.16	3.31	7.79
BS <sub>NOx</sub> [g/kWh]	0.46	2.52	0.33
BS <sub>soot</sub> [g/kWh]	0.01	0.015	0.018
BS <sub>FC</sub> [g/kWh]	-	230.17	213.87

The findings show that the concept of DMDF permits the specific fuel consumption to be decreased by 7% on average compared to the RCCI/CDC concept. In addition, with DMDF mode, NO<sub>x</sub> emissions are about 87% lower, fulfilling the EURO VI requirements without the need for a selective catalyst reduction (SCR) system. In comparison, for DMDF, HC and CO emissions are approximately 2 and 10 times greater than RCCI/CDC case, respectively. Although the RCCI strategy is a promising combustion mode, very high UHC and CO emissions levels restrict its application at very low loads and pose a further challenge for the diesel oxidation catalyst (DOC). Furthermore, the diffusive dual-fuel combustion applied at high engine load produces significant soot that should be minimized within the DPF [76]. A few studies have been carried out recently to determine the response of DOC and DPF systems when used for the RCCI employing experimental and modelling approaches [71, 77, 78]. The DOC results revealed poor conversion performance, where the exhaust temperature is low at low load operating conditions (see Fig. 12). On the other hand, the thermal inertia under transient conditions, allowed improved low load DOC behavior, achieving DOC emissions one order of magnitude lower than those from the steady-state measurements. It has also been shown that the most of the nucleation mode and part of the accumulation mode from the dual-fuel RCCI combustion can be eliminated by DOC [79]. Regarding the DPF, it has been shown that the low concentration of NO<sub>x</sub> and soot emissions created during combustion does not

result in significant changes in the  $\text{NO}_2/\text{NO}_x$  ratio before and after the DPF, suggesting a low level or absence of passive regeneration. In the case of active regeneration, both the operating conditions of CDC and DMDF obtained adequate reductions in the overall soot trapped due to the rise in exhaust temperature as a result of the HC and CO conversion promoting active regeneration in the DMDF strategy.

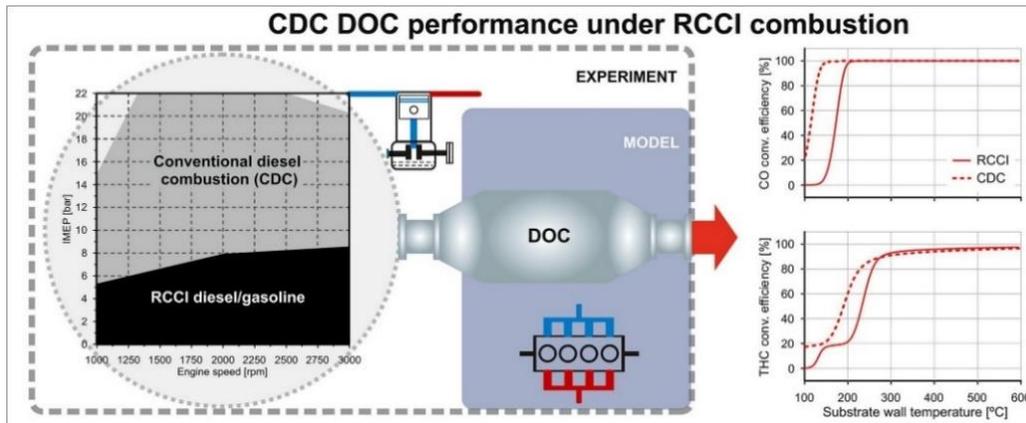


Fig. 12. Schematics of the research methodology for DOC study in RCCI strategy (Reprinted from [78] with the permission of Elsevier)

For Diesel-ignited natural gas engine concepts, reported studies about combustion mode switching are limited. Indrajana et al. [80] proposed a model-based control development approach to deal with the large number of control inputs, coupling between air and fuel path, mode-switching dynamics, and sign changes in a systematic way in dual fuel engines. Previously developed COM [53] was extended with a new CDF model to simulate both CDF and RCCI operation. The CL controller combines static decoupling with next-cycle CA50-IMEP-Blend ratio control. For a mode-switching sequence in a low load operating point, the CL controlled engine demonstrated stable behavior and good reference tracking. Some researchers have also been working on CL control schemes for combustion mode transitions in RCCI engines using other combinations of fuels such as ethanol/Diesel [81]. During mode transitions, the changes of the AFR are smaller than those observed in natural gas/Diesel dual-

fuel engines, where, due to shortcomings of today's CNG catalysts, the only feasible dual-fuel operation is with stoichiometric exhaust gas conditions. Hence, the research focused on the actuation of the fuel injection, while the positions of the air path actuators are held constant or are chosen based on a steady-state lookup table [82].

Recently, Guardia et al. [83] used a real-time cycle-to-cycle CL combustion control with in-cylinder pressure signal as a feedback applied to a dual fuel engine. A control concept was designed for controlling the IMEP and the combustion phasing at a desired value while keeping the MPRR under a defined and safe threshold in all the combustion modes used over the engine map (RCCI to DDF). Two experimental validations are presented, being a disturbance rejection at stationary conditions and a significant IMEP transient from low to high load including combustion mode switching without exceeding the operation limits. According to such limitations, three different strategies have been investigated including, RCCI fully premixed, from idle up to 40% load, corresponding approximately to 8 bar IMEP; RCCI highly premixed, from 40% up to 75% load, about 15 bar IMEP; and DDF, from 75% up to full load as shown in Fig. 13. The developed control application used a real-time data acquisition and processing system combined with an embedded FPGA real-time controller for the injection management. Experimental tests were conducted in a medium-duty engine using gasoline as the port-injected fuel and diesel for the DI. At low load, RCCI combustion was used while a diffusive dual-fuel combustion was employed at higher loads. The developed controller proved the ability to activate such control in a transition between RCCI and DDF mode.

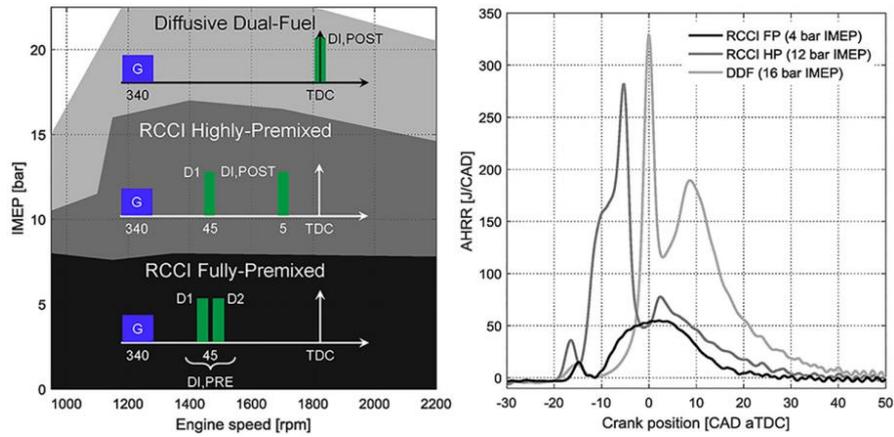


Fig. 13. RCCI combustion concept: injection strategies and AHRR profiles of the three combustion modes (Reprinted from [83] with the permission of SAGE).

From the findings reviewed in this section, it was also possible to switch combustion modes readily while the engine was running with just the CL controller. Most emissions followed the steady-state values, except for HC, which spiked when RCCI was switched to CDC. Switching between RCCI and CDC during a transient speed and load test would be of interest. Mode switching may be very important if low temperature oxidation catalysts are not available. Without appropriate oxidation catalysts, commercial implementation of RCCI may be difficult. Another use could be at high load where the combustion noise is limiting for RCCI. Switching to CDC could increase the power density of the engine in areas where the engine emission regulations are less stringent. RCCI will require additional controls to match the CDC load capabilities, including model-based control to account for combustion chamber wall temperatures and PFI fueling transient effects, including fuel build up on the intake runner walls.

## 5. Effect of alternative fuels on RCCI transient performance

In view of the attraction of RCCI combustion in terms of reactivity control, many researchers have devoted their attention to the investigation of alternative fuels. In addition to conventional low and high reactive fuels (i.e., gasoline and diesel), various types of fuels can

be used with dual-fuel RCCI combustion [15]. The majority of research on low reactivity fuels has considered gaseous fuels, e.g., natural gas [84-86], syngas [87-89], alcoholic fuels like ethanol [90, 91], methanol [92] and butanol [93, 94], and the others focused on high reactivity fuels, such as biodiesel [95, 96]. However, the main focus of these studies was on steady-state operation.

Hanson et al. [97] performed experiments on a light-duty multi-cylinder RCCI engine using production level engine hardware. The gasoline was replaced with E20 and tests were carried out over the US EPA FTP75 test cycle on a large speed/load map reflecting the light-duty vehicle operation. ULSD was substituted with B20 in another series of experiments and tests were conducted at loads of 2.0, 2.6 and 4.2 bar BMEP, and at engine speeds of 2000, 1500 and 2300 rpm. It was found that with E20, due to the lower tendency of ethanol for auto-ignition, the peak load could be increased from 8 bar to 10 bar BMEP. Use of E20 was found to minimize the required fraction of gasoline PFI, which led to increased NO<sub>x</sub> emissions. However, replacing ULSD with B20 was shown to improve the combustion efficiency at low loads and would allow a reduced fraction of PFI. In the second part of this study, E85 and B20 were selected as the PFI and the DI fuels, respectively. By using E85 as the PFI fuel, it was possible to achieve 11 bar BMEP at 3000 rpm compared to 10 bar with E20, while meeting MPRR operating limits. The 3000 rpm was selected as the engine speed because with RCCI, the highest turbocharger efficiency was achieved, an optimized RCCI engine could lower the engine speed for peak output with improved turbocharger performance. Fig. 14 shows the cylinder pressure and HRR for this operating condition. It can be observed that the BTE for RCCI was 43% compared to 40% for CDC at this operating condition.

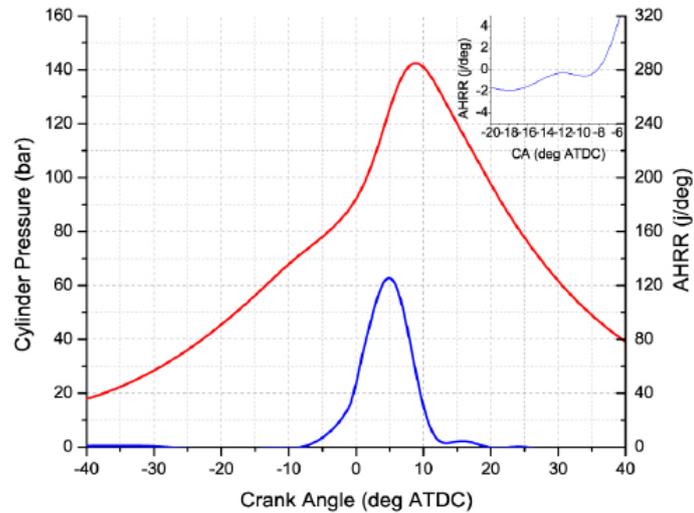
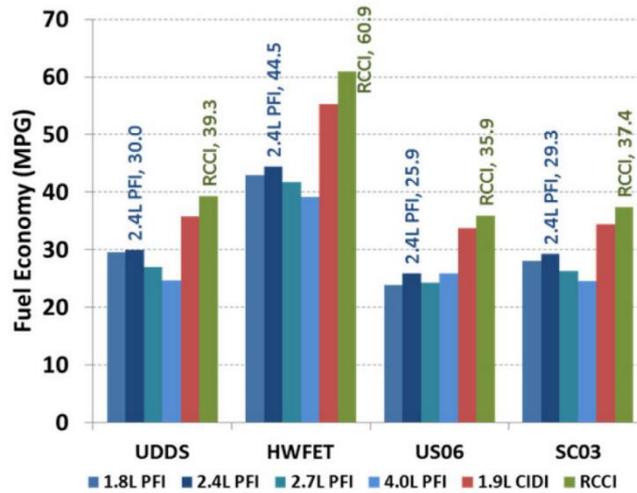


Fig. 14. E85/B20 RCCI cylinder pressure and heat release rate at  $N = 3000$  rpm (Reprinted from [97] with the permission of SAE)

In 2014, Curran et al. [98] investigated RCCI combustion ability to minimize drive cycle fuel efficiency and emissions by simulating fuel economy and emissions for an RCCI-enabled multi-mode vehicle operating over a variety of driving cycles using multi-mode RCCI experimental engine maps with E30 and ULSD fuels, and compared them to CDC and PFI petrol engines ranging from 1.8L to 4.0L. Simulations were carried out assuming a conventional mid-size passenger vehicle with an automatic transmission optimized for each engine. The simulated fuel economy results are shown in Fig. 15 for all engines in the mid-size passenger car with fuel economy optimized transmissions. The 2.4L PFI engine was proven to provide the best among the PFI engines in terms of fuel economy. The results of the modeled fuel economy indicated a 10 percent improvement over the CDC baseline with the city and highway cycles and 6- 8 percent with the RCCI/CDC maps on the supplementary drive cycles. Compared to the 2.7 PFI baseline, which showed 30% fuel efficiency increase over the 2.4L PFI baseline, the RCCI/CDC engine was found to have more than 40 percent fuel economy increase over all drive cycles.

The use of E30 for the low-reactivity fuel was also shown to shift the coverage of the drive cycle to a higher load. However, the high HC and CO emissions in the simulations along with the reduced exhaust temperature will pose a challenge to comply with Federal emissions regulations and may need change of the operating strategy at low load or advancements in catalyst technology.



Engine Size	1.9 CIDI	1.8L PFI	2.4L PFI	2.7L PFI	4.0L PFI
UNIT	MPG	MPG	MPG	MPG	MPG
UDDS	10.1 %	33.1%	31.1%	45.8%	59.2%
HWFET	10.1%	41.6%	36.8%	45.7%	55.4%
US06	6.3%	50.5%	38.4%	47.4%	38.2%
SC03	8.3%	33.1%	27.7%	41.9%	52.0%

Fig. 15. Performance and changes in fuel economy for all PFI engines, CDC only operates with the CIDI base engine and multi-mode RCCI/CDC (Reprinted from [98] with the permission of SAE)

In order to enable the RCCI strategy for commercial applications, efforts have been made to investigate single-fuel RCCI by utilizing a single fuel tank with a low reactivity fuel, together with a small secondary tank for a cetane improver. In these studies, a low reactive fuel was used as a PFI, as well as the DI fuel when doped with small amount of cetane improver [99]. Another way towards commercialization is to achieve single-fuel RCCI using a mixture of reformer gas and high reactive fuel [100] or using gasoline/diesel mixtures (i.e., dieseline)

[101]. Gross [102] experimentally examined the transient performance of dieseline45 (mixture of diesel and gasoline) as the high reactivity fuel for RCCI combustion in the light-duty multi-cylinder diesel engine and compared to results of gasoline/diesel RCCI combustion. Transient load steps were carried out in an upload and download scenario between 2.6 bar BMEP and 4 bar BMEP at a constant engine speed of 1500 rpm. Fig. 16 compares the combustion performance of the gasoline/diesel, gasoline/dieseline45 and dieseline45/dieseline45 cases. As can be seen, the single-fuel approach displays a higher maximum pressure rise rate for the high load period, but still stays within the self-imposed limits. Here, increased PFI fractions and thus a higher quantity of premixed fuel causes a simultaneous onset of combustion throughout the combustion chamber with increased peak HRR levels and a shortened combustion duration. Dieseline45/dieseline45 depicts the highest overshoot of about 3CAD for the download case and about 5 CAD for the upload case. In the download case, the targeted values are reached after about 90 cycles, while the upload case could not recover within the number of cycles recorded. This is most likely caused by cylinder wall temperature effects, that are not accounted for in steady-state calibration maps. Cylinder walls are cooler from running at low load, causing a delay in combustion due to slower kinetic reaction rates. On the other hand, high cylinder wall temperatures from running at high load in combination with an increase in DI fuel amounts and hence increased stratification cause the combustion phasing to be advanced during the download phase as already reported by Hanson [45].

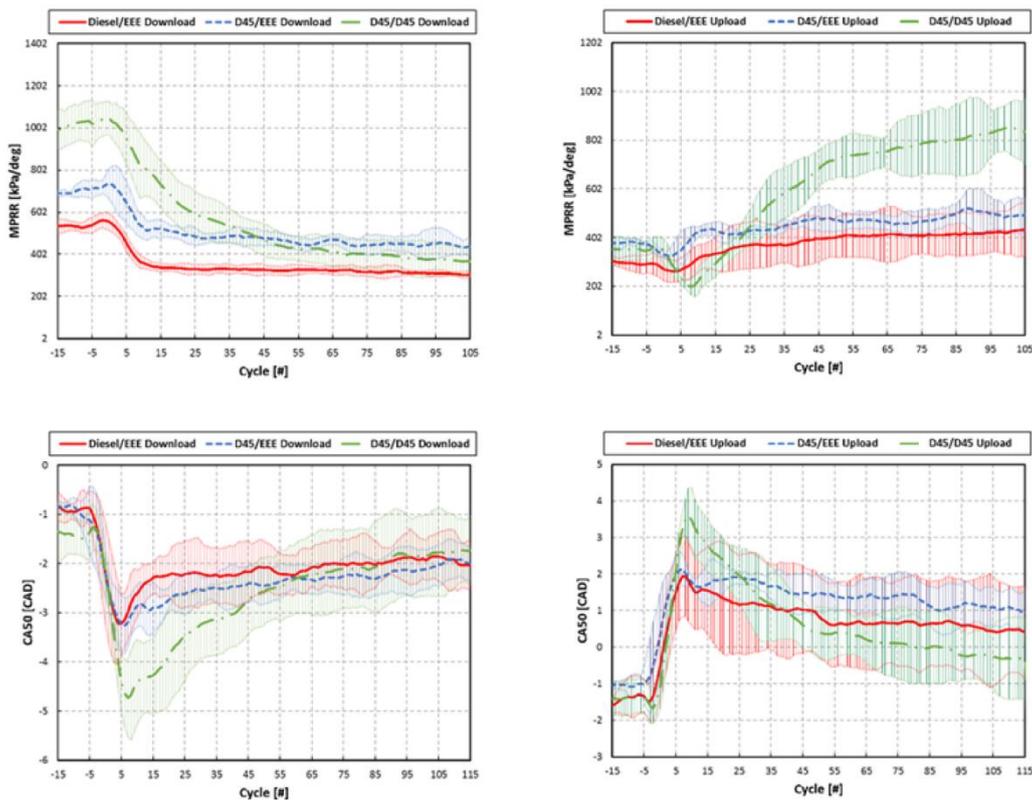


Fig. 16. Combustion performance for the download and upload cases (Reprinted from [102])

Comparing the emission results in Fig. 17, it can be seen that HC was highest, and NO was lowest for the single-fuel RCCI operation. The cause for the spike at the onset of the transient was attributed to the cooler combustion chamber walls and port-fuel effects. HC emissions are fairly constant across the load change for both the gasoline/diesel and the gasoline/dieseline45 case. The single-fuel case on the other hand shows an increase in HC with increasing load and vice-versa. The single-fuel HC emissions are increased, especially for the high load period, due to the high quantities of premixed fuel, hence increasing the charge equivalence ratio and reducing the amount of DI fuels. While the single-fuel approach shows low NO levels overall, the gasoline/diesel and gasoline/dieseline45 cases display higher NO levels from the increase in DI fraction. In addition, the difference between the high and low

load periods for the gasoline/diesel and gasoline/dieseline45 are much higher compared to the dieseline45/dieseline45.

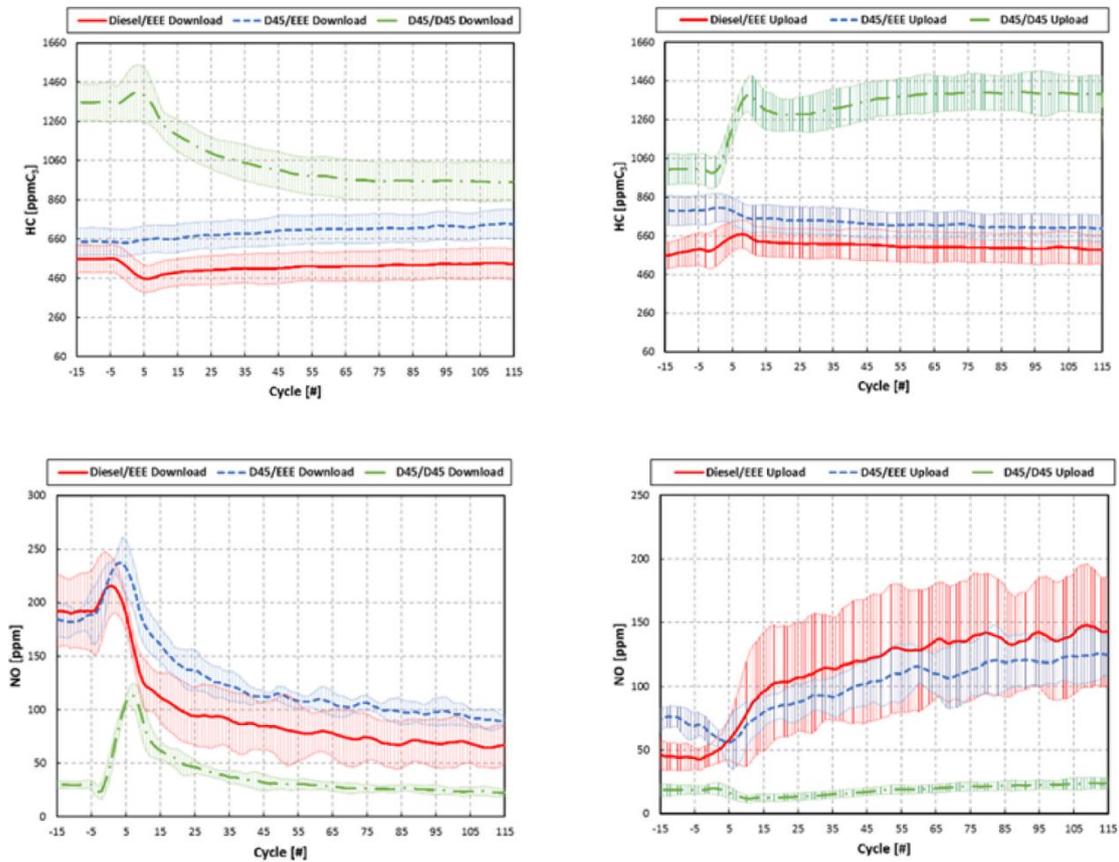


Fig. 17. Emissions performance for the download and upload cases (Reprinted from [102])

In another research work, Gross and Reitz [103] used a "single-fuel" method for RCCI combustion using PFI gasoline and DI injection of gasoline mixed with a small amount of cetane improver 2-ethylhexyl nitrate (2-EHN) with a 3% volume percentage under transient conditions, and compared it to the transient RCCI combustion process with gasoline/diesel. Results indicated that single-fuel RCCI operation can be accomplished, but involves major changes in operating conditions, and for gasoline/gasoline–EHN operation NO<sub>x</sub> emissions were significantly increased. It was also noted that the NO emissions were increased above the

fuel-bound threshold triggered by changes to the injection strategy. Furthermore, even with most of the fuel being gasoline, the results for HC for EHN were the same or lower than for diesel, particularly for high loads. During the combustion of EHN, smoke opacity was not a factor, as it was almost non-existent and constant during changes in load. It can be summarized that the unique fuel properties of these biofuel blends as well as single-fuel mode with cetane improver can increase the benefits of the use of RCCI combustion compared to CDC in automotive engines.

Overall, it was found that the RCCI engine was able to operate with variety of biofuels with only minor changes to the fuel injection and air system parameters. Ethanol fuel blends offered higher peak load, which allowed for a higher peak BTE. B20 was also shown to increase the transient response of the combustion phasing. Finally, E20 blends were shown to offer lower NO spike during transient testing due the lower PFI fractions. In addition, single-fuel RCCI operation and use of biofuels are a promising way to commercialize RCCI in short term.

## **6. RCCI concept in hybrid vehicle configuration**

Despite the advancements in the field of combustion, it is still a challenge to meet the constraints in terms of local and GHG emissions. In this sense electrification is becoming increasingly widespread in the OEMs to reduce the total CO<sub>2</sub> generated in their fleet. Since 2010, the production of electric vehicles (EVs) and hybrid electric vehicles (HEVs) has achieved remarkable progress [104]. Moreover, continuous efforts are being made to encourage a better range and lower life cycle GHG emissions from these vehicles in order to make them commercially competitive to IC engine powered vehicles. Combined with advanced combustion modes, electrification seems to have potential to reduce the overall CO<sub>2</sub> generated emissions by the vehicle fleets [105, 106]. In comparison to conventional SI engine, LTC aims to increase fuel economy for HEVs, where the electrification of the powertrain will provide extra power to drive the vehicle and decouple the engine and the battery, making it easier for

the engine to operate in a high-efficiency area [107]. A considerable amount of work has been conducted to investigate the various LTC strategies such as the HCCI concept in series HEVs [108, 109]. Some researchers have recently tested the use of RCCI combustion mode in mild and full HEVs [110, 111]. The key objective was to determine the advantages of combining a hybrid vehicle system with an advanced combustion engine operating in RCCI mode. The second objective was to establish a methodology for optimizing hybrid powertrains based on an advanced combustion engine which has already been developed.

In 2015, RCCI combustion was first used in a hybrid vehicle [38]. The demonstrator vehicle was a 2009 Saturn Vue that was modified using a 1.9L GM diesel engine in RCCI mode. The engine is coupled to a 90 kW AC motor, serving as an electrical generator to charge a 14.1 kW-hour lithium-ion traction battery pack that is powered by a 75 kW drive motor. Complete vehicle testing was carried out at Oak Ridge National Laboratory's Vehicle Research Laboratory (ORNL) and chassis dynamometer experiments were carried out at the Ford Motor Company's Vehicle Emissions Research Laboratory (VERL). The fuel economy and emission data from the hybrid platform were compared with data from the EPA and Argonne National Laboratory (ANL) for the Chevrolet Volt in order to allow meaningful comparisons to production vehicles. Fig. 18 shows tailpipe emission results compared to the normal Volt and US EPA Tier 2 Bin 5 standard. Compared to the Ford data, despite the improved HC emissions, it was observed that they are still too high. Given that the current exhaust aftertreatment does not reduce the NO<sub>x</sub> emissions, additional improvements to the fuel injection strategy are essential to get the NO<sub>x</sub> emissions closer to the 0.043 g/km target. Also, PM was tested at ORNL for the RCCI HWFET. PM emissions of the RCCI were 1.15 mg/km. The HWFET does not have a PM standard, but the PM emissions are low, particularly when compared with the 1.86 mg/km EPA Tier 3 standard and the 6.21 mg/km Tier 2 standard, which are utilized as a

reference frame only. They demonstrated that a vehicle with an RCCI engine could be run over a US EPA test cycle.

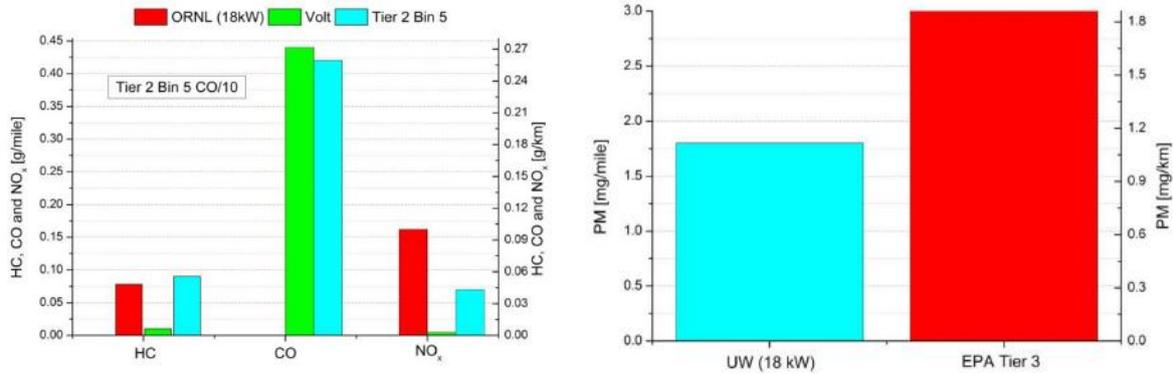


Fig.18. Series hybrid UW HWFET emissions compared to the Series-Parallel Hybrid Chevrolet Volt and US EPA Tier 2 Bin 5 and Tier 3 standard levels (Reprinted from [38] with the permission of SAE)

ORNL researchers [112, 113] evaluated simulated fuel economy and engine emissions from lean gasoline direct injection (GDI), RCCI, CDC and PFI engines in conventional and hybrid light-duty vehicles using Autonomie simulation kit. Dynamometer measurements were used to produce engine performance maps of a BMW 120i, 2.0 L engine, a Saab 2.0-L, fuel-flexible, TC engine, a 4-cylinder, 1.9L GM TC diesel engine, and a modified version of the GM diesel engine. Since the RCCI operating range did not cover the entire speed and load specifications of the simulated light-duty drive cycles, a multi-mode CDC/RCCI mode was utilized such that the engine was operated in RCCI mode whenever possible, but was converted to CDC at the maximum and lowest engine operating points where RCCI combustion was not practical. Fig. 19 depicts the fuel economy simulated for both conventional and hybrid vehicles powered by each engine type. In view of the fact that RCCI requires two fuels, for the CDC/RCCI case diesel equivalent fuel economy was used to simplify the study. The best and worst fuel economies for conventional powertrain cases were obtained with CDC/RCCI and

PFI, accordingly. It was demonstrated that the fuel economy for CDC-only and lean GDI are substantially higher than for PFI. CDC/RCCI achieves better fuel economy over all simulated drive cycles, relative to CDC only. In specific, the advantages for the highway driving cycle are rising substantially. Lean GDI has a 17–23% greater fuel economy than PFI, due to the fact that the lean GDI engine efficiency is considerably higher than PFI over the simulated drive cycles. However, the fuel economy of lean GDI is still less than the cases allowed by CDC-only and RCCI. Specifically, these findings do not consider any fuel consumption needed for pollution control devices which could significantly modify the comparisons as explained below.

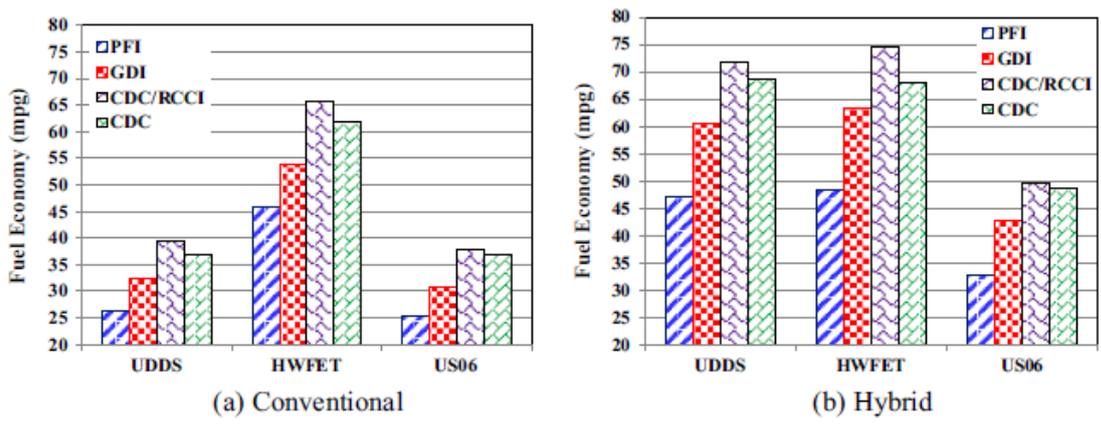


Fig. 19. Simulated vehicle fuel economy powered by various combustion engines over different city and highway drive cycles (Reprinted from [113] with the permission of Elsevier)

Use of the advanced combustion and hybridization would offer substantial benefit to the light duty fuel economy. However, it is also important to analyze how these innovations compare with the new US EPA Tier 3 emission standards. Table 3 compares the estimated emission cuts that the new legislation will entail. The most difficult form of pollution is non-methane organic gases (NMOG)+NO<sub>x</sub> emissions, which for most situations needs approximately 99% reduction. Furthermore, each of the advanced combustion technologies faces various challenges. Hybridization decreases emissions for simulations except for the

estimated CDC PM emissions; hence, hybridization will reduce the size and overall cost of the aftertreatment system. Hybridization also requires engine start-stop cycling, which can lower exhaust temperatures and affect the efficiency of the catalyst.

Overall, for both non-hybrid and hybrid powertrains, vehicles with RCCI-enabled engines were expected to have the highest fuel economy for all drive-cycles. Like lean GDI, hybridization tended to increase incentives to exploit the efficiency benefits of running on RCCI mode. NO<sub>x</sub> emissions from the RCCI engine-out were low and significantly decreased with increased use of this mode enabled by hybridization. Although the NO<sub>x</sub> level for RCCI were very low, due to high CO and HC emissions and low exhaust temperatures, meeting the NO<sub>x</sub>+NMOG Tier 3 Bin 30 regulation is very difficult. The latter feature of RCCI is of concern since it was estimated that exhaust temperature would fall occasionally below 200<sup>0</sup> C, where CO and HC oxidation would become challenging.

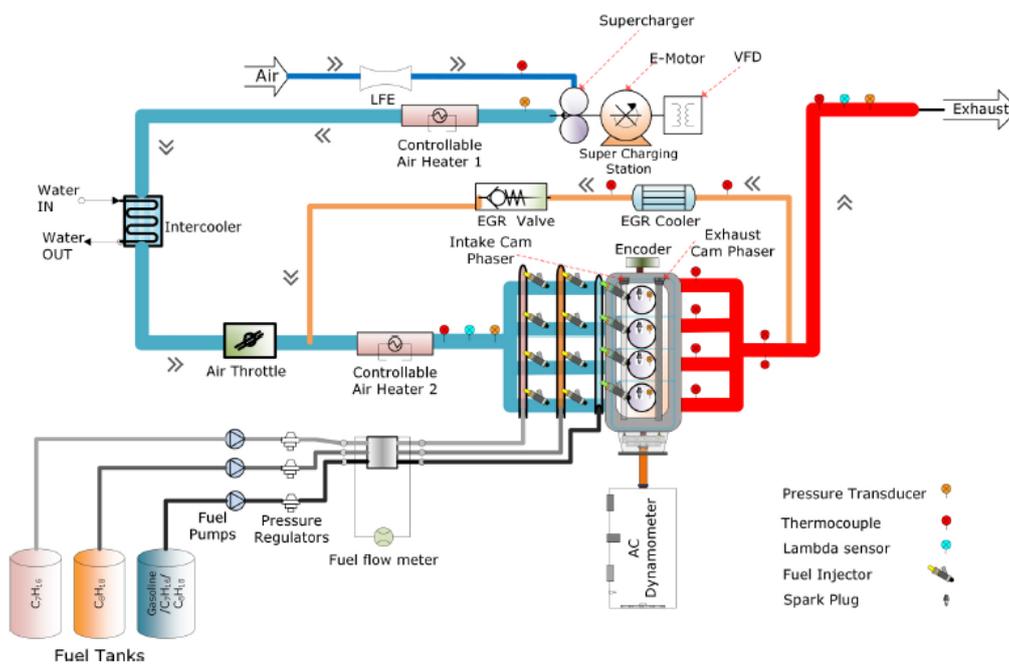
At MTU, Solouk and Shahbakhti [114-118] developed a multi-mode LTC-SI engine incorporated in HEV over the driving cycle to increase the overall fuel efficiency. The stock SI engine was converted to an LTC-SI engine in multi-mode which can be seen in Fig. 20, and the LTC strategy was achieved in both HCCI and RCCI modes.

Table 3. Estimated rate of emission reductions required to achieve U.S. EPA Tier 3 Bin 30 regulation (Reprinted from [113] with the permission of Elsevier)

<b>Combustion</b>	<b>Drive cycle Unit</b>	<b>CO reduction</b>	<b>NMOG+NO<sub>x</sub> reduction</b>	<b>PM reduction</b>
PFI	Conventional hybrid	87.2%	99.4%	0.0%
		79.2%	99.2%	0.0%
Lean GDI	Conventional hybrid	81%	99.3%	34.3%
		74%	99.1%	0.0%
CDC/RCCI	Conventional hybrid	84.2%	99.1%	-
		66.8%	98.6%	-
CDC-only	Conventional hybrid	76.1%	98.2%	82.6%
		0.0%	96.8%	85.9%



(a)



(b)

Fig. 20. (a) Developed experimental test bench for the LTC-based range extender with BEV powertrain with a 465 hp AC dynamometer at MTU; (b) fuel-flexible multi-mode LTC-SI engine test system schematics (Reprinted from [54] with the permission of Elsevier)

The fuel consumption of the vehicle is shown in Fig. 21 over EPA Urban Dynamometer Driving Schedule (UDDS: represents city driving conditions for light duty vehicle testing) and HWFET cycles. The findings demonstrate the superiority of the LTC-SI multimode

engine in the mild hybrid over the single-mode SI. However, this improvement is lower over the HWFET driving cycle, because the engine operating points are largely placed in fuel-efficient regions independent of the level of electrification. They found 1.4% to 8.8% reduction in fuel consumption in the equivalent powertrain design for the hybrid electric platform with the multi-mode LTC-SI engine. Furthermore, the results for the UDDS driving cycle showed that the full advantage of the LTC-SI multi-mode engine is achieved at a mild electrification level, where the running time of the LTC mode increases drastically from 1.5 percent in Plug-in Hybrid Electric Vehicle (PHEV) to 30.5% in mild HEV.

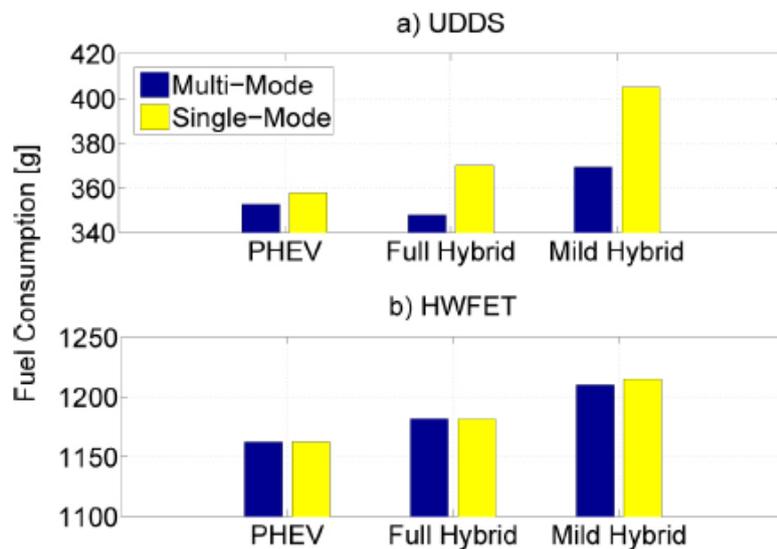


Fig. 21. Fuel consumption in two driving cycles and three electrification stages for multi-mode and single mode engines (Reprinted from [117] with the permission of SAE)

Researchers at MTU also studied the optimum fuel consumption improvement in a light duty battery electric vehicle (BEV) configuration with a multi-mode LTC-SI range extender. Fig. 22 displays an increase in fuel consumption of the LTC-SI multimode and single-mode LTC range extenders over a single-mode SI engine in the BEV configuration. It shows that in the multimode case, the maximum reduction in fuel consumption is 12.4% in the UDDS, which is 1.4% higher than the best single-mode one achieved in HCCI engine. The multi-mode engine

showed the minimum fuel consumption for driving cycles resulting in a greater discrepancy between the BTE of HCCI and RCCI modes [118].

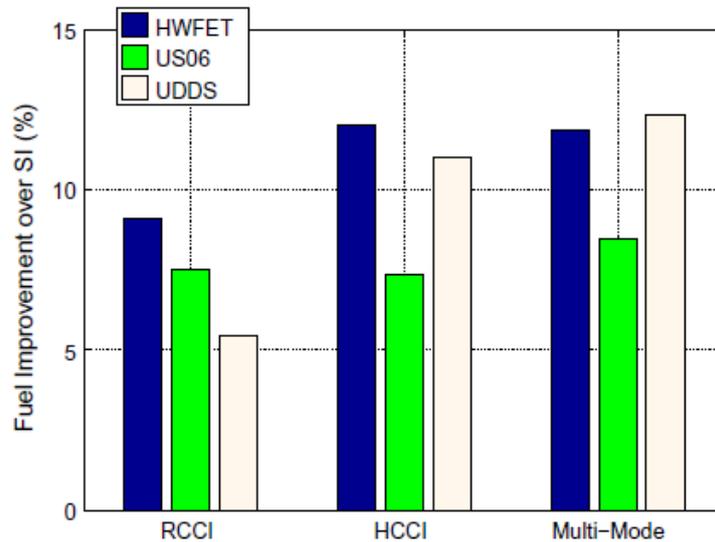


Fig. 22. Reduction of fuel consumption of BEV operating with various range extender engines over the SI engine during the driving cycles UDDS, HWFET and US06 (Reprinted from [118] with the permission of Elsevier)

Recently, a number of research studies on the use of the RCCI strategy in HEV configuration have been carried out at CMT-UPV [119-123]. Initial studies have shown that the use of hybrid series vehicles in combination with RCCI substantially decreases the vehicle's overall fuel consumption while retaining the NO<sub>x</sub> and soot engine-out emissions under the Euro 6 limits. Such a finding directly affects the final after-treatment costs, as the need for DPF and SCR systems can be minimized [119]. In the case of a series hybrid vehicle concept equipped with a retrofitted diesel engine to operate in RCCI mode with ethanol–diesel fuels over the WLTC and RDE driving cycles was studied. The results show an average reduction for the engine-out NO<sub>x</sub>, soot and CO<sub>2</sub> of 90%, 98% and 10% respectively, thus satisfying the Euro 6 regulation. However, the cost of a series hybrid powertrain makes it less competitive

than the more widespread solution of parallel hybrid architecture. In the work of Benajes et al. [121], study with the diesel-gasoline RCCI engine was performed for both the parallel and mild hybrid architectures. In particular, numerical analysis was performed by implementing a supervisory controller for the powertrain energy management built with Rule-Based Control (RBC), which requires great calibration effort. Parallel hybrid vehicles integrate a supervisory energy management control unit, which has the key task to best split the power request between the IC engine and the electric machine while operating with a charge sustaining mode, which means that the battery energy content must be preserved. For more than two decades, different control strategies have been investigated for this purpose. Rule-based control strategies, also called heuristic strategies, are an ensemble of ad-hoc rules which define the operational status of the IC engine and the electric machine for each operative case of the vehicle, according to some control parameters as, for instance, the vehicle speed and the rechargeable energy storage system (RESS) state: complex design of these kind of strategies is able to provide very good results in terms of fuel economy, when compared to the benchmark solutions obtained with dynamic programming (DP).

Garcia et al. [124] compared energy management strategies comparison for a parallel full hybrid electric vehicle using RCCI combustion. Adaptive Equivalent Minimization Control Strategy and Rule-Based Control strategy, while dynamic programming was used to size the electric grid of the powertrain to provide the best optimal solution in terms of fuel economy and emissions abatement. The results showed a great potential of the parallel full-hybrid electric vehicle powertrain equipped with the dual-mode engine to reduce the engine-out emissions, also to increase fuel economy with respect to the homologation fuel consumption of the baseline vehicle. The optimal supervisory control strategy was found to be the emissions-oriented Adaptive Equivalent Minimization Control Strategy, which scores a simultaneous

reduction of 12% in fuel consumption, 75% in engine-out nitrogen oxides emissions and 82% in engine-out soot, with respect to the baseline conventional diesel combustion engine vehicle.

In a series of experimental and computational simulations, Benajes et al. [121] investigated a parallel full HEV and a mild hybrid vehicle (MHEV) based on a WLTC to achieve lower fuel consumption and NOx emissions compared to a conventional engine. The hybrid vehicles were simulated using both CDC and diesel-gasoline RCCI combustion modes. Each powertrain has been designed with respect to component capacity (battery, electric motors ...), engine operating points, energy management strategy and gear ratios. Experimental tests were conducted using the Euro 4 GM 1.9L light-duty engine in single-cylinder engine configuration without any aftertreatment system being used. The vehicle chosen to carry out the simulations was the Opel Vectra using ignition compression engine in the experimental tests.

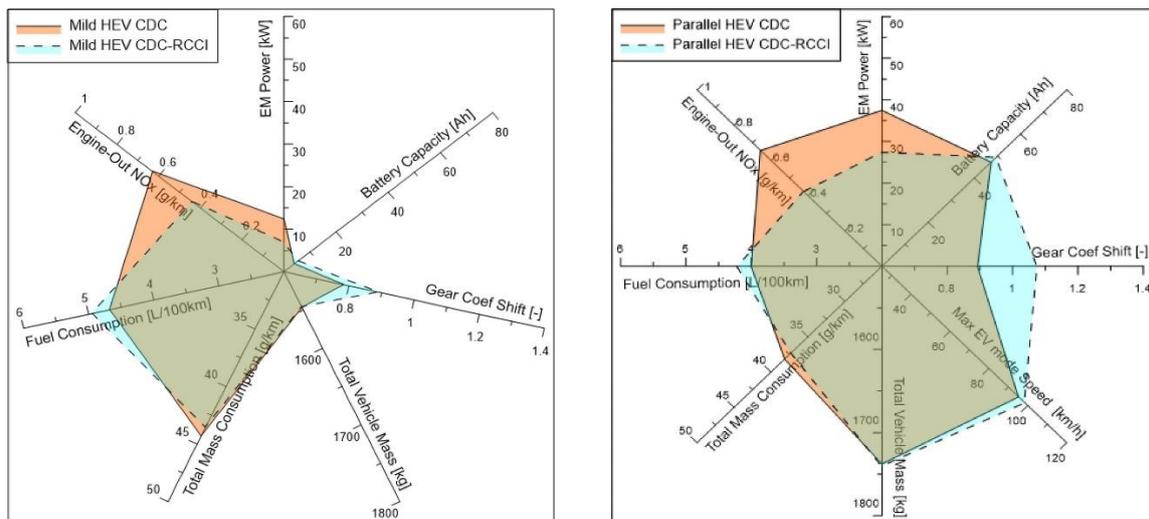


Fig. 23. Main parameters of optimum case for CDC-RCCI and CDC engine maps: (a) Mild hybrid; (b) Parallel hybrid (Reprinted from [121] with the permission of Elsevier).

In the spider graph of Fig 23., a summary of the optimum cases was given. CDC-RCCI increases overall mass consumption as mentioned above, with a major reduction in NOx emissions. The size of electric motor size and battery capacity were more similar among the

two combustion modes, since the RCCI mode on the CDC map allows the development of lower NO<sub>x</sub> in the 2500 rpm region. Meanwhile, the CDC needs to keep engine speed in the lower zone so as not to generate high NO<sub>x</sub> emissions. As depicted in Fig. 23, in terms of battery capacity, the best cases were observed around 50 Ah, which reflects the high battery capacity. Moreover, the optimal was reached in the zone of medium EM size for the electric motor capacity.

In recent years, due to the growing concern regarding climate change, many governmental organizations and researchers have concentrated on the life cycle analysis (LCA) [125, 126] to measure the effect on GHG emissions and other parameters for new technologies. Some researchers [122] tried to describe multiple powertrains in a passenger car using the RCCI combustion mode with different hybrid platform configuration. In the latest European homologation method, numerical and experimental tests were carried out to determine the fuel consumption and emissions. In addition, a cradle-to-grave LCA was conducted to account for all stages of the development, use and disposal of vehicles. To do this, the impact of the growth, maintenance, re-cycling and disposal cycle of fuel (liquid and electricity), traditional and hybrid electrical components (electric motors, batteries, etc.), was included. It was found that combining dual-fuel combustion with mild and full electrified hybrid modes makes extra fuel consumption gains with a maximum of 25% full hybrid electric vehicle compared to the OEM. Fig. 24 indicates CO<sub>2</sub> and GHG-100 emissions for both hybrid and non-hybrid technologies. The dotted line shows the OEM diesel vehicle baseline scenario. With a minimum for PHEV, a sharp decrease can be seen with the electrification level. The LCA shows that the PHEVs can achieve a 12% reduction in total CO<sub>2</sub> compared to the full hybrid electric vehicle and a 30% reduction compared with the no-hybrid diesel configuration.

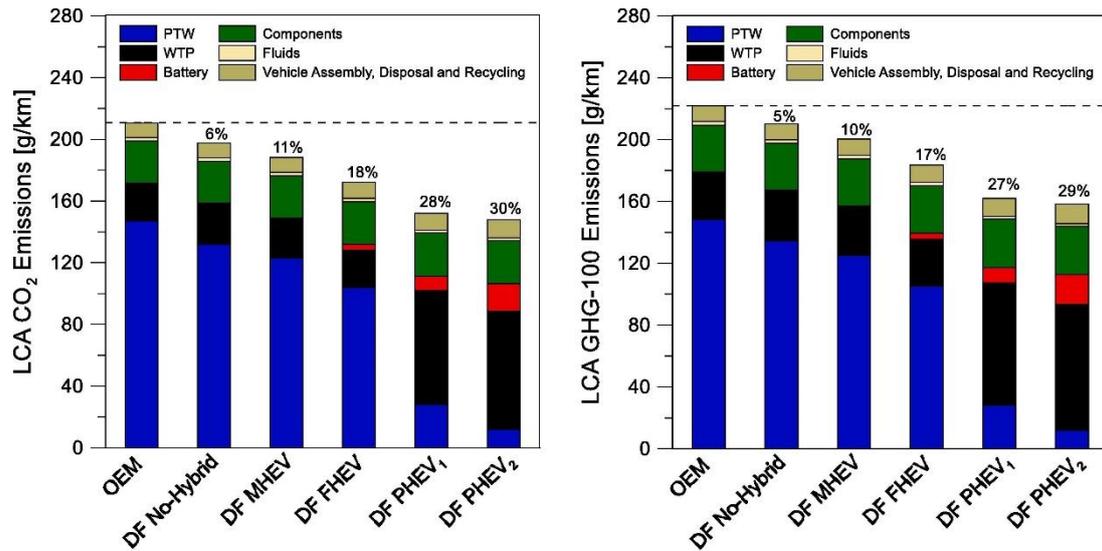


Fig. 24. The results of CO<sub>2</sub> and GHG-100 emissions for the hybrid and no-hybrid vehicles derived from LCA study (Reprinted from with the permission of Elsevier).

Garcia et al. [120, 123, 127-129] also assessed the potential for combining various successful CO<sub>2</sub> and other emission reduction technologies. In a series hybrid vehicle model, an RCCI concept and a pre-chamber ignition system (PCIS) were simulated with ethanol/bioethanol and diesel fuels. Firstly, the data analyzed from the simulation was optimized by combining experiment design and the Kriging fitting process. Then, under two separate driving cycles, the WLTC and RDE, the results obtained for the hybrid and CDC are compared. A DOC model is then used to measure the HC and CO emissions from the tailpipe using the hybrid LTC concept. Subsequently, an LCA was carried out to review the bioethanol's global potential for reducing GHG emissions. Fig. 25 demonstrates the LCA CO<sub>2</sub> emissions for the various vehicle platforms using US-produced fuels. The left bar graph depicts the CO<sub>2</sub> emissions without taking the biogenic indicator into account and the impact of land use changes. It was found that the gasoline 2021 concept and the battery electric vehicle have the lowest values. Battery and electricity production emissions for bioethanol vehicles are even lower than the Well-to-Wheels (WTW). However, the trend is reversed when considering

biogenic impact and the transition in land use of bio-ethanol. Both E100 or E85 models resulted in lower overall LCA CO<sub>2</sub> emissions than BEV or gasoline concepts. The biogenic effect ignores the CO<sub>2</sub> emissions from the tailpipe and is greater than the influence of land use change. The output of fuel and vehicles are therefore the parameters which have impact in the overall result. The range extensor SI E100 was also found to be the best case, followed by the SI no-hybrid.

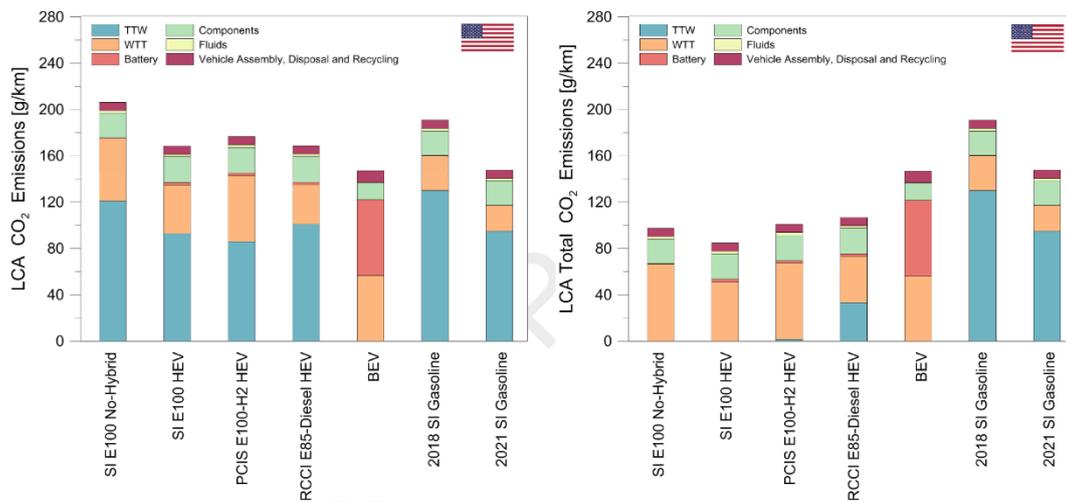


Fig. 25. LCA CO<sub>2</sub> emissions in US scenario with and without taking into account the biogenic indicator and land use change effects (Reprinted from [120] with the permission of Elsevier).

In the most recent work, García et al. [130] studied the potential of RCCI combustion in two medium duty trucks (18-ton and 25-ton maximum payload) with full hybrid P2 architecture. It was found that the hybridization allows the de-rating of the engine from 350 hp (OEM CDC maximum power) to 210 hp. The compression ratio was reduced from 17.0 to 12.5 and six gasoline PFI injectors and a low pressure EGR system was added. The numerical modeling of a complete truck model was performed in GT-Suite. The model was previously calibrated with on road experimental results with the OEM powertrain. The results showed that with the boost mode operation is possible to achieve higher wheel torque output than the

conventional diesel powertrain. The de-rating of the engine is a commonly approach by OEMs to satisfy several truck platforms with the same engine. Therefore, the application with RCCI mode plus the electrification is a potential solution for the peak pressure gradient inside the combustion chamber. A ruled based controller was used with a special calibration to optimum fuel consumption. The study demonstrated that is possible in transient conditions to fulfill EU VI NO<sub>x</sub> and soot emissions while achieving 2025 European CO<sub>2</sub> targets (15% of reduction versus OEM diesel powertrain). The study also showed that 600 V combined with battery size of 8 kWh and 13 kWh for the 18-ton and 25-ton Truck is the best cost-effective selection. This result was achieved after a balance between currently battery cost and CO<sub>2</sub> penalties estimated by the European Union for 2025. The main benefits of the electrification of the powertrain are the higher ICE control over the best operative points of the RCCI ICE and the recovery of the braking energy.

Since RCCI studies are of great interest for future research, Table 4 summarizes the main RCCI combustion studies in hybrid configurations for vehicle applications. Overall, Results reviewed showed that PHEV technology along with use of RCCI has also the potential to reduce local and global pollutant emissions. The PHEV has the greatest advantages in terms of minimizing fuel consumption and engine-out emissions, and the 50 g/km CO<sub>2</sub> goal for medium battery sized PHEVs can be met, whereas the NO<sub>x</sub> and soot rates are below the Euro 6 limits. The RCCI strategy also offers a great potential for fuel saving in SHEV configuration, which can be up to 12.6% higher over a modern SI engine.

Table 4. RCCI combustion studies in hybrid configurations for vehicle applications.

Authors`	Research objectives	Engine/motor type and Experiments	Modeling/Simulations	Main results
Hanson et al. [38]	Fuel economy testing of an RCCI engine integrated in a series hybrid vehicle under FTP75 and HWFET cycles	2009 Saturn Vue chassis and a modified 1.9L turbo-diesel engine with RCCI combustion. The engine was coupled to a 90 kW AC motor serving as an electrical generator to charge a 14.1 kW-AC lithium-ion traction battery pack which is driven to the rear wheels by a 75 kW drive motor	---	A vehicle with an RCCI engine could be run over a test period for US EPA certification. The load-sustaining fuel economy of the Chevrolet Volt was 5.6 vs 5.11 L/100 km due to higher series hybrid powertrain losses compared to the parallel configuration of the Volt series. Based on the experimental and simulated results of the HWFET, it was calculated that the vehicle can meet US EPA Tier2 bin5 NOx emissions on the HWFET while achieving 4.4L/100 km.
Gao et al. [113]	Simulation of high-efficiency combustion driving cycles (Lean GDI and RCCI modes) on fuel economy and exhaust emissions in light-duty vehicles	A modified GM, four-cylinder, 1.9L TC diesel engine operating in RCCI mode	Autonomie software was used to simulate both conventional and hybrid powertrain configurations	Hybridization increases energy efficiency and lean GDI and RCCI pollution management. Lean combustion modes GDI and RCCI substantially lower the exhaust temperatures. Overall, it is anticipated that advanced combustion engines for passenger cars (enabled for lean GDI, RCCI) would require substantial fuel efficiency gains relative to current PFI engines. The use of these advanced combustion engines in hybrid vehicles tend to deliver even greater benefits in terms of fuel economy.
Solouk and Shahbakhti [115]	Work on energy efficiency and fuel economy of RCCI engine developed into series hybrid electric vehicle (SHEV) architecture using various forms of energy management (EMC) strategies	GM Z19DTH diesel engine converted for RCCI operation 1.9L, CR= 15.1, rpm= 1000–3500	Matlab/Simulink was used to develop a forward-in-power HEV model	The simulation results indicated a fuel economy gain of 13.1 -14.2 %by using an RCCI engine for various driving cycles over a conventional SI engine in SHEV. Compared to a conventional CI engine, this fuel economy saving is limited to 3%, though NOx emissions are slightly lower. Simulation tests indicated that in more intense driving cycles

Solouk and  
Shahbakhti [116]

Research on the possible fuel efficiency of using a multi-mode (SI / HCCI / RCCI) LTC engine in a series Extended range electric vehicles (EREV) under the UDDS and HWFET cycles

GM 2.0 L Ecotec DI Turbocharged SI engine CR=9.2 E-motor is a 100 kW Remy synchronous induction, RMS PM100DX inverter, 5 kWh/65 kW LG Chem battery.

An in-house Matlab code was implemented to determine the combustion and efficiency parameters using the data acquired from dSPACE®, LabVIEW® and ACAP. The RCCI engine is integrated in a series hybrid powertrain based on a 2009 Saturn Vue vehicle

(e.g., US06), the RCCI engine provides more fuel economy improvement compared to less extreme driving cycles (e.g., UDDS).

The results indicated that the multi-mode LTC engine provides an increase of 2% more fuel economy over the best single-mode LTC engine operation. Both findings depend on the type of driving cycle and the fuel penalty for switching mode. Depending on the mode-switching fuel penalty value, the HCCI and RCCI engine modes can be the dominant optimal engine operating modes.

Solouk and  
Shahbakhti [117]

Experimental and numerical analysis of a multi-mode (SI/HCCI/RCCI) LTC-SI engine integrated with a parallel hybrid electric configuration under UDDS and HWFET cycles

GM 2.0 L Ecotec DI Turbocharged SI engine CR=9.2 E-motor is a 100 kW Remy synchronous induction, RMS PM100DX inverter, 5 kWh/65 kW LG Chem battery.

An in-house Matlab code was implemented to determine the combustion and efficiency parameters using the data acquired from dSPACE®, LabVIEW® and ACAP. The RCCI engine is integrated in a series hybrid powertrain based on a 2009 Saturn Vue vehicle

The simulation results showed a reduction in fuel consumption for the hybrid electrical powertrain with the LTC-SI multi-mode engine over a single-mode SI engine on the same powertrain configuration from 1.4% to 8.8%. In addition, the results for the UDDS driving cycle showed that the maximum benefit of the LTC-SI multi-mode engine is reached at a mild level of electrification, where the running time of the LTC mode increases drastically from 1.5% in PHEV to 30.5% in mild HEV.

Solouk and  
Shahbakhti [118]

Investigating the optimum fuel consumption improvement of a multi-mode (SI / HCCI / RCCI) LTC-SI range extender in a light-duty BEV configuration

GM 2.0 L Ecotec DI Turbocharged SI engine CR=9.2 E-motor is a 100 kW Remy synchronous induction, RMS PM100DX inverter, 5 kWh/65 kW LG Chem battery.

An in-house Matlab code was implemented to determine the combustion and efficiency parameters using the data acquired from dSPACE®, LabVIEW® and ACAP.

The simulation findings suggested that the single-mode HCCI and RCCI range extenders give fuel consumption increase of 11.0 per cent and 5.4 per cent respectively over a single-mode SI range extender in the city driving period. Such developments increase to 12.1% and 9.1% in the motorway cycles. Up to 1.4% higher fuel efficiency is achieved in multi-mode operation over various driving

Solouk and Shahbakhti [131]	Explore the ability of a multi-mode (SI / HCCI / RCCI) LTC-SI engine being incorporated in a parallel hybrid electric configuration;	A 2.0-l LTC-SI GM Ecotec LHU fuel-flexible engine and a 100-kW electrical powertrain connected to a 465 hp double-ended AC dynamometer E-motor is a 100 kW synchronous induction Remy, a 5 kWh/65 kW lithium-ion LG Chem battery.	An in-house Matlab code was implemented to determine the combustion and efficiency parameters using the data acquired from dSPACE @, LabVIEW @ and ACAP.	periods compared to single-mode operation HCCI/RCCI. As the driving cycle average required power increases, the HCCI mode predominates in the contribution of RCCI mode.  The results for the driving cycle of UDDS showed that the full advantage of the LTC-SI multi-mode engine is realized in the mild electrification stage, where the running time of the LTC mode increases dramatically from 5.0% in a PHEV to 20.5% in a mild HEV. In contrast with complete electrified vehicles such as PHEVs, in the multi-mode LTC-SI system, mild electrified vehicles such as mild HEVs are best suited for increasing fuel economy. The PHEV however has the lowest fuel consumption among the other stages of electrification.
Benajes et al. [119]	Explore the ability of series hybrid vehicle (SHV) CDC and RCCI to offer low engine-output and CO <sub>2</sub> emissions under the RDE and WLTC driving cycles	GM 1.9L light-duty CDC and diesel-gasoline RCCI engine in single-cylinder engine	The Opel Vectra is the vehicle selected to do the simulations. The analysis of the different powertrains proposed was tested using Gamma Technologies @'s commercial program GT-Suite.	Compared with the CDC scenario, the RCCI-SHV definition decreases the CO <sub>2</sub> emissions by half. The use of operating conditions optimized to meet Euro 6 limits as battery charging points allowed a SHV concept that presents NO <sub>x</sub> and soot emissions within regulation limits to be obtained without DPF and SCR systems being needed. The use of SHV in combination with RCCI substantially decreases the vehicle's overall fuel consumption while maintaining the emission rate of NO <sub>x</sub> and soot below the Euro 6 limits.
Benajes et al. [121]				The CDC-RCCI dual-mode model demonstrated changes in NO <sub>x</sub> and soot

	<p>Experimental and computational simulations to investigate the ability of a parallel complete hybrid electric vehicle (P2-FHEV) and a mild hybrid vehicle (MHEV) to achieve lower fuel consumption and NO<sub>x</sub> emissions than a traditional WLTC-cycle powertrain</p>	<p>Euro 4 GM 1.9L light-duty CDC and RCCI diesel-petrol engine in single-cylinder engine configuration and without any post-treatment system</p>	<p>The Opel Vectra is the vehicle selected to do the simulations. The analysis of the different powertrains proposed was tested using Gamma Technologies ®'s commercial program GT-Suite.</p>	<p>emissions, with comparable energy consumption and CO<sub>2</sub> emissions values compared to CDC. The parallel architecture offers a reduction in fuel consumption of about 20% compared to CDC. In addition, the mild hybrid technology with start-stop, torque assist, and regenerative braking capability demonstrated a reasonable balance between complexity and gain in fuel consumption.</p>
<p>Benajes et al. [122]</p>	<p>Experimental and numerical simulations to test the ability of hybrid electric vehicles with dual-fuel Mild (MHEV), Complete (FHEV) and Plug-in (PHEV) compared to OEM and traditional dual-fuel powertrain in the WLTC loop along with a life cycle review (LCA);</p>	<p>Euro 4 GM 1.9L light-duty CDC and RCCI diesel-petrol engine in single-cylinder engine configuration and without any post-treatment system</p>	<p>The Opel Vectra is the vehicle selected to do the simulations. The analysis of the different powertrains proposed was tested using Gamma Technologies ®'s commercial program GT-Suite. The LCA study is carried out with the GREET (the open source calculator developed by the national laboratory of Argonne);</p>	<p>Results show the PHEV has the highest fuel consumption and engine-out emission benefits. With this technology, the 50 g/km CO<sub>2</sub> aim for PHEVs with a medium battery size (15 kWh) can be achieved while NO<sub>x</sub> and soot rates are below the Euro 6 limits. Additionally, the RCCI technology demonstrates great advantages for the other hybrid platforms in achieving the Euro 6 soot point. The LCA shows that the PHEVs can achieve a 12% reduction in total CO<sub>2</sub> compared to the FHEVs, and a 30% reduction compared to the no-hybrid diesel model.</p>
<p>Garcia et al. [120]</p>	<p>Assessment of the range extender series hybrid vehicle utilising three combustion modes SI, PCIS and RCCI fuelled with bio-ethanol, as well as a numerical model LCA</p>	<p>The vehicle chosen to conduct the simulation is a Class B (Ford Fiesta) passenger car, which equips the SI engine used in one of the test benches.</p>	<p>The GT-Suite interface produced a 0D-powertrain application. The model was fed experimental results obtained in two motor test beds to accurately replicate the ICE behavior</p>	<p>The findings showed that a Class B vehicle may be fitted with a de-rated ICE working under advanced bioethanol-fueled combustion concepts. The RCCI mode had the full potential to reduce NO<sub>x</sub> emissions. However, by using high levels of H<sub>2</sub> the PCIS allowed to reduce the tank to wheel CO<sub>2</sub> emissions by up to 60 g/km.</p>

Garcia et al.  
[[130]]

Study the potential of RCCI combustion in hybrid trucks to reduce CO<sub>2</sub>, NO<sub>x</sub> and soot emissions.

Volvo Truck FL 18-ton and FE 25-ton. Engine use is a six-cylinder engine adapted for RCCI diesel-gasoline mode.

The GT-Suite interface produced a 0D-powertrain application. The model was fed experimental results obtained in a multi-cylinder engine test bench. The vehicle was validated with on road measurements for the diesel conventional powertrain.

2025 CO<sub>2</sub> targets for trucks can be achieved with the RCCI + hybrid technology. The vehicles achieve EU VI legislation for all payloads and driving cycles tested. The P2 with battery size of 8 kWh for FL 18-ton and 13 kWh for the FE 25-ton are the most cost-effective solutions.

---

## 7. Discussion and Future outlook

RCCI has been shown to be able to operate under transient conditions, which is a big step towards mass production applications; however, the precise feedback control system to control the engine parameters is necessary to minimize cycle-to-cycle variation and to ensure consistent and safe operation. In RCCI transient operation, transient effects of cylinder wall temperature, port injected fueling and thermal inertia of engine components play a significant role, and it has to be taken into account during obtaining optimized calibration maps and choosing control strategies. In addition, these factors usually cause a spike in emissions at the onset of load change.

Another challenge which inhibits commercialization of RCCI is being dual fuel nature and the difficulties of having two different separate tanks and two different injector systems. Single fuel RCCI operation can be achieved by utilizing single fuel tank with a low reactivity fuel together with a small secondary tank for a cetane improver or by generating the secondary fuel from the primary fuel through catalytic fuel reforming. Use of on-board fuel reforming can lead to a promising result, however, further investigations are needed for its transient operation and control system.

A mass-production application of the RCCI technology could alter conventional exhaust aftertreatment systems. Advanced aftertreatment systems are likely to become a significant limiting factor, particularly until more efficient catalysts for HC and CO oxidation at low temperatures become available. It was shown that 100% conversion efficiency for CO and more than 90% for UHC can be achieved with advanced DOC during long engine service periods.

The PHEV with RCCI combustion engine has shown the greatest advantages in terms of minimizing fuel consumption and engine-out emissions, and the 50 g/km CO<sub>2</sub> goal for medium battery sized PHEVs can be met, whereas the NO<sub>x</sub> and soot rates are below the Euro 6 limits.

Furthermore, RCCI strategy offers a great potential for fuel saving in SHEV configuration, which can be up to 12.6% higher over a modern SI engine.

Future work can consider investigations of RCCI combustion using alternative carbon-free fuels in single-fuel and transient mode operation. Co-optimization of fuels and engine systems could be developed to additionally leverage benefits in terms of efficiency and emissions improvement [132]. The work will focus on the application of transient RCCI control to tackle complex and real-world drive cycles. This includes full engine map operation, which is expected to include mode switching between dual fuel and RCCI combustion using advanced model-based controllers. This will set challenging tracking requirements to the coordinated air-fuel path strategy, while meeting constraints including RI, MPRR, and maximum allowable cyclic variability (e.g.  $COV < 5\%$ ). The progress in modelling and experiments is paving the way for future RCCI research concentrating on multi-cylinder engine controls and the emissions. The engine-out emissions, combustion noise, combustion stability, and safety should be directly incorporated as constraints in the design of optimal RCCI combustion controller.

In order to operate at high loads and handle large load transients, more model-based feedback controls should be required, while meeting the constraints on emission and combustion stability. With regards to COM approach, in order to improve the currently available models, a deeper study of the RCCI combustion modelling must be carried out under a wider range of operating conditions. Furthermore, efficient control of RCCI engines in real time during transient operation is challenging due to the need for high fidelity combustion models. Data-driven models can be implemented integrated to optimization methodologies to address these challenges and precisely predict engine performance [133]. More control inputs can be also considered to allow independent control of CA50, IMEP while being able to independently adjust MPRR and  $COV_{IMEP}$  within desired limits.

RCCI combustion with hybrid electrified powertrain has shown a large potential in order to meet the future emission legislations. RCCI engines can be optimally designed for HEV application, allowing high efficiency RCCI operation at target engine speed and loads, thus reducing the control challenges and calibration of RCCI engines. For hybrid configuration research, investigating biofuels and synthetic/e-fuels [134-137] in RCCI concepts according to upcoming emissions regulations for CO<sub>2</sub> will be of particular interest. In addition, since most of literature research focused on light duty vehicles, multi-mode hybrid powertrain can be investigated for commercial and medium/heavy duty trucks to achieve CO<sub>2</sub> target reductions.

## **8. Conclusion**

The present review shed light on the commercial viability of RCCI combustion strategy in automotive applications. Initial results from RCCI, showed that it takes higher number of cycles to reach the desired loads but with model-based control techniques the desired load can be obtained with much lower number of cycles. Single fuel RCCI can reduce HC emissions but NO<sub>x</sub> significantly increased, however high CO/HC emissions at low load is an inhibiting factor for RCCI to be commercialized. Replacement of gasoline with alcohols (e.g., E85) has increased the maximum achievable load during transient operation, and can be considered as the promising fuel for RCCI vehicular applications. In addition, switching to CDC could increase the power density of the engine at high loads in areas where the engine emission regulations are less stringent. The dual-mode CDC-RCCI also demonstrated improvements in NO<sub>x</sub> and soot emissions in hybrid systems, with comparable energy consumption and CO<sub>2</sub> emissions compared to CDC values. With regard to implementing RCCI engine controllers, it was found that advanced controllers perform well for a wide range of engine operating conditions and are stable when the operating region moves outside the calibrated region. It is important to choose the optimum control variable in different operating regions. Thus, a

framework can be implemented to select among different control variables. Results reviewed here, showed that PHEV technology along with use of RCCI engine has the potential to reduce local and global pollutant emissions. Overall, this review demonstrates the great commercial viability of RCCI combustion for automotive application in the short and medium-term.

## References

- [1] Reitz RD. Directions in internal combustion engine research. *Combustion and Flame*. 2013;1:1-8.
- [2] Kalghatgi G. Development of fuel/engine systems—the way forward to sustainable transport. *Engineering*. 2019.
- [3] Yao M, Zheng Z, Liu H. Progress and recent trends in homogeneous charge compression ignition (HCCI) engines. *Progress in energy and combustion science*. 2009;35:398-437.
- [4] Dempsey AB, Walker NR, Gingrich E, Reitz RD. Comparison of low temperature combustion strategies for advanced compression ignition engines with a focus on controllability. *Combustion Science and Technology*. 2014;186:210-41.
- [5] Saxena S, Bedoya ID. Fundamental phenomena affecting low temperature combustion and HCCI engines, high load limits and strategies for extending these limits. *Progress in Energy and Combustion Science*. 2013;39:457-88.
- [6] Agarwal AK, Singh AP, Maurya RK. Evolution, challenges and path forward for low temperature combustion engines. *Progress in Energy and Combustion Science*. 2017;61:1-56.
- [7] Kokjohn SL, Hanson RM, Splitter D, Reitz R. Fuel reactivity controlled compression ignition (RCCI): a pathway to controlled high-efficiency clean combustion. *International Journal of Engine Research*. 2011;12:209-26.
- [8] Kokjohn SL, Hanson RM, Splitter DA, Reitz RD. Experiments and modeling of dual-fuel HCCI and PCCI combustion using in-cylinder fuel blending. *SAE International Journal of Engines*. 2009;2:24-39.
- [9] Kokjohn S, Hanson R, Splitter D, Kaddatz J, Reitz R. Fuel reactivity controlled compression ignition (RCCI) combustion in light-and heavy-duty engines. *SAE International Journal of Engines*. 2011;4:360-74.
- [10] Singh AP, Kumar V, Agarwal AK. Evaluation of comparative engine combustion, performance and emission characteristics of low temperature combustion (PCCI and RCCI) modes. *Applied Energy*. 2020;278:115644.
- [11] Splitter D, Hanson R, Kokjohn S, Reitz RD. Reactivity controlled compression ignition (RCCI) heavy-duty engine operation at mid-and high-loads with conventional and alternative fuels. *SAE Technical Paper*; 2011.
- [12] Kakaee A-H, Rahnama P, Paykani A. CFD study of reactivity controlled compression ignition (RCCI) combustion in a heavy-duty diesel engine. *Periodica Polytechnica Transportation Engineering*. 2015;43:177-83.
- [13] Benajes J, García A, Monsalve-Serrano J, Villalta D. Exploring the limits of the reactivity controlled compression ignition combustion concept in a light-duty diesel engine and the influence of the direct-injected fuel properties. *Energy conversion and management*. 2018;157:277-87.
- [14] Kakaee A, Rahnama P, Paykani A. Numerical study of reactivity controlled compression ignition (RCCI) combustion in a heavy-duty diesel engine using 3D-CFD coupled with chemical kinetics. *International Journal of Automotive Engineering*. 2014;4:792-804.

- [15] Paykani A, Kakaee A-H, Rahnama P, Reitz RD. Progress and recent trends in reactivity-controlled compression ignition engines. *International Journal of Engine Research*. 2016;17:481-524.
- [16] Benajes J, García A, Monsalve-Serrano J, Boronat V. Achieving clean and efficient engine operation up to full load by combining optimized RCCI and dual-fuel diesel-gasoline combustion strategies. *Energy Conversion and Management*. 2017;136:142-51.
- [17] Samulski MJ, Jackson CC. Effects of steady-state and transient operation on exhaust emissions from nonroad and highway diesel engines. SAE Technical Paper; 1998.
- [18] Swain DM, Jackson CC, Lindhjem CE, Hoffman GJ. A method for comparing transient NOx emissions with weighted steady state test results. SAE Technical Paper; 1998.
- [19] Reitz RD, Duraisamy G. Review of high efficiency and clean reactivity controlled compression ignition (RCCI) combustion in internal combustion engines. *Progress in Energy and Combustion Science*. 2015;46:12-71.
- [20] Mikulski M, Balakrishnan PR, Hunicz J. Natural gas-diesel reactivity controlled compression ignition with negative valve overlap and in-cylinder fuel reforming. *Applied Energy*. 2019;254:113638.
- [21] Olsson J-O, Tunestål P, Johansson B. Closed-loop control of an HCCI engine. *SAE Transactions*. 2001:1076-85.
- [22] Willems F, Kupper F, Ramesh S, Indrajana A, Doosje E. Coordinated air-fuel path control in a diesel-E85 RCCI engine. SAE Technical Paper; 2019.
- [23] Dalha I, Said MA, Karim ZA, Firmansyah F. Strategies and methods of RCCI combustion: A review. *AIP Conference Proceedings: AIP Publishing*; 2018. p. 030006.
- [24] Splitter D, Wissink M, DelVescovo D, Reitz R. Improving the understanding of intake and charge effects for increasing RCCI engine efficiency. *SAE International Journal of Engines*. 2014;7:913-27.
- [25] Mikulski M, Balakrishnan PR, Doosje E, Bekdemir C. Variable valve actuation strategies for better efficiency load range and thermal management in an RCCI engine. SAE Technical Paper; 2018.
- [26] Bharath AN, Reitz R, Rutland C. Divided Exhaust Period Implementation in a Light-Duty Turbocharged Dual-Fuel RCCI Engine for Improved Fuel Economy and Aftertreatment Thermal Management: A Simulation Study. *SAE International Journal of Engines*. 2018;11:1251-72.
- [27] Pachiannan T, Zhong W, Rajkumar S, He Z, Leng X, Wang Q. A literature review of fuel effects on performance and emission characteristics of low-temperature combustion strategies. *Applied Energy*. 2019;251:113380.
- [28] Valladolid PG, Tunestål P, Monsalve-Serrano J, García A, Hyvönen J. Impact of diesel pilot distribution on the ignition process of a dual fuel medium speed marine engine. *Energy Conversion and Management*. 2017;149:192-205.
- [29] Mikulski M, Ramesh S, Bekdemir C. Reactivity Controlled Compression Ignition for clean and efficient ship propulsion. *Energy*. 2019;182:1173-92.
- [30] Chuahy FD, Kokjohn SL. Effects of reformed fuel composition in “single” fuel reactivity controlled compression ignition combustion. *Applied Energy*. 2017;208:1-11.
- [31] Hariharan D, Boldaji MR, Yan Z, Mamalis S, Lawler B. Single-fuel reactivity controlled compression ignition through catalytic partial oxidation reformation of diesel fuel. *Fuel*. 2020;264:116815.
- [32] Hariharan D, Gainey B, Yan Z, Mamalis S, Lawler B. Experimental study of the effect of start of injection and blend ratio on single fuel reformat RCCI. *Journal of Engineering for Gas Turbines and Power*. 2020;142.

- [33] Li Y, Jia M, Xu L, Bai X-S. Multiple-objective optimization of methanol/diesel dual-fuel engine at low loads: A comparison of reactivity controlled compression ignition (RCCI) and direct dual fuel stratification (DDFS) strategies. *Fuel*. 2020;262:116673.
- [34] Xu G, Jia M, Li Y, Chang Y, Liu H, Wang T. Evaluation of variable compression ratio (VCR) and variable valve timing (VVT) strategies in a heavy-duty diesel engine with reactivity controlled compression ignition (RCCI) combustion under a wide load range. *Fuel*. 2019;253:114-28.
- [35] García A, Monsalve-Serrano J, Roso VR, Martins MES. Evaluating the emissions and performance of two dual-mode RCCI combustion strategies under the World Harmonized Vehicle Cycle (WHVC). *Energy Conversion and Management*. 2017;149:263-74.
- [36] García A, Piqueras P, Monsalve-Serrano J, Sari RL. Sizing a conventional diesel oxidation catalyst to be used for RCCI combustion under real driving conditions. *Applied Thermal Engineering*. 2018;140:62-72.
- [37] Chuahy FD, Kokjohn SL. Solid oxide fuel cell and advanced combustion engine combined cycle: A pathway to 70% electrical efficiency. *Applied energy*. 2019;235:391-408.
- [38] Hanson R, Spannauer S, Gross C, Reitz RD, Curran S, Storey J, et al. Highway fuel economy testing of an RCCI series hybrid vehicle. *SAE Technical Paper*; 2015.
- [39] Li J, Yang W, Zhou D. Review on the management of RCCI engines. *Renewable and Sustainable Energy Reviews*. 2017;69:65-79.
- [40] Hagen JR, Filipi Z, Assanis DN. Transient diesel emissions: analysis of engine operation during a tip-in. *SAE Technical Paper*; 2006.
- [41] Rakopoulos CD, Giakoumis EG. Diesel engine transient operation: principles of operation and simulation analysis: Springer Science & Business Media; 2009.
- [42] Glewen W, Heuwetter D, Foster DE, Andrie M, Krieger R. Analysis of deviations from steady state performance during transient operation of a light duty diesel engine. *SAE International Journal of Engines*. 2012;5:909-22.
- [43] Saracino R, Gaballo MR, Mannal S, Motz S, Carlucci A, Benegiamo M. Cylinder pressure-based closed loop combustion control: A valid support to fulfill current and future requirements of diesel powertrain systems. *SAE Technical Paper*; 2015.
- [44] Candel S. Combustion dynamics and control: Progress and challenges. *Proceedings of the combustion institute*. 2002;29:1-28.
- [45] Hanson RM. Experimental investigation of transient RCCI combustion in a light duty diesel engine: The University of Wisconsin-Madison; 2013.
- [46] Hanson R, Reitz RD. Transient RCCI operation in a light-duty multi-cylinder engine. *SAE International Journal of Engines*. 2013;6:1694-705.
- [47] Arora JK, Shahbakhti M. Real-Time Closed-Loop Control of a Light-Duty RCCI Engine During Transient Operations. *SAE Technical Paper*; 2017.
- [48] Kondipati NNT, Arora JK, Bidarvatan M, Shahbakhti M. Modeling, design and implementation of a closed-loop combustion controller for an RCCI engine. *American Control Conference (ACC), 2017: IEEE; 2017*. p. 4747-52.
- [49] Hanson R, Reitz RD. Experimental investigation of engine speed transient operation in a light duty RCCI engine. *SAE International Journal of Engines*. 2014;7:888-901.
- [50] Chung J, Min K, Oh S, Sunwoo M. In-cylinder pressure based real-time combustion control for reduction of combustion dispersions in light-duty diesel engines. *Applied Thermal Engineering*. 2016;99:1183-9.
- [51] Wu Y, Hanson R, Reitz RD. Investigation of combustion phasing control strategy during reactivity controlled compression ignition (RCCI) multicylinder engine load transitions. *Journal of Engineering for Gas Turbines and Power*. 2014;136:091511.

- [52] Sadabadi KK, Shahbakhti M. Dynamic Modelling and Controller Design of Combustion Phasing for an RCCI Engine. ASME 2016 Dynamic Systems and Control Conference: American Society of Mechanical Engineers; 2016. p. V002T20A4-VT20A4.
- [53] Indrajana A, Bekdemir C, Luo X, Willems F. Robust multivariable feedback control of natural gas-diesel RCCI combustion. IFAC-PapersOnLine. 2016;49:217-22.
- [54] Raut A, Irdmoua BK, Shahbakhti M. Dynamic modeling and model predictive control of an RCCI engine. Control Engineering Practice. 2018;81:129-44.
- [55] Khodadadi Sadabadi K, Shahbakhti M, Bharath AN, Reitz RD. Modeling of combustion phasing of a reactivity-controlled compression ignition engine for control applications. International Journal of Engine Research. 2016;17:421-35.
- [56] Guardiola C, Pla B, Bares P, Barbier A. A combustion phasing control-oriented model applied to an RCCI engine. IFAC-PapersOnLine. 2018;51:119-24.
- [57] Willems F. Is cylinder pressure-based control required to meet future HD legislation? IFAC-PapersOnLine. 2018;51:111-8.
- [58] Bekdemir C, Baert R, Willems F, Somers B. Towards control-oriented modeling of natural gas-diesel RCCI combustion. SAE Technical Paper; 2015.
- [59] Bidarvatan M, Shahbakhti M, Jazayeri S, Koch C. Cycle-to-cycle modeling and sliding mode control of blended-fuel HCCI engine. Control Engineering Practice. 2014;24:79-91.
- [60] Del Re L, Allgöwer F, Glielmo L, Guardiola C, Kolmanovsky I. Automotive model predictive control: models, methods and applications: Springer; 2010.
- [61] Ravi N, Roelle MJ, Liao H-H, Jungkunz AF, Chang C-F, Park S, et al. Model-based control of HCCI engines using exhaust recompression. IEEE Transactions on Control Systems Technology. 2009;18:1289-302.
- [62] Kakooe A, Bakhshan Y, Barbier A, Bares P, Guardiola C. Modeling combustion timing in an RCCI engine by means of a control oriented model. Control Engineering Practice. 2020;97:104321.
- [63] Raut A, Bidarvatan M, Borhan H, Shahbakhti M. Model predictive control of an RCCI engine. 2018 Annual American Control Conference (ACC): IEEE; 2018. p. 1604-9.
- [64] Irdmoua B, Rizvi SZ, Veini JM, Nabert J, Shahbakhti M. Data-driven Modeling and Predictive Control of Combustion Phasing for RCCI Engines. 2019 American Control Conference (ACC): IEEE; 2019. p. 1617-22.
- [65] Basina LA, Irdmoua BK, Velni JM, Borhan H, Naber JD, Shahbakhti M. Data-driven Modeling and Predictive Control of Maximum Pressure Rise Rate in RCCI Engines. 2020 IEEE Conference on Control Technology and Applications (CCTA): IEEE; 2020. p. 94-9.
- [66] Garcia P, Tunestal P. Experimental investigation on CNG-diesel combustion modes under highly diluted conditions on a light duty diesel engine with focus on injection strategy. SAE International Journal of Engines. 2015;8:2177-87.
- [67] Doosje E, Willems F, Baert R. Experimental demonstration of RCCI in heavy-duty engines using diesel and natural gas. SAE Technical Paper; 2014.
- [68] Hanson R, Reitz R. Investigation of Cold Starting and Combustion Mode Switching as Methods to Improve Low Load RCCI Operation. Journal of Engineering for Gas Turbines and Power. 2016;138:092802.
- [69] Benajes J, García A, Monsalve-Serrano J, Balloul I, Pradel G. An assessment of the dual-mode reactivity controlled compression ignition/conventional diesel combustion capabilities in a EURO VI medium-duty diesel engine fueled with an intermediate ethanol-gasoline blend and biodiesel. Energy Conversion and Management. 2016;123:381-91.
- [70] Benajes J, García A, Monsalve-Serrano J, Sari RL. Fuel consumption and engine-out emissions estimations of a light-duty engine running in dual-mode RCCI/CDC with different fuels and driving cycles. Energy. 2018;157:19-30.

- [71] García A, Monsalve-Serrano J, Villalta D, Sari RL. Performance of a conventional diesel aftertreatment system used in a medium-duty multi-cylinder dual-mode dual-fuel engine. *Energy conversion and management*. 2019;184:327-37.
- [72] García A, Monsalve-Serrano J, Villalta D, Sari R. Fuel sensitivity effects on dual-mode dual-fuel combustion operation for different octane numbers. *Energy Conversion and Management*. 2019;201:112137.
- [73] Xu G, Monsalve-Serrano J, Jia M, García A. Computational optimization of the dual-mode dual-fuel concept through genetic algorithm at different engine loads. *Energy Conversion and Management*. 2020;208:112577.
- [74] Benajes J, García A, Monsalve-Serrano J, Boronat V. Gaseous emissions and particle size distribution of dual-mode dual-fuel diesel-gasoline concept from low to full load. *Applied Thermal Engineering*. 2017;120:138-49.
- [75] Macián V, Bermúdez V, Villalta D, Soto L. Effects of low-pressure EGR on gaseous emissions and particle size distribution from a dual-mode dual-fuel (DMDF) concept in a medium-duty engine. *Applied Thermal Engineering*. 2019;163:114245.
- [76] Benajes J, Pastor JV, García A, Monsalve-Serrano J. The potential of RCCI concept to meet EURO VI NO<sub>x</sub> limitation and ultra-low soot emissions in a heavy-duty engine over the whole engine map. *Fuel*. 2015;159:952-61.
- [77] Benajes J, García A, Monsalve-Serrano J, Sari RL. Experimental investigation on the efficiency of a diesel oxidation catalyst in a medium-duty multi-cylinder RCCI engine. *Energy conversion and management*. 2018;176:1-10.
- [78] Piqueras P, García A, Monsalve-Serrano J, Ruiz MJ. Performance of a diesel oxidation catalyst under diesel-gasoline reactivity controlled compression ignition combustion conditions. *Energy Conversion and Management*. 2019;196:18-31.
- [79] Ren S, Wang B, Zhang J, Wang Z, Wang J. Application of dual-fuel combustion over the full operating map in a heavy-duty multi-cylinder engine with reduced compression ratio and diesel oxidation catalyst. *Energy Conversion and Management*. 2018;166:1-12.
- [80] Indrajana A, Bekdemir C, Feru E, Willems F. Towards model-based control of RCCI-CDF mode-switching in dual fuel engines. *SAE Technical Paper*; 2018.
- [81] Divekar P, Han X, Tan Q, Asad U, Yanai T, Chen X, et al. Mode switching to improve low load efficiency of an ethanol-diesel dual-fuel engine. *SAE Technical Paper*; 2017.
- [82] Hutter R, Hänggi S, Albin T, Onder CH. Optimal transition control between combustion modes in a Diesel-ignited gas engine. *Control Engineering Practice*. 2020;97:104327.
- [83] Guardiola C, Pla B, Bares P, Barbier A. Closed-loop control of a dual-fuel engine working with different combustion modes using in-cylinder pressure feedback. *International Journal of Engine Research*. 2020;21:484-96.
- [84] Paykani A, Kakaee A-H, Rahnama P, Reitz RD. Effects of diesel injection strategy on natural gas/diesel reactivity controlled compression ignition combustion. *Energy*. 2015;90:814-26.
- [85] Kakaee A-H, Rahnama P, Paykani A. Influence of fuel composition on combustion and emissions characteristics of natural gas/diesel RCCI engine. *Journal of Natural Gas Science and Engineering*. 2015;25:58-65.
- [86] Kakaee A-H, Jafari P, Paykani A. Numerical Study of Natural Gas/Diesel Reactivity Controlled Compression Ignition Combustion with Large Eddy Simulation and Reynolds-Averaged Navier–Stokes Model. *Fluids*. 2018;3:24.
- [87] Rahnama P, Paykani A, Reitz RD. A numerical study of the effects of using hydrogen, reformer gas and nitrogen on combustion, emissions and load limits of a heavy duty natural gas/diesel RCCI engine. *Applied energy*. 2017;193:182-98.

- [88] Rahnama P, Paykani A, Bordbar V, Reitz RD. A numerical study of the effects of reformer gas composition on the combustion and emission characteristics of a natural gas/diesel RCCI engine enriched with reformer gas. *Fuel*. 2017;209:742-53.
- [89] Kousheshi N, Yari M, Paykani A, Saberi Mehr A, de la Fuente GF. Effect of Syngas Composition on the Combustion and Emissions Characteristics of a Syngas/Diesel RCCI Engine. *Energies*. 2020;13:212.
- [90] Benajes J, Molina S, García A, Monsalve-Serrano J. Effects of direct injection timing and blending ratio on RCCI combustion with different low reactivity fuels. *Energy Conversion and Management*. 2015;99:193-209.
- [91] Curran S, Hanson R, Wagner R. Effect of E85 on RCCI performance and emissions on a multi-cylinder light-duty diesel engine. *SAE Technical Paper*; 2012.
- [92] Li Y, Jia M, Liu Y, Xie M. Numerical study on the combustion and emission characteristics of a methanol/diesel reactivity controlled compression ignition (RCCI) engine. *Applied energy*. 2013;106:184-97.
- [93] DelVescovo D, Wang H, Wissink M, Reitz RD. Isobutanol as both low reactivity and high reactivity fuels with addition of di-tert butyl peroxide (DTBP) in RCCI combustion. *SAE International Journal of Fuels and Lubricants*. 2015;8:329-43.
- [94] Mohammadian A, Chehrmonavari H, Kakaee A, Paykani A. Effect of injection strategies on a single-fuel RCCI combustion fueled with isobutanol/isobutanol+ DTBP blends. *Fuel*. 2020;278:118219.
- [95] Li J, Yang W, An H, Zhao D. Effects of fuel ratio and injection timing on gasoline/biodiesel fueled RCCI engine: A modeling study. *Applied Energy*. 2015;155:59-67.
- [96] Hanson R, Curran S, Wagner R, Reitz R. Effects of biofuel blends on RCCI combustion in a light-duty, multi-cylinder diesel engine. *SAE International Journal of Engines*. 2013;6:488-503.
- [97] Hanson R, Curran S, Wagner R, Reitz RD. Effects of biofuel blends on RCCI combustion in a light-duty, multi-cylinder diesel engine. *SAE International Journal of Engines*. 2013;6:488-503.
- [98] Curran S, Gao Z, Wagner R. Reactivity controlled compression ignition drive cycle emissions and fuel economy estimations using vehicle systems simulations with E30 and ULSD. *SAE International Journal of Engines*. 2014;7:902-12.
- [99] Dempsey AB, Walker NR, Reitz R. Effect of cetane improvers on gasoline, ethanol, and methanol reactivity and the implications for RCCI combustion. *SAE International Journal of Fuels and Lubricants*. 2013;6:170-87.
- [100] Chuahy FD, Kokjohn SL. High efficiency dual-fuel combustion through thermochemical recovery and diesel reforming. *Applied Energy*. 2017;195:503-22.
- [101] Zhang F, Xu H, Rezaei SZ, Kalghatgi G, Shuai S-J. Combustion and emission characteristics of a PPCI engine fuelled with diesel. *SAE Technical Paper*; 2012.
- [102] Gross CW. Investigation of RCCI operation with customized pistons in a light-duty multi-cylinder engine using diesel. The University of Wisconsin-Madison; 2016.
- [103] Gross CW, Reitz RD. Transient "Single-Fuel" RCCI Operation With Customized Pistons in a Light-Duty Multicylinder Engine. *Journal of Engineering for Gas Turbines and Power*. 2017;139:032801.
- [104] Weiss M, Zerfass A, Helmers E. Fully electric and plug-in hybrid cars-An analysis of learning rates, user costs, and costs for mitigating CO<sub>2</sub> and air pollutant emissions. *Journal of cleaner production*. 2019;212:1478-89.
- [105] Taymaz I, Benli M. Emissions and fuel economy for a hybrid vehicle. *Fuel*. 2014;115:812-7.

- [106] García A, Monsalve-Serrano J, Sari R, Dimitrakopoulos N, Tunér M, Tunestål P. Performance and emissions of a series hybrid vehicle powered by a gasoline partially premixed combustion engine. *Applied Thermal Engineering*. 2019;150:564-75.
- [107] Hong J, Zhao L, Lei Y, Gao B. Architecture optimization of hybrid electric vehicles with future high-efficiency engine. *Energies*. 2018;11:1148.
- [108] Lawler B, Ortiz-Soto E, Gupta R, Peng H, Filipi ZS. Hybrid electric vehicle powertrain and control strategy optimization to maximize the synergy with a gasoline HCCI engine. *SAE International Journal of Engines*. 2011;4:1115-26.
- [109] Ahn K, Whitefoot J, Babajimopoulos A, Ortiz-Soto E, Papalambros PY. Homogeneous charge compression ignition technology implemented in a hybrid electric vehicle: System optimal design and benefit analysis for a power-split architecture. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*. 2013;227:87-98.
- [110] Chan CC. The state of the art of electric, hybrid, and fuel cell vehicles. *Proceedings of the IEEE*. 2007;95:704-18.
- [111] Mi C, Masrur MA. *Hybrid electric vehicles: principles and applications with practical perspectives*: John Wiley & Sons; 2017.
- [112] Gao Z, Curran S, Daw CS, Wagner RM. Light-duty drive cycle simulations of diesel engine-out exhaust properties for an RCCI-enabled vehicle. Oak Ridge National Laboratory (ORNL); Fuels, Engines and Emissions Research Center; 2013.
- [113] Gao Z, Curran SJ, Parks JE, Smith DE, Wagner RM, Daw CS, et al. Drive cycle simulation of high efficiency combustions on fuel economy and exhaust properties in light-duty vehicles. *Applied Energy*. 2015;157:762-76.
- [114] Solouk A, Shahbakhti M, Mahjoob MJ. Energy management and control of a hybrid electric vehicle with an integrated low temperature combustion (LTC) engine. *Proceedings of the ASME Dynamic Systems and Control Conference, San Antonio, TX, USA2014*.
- [115] Solouk A, Shahbakhti M. Energy Optimization and Fuel Economy Investigation of a Series Hybrid Electric Vehicle Integrated with Diesel/RCCI Engines. *Energies*. 2016;9:1020.
- [116] Solouk A, Shakiba-herfeh M, Kannan K, Solmaz H, Dice P, Bidarvatan M, et al. Fuel Economy Benefits of Integrating a Multi-Mode Low Temperature Combustion (LTC) Engine in a Series Extended Range Electric Powertrain. *SAE Technical Paper*; 2016.
- [117] Solouk A, Shakiba-herfeh M, Shahbakhti M. Analysis and Control of a Torque Blended Hybrid Electric Powertrain with a Multi-Mode LTC-SI Engine. *SAE International Journal of Alternative Powertrains*. 2017;6:54-67.
- [118] Solouk A, Tripp J, Shakiba-Herfeh M, Shahbakhti M. Fuel consumption assessment of a multi-mode low temperature combustion engine as range extender for an electric vehicle. *Energy Conversion and Management*. 2017;148:1478-96.
- [119] Benajes J, García A, Monsalve-Serrano J, Sari R. Potential of RCCI series hybrid vehicle architecture to meet the future CO<sub>2</sub> targets with low engine-out emissions. *Applied Sciences*. 2018;8:1472.
- [120] García A, Monsalve-Serrano J, Martínez-Boggio S, Roso VR, Santos NDSA. Potential of bio-ethanol in different advanced combustion modes for hybrid passenger vehicles. *Renewable Energy*. 2019.
- [121] Benajes J, García A, Monsalve-Serrano J, Martínez-Boggio S. Optimization of the parallel and mild hybrid vehicle platforms operating under conventional and advanced combustion modes. *Energy Conversion and Management*. 2019;190:73-90.
- [122] Benajes J, García A, Monsalve-Serrano J, Martínez-Boggio S. Emissions reduction from passenger cars with RCCI plug-in hybrid electric vehicle technology. *Applied Thermal Engineering*. 2020;164:114430.

- [123] García A, Monsalve-Serrano J. Analysis of a series hybrid vehicle concept that combines low temperature combustion and biofuels as power source. *Results in Engineering*. 2019;1:100001.
- [124] García A, Carlucci P, Monsalve-Serrano J, Valletta A, Martínez-Boggio S. Energy management strategies comparison for a parallel full hybrid electric vehicle using Reactivity Controlled Compression Ignition combustion. *Applied Energy*. 2020;272:115191.
- [125] Samaras C, Meisterling K. Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy. ACS Publications; 2008.
- [126] Tagliaferri C, Evangelisti S, Acconcia F, Domenech T, Ekins P, Barletta D, et al. Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. *Chemical Engineering Research and Design*. 2016;112:298-309.
- [127] Benajes J, Garcia A, Monsalve-Serrano J, Martinez S. Dual-Fuel Ethanol-Diesel Technology Applied in Mild and Full Hybrid Powertrains. SAE Technical Paper; 2019.
- [128] García A, Monsalve-Serrano J, Martínez-Boggio S, Wittek K. Potential of hybrid powertrains in a variable compression ratio downsized turbocharged VVA Spark Ignition engine. *Energy*. 2020:117039.
- [129] Benajes J, García A, Monsalve-Serrano J, Martinez S. Plug-in Electric Vehicles fueled with Green Fuels in LTC mode. SAE Technical Paper; 2020.
- [130] García A, Monsalve-Serrano J, Martinez-Boggio S, Gaillard P, Poussin O, Amer AA. Dual fuel combustion and hybrid electric powertrains as potential solution to achieve 2025 emissions targets in medium duty trucks sector. *Energy Conversion and Management*. 2020;224:113320.
- [131] Solouk A, Shakiba-Herfeh M, Arora J, Shahbakhti M. Fuel consumption assessment of an electrified powertrain with a multi-mode high-efficiency engine in various levels of hybridization. *Energy Conversion and Management*. 2018;155:100-15.
- [132] Paykani A, Frouzakis CE, Boulouchos K. Numerical optimization of methane-based fuel blends under engine-relevant conditions using a multi-objective genetic algorithm. *Applied Energy*. 2019;242:1712-24.
- [133] Xia L, de Jager B, Donkers T, Willems F. Robust constrained optimization for RCCI engines using nested penalized particle swarm. *Control Engineering Practice*. 2020;99:104411.
- [134] Cai L, Jacobs S, Langer R, vom Lehn F, Heufer KA, Pitsch H. Auto-ignition of oxymethylene ethers (OMEn, n= 2–4) as promising synthetic e-fuels from renewable electricity: shock tube experiments and automatic mechanism generation. *Fuel*. 2020;264:116711.
- [135] Benajes J, García A, Monsalve-Serrano J, Sari R. Clean and efficient dual-fuel combustion using OMEx as high reactivity fuel: Comparison to diesel-gasoline calibration. *Energy Conversion and Management*. 2020;216:112953.
- [136] García A, Monsalve-Serrano J, Sanchís EJ, Fogué-Robles Á. Exploration of suitable injector configuration for dual-mode dual-fuel engine with diesel and OMEx as high reactivity fuels. *Fuel*. 2020;280:118670.
- [137] García A, Monsalve-Serrano J, Villalta D, Sari RL, Zavaleta VG, Gaillard P. Potential of e-Fischer Tropsch diesel and oxymethyl-ether (OMEx) as fuels for the dual-mode dual-fuel concept. *Applied Energy*. 2019;253:113622.