

Experimental Investigation of Engine Speed Transient Operation in a Light Duty RCCI Engine

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ABSTRACT

Reactivity Controlled Compression Ignition (RCCI) is an engine combustion strategy that utilizes in-cylinder fuel blending to produce low NO_x and PM emissions while maintaining high thermal efficiency. The current study investigates RCCI and conventional diesel combustion (CDC) operation in a light-duty multi-cylinder engine over transient operating conditions using a high-bandwidth, transient capable engine test cell. Transient RCCI and CDC combustion and emissions results are compared over an up-speed change from 1,000 to 2,000 rev/min. and a down-speed change from 2,000 to 1,000 rev/min. at a constant 2.0 bar BMEP load.

The engine experiments consisted of in-cylinder fuel blending with port fuel-injection (PFI) of gasoline and early-cycle, direct-injection (DI) of ultra-low sulfur diesel (ULSD) for the RCCI tests and the same ULSD for the CDC tests. At the selected engine load, a step speed change was commanded and both combustion modes were compared for performance and emissions using fast response HC, NO and PM instruments. Optimized intake conditions (i.e., intake pressure, temperature and exhaust gas recirculation (EGR)) were used to explore the robustness of RCCI using real-world operating conditions. It was found that the engine was able to operate in the RCCI combustion mode using production level engine hardware with significantly lower engine-out PM and NO_x emissions than CDC over the specified transient engine operating conditions.

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INTRODUCTION

Currently, as seen in the literature, a large fraction of fundamental engine research is conducted at steady-state operating conditions. In contrast, light-duty US Federal certification testing can involve operating the vehicle under simulated realistic operating conditions, usually over transient test cycles such as the US EPA FTP75 [1]. While it is convenient to use and/or extrapolate steady-state results to compare with transient results, the literature has shown that engine performance under steady-state conditions is not always a reliable indicator of transient or in-use emissions [2,3,4,5]. Significant portions of the total emissions are generated during the short periods when rapid speed or load changes occur [6].

Work by the US EPA [2] compared results of the ISO 8-mode steady-state duty cycle test with several transient test cycles for a number of different engines. They found that NO_x could be predicted within 10% but HC and PM were 60% under-predicted. Significant variation in emissions for each test cycle and each engine were found. Additional work [3] had better steady-state to transient agreement, but still had upwards of 60% under-prediction of HC and PM emissions. These results

show that it is very difficult to predict transient test cycle emissions based on steady-state results. These findings are important because low temperature combustion (LTC) strategies are being developed with most of the data in the literature being taken at steady-state. In order to assess their performance in vehicle operation, assumptions need to be made on how they will respond to transient operation and/or experiments need to be done to verify transient LTC performance. Such experiments are difficult to do because of the complex nature of LTC, so much less is known about transient LTC operation compared to high temperature combustion transient operation in the literature.

The focus of this paper is to investigate transient operation of Reactivity Controlled Compression Ignition (RCCI) combustion as compared to transient operation with conventional diesel combustion (CDC). RCCI uses two fuels with different auto-ignition characteristics such that there are optimized fuel reactivity and equivalence ratio gradients within the combustion chamber [7,8,9,10,11,12,13]. Having optimized reactivity stratification allows for low engine-out PM and NO_x emissions because of the low peak combustion temperature and control of the heat release rate (HRR) even over a wide range of

operating conditions. The use of two fuels also allows the global and local reactivities to be optimized on a cycle-by-cycle basis with use of an appropriate engine controller.

EXPERIMENTAL CONFIGURATION

Engine and Controls

The engine experiments were performed on a modified General Motors 1.9 liter EURO IV specification diesel engine equipped with standard production hardware, including a variable geometry turbine (VGT), a high pressure (HP) EGR system and variable swirl intake port geometry. Modifications were made to the engine in order to inject fuel into the intake manifold. The standard intake manifold was machined to accept the additional gasoline port-fuel injectors (PFI-0). Additionally, the OEM engine control unit (ECU) was replaced by a Drivven controller to allow full access to all relevant engine operating parameters and to allow for control over the additional port-fuel injectors. The Drivven system allows real-time control of the supplied 2-D torque-based engine maps for direct injection (DI) and PFI timing(s), fuel injection pressure, high pressure EGR quantity and swirl vane position. It must be noted that the Drivven controller is supplied as a steady-state controller with no transient tables or controls that would be present in the OEM controller.

Table 1 contains the engine specifications and an engine system schematic is shown in Figure 1. As previously mentioned, all standard production hardware was used with the exception of the intercooler, ECU, the exhaust system downstream of the turbine outlet and the PFI system. An air-to-water intercooler was used to replace the OEM air-to-air intercooler, but cooling water temperature and flow rates were set to replicate the intake temperatures seen with the OEM system.

Table 1. Engine Specifications

Engine Type	EURO IV Diesel
Bore	82 mm
Stroke	90.4 mm
Displacement	1.9 liters
Cylinder Configuration	Inline 4, 4 valves per cylinder
Swirl Ratio	Variable (2.2-5.6)
Compression Ratio	17.5
Piston Bowl Geometry	OEM Re-entrant bowl
EGR System	Hybrid High/Low Pressure, cooled
ECU (OEM)	Bosch EDC16
ECU (new)	Drivven
Common Rail Injectors	148° Included Angle 7 holes, 0.141 mm hole dia. 440 flow number.
Port Fuel Injectors	2.27 g/s steady flow 340 kPa fuel pressure

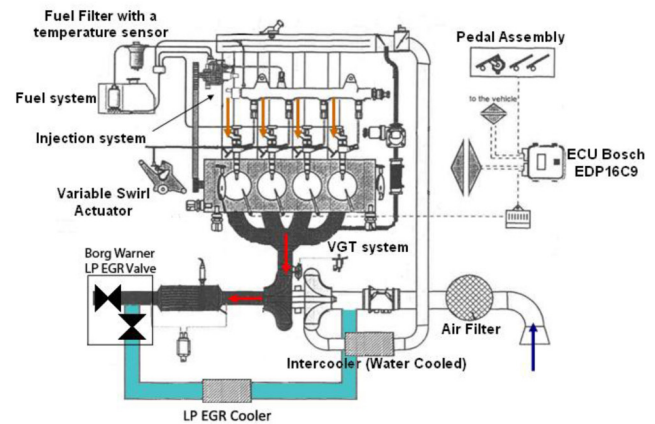


Figure 1. Schematic of the test engine

Controls

Two engine combustion phasing control strategies were used for RCCI, namely open-loop and closed-loop, while CDC was operated in open-loop only. For open-loop control, the Drivven controller was used with its original configuration with no feedback control of the combustion phasing. The Drivven controller operates by controlling the intake pressure, EGR, fuel injection parameters and common-rail fuel pressure by 2-D torque-based tables. Similar to how the OEM controller operates, from the desired pedal position, a desired torque value is calculated. From this torque value, a fueling rate is calculated based on the injection pressure and engine speed. The resulting tables are sized in 2 mm³/cycle and 500 rev/min. increments. The stock Drivven controller has tables populated with values for CDC that are a steady-state representation of the OEM 2005 EURO IV calibration. A direct comparison is not possible as the OEM results are proprietary and modifications for the Drivven system do not allow the use of the OEM controller. However, these values were found to give similar steady-state emissions results as those from the OEM controller [26]. For RCCI operation, additional tables to control the gasoline PFI system were added. Next, these tables were re-calibrated at steady-state with RCCI specific values to give the desired combustion phasing and emissions based on results from [7,8,9,10,11,12,13]. To operate the engine, the controller is given a simulated accelerator pedal command. From this pedal position command and the current engine speed, the interpolated table value is used for the appropriate engine control parameter, such as the PFI duration or target intake manifold pressure.

For closed-loop RCCI operation, the same torque-based controller was used with additional code to control combustion phasing on a cycle-by-cycle basis. For closed-loop operation, a PID controller was used to control combustion phasing. In the RCCI tests using closed-loop control, CA50 was calculated from the cylinder 2 pressure trace of each cycle and compared to a target value from a 2-D table (similar to the other tables). Based on the difference of the target vs. the measured value, the PID acts to bring the measured value towards the target value by manipulating a user defined control metric. Since

RCCI combustion phasing has been found to be most sensitive to the PFI to DI fueling ratio [9], it was chosen as the control metric. Thus, the RCCI closed-loop controller adjusts the PFI ratio on a cycle-by-cycle basis by adjusting the gasoline PFI and diesel DI injection duration commands to advance or retard CA50 as needed to match the target value.

Fuels

The fuels used in the tests were a 96 research octane number (RON), certification grade non-oxygenated gasoline and a certification grade ultra-low sulfur diesel (ULSD). The same ULSD was used in both the RCCI and CDC combustion modes. The fuel properties are shown in [Table 2](#) and [Table 3](#), respectively.

Table 2. Gasoline Fuel Properties

Lower Heating Value (MJ/kg)	42.86
Ethanol (%)	0
Specific Gravity (@ 15.6 °C)	0.742
H/C (-)	1.86
RON (-)	96.4
MON (-)	88.5
AKI (RON+MON)/2 (-)	92.5

Table 3. Diesel Fuel Properties

Lower Heating Value (MJ/kg)	41.2
Specific Gravity (@ 15.6 °C)	0.851
CN [-]	44.4
H/C [-]	1.702

Instrumentation

All data were acquired using the built-in data acquisition software in the Drivven controller on a crank-angle or cycle-basis, depending on the type of measurement. Cylinder pressure, manifold pressures and injection commands were sampled on a crank-angle basis at the crankshaft encoder resolution. All other data (i.e., the emissions, fueling commands, etc.) were acquired once per engine cycle. This system was an upgrade to a previous setup which had multiple data acquisition systems. Acquiring all the data on one system helped to ensure alignment of all the time-based signals.

Cylinder Pressure

Cylinder pressure was measured in all 4 cylinders; however, different pressure transducers were used in cylinders 1, 3 and 4 vs. cylinder 2. Cylinders 1, 3 and 4 utilized piezoresistive pressure sensing glow plugs from Borg Warner to give an

indication of combustion phasing to quantify cylinder-to-cylinder timing differences. Cylinder 2 utilized a Kistler 6058 transducer. The resulting cylinder 2 pressure data were used to calculate metrics such as combustion noise, maximum pressure rise rate (MPRR) and CA50. Cylinder 2 was found to have similar emissions, EGR and combustion phasing as the overall engine-out performance [15].

Gaseous Emissions

High speed measurements of NO and HC were provided by Cambustion CLD 400 and HFR 500 fast response emissions analyzers, respectively. Please note that the Cambustion system does not measure N₂O or NO₂ but only NO in the present study. The 10-90% response time of these instruments allows near-crank angle time resolution. For this work, NO or HC concentrations were averaged over all crank angles to give a single value for each cycle.

Oxygen concentrations were measured in the intake manifold near cylinder 2, in the intercooler, and in the exhaust manifold using commercially available wideband sensors. Using the intake and exhaust concentrations, the EGR was calculated using the standard methodology (i.e., the CO₂ ratio between the intake and exhaust) but was changed to use the O₂ ratio, as seen in [Equation 1](#). This method was used as the lab is not setup to measure intake CO₂.

$$EGR = \frac{\text{ambient } O_2 - \text{intake } O_2}{\text{ambient } O_2 - \text{exhaust } O_2}$$

(1)

Fuel Flow Rate

For steady-state fuel flow rate measurements, Endress and Hauser coriolis-type meters were used for both DI and PFI systems. However, they were not used for transient measurements as the instrument response time is too slow for cycle-resolved measurements. For transient tests, the DI and PFI fuel injection quantities were calculated based on the cycle averaged rail pressure and injection command duration. The PFI fuel quantity was calculated based on cycle averaged injection command duration only as the rail pressure was constant at 340 kPa. These tables were then populated with steady-state flow rate values determined by operating the engine at various injection and/or pressure commands.

Intake Air Flow Rate

Intake airflow was measured with the OEM mass airflow (MAF) sensor. By comparing to a laminar flow element, the stock MAF was found to adequately measure the airflow and was used to be able to make relative comparisons between the two combustion modes.

Smoke/PM

Transient exhaust smoke opacity was measured using an AVL 439 Opacimeter which can be converted to an approximate PM mass value using existing correlations for CDC [16, 17]. Since RCCI has little black carbon content (~1%), these correlations are likely to be inaccurate [18]. Steady-state filter smoke number (FSN) measurements were made with an AVL 415s Smokemeter.

Temperature and Pressure

General pressure and temperature measurements were made at multiple locations in the intake and exhaust manifolds, EGR system, and charge air cooler. An HBM T-40 in-line torque transducer was used to measure crankshaft torque. This combination of available instrumentation provided a comprehensive description of the engine system's state during each individual combustion cycle.

Additionally, all instrumentation-data that measured flow-based quantities was post processed to account for flow time delays using correlations developed by the specific equipment manufacturer.

Procedure

The engine was coupled to a hydrostatic dynamometer capable of rapid speed and load transients [19, 20]. Transient experiments were initiated by changing the accelerator pedal command to the ECU. The ECU interprets the pedal command as a desired torque output and adjusts all the relevant engine parameters accordingly from the stored table data. The current study was conducted for step engine speed transitions, i.e., increasing engine speed from 1,000 to 2,000 rev/min. or decreasing engine speed from 2,000 to 1,000 rev/min. at a constant engine load of 2.0 bar BMEP. An example of the pedal command change is seen in Figure 2. The desired pedal command is an instantaneous step change, but was found to be too rapid for the dynamometer to accurately control the engine speed. Thus, the pedal output was slowed using a rate limiting PID to emulate the OEM ECU behavior, as shown in Figure 2.

To show the progression of engine operation through the transient event, steady-state operating points were taken to obtain target values for combustion and emissions values. The engine was calibrated in both modes at these operating points (and all intermediate points) such that the controller could interpolate between values to allow smooth operation. Then, to conduct transient tests at the selected engine speed, the ECU was given a pedal command change, and the engine then operated through the successive steady-state table points. Differences seen between the steady-state and transient results indicate areas that could require additional controls to

minimize any negative effects on engine performance. Ideally, CDC performance would be better using an OEM controller (as would RCCI given similar levels of development time, etc.); however the goal of the work was to show both combustion modes with similar hardware.

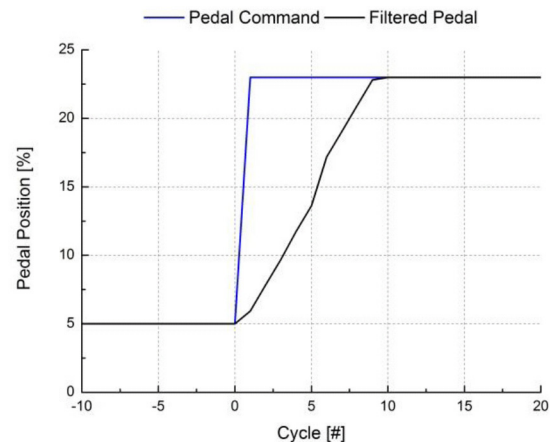


Figure 2. Example of commanded and filtered pedal command change for transient engine experiments

STEADY-STATE RESULTS

As stated above, the first part of the tests involved operating the engine at steady-state in both combustion modes to establish a baseline for comparison with transient operation. Specific operating conditions and results for the steady-state RCCI cases are shown in Table 4.

Table 4. RCCI Steady-State Run Conditions

	Run 1	Run 2	Run3	Run 4	Run 5
Engine Speed [rpm]	1,000	1,250	1,500	1,750	2,000
DI [mg/inj.]	1.99	3.18	3.57	3.75	4.01
PFI [mg/inj.]	7.14	5.75	4.91	4.56	4.4
Rail Press. [bar]	336	401	418	414	412
PFI Fraction [%]	78	64	58	55	48
Main SOI [deg. bTDC]	35	44	44	45	46
Intake Press. [bar]	1.03	1.02	1.03	1.03	1.03
Intake Temp. [°C]	50	61	82	90	91
EGR [%]	19	33	44	47	45

The RCCI calibration was set to meet emissions and noise targets with brake thermal efficiency (BTE) near or above the CDC calibration. The emissions targets for RCCI were NO <10 ppm, FSN <0.1 and MPRR <10 bar/deg. The baseline operating conditions for RCCI, such as the intake temperature and pressure, high pressure EGR rate and rail pressure were chosen using results from Refs. [21,22,23]. The intake pressures were set slightly lower than CDC to minimize pumping work, as less intake pressure is needed for RCCI to achieve low NO and PM emissions. Similarly, lower rail pressure was needed as much earlier injection timings are used and less rail pressure is needed to avoid cylinder wall impingement. Finally, the PFI fraction was set to bring the combustion phasing (i.e., CA50) to the desired value.

The RCCI combustion results are shown in Table 5. As can be seen, the combustion phasing was near TDC for all the cases. MPRR for all cases was less than 4.0 bar/deg. All the RCCI operating point's cylinder pressure and AHRR are shown in Figure 3.

Table 5. RCCI Steady-State Combustion Performance

	Run 1	Run 2	Run3	Run 4	Run 5
MPRR [bar/deg.]	3.6	4.0	3.6	3.6	3.6
GMEP [bar]	2.65	2.82	2.8	2.83	2.73
NMEP [bar]	2.48	2.64	2.6	2.65	2.54
BMEP [bar]	1.97	2.0	2.12	2.04	1.97
CA50 [deg. aTDC]	-2.7	-1.53	-0.31	0.15	-0.14

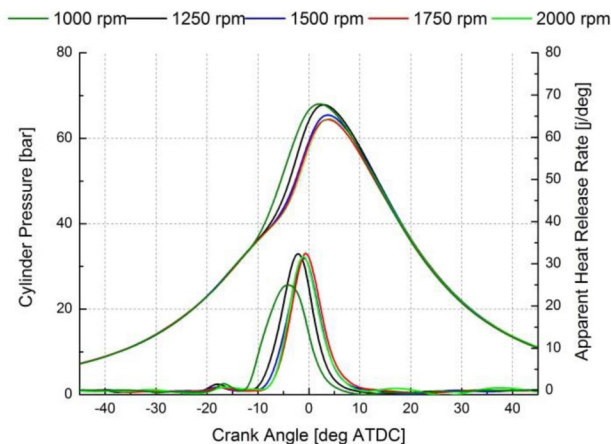


Figure 3. RCCI cylinder pressure and apparent heat release rate for the steady state cases

Emissions results, shown in Table 6, for the RCCI cases are also typical of previous SCE and MCE engine results where NO and PM are near zero and HC are elevated over CDC. NO did not meet the 10 ppm target at 1,000 rev/min. High HC levels result from using the stock piston geometry with its large top ring-land crevices [24].

Table 6. RCCI Steady-State Emissions

	Run 1	Run 2	Run3	Run 4	Run 5
Comb. Noise [dB]	67.8	75.3	78.9	82.7	85.5
BTE [-]	0.243	0.254	0.283	0.278	0.266
Phi [-]	0.37	0.44	0.48	0.53	0.53
FSN [-]	0.05	0.015	0.02	0.013	0.012
Opacity [%]	0	0	0	0	0
HC [ppmC1]	5392	4036	3667	3683	3305
NO [ppm]	15.5	8	8.65	9.1	11.8

Table 7 shows the corresponding run conditions for CDC. These values are Driven's approximation of the OEM EURO IV calibration using a pilot and main injection strategy.

Table 7. CDC Steady-State Run Conditions

	Run 1	Run 2	Run3	Run 4	Run 5
Engine Speed [rpm]	1,000	1,250	1,500	1,750	2,000
DI [mg/inj.]	8.75	8.70	8.63	8.36	8.44
PFI [mg/inj.]	0	0	0	0	0
Rail Press. [bar]	433	469	507	606	517
Main SOI [deg. bTDC]	-3	-0.3	0	1	1
Pilot advance [ms]	1.1	1.1	1.1	1.09	0.822
Pilot fraction [%]	8.53	8.77	8.67	8.49	8.43
Intake Press. [bar]	1.04	1.03	1.075	1.12	1.17
Intake Temp. [°C]	79	86	75	55	43
EGR [%]	13.8	21.6	26.8	26.8	26

The combustion results for CDC are shown in Table 8. As can be seen, combustion phasing is after TDC with much longer combustion durations than RCCI. The MPRR for all cases matched the levels of the OEM engine. All the CDC operating point's cylinder pressure and AHRR are shown in Figure 4.