

Analysis and Control of a Torque Blended Hybrid Electric Powertrain with a Multi-Mode LTC-SI Engine

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ABSTRACT

Low Temperature Combustion (LTC) engines are promising to improve powertrain fuel economy and reduce NO_x and soot emissions by improving the in-cylinder combustion process. However, the narrow operating range of LTC engines limits the use of these engines in conventional powertrains. The engine's limited operating range can be improved by taking advantage of electrification in the powertrain. In this study, a multi-mode LTC-SI engine is integrated with a parallel hybrid electric configuration, where the engine operation modes include Homogeneous Charge Compression Ignition (HCCI), Reactivity Controlled Compression Ignition (RCCI), and conventional Spark Ignition (SI). The powertrain controller is designed to enable switching among different modes, with minimum fuel penalty for transient engine operations. A Pontryagin's Minimum Principal (PMP) methodology is used in the energy management supervisory controller to study the powertrain energy flow and to select the optimum electrification level. The simulation results show 1.4% to 8.8% fuel consumption reduction for the hybrid electric powertrain with the multi-mode LTC-SI engine over a single-mode SI engine in the identical powertrain platform. Moreover, the results for the UDDS driving cycle show the maximum benefit of the multi-mode LTC-SI engine is realized in the mild electrification level, where the LTC mode operating time increases dramatically from 1.5% in Plug-in Hybrid Electric Vehicle (PHEV) to 30.5% in mild HEV.

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INTRODUCTION

Two-thirds of the petroleum consumption around the world is consumed in the transportation sector and half of that goes to passenger cars and light duty trucks [1]. Petroleum comprised 92% of U.S. transportation energy use in 2014 and prevalent consumption of petroleum-based fuels leads to high Greenhouse Gas (GHG) emission. For instance, in 2012, the European transportation sector was responsible for 19.7% of total GHG emissions and the aim is to cut it by 60% in 2050 [2]. In this context, automakers must reduce GHG emissions by introducing advanced fuel-efficient technologies and also by using alternative fuels. Low Temperature Combustion (LTC) engines encompass a family of Internal Combustion Engine (ICE) technologies, such as Homogeneous Charge Compression Ignition (HCCI), and Reactivity Controlled Compression Ignition (RCCI) engines, which have low engine-out NO_x and low soot emissions, and offer peak net indicated thermal efficiency as high as 53% [3]. Moreover, improvement in ICE fuel efficiency has the

largest potential in improving Hybrid Electric Vehicles (HEVs) fuel economy and reducing the GHG emission, compared to enhancement in other HEV component efficiency [4]. Thus, integrating fuel-efficient LTC engines in HEVs has the potential to improve vehicle fuel economy and decrease GHG emission.

However, utilizing the LTC engines in vehicles faces two major challenges: (i) limited engine operating range, and (ii) combustion control complexity particularly during transient engine operation. To tackle these two challenges, this paper investigates integration of an LTC engine with a parallel Hybrid Electric Vehicle (HEV) powertrain by taking advantage of torque assist from the electric motor. This allows the engine to be downsized and the engine operating points shift to the low and mid power level and operate in a narrow LTC operating range. In addition, this also significantly reduces the engine transient operation. Moreover, the parallel HEV is likely to be the dominant strong hybrid technology based on projected cost and effectiveness versus the currently-dominant power-split design [5].

In the first category, a CI engine has been used in different HEV architectures [6, 7, 8, 9, 10, 11, 12, 13, 14]. The CI engines have been mostly used in Sport Utility Vehicles (SUVs) and trucks [8, 10, 12, 12, 15]. In another category, SI engines have been used in HEV and EREV (Extended Range Electric Vehicle) configurations [16, 17, 18, 19, 20, 21]. Recently, Atkinson SI engines have become more popular in the market (e.g., Ford C-Max, Toyota Prius, Lexus RX 450h, and Honda Accord PHEV). In the study in reference [22], Toyota R&D group redesigned an engine based on the Atkinson cycle to improve the engine fuel efficiency. In addition, in [23], a Honda Accord PHEV was redesigned based on the Atkinson cycle and 10% lower fuel consumption was reported compared to the SI engine.

Moreover, in [30] we carried out the first study on integrating a multi-mode LTC engine with a series HEV architecture. The multi-mode LTC engine was able to switch between the HCCI, RCCI and conventional SI modes by incorporating a fuel penalty. The results show a 9% to 13.1% fuel economy improvement, compared to an identical series HEV platform running with a single-mode SI engine.

This paper is organized as follows. In the first section, the HEV experimental setup is explained. Next, the optimal control problem in the parallel HEV architecture and Pontryagin's Minimum Principle (PMP) optimization techniques are applied. Then, the results of the parallel HEV for the single-mode and multi-mode engine operations are discussed. Finally, the last section summarizes all findings from this paper.

HYBRID ELECTRIC POWERTRAIN EXPERIMENTAL SETUP

to operate in different ITC modes
conventional SI modes. The electric

Figure 1. Different types of ICEs and control techniques used in HEVs in previous studies.

powertrain is capable of realizing different levels of powertrain electrification and also has a proper control platform to implement HEV energy management strategies.

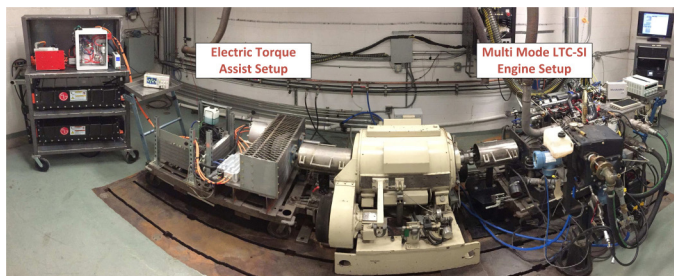


Figure 2. Developed LTC-Hybrid electric powertrain experimental test-bed utilizing a double-ended 465 hp AC dynamometer at Michigan Technological University.

The next two subsections present the details of the LTC engine and electric powertrain experimental setups, respectively. In addition, powertrain testing conditions for developing the HEV component models are explained.

Engine Setup

The engine setup includes a GM 2.0 L Ecotec Gasoline Direct Injection Turbocharged SI engine. Table 1 lists the baseline SI engine specifications.

Table 1. Parameters of the baseline engine in this study

Parameters	Value/Description
Engine Model	GM Ecotec LHU
Bore x Stroke	86 x 86 mm
Number of Cylinders	4
Displacement Volume	2.0 L
Compression Ratio	9.2:1
Connecting Rod Length	145.5 mm
Max Power	270 hp@6000 rpm
Fuel Injection System	Gasoline Direct Injection
Valve System	DOHC 4 Valves

The baseline SI engine was converted to a multi-mode LTC-SI engine as shown in Figure 3. LTC modes include HCCI and RCCI operations. Major changes to the baseline SI engine include (i) design and programming new Engine Control Unit (ECU), (ii) adding port fuel injection systems, and (iii) capability to adjust intake charge temperature, pressure, and dilution level through utilizing intake air heater, supercharger, and Exhaust Gas Recirculation (EGR) rate modulation, respectively. In the following, the configuration of the multi-mode LTC-SI engine is explained.

The engine is controlled using dSPACE MicroAutoBox (MABx) DS1511 and RapidPro units. Models for control of injectors, fuel pump, spark plugs, throttle body, cam phasers, supercharger and EGR

valve were developed in Matlab® Simulink. The intake and exhaust valves are actuated using cam phasors. All these models were integrated into a single engine management system, and these parameters were controlled and monitored online using the dSPACE ControlDesk®. Combustion analysis was performed using the ACAP system. The in-cylinder pressures were measured using PCB 115A04 piezo electric pressure transducers. The measured signal was amplified using a DSP 1104 CA charge amplifier and then sent to ACAP for post-processing. The encoder used for crank angle measurement had a resolution of 1 crank angle degree. ACAP was configured for the engine setup and the required combustion parameters were continuously evaluated for 100 cycles at each operating condition. National Instruments PXIe 1078 chassis system, which includes NI TB 4353, NI PXI 6225 and NI PXI 6722 modules were used for thermocouple measurement, pressure transducer measurement and dynamometer control, respectively.

Two fuel rails were installed at the interface of the intake manifold and cylinders for port fuel injection. A high-pressure fuel pump was used to supply fuel at 100-bar pressure to direct fuel injectors. In addition, a low-pressure external fuel pump was used to supply fuel at 3 bar pressure to the port fuel injectors. The injection system has the capability of supplying three fuels to the engine at the same time. The amount of fuel injected was controlled using dSPACE MABx. Temperatures (intake air, exhaust gas, coolant and oil gallery) and pressures (intake air, coolant and oil) were measured using K-type thermocouples with an accuracy of $\pm 0.75\%$ and piezo resistive pressure transducers with an accuracy of $\pm 0.5\%$, respectively. Two air heaters between the supercharging station and the intake manifold were used to pre-heat the intake air to the desired temperature. The mass flow rate of intake air was measured using Merriam MDT500 air flow measurement system. A 465 hp General Electric AC dynamometer was used to control the speed and load of the engine.

Experiments were performed for three different combustion modes namely SI, HCCI and RCCI. Operating conditions such as intake air temperature (T_{intake}), intake manifold pressure (P_{intake}), Research Octane Number (RON) of fuel, engine speed (N) and equivalence ratio (ϕ) were varied individually keeping the other parameters constant. The operating conditions used for each of the combustion modes are given in Table 2. The experiments were conducted for a range of engine speeds and a range of equivalence ratios between the knock and misfire limits. Thereby, the operating region and load limit for each combination of input parameters were determined. Using the data acquired from dSPACE®, LabVIEW® and ACAP, the combustion and performance parameters were calculated using an in-house Matlab code. The Brake Specific Fuel Consumption (BSFC) maps were generated and the load limits for each of the combustion modes were determined. Figure 4 shows the BSFC maps for SI, HCCI and RCCI combustion modes with engine speed (RPM) on the x-axis and brake torque (N.m) on the y-axis.

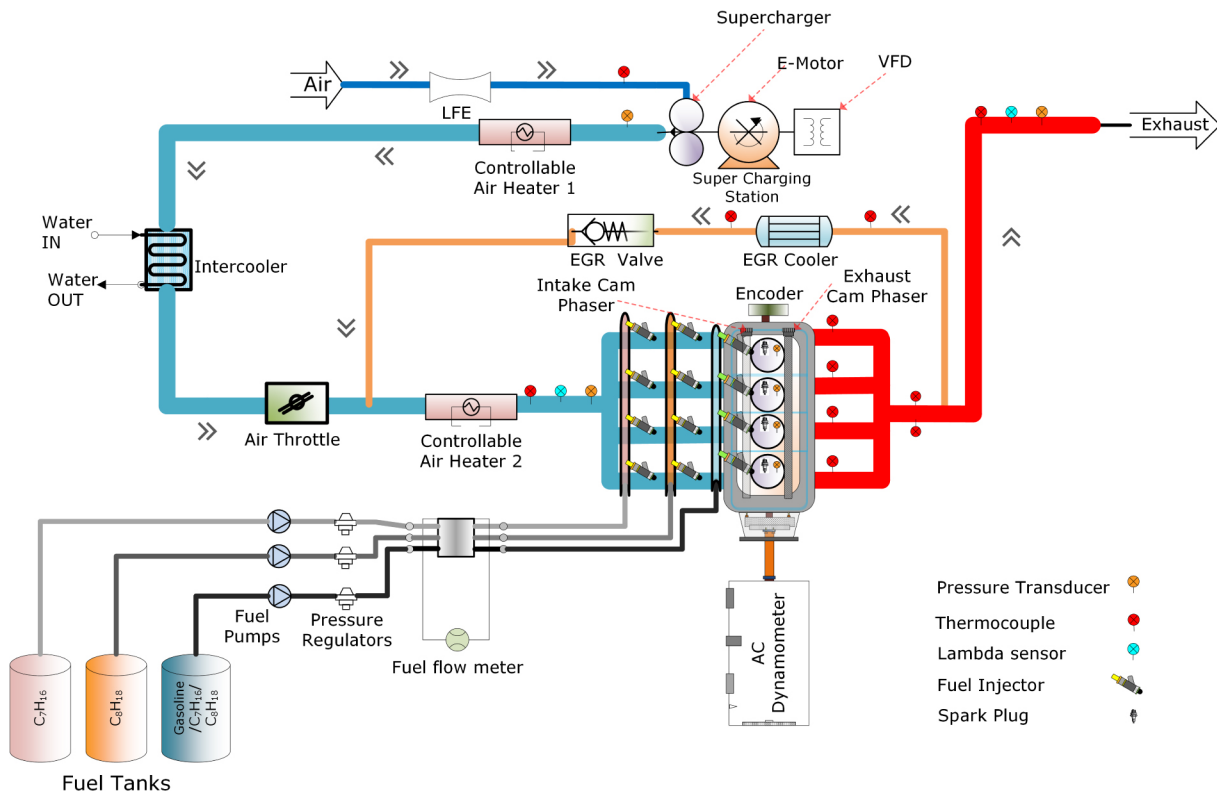


Figure 3. Schematic of fuel-flexible multi-mode LTC-SI engine test setup.

Table 2. Engine Operating Conditions

Combustion Mode	SI	HCCI	RCCI
Injection Rail Used	DI	PF1+PF12	DI+PF11
Fuel Type	Gasoline	n-heptane+ iso-octane	n-heptane + iso-octane
Engine Speed (rpm)	800-4000	800-1600	800-2200
SOI (CAD bTDC)	100	450	Variable
IVO (CAD bTDC)	-24.5	25.5	25.5
EVC (CAD bTDC)	22	22	22
T_{intake} (°C)	40	40,60,80,100	40,40,80,100
P_{intake} (kPa)	100	100	100
RON (-)	87	0-40 ¹	20-60 ¹

Electric Powertrain Setup

The electric powertrain setup includes a 100 kW synchronous induction Remy e-motor, an RMS PM100DX inverter, a 5 kWh/65 kW lithium-ion LG Chem battery, and a mechanical coupling to integrate the motor to the dynamometer. The mechanical drivetrain including the e-motor mount, coupling, and shafts are designed and manufactured at Michigan Technological University. The high voltage battery during the operation is connected to the e-motor through a designed pre-charge circuit. The MABx is used as a supervisory controller to monitor sub-level controllers (i.e., battery, e-motor, etc.). The MABx communicates control commands on the CAN bus to the sub-level controllers. The LG Chem battery temperature is controlled through a fan and all the cooling systems are controlled by the supervisory controller. A fault-action module was developed in Matlab® to manage the setup during faults and extreme conditions.

The driver commanded torque is carried out through a desired torque-based control strategy embedded in the inverter. The driver's desired speed setpoint is controlled by the dynamometer controller. The inverter controls the e-motor to track the reference torque, which is determined by the operator through the dSPACE ControlDesk® interface. Furthermore, the setup is capable of implementing the regenerative braking test scenarios to capture the braking energy and charges the battery. The regenerative braking happens when the torque command is negative or the motor direction is reversed.

Figure 5 illustrates the LG Chem battery charging and discharging power limits versus SOC. The LG Chem battery SOC operating window is from 70 to 30 percent. As it is expected the battery

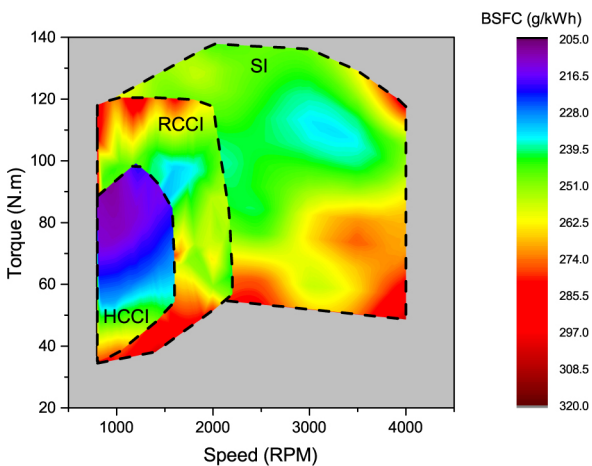


Figure 4. Experimental BSFC map of the developed multi-mode LTC-SI engine.

charging power is smaller when the battery is fully charged. However, the battery has a higher discharging power limit at high SOC. This data will be used in the powertrain modeling for the design of the supervisory energy management strategy.

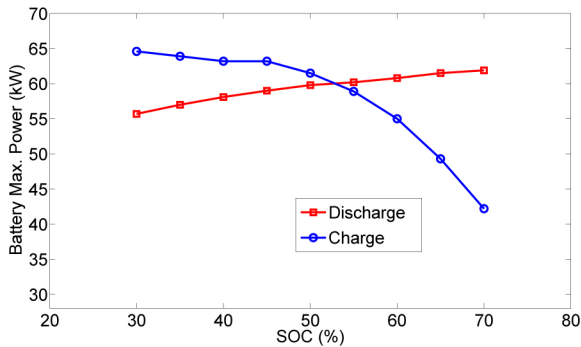


Figure 5. High voltage battery power limit variation vs. SOC at battery temperature of 25°C.

Figure 6 shows the e-motor efficiency map during different e-motor speeds and torques. The data is collected at the e-motor temperature of 70°C and the DC voltage of 320 V. Under these conditions, the e-motor efficiency ranges from 74 to 94 percent.

In the next section the designed optimal energy management strategy is presented. The optimal strategy is implemented for the parallel HEV model with the experimentally validated components using the collected data from the powertrain experimental setup.

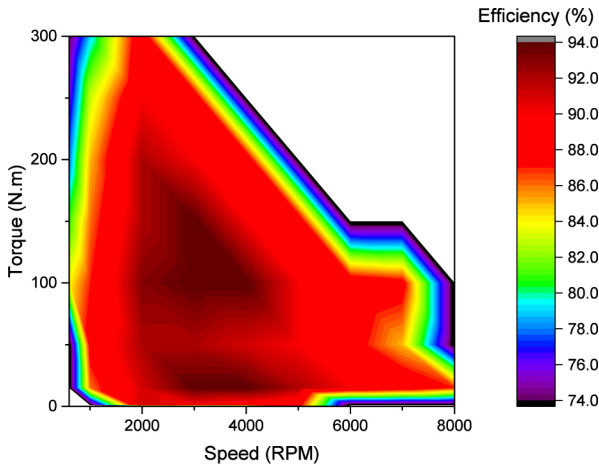


Figure 6. Efficiency map of the 100 kW synchronous PMSM Remy e-motor. Test conditions: e-motor temperature=70 °C, and DC bus voltage=320 V.

DESIGN OF OPTIMAL CONTROL

The goal of the optimal control in this study is to minimize the fuel consumption ($\dot{m}_f$) using the cost function defined by Eq. (1):

$$J(u(t)) = \int_0^T \dot{m}_f(t) dt \quad (1)$$

where, $\dot{m}_f$ is the rate of the engine fuel consumption and T is the time length of a driving cycle. Equation (2) shows the constraints for the HEV optimization problem.

$$|SOC_f - SOC_0| \leq \epsilon \quad (2a)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (2b)$$

$$P_{bat,min}(SOC) \leq P_{bat}(t) \leq P_{bat,max}(SOC) \quad (2c)$$

$$T_{eng,min}(\omega_{eng}) \leq T_{eng}(t, \omega_{eng}) \leq T_{eng,max}(\omega_{eng}) \quad (2d)$$

$$\omega_{eng,min} \leq \omega_{eng}(t) \leq \omega_{eng,max} \quad (2e)$$

$$T_{motor,min}(\omega_{mot}) \leq T_{motor}(t) \leq T_{motor,max}(\omega_{mot}) \quad (2f)$$

$$\omega_{motor,min} \leq \omega_{motor}(t) \leq \omega_{motor,max} \quad (2g)$$

The constraints in Eq. (2) are applied for the battery SOC operation window, battery power (P_{bat}), engine torque (T_{eng}), engine speed (ω_{eng}), e-motor torque (T_{motor}), and e-motor speed (ω_{motor}). This optimal control problem is solved using optimal control techniques that are described in the next section.

Pontryagin's Minimum Principal (PMP)

The PMP method is based on a general case of the Euler-Lagrange equation and originates from the Calculus of Variation. This method yields the necessary - not sufficient - conditions of the global optimal solution. The optimal trajectories derived from PMP will be the global optimal solution of the HEV problem if the obtained optimal trajectory is a unique trajectory that meets the necessary and boundary conditions [31]. The necessary condition for the PMP global optimality is explained in [31] and will be briefly explained in Subsection B. In Subsection A, the simulation model of the target vehicle is described. Moreover, a technique is introduced to determine the Hamiltonian values from the model.

A. Parallel HEV Model

In the parallel HEV architecture in this study, the engine is coupled to the e-motor through a clutch. The output shaft is connected to the drivetrain where an automatic six speed transmission connects the output shaft to the wheels. This limits the engine operating points to discrete gear ratio options. Figure 7 shows the parallel HEV architecture and Table 3 lists the vehicle parameters along with the transmission ratios used in this study. The static models and maps of the vehicle components are obtained from the experimental setup as explained in the previous section.