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Fuel consumption assessment of an electrified powertrain with a multi-mode high-efficiency engine in various levels of hybridization

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ABSTRACT

Powertrain electrification including hybridizing advanced combustion engines is a viable cost-effective solution to improve fuel economy of vehicles. This will provide opportunity for narrow-range high-efficiency combustion regimes to be able to operate and consequently improve vehicle's fuel conversion efficiency, compared to conventional hybrid electric vehicles. Low temperature combustion (LTC) engines offer the highest peak brake thermal efficiency (BTE) reported in literature, but these engines have narrow operating ranges. In addition, LTC engines have ultra-low soot and nitrogen oxides (NOx) emissions, compared to conventional compression ignition and spark ignition (SI) engines. In this study, an experimentally developed multi-mode LTC-SI engine is integrated into a parallel hybrid electric configuration, where the engine operation modes include homogeneous charge compression ignition (HCCI), reactivity controlled compression ignition (RCCI), and conventional 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 a multi-mode LTC engine in parallel HEV architecture with various hybridization levels. The amount of torque assist by the e-motor can change the LTC mode operating time, which leads to variation in the vehicle's fuel consumption. The results for the urban dynamometer driving schedule (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 5.0% in a plug-in hybrid electric vehicle (PHEV) to 20.5% in a mild HEV.

1. Introduction

The U.S. light-duty (LD) regulations require a fleet average of 4.3 l/100 km by 2025 in order to meet the 101 g/km CO_2 level [1]. In addition, in the European Union, the average fleet fuel consumption regulations for the new cars require 4.1 l/100 km by 2021 [2]. High efficiency engines along with powertrain electrification will play a critical role in meeting such stringent goals from the cost-effectiveness perspective [3–5]. Currently, the spark-ignition (SI) engine fueled with gasoline is the primary engine used in the LD vehicles in the U.S. [1]. Conventional compression ignition (CI) engines are noteworthy for the LD vehicles due to their higher efficiency. However, the CI engines require an expensive and complex aftertreatment system for particular matter (PM) and NO_x control [6]. To improve vehicular fuel economy and reduce aftertreatment expenses, various studies have investigated advanced combustion regimes to achieve higher thermal efficiencies than those in CI engines while mitigating engine-out emissions [7–9]. A promising advanced combustion regime is low temperature combustion (LTC), and consists of a family of variants including homogeneous charge compression ignition (HCCI), reactivity controlled compression ignition (RCCI), and partially-premixed charge compression ignition (PCCI) [10,11]. LTC engines can offer peak indicated thermal efficiency of 53% [9] with ultra low NO_x and PM engine-out emissions [9]. Even though the LTC engines benefit from higher thermal efficiencies and less expensive after treatment systems compared to conventional engines, they have narrow operating ranges and often require more complex combustion control which makes them challenging for application in automotive powertrains. As the fleet merges to a higher degree of powertrain electrification path, more opportunities for advanced combustion regimes (i.e., LTC) will arise. It is because the powertrain electrification allows the engine to be downsized and operated in a narrow-range high-efficiency combustion regimes as compared to the conventional powertrains.

Fig. 1 catagorizes the prior hybrid electric vehicle (HEV) studies based on different engine types including conventional (i.e., SI, CI, Atkinson) and advanced combustion (i.e., LTC) engines. In the first

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Nomenclature

Abbreviations

BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
EVC	exhaust valve closing
HEV	hybrid electric vehicle
HCCI	homogeneous charge compression ignition
HWFET	highway fuel economy test
ICE	internal combustion engine
IVO	intake valve opening
LD	light duty
LTC	low temperature combustion
LVD	longitudinal vehicle dynamic
OCV	open circuit voltage
PMP	Pontryagin's minimum principle
PHEV	plug-in hybrid electric vehicle
RCCI	reactivity controlled compression ignition
RON	research octane number
SOC	state of charge
SI	spark ignition
UDDS	urban dynamometer driving schedule

Symbols

λ	co-state [–]
C_d	vehicle aerodynamic drag coefficient [–]
$\dot{m}_f$	fuel consumption rate [g/sec]
f_r	rolling resistance coefficient [–]
ω	engine speed [rpm]
ω_{motor}	E-motor speed [rpm]
A	vehicle frontal area [m^2]
$\mathscr{H}$	Hamiltonian [g/sec]
M	vehicle total mass [kg]
n_c	mechanical coupling ration [–]
n_t	transmission ratio [–]
n_d	differential ratio [–]
$P_{motor,mech}$	traction mechanical power of e-motor [kW]
$P_{motor,e}$	Regen electrical power of e-motor [kW]
P_{bat}	battery power [kW]
P_{wheel}	power demand at wheel [kW]
P_{eng}	engine generated power [kW]
Q_{nom}	battery nominal energy capacity [Wh]
R	battery internal resistance [Ω]
V_{veh}	vehicle speed $[\frac{m}{sec}]$
r	wheel radius [m]
ρ	air density $\left[\frac{kg}{m^3}\right]$
θ	road slope [°]
m_{ij}	mode-switching fuel penalty [g]
u	control variable

Subscripts

bat	battery
drag	drag
eng	engine
e	electrical
grade	gradeability
gear	gearbox
intake	intake
min	minimum
max	maximum
motor	electric motor
mech	mechanical
nom	nominal
veh	vehicle
roll	rolling resistance

category, conventional SI and CI engines have been used in different HEV architectures. The SI engines have been integrated in HEV and range extender architectures [12–18]. Atkinson SI engines are popular in the market and are used in the Toyota Prius, Ford C-Max, Lexus RX 450 h, and Honda Accord. In Refs. [19,20], Toyota has achieved 10% lower fuel consumption compared to SI engine by converting the Honda Accords PHEV SI engine to the Atkinson cycle. The CI engines mostly have been integrated in trucks and sport utility vehicles (SUVs) [21–25].

In the second category, the LTC engines are integrated in different HEV architectures. Few studies are found in the literature that explores the LTC-HEV powertrain. Such powertrains are divided into two subcategories based on the LTC combustion regimes including the single-mode LTC and multi-mode LTC. In majority of the previous works, the engine has been flexible to switch from a single-mode LTC to a conventional mode [5,26–28], while in [29] we carried out the first study of integrating a multi-mode LTC engine in HEVs. Thus, the engine not only could switch to conventional modes, but also it could switch among different LTC modes. In the single-LTC mode subcategory, HCCI was the first type that was studied in electrified powertrains. In the first study at the United States Argonne National Laboratory, the effects of using a dual-mode SI-HCCI engine in different vehicle electrification levels were analyzed [27]. In both studies, in Ref. [26,28], the fuel economy benefits of the SI-HCCI engine are studied for parallel HEV architectures. In [30], we carried out the first study by utilizing a pure HCCI mode engine in a series hybrid powertrain and we found 12.6% improvement in fuel economy in comparison with a series HEV running with an SI engine over a combined US driving cycle consisting of UDDS, HWFET, and US06 cycles. In our next study [31], we investigated the impact of driving cycles, number of the engine operating points, and engine startup fuel penalty on both series HEV and extender range electric vehicle HCCI-based powertrains. RCCI was the second type of LTC engine that was studied in an HEV powertrain. In Ref. [32], researchers at the University of Wisconsin-Madison and Oak Ridge National Laboratory used an RCCI engine in a series-parallel hybrid electric powertrain and they found 12% fuel economy improvement over the similar HEV running with a modern SI engine in the HWFET driving cycle. In Ref. [33] we found 3% fuel economy improvement over diesel engine in a series HEV architecture by using an RCCI engine in the US06 driving cycle. In [5] the RCCI-CI engine is integrated in a power-split HEV architecture in which a rule-based energy management controller (EMC) was used for evaluating the fuel economy improvement.

Moreover, in [34] a multi-mode LTC engine was designed to switch between the HCCI, RCCI and conventional SI modes in a series HEV architecture. The results showed a 9.1–12.1% fuel economy improvement, compared to an identical series HEV platform running with a single-mode SI engine over the HWFET driving cycle. In [35] a multi-mode LTC engine was utilized is a torque-blended HEV architecture and preliminary optimization results were presented.

Building upon our previous works in [34,35], this paper presents the first study undertaken to investigate the fuel economy benefit of integrating a multi-mode LTC-SI engine with a parallel HEV with an advanced optimal control strategy, and incorporating measured fuel penalty map for mode switching and including constraints for required exhaust gas temperature to enable high conversion efficiency for

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