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Effects of control strategy on fuel consumption and gas emissions: application for series hybrid electric vehicle

In order to reduce harmful greenhouse gas emissions and fuel consumption, automakers are working to build new eco-friendly vehicles, such as hybrid vehicles. Hybrid electric vehicles have significant advantages over conventional cars, especially in terms of ecology. This article focuses on series hybrid electric vehicle (SHEV) as a means of transportation with promising potential for reducing environmental problems. The purpose of this paper is to compare fuel consumption and gas emissions for a SHEV controlled by two different types of control strategies, the thermostat control strategy (TCS) and the power follower control strategy (PFCS), in urban and highway driving cycles. The control strategy must determine, at all times, the power distribution between the internal combustion engine (ICE) and the battery, so as to meet energy needs and other constraints, as well as the fuel consumption and harmful emissions are minimized. Simulation of SHEV was performed using the ADVISOR software.

Keywords: Series hybrid electric vehicle; thermostat control strategy; power follower control strategy; fuel consumption; gas emissions; drive cycle.

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1. Introduction

After the transport revolution of the twentieth century, the automobile quickly became the main mean of travel in several cities. In 2005, the number of vehicles traveling the planet is nearly 890 million. In 2007, the billion was exceeded. From 1955 to 2005, the increase in their number was about three times faster than population growth! [1] Global automotive production reached a record in 2017, exceeding 97 million manufactured units including 73 million passenger cars [1].

According to the United Nations, the global vehicle fleet is expected to reach 3 billion cars by 2050 [1]. Those cars will then cover all the needs of long distance journey. However, this marvel of technology is free of problems, at different levels.

Pollution related to road traffic is a disaster in urban agglomerations where road transport is one of the main sources of air pollution. It is the dominant sector in the emission of carbon monoxide (CO), nitrogen oxides (NOx) and fine particulate matter (PM10) [2].

Road traffic alone is responsible for about 13% of global CO_2 emissions, the main greenhouse gas (GHG). However, GHGs contribute to global warming, which seriously endangers the stability of our societies [1].

Furthermore, particles (PM), nitrogen dioxide (NO2) and ground-level ozone (O_3) are the most harmful to human health, especially those living in urban areas [2]. Air pollution also has significant economic implications: reduced life expectancy, increased medical costs and lower productivity throughout the economy due to work stoppages for health issues. Air

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pollution has also a negative impact on ecosystems, damaging soils, forests, lakes and rivers and reducing agricultural yields [1].

As the main source of air pollution in large cities, the car stands out and even develops diseases such as asthma and chronic bronchitis. On average, air pollution causes the premature death of 7 million people worldwide each year, according to the World Health Organization and the Ministry of Sustainable Development [1].

Moreover, the majority of transport depends on oil and it is clear that road traffic is the first consumer [2]. This demand is increasing with the proliferation of private vehicles that contributes to international pressures on the supplier's price and access [1].

Prices at the pump remain on the rise. They vary according to several parameters such as the oil price per barrel, as well as the level of stocks of petroleum products and demand.

Confronted with global challenges such as air pollution and energy dependency, car manufacturers are adapting more or less quickly and successfully to make the car less polluting by offering more environmentally friendly means of transport, such as the hybrid electric vehicle [2].

Hybrid cars have significant advantages over conventional cars, particularly in terms of ecology [2]. The former rejects a reduced amount of greenhouse gases. In addition, they are also much economic, they consume a fuel quantity 10 to 50% lower compared to gasoline engines [3].

These advantages explain why hybrid electric vehicle (HEV) are continuing their development and making a lasting impact on the automotive market. Of the 2.110.751 passenger cars registered in France in 2017, 81.547 were hybrid cars (3.86%), according to data from the French Automobile Manufacturers Committee [4].

A hybrid electric vehicle is an automobile that uses two types of energy sources to move, one of which is electric [5]. In general, the hybrid vehicle includes a battery and a fuel reservoir associated with machine of energy conversion, such as electric motors and an internal combustion engine (ICE), generally gasoline. It can therefore be considered that the hybrid electric vehicle is a combination of a conventional vehicle and an electric vehicle, which allows, on the one hand, to reduce the size and consumption of the engine and improve its efficiency compared to the conventional vehicle and, on the other hand, to reduce the battery size compared to that used in the electric vehicle.

Given that transport emissions are among the main causes of climate change in urban areas, hybrid vehicles can be considered as a solution to reduce air pollution, especially the series hybrid electric vehicle (SHEV), seen as an electric vehicle assisted by a thermal motor [2].

The SHEV is characterized by (a) good efficiency of energy in all-electric mode, (b) simplicity of engine control and (c) good performance in urban driving cycles [2].

This paper is organized as follows. In section 3, a brief modeling of the drivetrain system of SHEV is presented. Section 4 is devoted to presenting the operating principle of the control strategies applied to the SHEV. The driving cycles used in the vehicle simulation are mentioned in section 5. In this section, a comparison of the different simulation results is presented. The conclusion and some perspectives are given in the sixth and final section of the document.

2. Notation

The notation used throughout the paper is stated below.

a	Acceleration of the vehicle
A_f	Frontal area of the vehicle
C_d	Aerodynamic drag coefficient
C_{RR}	Rolling resistance coefficient
CO	Carbon monoxide
$CO2$	Carbon dioxide
EM	Electric motor
F_{acc}	Force related to the vehicle acceleration
F_{aero}	Aerodynamic drag
F_p	Force related to the slope of the road
F_{roul}	Rolling resistance
F_{tot}	Propulsive force
$FTP-75$	Federal test procedure
g	Gravity acceleration
GHG	Greenhouse gas
HC	Hydrocarbon
HEV	Hybrid electric vehicle
$HWFET$	Highway Fuel Economy Test
ICE	Internal combustion engine
$Li-ion$	Lithium-ion
$M_{véh}$	Total mass of the vehicle
$NO2$	Nitrogen dioxide
NOx	Nitrogen oxide
$O3$	Ozone
p	Maximum gradeability
$PFCS$	Power follower control strategy
$PMSM$	Permanent magnet synchronous motor
$PM10$	Fine particles
R_{roue}	Wheel radius
$SHEV$	Series hybrid electric vehicle
SOC	State of charge of the battery
SOC_{high}	Higher state of charge
SOC_{low}	Lower state of charge
t_a	Acceleration time
TCS	Thermostat control strategy
$UDDS$	Urban Dynamometer Driving Schedule
V_{max}	Maximum speed
V_{veh}	Speed of the vehicle
α	Angle of the road
ρ	Air density
σ	Coefficient of inertia

3. Drivetrain system of series hybrid electric vehicle

The SHEV is considered the simplest architecture thanks to the absence of the mechanical coupling between the engine and the wheels as well as the lack of coupling tool between the ICE engine and the electric motor (EM) [6].

In SHEV architecture, presented in Fig. 1, the electric motor is responsible for producing the traction power of the vehicle while the engine, coupled to a generator, is used for the production of electrical energy [7]. In addition, the EM can be powered by electrical energy through the battery [8].

The advantage of this configuration is that the ICE operates at its optimum operating point, regardless of the power demanded of the wheels [9].

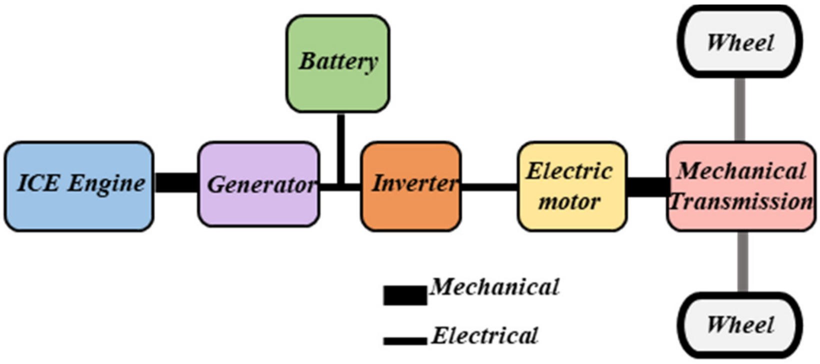

Fig. 1. Configuration of the SHEV

The vehicle, whose parameters and performances are indicated in Table 1, requires a traction force F_{tot} to move.

Table 1. Vehicle parameters and performances

Parameters	Symbol	Value	Unit
Total mass of the vehicle	$M_{véh}$	1390	kg
Gravity acceleration	g	9.81	m/s²
Rolling resistance coefficient	C_{RR}	0.015	-
Aerodynamic drag coefficient	C_d	0.4	-
Air density	ρ	1.23	kg/m³
Frontal area of the vehicle	A_f	2	m²
Coefficient of inertia	σ	1.01	-
Wheel radius	R_{roue}	0.26	M
Maximum speed	$Vmax$	150	km/h
Acceleration time (0 to 100 km/h)	t_a	8.1	S
Gradeability at 100 km/h	p	5	%
Minimum SOC	SOC_{low}	40	%
Maximum SOC	SOC_{high}	80	%

This force, as shown in Fig. 2, depends on the following forces [10]:

- The aerodynamic force :

$$F_{aero} = \frac{1}{2} \rho A_f C_d V_{max}^2 \quad (1)$$

- The rolling resistance force :

$$F_{roul} = C_{RR} M_{veh} g \quad (2)$$

- The force related to the profile of the road:

$$F_p = M_{veh} g \sin\alpha \approx M_{veh} g p \quad (3)$$

- The force due to the acceleration:

$$F_{acc} = \sigma M_{veh} a = \sigma M_{veh} \frac{dV}{dt} \quad (4)$$

Therefore, the traction force is expressed as follows:

$$F_{tot} = \frac{1}{2} \rho A_f C_d V_{max}^2 + C_{RR} M_{veh} g + M_{veh} g p + \sigma M_{veh} a \quad (5)$$

The traction chain of the SHEV consists mainly of a battery, an engine and two electric machines, one is a traction electric motor and the other is a generator that ensures transformation of the engine's mechanical energy to an electric energy [2].

The specifications of the various components of the traction chain are shown in Table 2.

Table 2. Specifications of the main components of the vehicle drivetrain

Parameters	Value	Unit
Electic motor (PMSM)		
Maximum power	104.4	kW
Maximum torque	564	Nm
Maximum speed	4400	rpm
Engine (Spark Ignition)		
Maximum power	54.31	kW
Maximum torque	107	Nm
Maximum speed	5700	rpm
Generator (PMSM)		
Maximum power	48.9	kW
Battery (Li-ion)		
Maximum power	122	kW
Nominal capacity (cell)	6	Ah

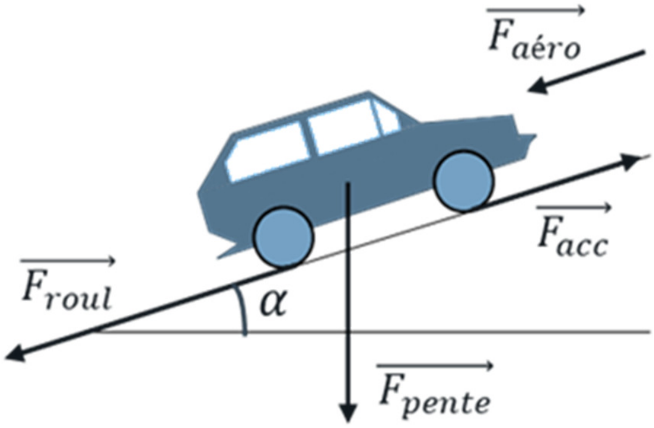

Fig. 2. Forces acting to the vehicle

4. Control strategy

To achieve the objective of minimizing emissions and fuel consumption while maintaining the performance of the SHEV, it is necessary to choose the control strategy that satisfies the driver's energy demand.

A Control strategy (CS) is a set of algorithms implemented in the controller of the vehicle to control the generation and the flow of energy between the drivetrain components in an optimal way, as shown in the Fig. 3 [11].

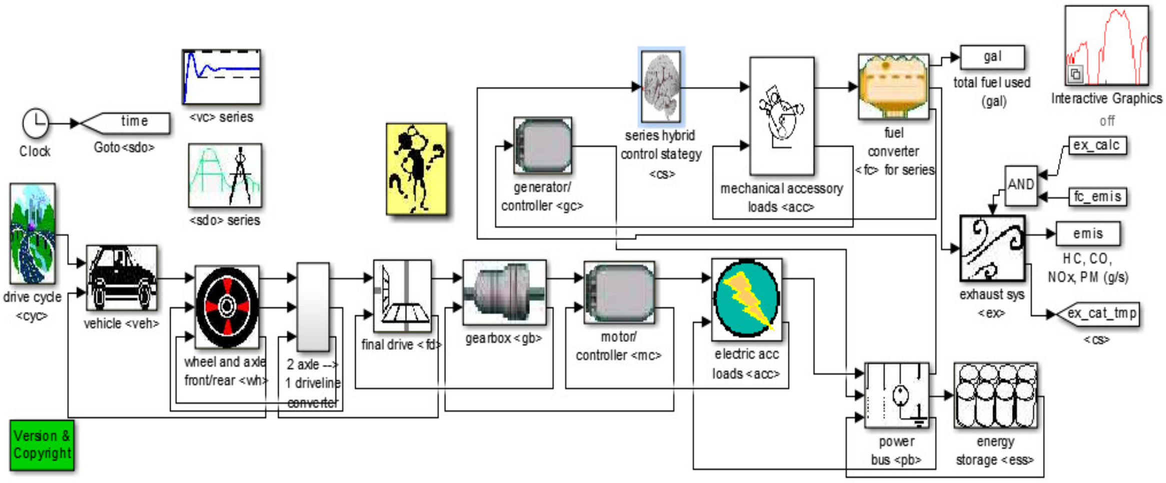

Fig. 3. Block diagram of SHEV

This strategy must meet the following objectives:

- ensure the instantaneous sharing of power between the two sources to meet the driver's demand,

- control the state of charge (SOC) of the battery which is a very important parameter to properly control the operation of the battery.

The CS, therefore, calculates the start / stop commands of the engine, the operating points of each traction component as well as the succession of phases of charge / discharge of the battery [12].

In practice, there are several types of control strategy that can be applied to a drivetrain for vehicles. The control strategy of a SHEV mainly includes "thermostat control strategy" and "power follower control strategy".

The thermostat control strategy (TCS) is also called the on–off control strategy. In this simple control strategy, the power distribution depends mainly on the state of charge (SOC) of the battery, as shown in the Fig. 4. The SOC must be maintained between the two, namely upper and lower, predefined limits by simply turning on or off the engine [13].

The TCS is described as follows:

- The engine turns on when SOC reaches its lower limit SOC_{low},
- The engine turns off when SOC reaches its upper limit SOC_{high}, and
- The engine runs at its most efficient speed and torque.

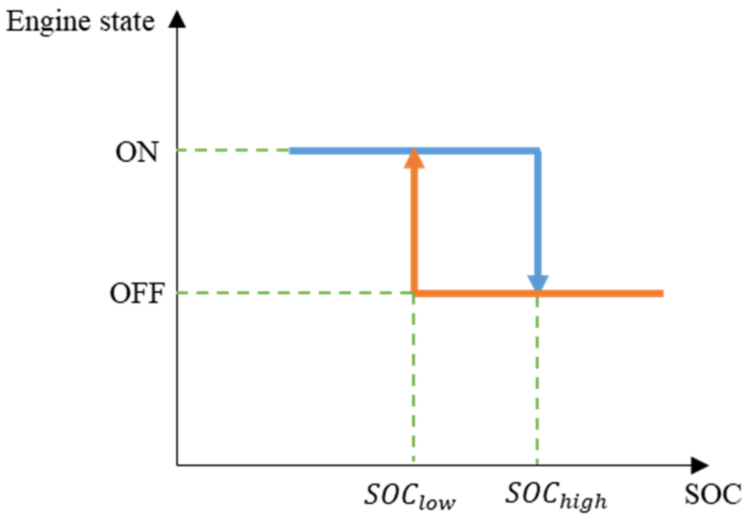

Fig. 4. Engine state in TCS

The power follower control strategy (PFCS), presented in Fig. 5 [14], operates the ICE in the same way as a conventional vehicle where the engine's controlled power intently follows the power demanded.

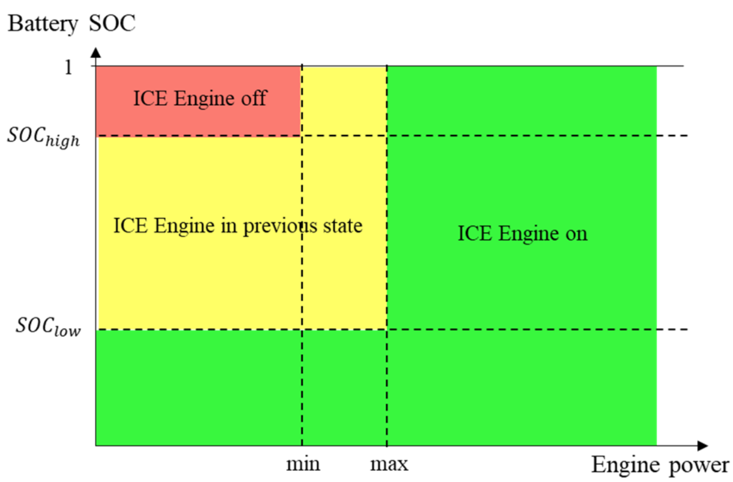

Fig. 5. Battery state of charge in PFCS

The PFCS is described as follows:

- The engine is assumed to be the main power source, and
- The output power of the ICE must be controlled to follow the power requirements of the vehicle [15].

Hence, the engine is active in almost all driving conditions, except for a low required driving power and for state of charge of the battery higher than the upper limit value ($SOC>SOC_{high}$).

5. Simulation and results

The objective of the present work is to choose a control strategy to minimize gas emissions and fuel consumption, in comparison the results obtained by applying two different control strategies using the ADVISOR software.

5.1. Drive cycle

ADVISOR is a software that allows testing a vehicle on different driving cycles. The results of a simulation are forecasts of emissions, fuel consumption and vehicle performance [7].

In order to determine gas emissions and fuel economy, it is necessary to know the typical use patterns of the vehicle.

The driving cycle is a curve representing speed in function of the time.

The choice of the driving cycle determines the operating conditions of the vehicle such as changes in gear ratios, acceleration, braking ... It has a more or less significant influence on the emissions and fuel consumption of the vehicle [16].

The simulation of the vehicle is carried out on two different driving cycles:

- Urban driving cycle: The chosen cycle is the Urban Dynamometer Driving Schedule (UDDS), represented in Fig. 6, which is equivalent to the first two bags of the Federal Test Procedure (FTP-75). It is used for the test of light vehicle by representing the driving conditions in the city [2].

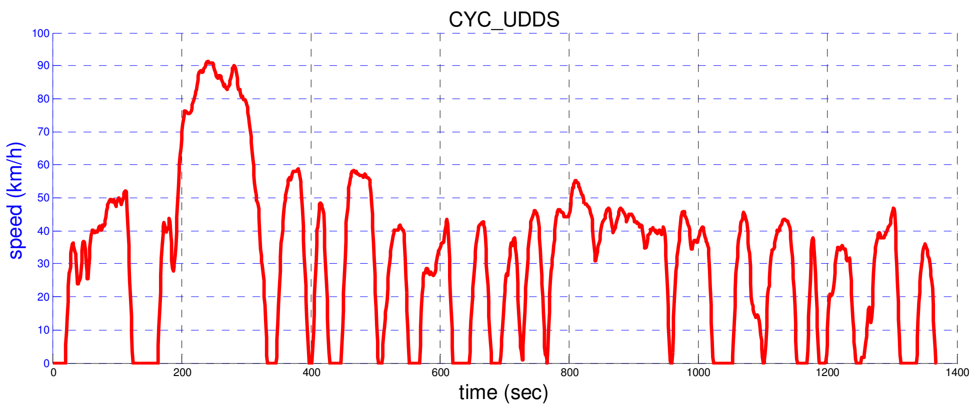

Fig. 6. UDDS cycle speed profile

- Highway driving cycle: The Highway Fuel Economy Test (HWFET) cycle, represented in Fig. 7, is selected from the various cycles of this type. It is used to evaluate fuel consumption on a highway-type driving cycle [2].

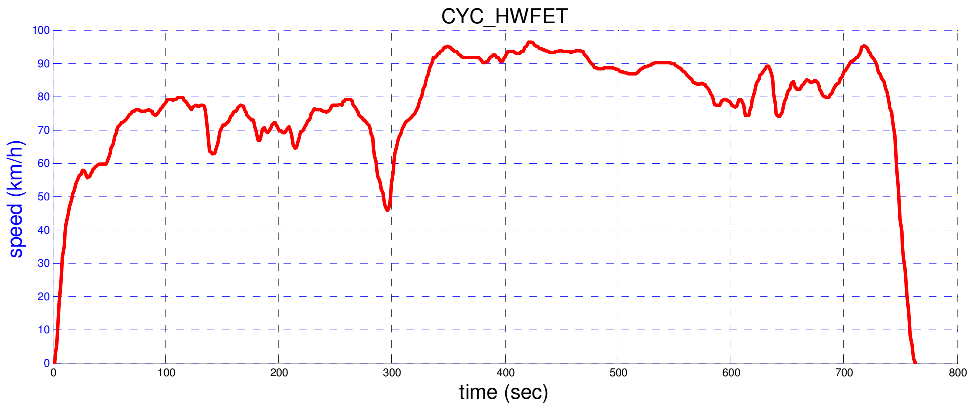

Fig. 7. HWFET cycle speed profile

5.2. Fuel consumption and gas emissions

To compare the gas emissions and fuel consumption of the SHEV controlled by the TCS and the PFCS, the simulation is carried out over two different driving cycles (urban and highway) under the same conditions. Gas emissions and fuel consumption are the result of ICE operation.

The variations of SOC and engine torque under the UDDS and HWFET driving cycles are illustrated in Fig. 8.

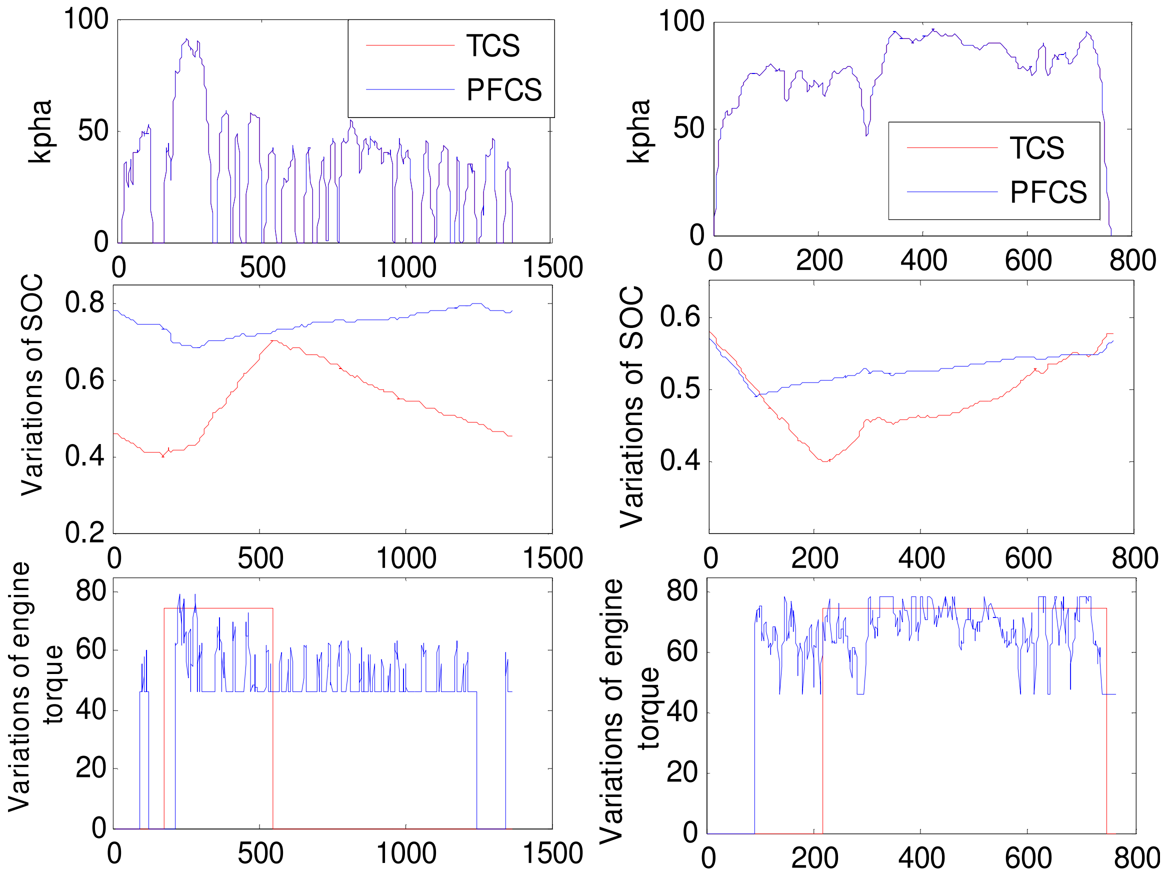

Fig. 8. Battery SOC history and engine torque in the (a) UDDS and the (b) HWFET driving cycles

As shown in Fig. 8, for both UDDS and HWFET driving cycles, the operation of the TCS-controlled vehicle is battery-based until it reaches SOC_{low}, where the engine operates to charge the battery until it reaches SOC_{high}. While for the vehicle controlled by the PFCS the engine is the responsible of this operation. The battery works just to help the engine, so it does not reach its SOC_{low} limit for PFCS.

Fig. 9 reveals the operating points of the engine for both control strategies. The PFCS operating region is larger than the TCS due to its nature of using ICE as the primary source of energy. It is clear also that the majority of the operating points of the engine using the PFCS are concentrated in the optimum area of the engine efficiency map.

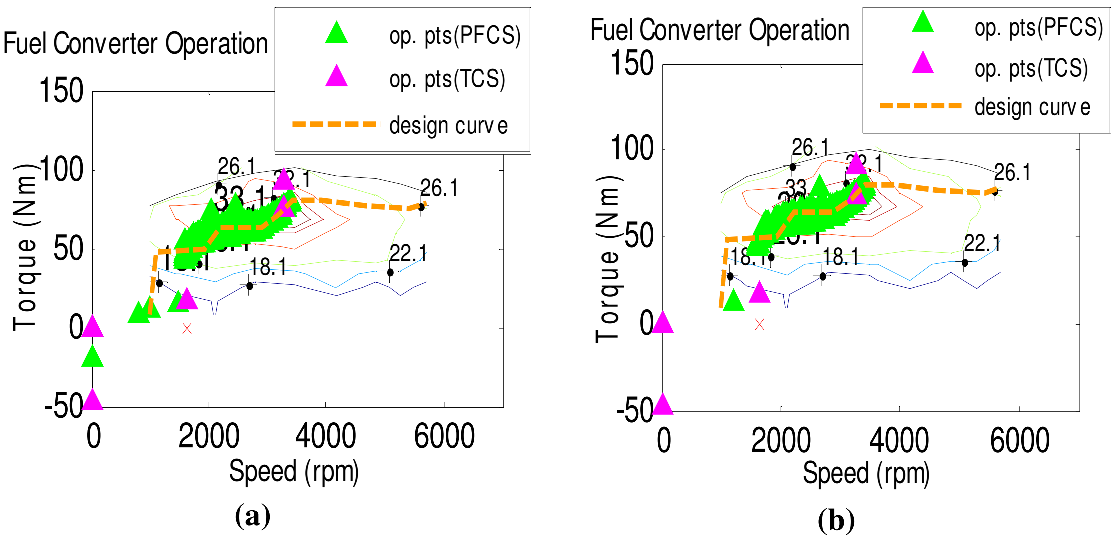

Fig. 9. Engine operating points in the (a) UDDS and the (b) HWFET driving cycles

Fig. 10 compares the fuel converter efficiency of the SHEV controlled by the TCS with that controlled by the PFCS in the UDDS and HWFET driving cycles. For both cycles, the engine of the SHEV operates at its most efficient operating point by applying the thermostat control strategy. the efficiency of the SHEV engine with the PFCS is lower compared to that controlled by the TCS which justifies the highest fuel consumption of the vehicle controlled by the PFCS compared to that controlled by the TCS.

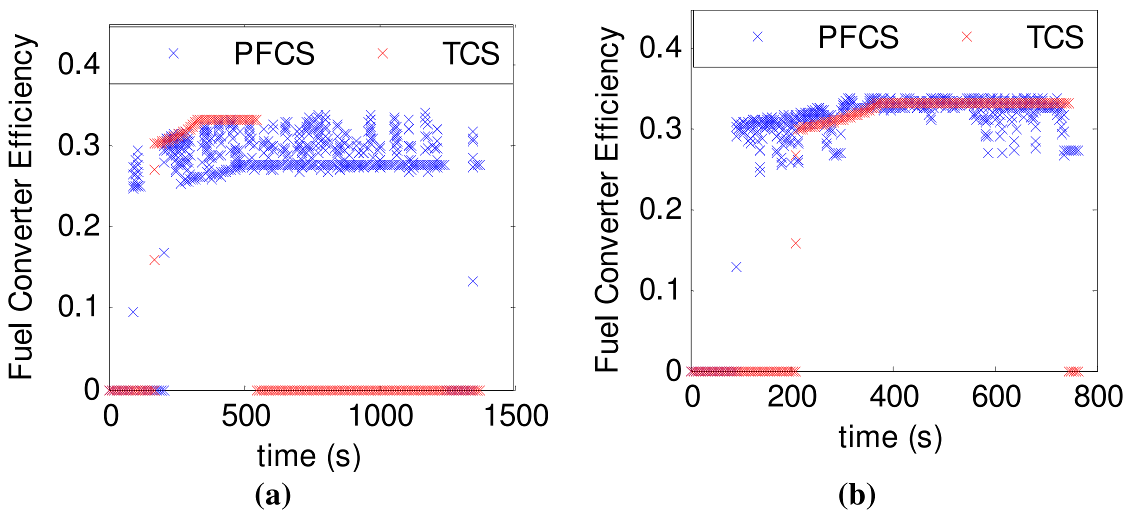

Fig. 10. Fuel converter efficiency in the (a) UDDS and (b) HWFET driving cycles

The results of these simulations are summarized in Table 3.

Table 3. Emissions and fuel consumption values

Parameters		UDDS cycle test		HWFET cycle test		Units
		TCS	*PFCS*	*TCS*	*PFCS*	
Fuel consumption		7.7	9.7	7.8	8.1	L/100km
Emission	HC	0.557	0.554	0.44	0.436	g/km
	CO	2.519	1.839	1.943	1.626	
	NOx	0.739	0.576	0.627	0.544	

As evident from Table 3, the PFCS-based vehicle consumes more fuel than the TCS because it adopts the engine as a main source. On the other hand, the gas emissions are lower for the PFCS-controlled vehicle.

6. Conclusion

In this study, a comparison of emissions and fuel consumption was made for an SHEV controlled by two different control strategies: the thermostat control strategy and the power follower control strategy. With the TCS, the engine runs at its highest level of efficiency each time it is turned on, without necessarily providing optimum overall efficiency. With the PFCS, the ICE / generator output power follows the power desired to minimize battery charge and discharge, and the battery SOC remains constant, but the engine operates in a wider area. With this strategy, the efficiency of the battery is optimized. In addition, the study findings demonstrate that emissions of a vehicle controlled by the TCS are higher than that controlled by the PFCS, but its fuel consumption is lower.

Following the results obtained, it is evident that the proposed control strategies do not guarantee fuel consumption or greenhouse gas emissions rates closer to optimal. Other strategies should be explored in order to propose more efficient algorithm to solve the problem of SHEV optimization parameters.

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