Applied Thermal Engineering 91 (2015) 694–705

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Fully optimized energy management for propulsion, thermal cooling and auxiliaries of a serial hybrid electric vehicle

Francisco José Jiménez-Espadafor [a,*,1], Daniel Palomo Guerrero [a,1], Elisa Carvajal Trujillo [a,1], Miguel Torres García [a,1], Johan Wideberg [b,2]

[a] Department of Energy Engineering, Seville University, Spain, Camino de los Descubrimientos, s/n, 41092 Sevilla, Spain
[b] Transport Engineering Department, Seville University, Spain, Camino de los Descubrimientos, s/n, 41092 Sevilla, Spain

HIGHLIGHTS

- Fuel consumption reduction of SHEV depends on propulsion, cooling and auxiliaries.
- Energy consumption of cooling system change a lot with vehicle loads.
- An appropriate cooling design improves fuel consumption along vehicle service life.

ARTICLE INFO

Article history:
Received 23 February 2015
Accepted 11 August 2015
Available online 20 August 2015

Keywords:
Hybrid electrical vehicle
Optimal energy management
Cooling system

ABSTRACT

Energy management in vehicles is a relevant issue, especially in the case of electric vehicles (EV) or hybrid vehicles (HEV) where different energy demands have to be satisfied from the primary energy source.

In this work two energy management strategies are applied to a serial hybrid High Mobility Multi-purpose Wheeled Vehicle in order to analyze the potentiality of the reduction of fuel consumption. A one-dimension numerical model of the serial hybrid vehicle was established. This model integrates hybrid vehicle propulsion, internal combustion engine cooling, electric engine and appliances cooling and energy consumption from auxiliary equipment. All the energy required for the vehicle comes from the internal combustion engine that is coupled to a generator. This injects energy to constant electrical tension into the power bus that can be stored in batteries and ultracapacitors or feed to the propulsion engines and the auxiliaries. Electrical storage systems can also inject energy into the power bus to satisfy any demand. The cooling system is integrated by radiators, electrically controlled pumps, fan and valves and all the equipment present a maximum allowable outlet water temperature that cannot be passed. Vehicle propulsion loads and ambient air conditions have been estimated from a route usually followed by ground troops where position, velocity and acceleration are available.

Based on the previous model, two control strategies for the combined control of propulsion, cooling and auxiliaries' energy supply were proposed and evaluated. As a result and considering the expected useful life of the vehicle, the best energy management strategy is able to avoid the consumption of more than 50,000 L of diesel fuel avoiding the emissions of 177 tons of CO_2.

1. Introduction

Worldwide road transport represent a significant part of the global oil and natural gas consumption and therefore of the carbon dioxide emissions. Mainly due to cost, transformation technology and production issues, biofuels are far to be a total alternative to oil and natural gas in the transport sector. Otherwise, in the medium term full electric vehicle is not ready to be a substitute to the internal combustion engine due to technology challenges regarding

* Corresponding author. Tel.: +34 95 4487245.
E-mail addresses: fcojjea@us.es (F.J. Jiménez-Espadafor), wideberg@us.es (J. Wideberg).
[1] Tel.: +34 95 4487245.
[2] Tel.: +34 95 4482280.

http://dx.doi.org/10.1016/j.applthermaleng.2015.08.020

Nomenclature

AD	auxiliary devices
BM	battery modules
CA	compact alternator
DC/DC	direct current/direct current converter
EM	electrical motor
EMS	energy management strategy
GPS	global positioning system
EV	electrical vehicles
HEV	hybrid electric vehicles
HMMWV	high mobility multipurpose wheeled vehicle
HVAC	heating, ventilation and air conditioning
ICE	internal combustion engine
PB	power bus
SHEV	serial hybrid electric vehicles
UC	ultracapacitor
$T_{i,\ i=1,\ 2,\ 3,\ 4,\ 6,\ 7}$	thermocouples/temperature

capacity of energy storage systems and adequacy of electrical grid. Compared to internal combustion engine (ICE), Hybrid Electric Vehicles (HEV) offer benefits for both fuel consumption and decreasing emission of pollutants. Although there are commercial vehicles with this technology, many challenges have to be addressed in order to reduce the total fuel consumption as those related to full energy management.

HEV can pick up kinetic energy through braking and store it for later use improving fuel economy up to 20% [1]. In Serial Hybrid-Electric Vehicles (SHEV), the electrical traction engines are not coupled to the ICE mechanically which allows more flexibility to the ICE to operate at the highest attainable efficiency independent from demanded torque and speed for the propulsion of the vehicle [2].

Aside of propulsion, cooling system supposes a significant part of the total energy consumption of the HEV; at part load could be more than 50% [3,4]. Also it has to be considered that energy demands of Heating, Ventilation and Air Conditioning (HVAC) depend with the number of occupants, solar radiation, wind/vehicle speed, atmospheric temperature, cabin design and the nature of the HVAC system [5,6]. In this work the potential of reduction in fuel consumption of a High Mobility Multipurpose Wheeled Vehicle (HMMWV) is analyzed for two energy management strategies (EMS) that include the cooling system, showing an impressive saving of fuel. The vehicle energy consumption comes from the propulsion system, the auxiliaries and the thermal management of the SHEV. The latter consider the electric devices, the generator, the wheel electric motor-generators and the cooling of the ICE. The importance of considering the thermal management as a procedure to reduce fuel consumption in ICE has been demonstrated in Ref. [7] where Caresana et. Alter show the fuel economy that can be achieved through the adoption of thermal management in a passenger car run between 6% and 12%, depending on the standard driving cycle considered. Regarding hybrid vehicles, cooling system design and performance is capturing attention due to the interest to maximize fuel efficiency, engine performance and system life [3,8]. The increase of high-power electronics devices present in HEV that have to dissipate thermal energy has highlighted the need for devising thermal management systems able to respond to power peaks and simultaneously to part load conditions [9]. Continuous variable transmission, a component of the propulsion system of some types of HEV, needs to dissipate thermal energy in order to gain higher efficiency and therefore a thermal management system should be considered for improve fuel consumption [10].

Regarding the optimization of the energy management system two general trends can be considered [11];

- Optimization-Based Strategies
- Ruled-Based Strategies

The first one is commonly used when the driving cycle is fixed and the second one is appropriated when the driving cycle is unknown, as it is the case for vehicle control. The paper is structured in three parts. Section 2 deals with main vehicle characteristics and power fluxes, in particular from Section 2.3–2.5 detailed system descriptions are given with the focus on performance curves. The integration of the cooling system is presented in Section 3 with the description of the thermal management strategies. Section 4 presents the optimization rules applied to the vehicle along the driving cycle considered in Section 5. Finally at Section 6 the results are compared.

2. Description of the system

This section shows the architecture of the SHEV being the main physical characteristics shown in Table 1.

The power plant structure is shown in Fig. 1. It is composed by an ICE coupled to a compact alternator (CA) which can supply power not only to propulsion but also to battery modules (BM) and auxiliary devices (AD) such as illumination, suspension and steering systems, air conditioned, cooling fans and pumps, electronics and tactical equipment among others. Ultracapacitors (UC) are included as additional high-rate power storage system. Direct Current/Direct Current converters (DC/DC) adapt voltage and current conditions between the storage equipment and the power bus (PB). Propulsion to wheels is supplied by eight electrical motor (EM).

2.1. Power fluxes

Different power fluxes, unidirectional and bidirectional arrows in Fig. 1 are possible depending on energy needs. Since the generator is the only component mechanically coupled to ICE, when energy is required electrical power is supplied from ICE to PB and it is distributed to the consumers. Three cases are possible:

- Battery charge: when propulsion and auxiliary loads are satisfied, energy remaining is sent to BM. UC are not allowed to be charged directly by energy coming from ICE.
- Battery discharge: if ICE cannot supply whole power demands, BM and UC inject additional power but guarantying a minimum battery charge level.
- Regenerative braking: mechanical energy from braking is used to charge BM and UC.

Table 1
SHEV specifications.

Weight	22,000 kg
Frontal width	2.8 m
Frontal height	2.4 m
Number of power wheels	8
Maximum speed	80 km/h
Maximum slope	25%