Journal of Power Sources 196 (2011) 3360–3370

Contents lists available at ScienceDirect

Journal of Power Sources

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

A numerical investigation on the efficiency of range extending systems using Advanced Vehicle Simulator

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ARTICLE INFO

Article history:
Received 6 August 2010
Received in revised form 22 October 2010
Accepted 26 October 2010
Available online 9 November 2010

Keywords:
ADVISOR
Electric vehicle
Range extender
Series hybrid electric vehicle
Rotary engine
Wankel engine

ABSTRACT

Series plug-in hybrid electric vehicles of varying engine configuration and battery capacity are modeled using Advanced Vehicle Simulator (ADVISOR). The performance of these vehicles is analyzed on the bases of energy consumption and greenhouse gas emissions on the tank-to-wheel and well-to-wheel paths. Both city and highway driving conditions are considered during the simulation. When simulated on the well-to-wheel path, it is shown that the range extender with a Wankel rotary engine consumes less energy and emits fewer greenhouse gases compared to the other systems with reciprocating engines during many driving cycles. The rotary engine has a higher power-to-weight ratio and lower noise, vibration and harshness compared to conventional reciprocating engines, although performs less efficiently. The benefits of a Wankel engine make it an attractive option for use as a range extender in a plug-in hybrid electric vehicle.

1. Introduction

1.1. Energy and transportation

Since the beginning of the twentieth century, combustion of fossil fuels has been a primary source of energy for the industrial world. Fossil fuels such as petroleum are a finite resource, and it is predicted that the release of greenhouse gases (GHG) from burning fossil fuels contributes to global warming [1] and can lead to health complications in afflicted communities. The U.S. Energy Administration estimates that almost 2/3 of total demand for petroleum is from the transportation sector [2]. Assuming that daily production holds steady at 63.5 million barrels, global oil reserves are conservatively predicted to last approximately fifty years [3]. There is great potential for the reduction of petroleum consumption by converting the current vehicle fleet from conventional vehicles powered by reciprocating gasoline or diesel engines, to battery electric vehicles which draw their energy from the electricity grid. Unfortunately, the limited range of battery electric vehicle [4] suggests that the needs of the average U.S. commuter will not be met without a supplementary energy source. One solution is to couple the strengths of the battery electric vehicle with the extended range of a petroleum fueled vehicle in a hybrid drive train. This alternative to the single fuel conventional vehicle is the plug-in hybrid electric vehicle (PHEV). These vehicles may be primarily powered by grid electricity, stored in an on-board battery system, with additional electricity generated by an on-board fuel converter. This vehicle configuration is termed the series PHEV, and the supplemental electricity generation system is termed the range extender.

With a transformation of the vehicle fleet on the horizon, it is important to intelligently select future vehicle technologies. This study demonstrates the use of virtual simulations to predict the effectiveness of different technologies for extending the range of battery electric vehicles. Performance characteristics in all-electric and range-extending modes are quantified on a well to wheel basis, comparing energy consumption and GHG emissions. Numerical simulation of energy consumption by various automotive range extending technologies can aid to focus and accelerate experimental research on energy storage and conversion for advanced vehicles.

We compare the performance of the reciprocating (spark ignition) engine to the Wankel (rotary) combustion engine when used as a range extender for a series PHEV. The Wankel engine has the advantage of a high power-to-weight ratio, more compact size and packaging, and reduced noise, vibration and harshness (NVH) compared to the reciprocating engine. These benefits come at the expense of lower fuel economy.

1.2. Hybrid system simulation

Hybrid vehicle development carries with it all the traditional challenges of automotive design, with added complexity from

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doi:10.1016/j.jpowsour.2010.10.086

incorporation of hybridized drive train components. The research process for hybrid systems can be simplified by utilizing computer simulations to identify the most favorable vehicle configuration for given operating conditions. The literature has demonstrated different objectives and methods of approach for numerical analysis of hybrid vehicles. Automotive simulation models have been recently developed to yield vehicle performance, energy storage requirements and power conversion efficiency for given driving conditions. Brown et al. [5] developed and validated a "Light, Fast and Modifiable" platform for optimizing a hybrid power train with a forward-facing model that includes a driver component. Their approach resulted in a flexible simulation tool that is sufficiently reliable to predict the behavior of different hybrid power train configurations. While the work in [5] aimed to simulate and study the hybrid drive train as a whole, other researchers such as Gökdere et al. [6] have developed virtual prototypes with particular focus on the electronic aspects of power conversion. Still others have used basic modeling techniques to simplify the complex relationships between a hybrid vehicle energy storage system and the vehicle performance [7].

To date, the academic community does not have literature on numerical simulations of the Wankel engine for use in light-duty transportation. This study utilizes Advanced Vehicle Simulator (ADVISOR) for simulation of vehicle performance and energy consumption using the Wankel engine as compared to more traditional range extenders. The ADVISOR software package was developed by the National Renewable Energy Laboratory (NREL) to aid in the development of alternatively powered vehicles. It was intended to ease the numerical simulation process for vehicles under development. ADVISOR uses a combined backward-forward approach [8] that enables the software to accurately model advanced batteries and power train components while maintaining a relatively fast simulation speed. It has been demonstrated as a reliable tool for studying energy consumption and vehicle performance [9–11] and for testing energy-related control schemes [12]. Previous work by the authors has shown ADVISOR to be useful for optimization of hybrid power train configuration [13].

Well to tank energy use and greenhouse gas data are obtained through use of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) software package, produced by the U.S. Department of Energy. The GREET model simulates energy use and emissions associated with the production and distribution of transportation fuels.

1.3. Rotary engine

The Wankel (or "rotary") engine is lighter and more easily packaged as a range extending module in a hybrid electric vehicle compared to other candidates such as reciprocating engines and fuel cells [14]. The Wankel engine produces twice as many combustion events per revolution compared to a reciprocating 4-stroke engine, and thus has superior power density. The output shaft of the Wankel engine is centered relative to the rotor housing, and can be easily coupled with a generator to produce electricity. Due to strictly rotary (as compared to reciprocating) motion, and more frequent air intake/exhaust events, the Wankel has relatively low NVH, second only to the fuel cell. Reduced NVH is especially critical when extending the range of the electric vehicle, as the occupants of the vehicle will be accustomed to the smooth and silent operation of their electric traction system, and may dislike the NVH produced by a conventional power train unit with a reciprocating engine range extender.

The advantages of the Wankel engine come at the cost of reduced fuel economy. The combustion chamber of the Wankel engine is long and narrow, giving it a high surface area to volume ratio. This negatively affects the thermodynamic efficiency of combustion due to heat transfer with the chamber's walls. In addition, flame quenching can occur at the trailing edge of the combustion chamber, causing increased hydrocarbon emissions and reduced fuel efficiency. Both inefficiencies are thought to be improved by utilizing direct-injected stratified charge (DISC) combustion, which localizes the combustion event to a small pocket on the rotor face [15]. The data used for this paper is based on the projected performance of a DISC engine with a minimum brake specific fuel consumption (BSFC) of 270 g kWh^{-1} [16]. Even prior to the simulation study outlined in [16], DISC engines had been developed which could achieve a BSFC as low as 237.3 g kWh^{-1} on gasoline fuel [17]. In contrast, the reciprocating engines analyzed herein achieved 206.7 g kWh^{-1} BSFC at peak efficiency.

The goal of this study is to determine whether the positive aspects of the Wankel engine can offset its poorer fuel economy when used as a range extender for a PHEV. The simulations described in this study are used to analyze vehicle energy consumption under different range-extender configurations to determine the most optimal application of the Wankel engine.

Nomenclature

ADVISOR	Advanced Vehicle Simulator
AER	all-electric range
BSFC	brake-specific fuel consumption
CVT	continuously variable transmission
DISC	direct injected stratified charge
GHG	greenhouse gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
kWh	kilowatt-hour
mph	miles per hour
mpg	miles per gallon
NASA	National Aeronautics and Space Administration
NVH	noise, vibration and harshness
PHEV	plug-in hybrid electric vehicle
VMT	vehicle-miles travelled

2. Vehicle design

Advanced Vehicle Simulator (ADVISOR) is a software package that is designed to simulate the performance of hybrid electric vehicles when driven over user-defined driving cycles. For this study, ADVISOR was used to estimate the efficiency of vehicles with different all-electric ranges (AERs) powered with different range extending engines. Sizing of the reciprocating engine is discussed in Section 3.

2.1. Rotary engine model

A Wankel engine was modeled in ADVISOR in order to enable vehicle simulation for this study. ADVISOR uses a matrix of BSFC referenced horizontally by engine speed and vertically by engine torque to determine the efficiency regions of an engine. These values are used during simulation to optimize the fuel efficiency of the vehicle. Detailed engine characterization data was required to construct such a matrix. In 1990, the National Aeronautics and Space Administration (NASA) simulated the performance of a DISC Wankel engine using MIT engine simulation code [16]. Results for a 75 kW class Wankel engine are shown in Fig. 1.

The data published by NASA was simulated utilizing a model based on a Wankel engine designed by Outboard Marine Corporation (Freedom Motors Rotopower product line). Research is being carried out at the University of California, Davis to improve the