

Comparative Analysis of Internal Combustion Engine and Fuel Cell Range Extender

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ABSTRACT

Fuel cells offer a high-efficiency and low-emission alternative to internal combustion engines (ICE) in vehicle applications. The fuel cell is silent, vibration free and zero emissions at point of use which allows the vehicle engineer considerably greater operational flexibility than with an ICE. The engineer is no longer constrained by the need to maintain discrete power levels to minimise noise intrusion, or switch the 'engine' off at low vehicle speeds to reduce noise and vibration. This paper presents simulation work comparing the performance of a typical B-segment electric vehicle with either a fuel cell or an ICE range extender over a number of real-world drive cycles. Intelligent Energy's 'Gen4' air cooled fuel cell system is detailed as the fuel cell range extender, a typical 660cc naturally aspirated gasoline engine is considered for comparison. The results show that a fuel cell can be operated for a greater portion of an urban drive cycle than an ICE, which in turn means a lower power range extender can meet urban and extra-urban drive cycle average power requirements. As it is nearly silent, the fuel cell is also free to follow the driving power demand as far as possible, reducing charging and discharging losses in the battery and DC/DC converter. The analysis suggests up to 40% less fuel energy is required from the fuel cell compared to an ICE to cover the same distance, and that a fuel cell can match the performance of a combustion engine range extender with up to twice the rated power output.

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INTRODUCTION

With increasing concerns throughout the world about passenger car exhaust emissions and their effect on the climate and local air quality in major cities, many governments are incentivising the purchase of ultra-low carbon vehicles with battery electric, plug-in hybrid and fuel cell powertrains [1, 2, 3]. It is widely recognised that mass market battery electric vehicles are compromised by short driving range and long recharge times [4]. Plug-in hybrid vehicles offer a solution in that they can be operated with zero tailpipe emissions as a battery electric vehicle, but when the need arises there is an auxiliary on-board power source, typically a conventional gasoline or diesel engine, which has the advantage of rapid refuelling.

There are a large number of papers in the literature simulating the behaviour of hybrid vehicles over specific drive cycles in order to explore different aspects of hybrid vehicles such as optimisation of architecture and component sizes [5], balance of on-board energy storage [6] and on-board power management strategy [7]. Typically these studies use a computational model of a vehicle to explore the wide range of possible vehicle configurations, control strategies, drive cycles and driver behaviour. Vehicle drive cycle simulations fall into two main categories: forward facing and backward facing. Backward facing simulations start with a vehicle speed-time profile and from this, calculate the torque, power, etc. required to exactly follow that profile [8]. The advantage of this approach is

computational efficiency and coding simplicity: typically simulations to determine drive cycle energy consumption are backward facing. The drawback of this approach is that no explicit driver model or control signals are necessary and therefore direct modelling and development of control systems can be difficult. Forward facing codes generally take a driver model as the starting point and derive control signals such as throttle, brake etc. as the driver model attempts to follow a vehicle speed vs. time profile. Forward facing simulations are used most in control system development and peak vehicle performance prediction with a given set of powertrain components, and make up the majority of the commercially available software suites [9, 10]. From the broader set of hybrid vehicle architecture studies, simulations of fuel cell hybrid vehicles specifically are available in the literature, the focus of recent studies has been the optimisation of the fuel cell power management strategy [11].

A fuel cell model may fall into one of three categories: analytical, semi-empirical, or mechanistic (theoretical). Analytical models are approximate and do not include the details of transport processes occurring within the cell. They are limited to predicting voltage losses and water management requirements for simple designs and are useful for making quick calculations of simplified systems. Semi-empirical modelling combines theoretically derived differential and algebraic equations with empirically determined relationships. Empirical relationships are employed when the physical phenomena are difficult to model or the theory governing the phenomena is not

well understood. Mechanistic modelling has received the most attention in the literature and is reviewed comprehensively by Cheddie et al [12]. In mechanistic modelling, differential and algebraic equations are derived based on the physics and electrochemistry governing the phenomena internal to the cell, and solved using a variety of numerical methods.

The simulation work presented in this paper uses a forward facing code developed in-house at Intelligent Energy, as this approach gives the necessary flexibility to consider radically new vehicle architectures, power management strategies and types of auxiliary power units i.e. fuel cells. The fuel cell model in this work is semi-empirical, derived from Intelligent Energy's extensive fuel cell characterisation data.

MODEL COMPONENTS

Vehicle Model

The retarding force due to aerodynamic drag, rolling resistance and the effect of road gradient is calculated according to [equation \(1\)](#).

$$F_{\text{vehicle}} = \frac{1}{2} \rho A C_d U^2 + \mu_{rr} mg + mg \sin \theta \quad (1)$$

Where ρ is the density of air, C_d is the non-dimensional coefficient of drag, A is the vehicle frontal area, U is vehicle speed, μ_{rr} is the non-dimensional coefficient of rolling resistance, m is the vehicle mass, g is the acceleration due to gravity, and θ is the angle of the road incline. The power dissipated by the vehicle, in Watts, as a result of these drag forces (P_{vehicle}) can be calculated using [equation \(2\)](#).

$$P_{\text{vehicle}} = F_{\text{vehicle}} U \quad (2)$$

Energy conversion losses incurred in the mechanical transmission, electric motor and power electronics are included in the model using two dimensional efficiency maps. The energy loss associated with charge transfer to and from the battery is calculated from a first order internal resistance model using [equation \(3\)](#), where I is the battery current and R is the battery internal resistance.

$$P_{\text{losses, bat}} = I^2 R \quad (3)$$

[Table 1](#) gives the key assumptions about the vehicle in this work, chosen to represent a typical B-segment passenger car.

The general vehicle architecture for a Range Extender Electric Vehicle (REEV) assumed throughout this work is shown in [figure 1](#). The range extender is assumed to be an internal combustion engine or fuel cell as appropriate.

Table 1. Vehicle model parameters

Kerb mass	1,500 kg
Drag coefficient, C_d	0.31
Frontal area, A	2.1 m ²
Rolling resistance coefficient, μ_{rr}	0.008
Battery energy capacity	24 kWh (19.2 kWh usable)
Peak/continuous motor power	75 kW / 50 kW
Peak/continuous motor torque	250 Nm / 150 Nm
Transmission ratio	9.0:1
12V electrical accessory power	300 W

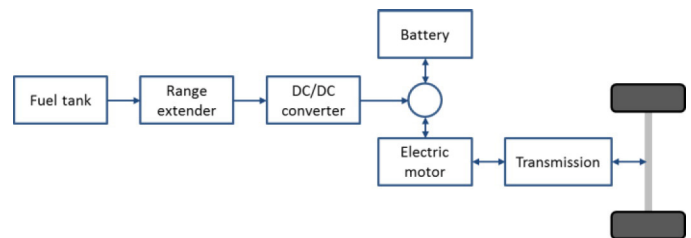


Figure 1. General REEV architecture

Range Extender - Internal Combustion Engine Model

The ICE Auxiliary Power Unit (APU) model is based on a 3-cylinder 660 cc gasoline engine connected to an electrical generator with a maximum continuous power rating of 30 kW. Several dedicated range extender engines [13, 14, 15] have been developed with power outputs of up to 30 kW for B- and C-segment passenger cars to sustain the battery charge in a range-extended electric powertrain. The efficiency of the ICE and generator across its speed and torque curve is shown in [figure 2](#), these data having been collected from a dynamometer test of a 660 cc engine. In this work the on-board gasoline fuel tank is assumed to be 10 litres capacity.

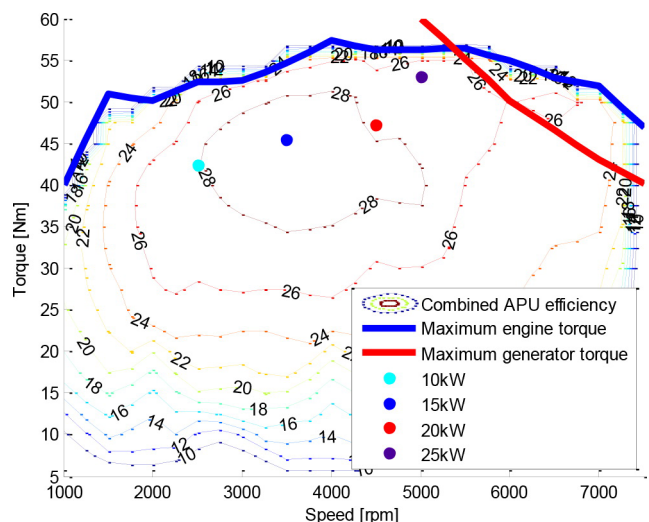


Figure 2. ICE plus generator efficiency map

Range Extender - Fuel Cell Model

The Gen4 fuel cell system is a self-contained air cooled fuel cell system based on Intelligent Energy's AC64 fuel cell stack technology, shown in [figure 3](#). The current and voltage characteristics of a cell in the AC64 stack, which are used in this work, are shown in [figure 4](#). The Gen4 unit, shown in [figure 5](#), has integrated air management; hydrogen gas management including inlet solenoid and pressure sensor; fans to supply air for power generation and cooling; electronics for control and communication, and power switching; low temperature operation equipment to allow operation in sub-zero conditions. The current and voltage characteristics of the Gen4 system, which are used in this work, are shown in [figure 6](#).



Figure 3. AC64 fuel cell stacks

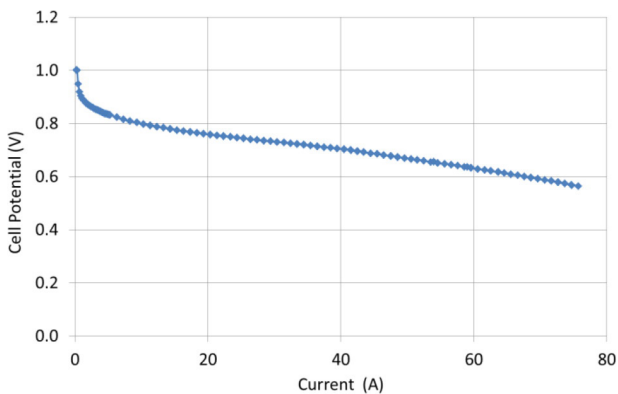


Figure 4. AC64 fuel cell I-V characteristic



Figure 5. Gen4 fuel cell system

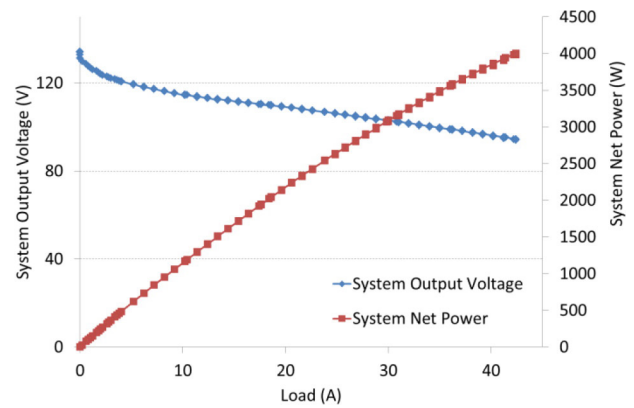


Figure 6. Gen4 system I-V characteristic

In this work the fuel cell APU is considered to be comprised of two Gen4 units, giving a total peak power output of 7.8 kW and total mass of 39.8 kg. The capacity of the on-board hydrogen fuel storage system is assumed to be 1.5 kg in order to make approximately the same energy available to the vehicle from the hydrogen and fuel cell system, as for the gasoline and ICE system.

Vehicle Power Management Strategies

The power management strategy determines how the power from the battery and range extender is managed to meet the total power requirements of the vehicle. The different characteristics of the two range extender options lend themselves to different power management strategies.

The ICE power management strategy switches the ICE on when the battery state of charge (SOC) drops below 15% in order to maximise the battery-only operation of the vehicle. This strategy is used by manufacturers of this type of vehicle as it gives the minimum CO₂ rating when tested according to the ECE-R101 test procedure [16]. If the vehicle power demand is low and the battery SOC subsequently reaches 20%, the ICE is turned off. This mode of operation continues until the fuel tank is empty, whereupon the vehicle returns to battery-only operation until the battery SOC reaches the lower operating limit of 10%.

The ICE power management strategy constrains the ICE to operate at four discrete power points once switched on, switching between these load points is based on vehicle speed as shown in [figure 7](#). The load points are chosen to give the best possible efficiency from the ICE and are shown in [figure 2](#). To reflect real world power management strategies in plug-in hybrid or range extended vehicles to minimise noise and vibration in the passenger compartment, the ICE is turned off when the vehicle speed drops below 15 km/h, and on again when it rises above 30 km/h. It is, of course, possible to operate the ICE across a continuous range of output power levels but the ICE is not efficient at part load and in practice the constant varying of engine speed, and hence associated frequency of noise and vibration, has anecdotally been found to be intrusive.