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Analysis of a fuel cell hybrid commuter railway vehicle

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ABSTRACT

This study presents paper presents an analysis of the potential CO_2 savings that could be gained through the introduction of hydrogen-powered fuel cells on a commuter-style railway route. Vehicle is modelled as a fuel cell series hybrid. The analysis consists of power/energy flow models of a fuel cell stack, battery pack and hybrid drive controller. The models are implemented in a custom C# application and are capable of providing key parametric information of the simulated journey and individual energy drive components. A typical commuter return journey between Stratford Upon Avon and Birmingham is investigated. The fuel cell stack and battery pack behaviour is assessed for different stack sizes, battery sizes and control strategies to evaluate the performance of the overall system with the aim of understanding the optimum component configuration. Finally, the fuel (H_2) requirements are compared with typical diesel and hybrid-diesel powered vehicles with the aim of understanding the potential energy savings gained from such a fuel cell hybrid vehicle.

1. Introduction

Railway transport is arguably one of the least environmentally damaging forms of transport [1]. Widely deployed electrification means that the majority of passenger kilometres generate zero emissions at the point of use. Railways also share in the CO_2 benefits that occur through increasing de-carbonization of grid electricity. On the other hand, the extremities of most railway networks contain lightly-loaded routes that are uneconomic to electrify [2]. The vehicles that operate on these routes are currently diesel powered, and therefore are exposed to future fuel supply issues and uncertain future costs. In the short- to medium-term, these vehicles could be replaced or re-engineered to utilize hybrid propulsion systems, with a view to replace eventually the diesel prime mover with a fuel cell when reliability can be proven and an economic case can be made.

Hybrid devices produce near-zero emissions at the point of use. Today, much research is taking place into the use of fuel cells, which can range in output power from a few to several thousand kilowatts, in transport applications such as automobiles, buses, locomotives, ships, and submarines. Many different types of fuel cell are now available and in transport sectors the most popular is the proton exchange membrane (PEM) based technology. PEM fuel cells (PEMFCs) offer a valid alternative for transportation vehicles [3] and the literature contains some analysis of fuel cell locomotives in applications such as tunneling, mining [4] and hybrid shunt locomotives [5]. The existing analysis [6,7] provides a suitable foundation on which to develop this investigation.

As fuel cells run on hydrogen as opposed to fossil fuels such as coal, petroleum, and natural gas they have the potential of being a carbon-neutral source of energy. At present, the challenge is the efficient extraction and delivery of hydrogen. There are many technologies available to obtain hydrogen, of which the most popular is the steam reforming of natural gas. Currently, this is the most energy-efficient and large-scale method of hydrogen production [8–10], but CO_2 is produced in this process:

$$CH_4 + 2H_2O + \text{Energy} \rightarrow 4H_2 + CO_2 \quad (1)$$

The simplest carbon-neutral method of obtaining H_2 is by electrolysis of water:

$$H_2O + \text{Energy} \rightarrow H_2 + \frac{1}{2}O_2 \quad (2)$$

If the electrical energy for this process is obtained from renewable sources (i.e., hydropower, solar energy or wind energy) it is possible to produce hydrogen with no impact on greenhouse gases [11].

In this study, paper the effects of a hybrid energy propulsion drive on a commuter rail vehicle are investigated. The behaviour of the fuel cell stack and battery pack is assessed for different stack sizes, battery sizes and control strategies to evaluate the

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Table 1
Journey details (Stratford Upon Avon to Birmingham Moore Street).

Start location	Stratford Upon Avon Station
End location	Stratford Upon Avon Station (via Birmingham Moore Street Station)
Stations	34
Station list	Stratford Upon Avon, Wilmcote, Wootton Wawen, Henley in Arden, Danzey, Wood End, The Lakes, Earlswood, Wythall, Whitlocks End, Shirley, Yardley Wood, Hall Green, Spring Road, Tyseley, Small Heath, Bordesley, Birmingham Moore Street (and back)
Journey length	78.58 km

performance of the overall system with the aim of understanding the optimum component configuration. Finally, the fuel (H_2) requirements are compared with a typical diesel and hybrid-diesel powered vehicles with the aim of understanding the potential energy and CO_2 savings gained from such a fuel cell hybrid vehicle.

2. Journey details

All results reported in this investigation are centred around a Class 150 Diesel Multiple Unit (DMU) railway vehicle running along a segment of the Birmingham Snow Hill Line in the United Kingdom between Stratford Upon Avon and Birmingham Moore Street Station. Details of the selected journey and vehicle are given in Tables 1, 2 and Fig. 1(a) and (b).

3. Railway vehicle simulation

The basic forces that govern the behaviour of a railway vehicle are shown in Fig. 2. The vehicle response is achieved by solving the equation of motion by using Lomonossoff's equation [12]:

$$M_e \frac{d^2 s}{dt^2} = F - R - Mg \sin\alpha \qquad (3)$$

where M is the total mass of the vehicle; M_e is the inertial mass of the vehicle; g is the gravitational acceleration; R is the resistance to motion the vehicle experiences while moving along the track; $\sin\alpha$ is the gradient of the track; F is the total tractive effort produced at the powered wheels of the vehicle; s is the vehicle displacement.

The term R is the resistance to motion encountered by the vehicle (apart from gravity). This is made up of the sum of mechanical friction, frictional losses due to the vehicle interacting with the running rails, and aerodynamic drag. With help from the following Davis Equation, the total resistance to motion (R_t) can be expressed empirically as:

$$R_t = A + B\frac{ds}{dt} + C\left(\frac{ds}{dt}\right)^2 + D\frac{Mg}{r} + Mg\alpha \qquad (4)$$

where ds/dt is the velocity of the vehicle; r is the radius of track curvature; α is the gradient angle of the track ($\sin\alpha \approx \alpha$, where, $\alpha \to 0$); A, B, C and D are constants.

Table 2
Vehicle characteristics for a Class 150 DMU.

Railway vehicle	British Rail, Class 150 DMU
Mass	76.5×10^3 kg
Number of seats	124
Speed (max)	$33.5\ \mathrm{m\,s^{-1}}$ ($\approx$ 75 mph)
Tractive effort (max)	$\approx$ 40.0 kN
Tractive power (max; at wheels)	374 kN
Base speed	$8\ \mathrm{m\,s^{-1}}$ ($\approx$ 18 mph)
Percentage of powered axles	50%
Acceleration mass coefficient (λ)	0.08
Davis equation coefficients	$A = 2.09 \times 10^3$ N $B = 9.83\ \mathrm{N\,m^{-1}\,s}$ $C = 6.51\ \mathrm{N\,m^{-2}\,s^2}$ $D = 0.00\ \mathrm{kg^{-1}}$

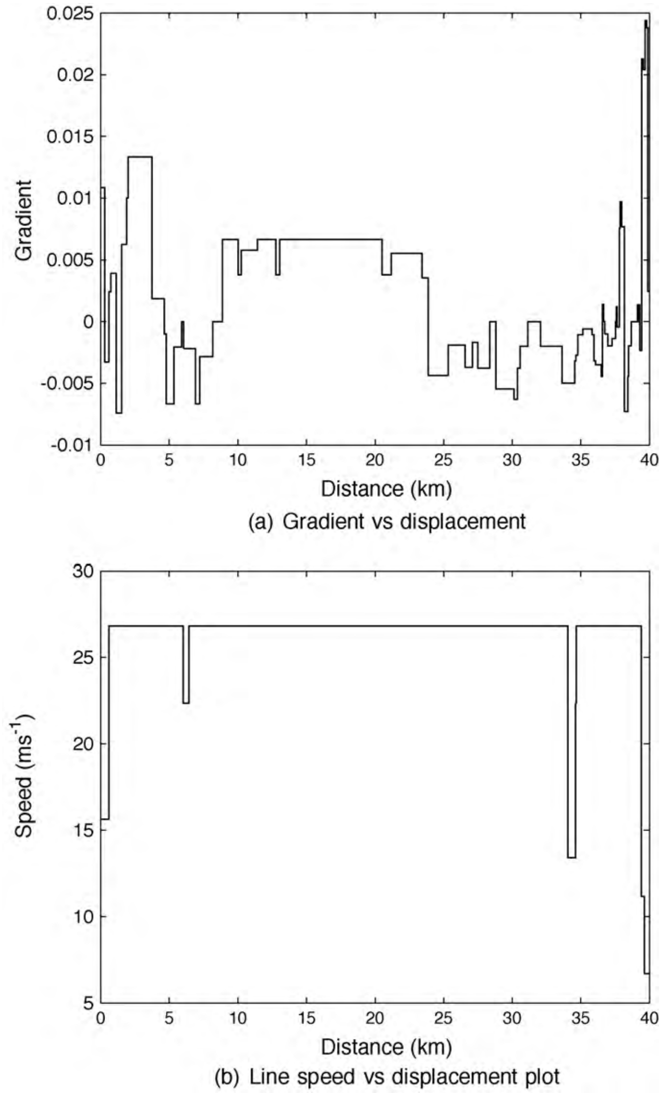

Fig. 1. (a and b) Details of simulated route between Stratford upon Avon to Birmingham Moore Street.

The vehicle response can be calculated for a given track and vehicle characteristic by solving the following equation:

$$M_e \frac{d^2 s}{dt^2} = TE - \left[A + B\frac{ds}{dt} + C\left(\frac{ds}{dt}\right)^2 + D\frac{Mg}{r} + Mg\alpha\right] \qquad (5)$$

where TE is the total tractive effort delivered by the powered wheels; A, B, C and D can be determined by vehicle characteristic data obtained by run-down tests or by the use of the

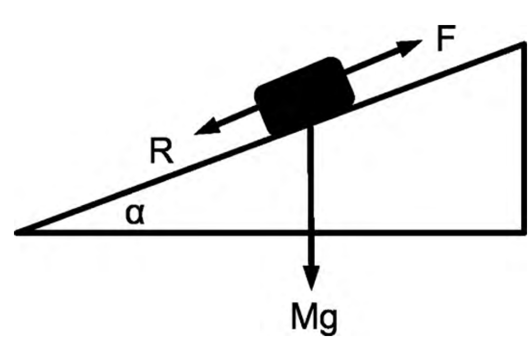

Fig. 2. Forces acting upon a typical railway vehicle.