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Performance evaluation of the hydrogen-powered prototype locomotive 'Hydrogen Pioneer'

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HIGHLIGHTS

- The performance of the UK's first hydrogen-powered locomotive was evaluated.
- Empirical measurements of vehicle performance were gathered.
- Behaviour of a hydrogen hybrid drive train for railway propulsion was analysed.
- Vehicle and power-plant efficiency in a number of scenarios was examined.
- Little difference between duty cycle and steady state vehicle operation was observed.

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ABSTRACT

The narrow-gauge locomotive 'Hydrogen Pioneer', which was developed and constructed at the University of Birmingham, was employed to establish the performance of a hydrogen-hybrid railway traction vehicle. To achieve this several empirical tests were conducted. The locomotive utilises hydrogen gas in a Proton Exchange Membrane Fuel Cell power-plant to supply electricity to the traction motors or charge the on-board lead-acid batteries. First, the resistance to motion of the vehicle was determined, then operating tests were conducted for the speeds 2 km h^{-1}, 6 km h^{-1}, 7 km h^{-1}, and 10 km h^{-1} on a 30 m straight, level alignment resembling light running. The power-plant and vehicle efficiency as well as the performance of the hybrid system were recorded. The observed overall duty cycle efficiency of the power-plant was from 28% to 40% and peak-power demand, such as during acceleration, was provided by the battery-pack, while average power during the duty cycle was met by the fuel cell stack, as designed. The tests establish the proof-of-concept for a hydrogen-hybrid railway traction vehicle and the results indicate that the traction system can be applied to full-scale locomotives.

1. Introduction

The majority of the world-wide energy demand for railway motive power is currently supplied by diesel [1], but concerns about point-of-use emissions and total greenhouse gas contributions as well as petroleum supply security require alternative solutions for railway lines that are not economical to electrify. Hydrogen, being a secondary energy, allows a mix of production feedstocks and leaves as point-of-use exhaust pure water if utilised in fuel cells [2]. For these reasons hydrogen-powered railway propulsion offers an alternative to diesel and this has been considered in several studies [3–8], and the application of fuel cells as power-plants for railway vehicles has been discussed [9–12]. The annual International Hydrail Conference, www.hydrail.org, is dedicated to the topic of hydrogen-powered railway vehicles and hydrogen fuel cells as power-plants for railway motive power. In addition to these studies and the conference series, some prototypes have been constructed [13–18]. In 2012, the first commercial fleet of five hydrogen-powered locomotives was introduced in South Africa for use in a mine [19], and four hydrogen-powered trams will be brought into commercial operation in Aruba during 2013 [20].

The UK's first hydrogen-powered locomotive was developed and demonstrated at the University of Birmingham in June 2012 [7]. This narrow-gauge hybrid locomotive, the 'Hydrogen Pioneer', was employed for an empirical performance evaluation. The vehicle uses gaseous hydrogen in a Proton Exchange Membrane (PEM) Fuel Cell to generate power for traction or charging of the on-board lead-acid batteries, which are also re-charged during braking. A DC to DC converter, together with the fuel cell stack forms the power-plant of the Hydrogen Pioneer. The electrical drive-train, or DC bus, can be fed either from the power-plant or the battery-pack

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Table 1
Hydrogen Pioneer hybrid locomotive parameters.

Parameter	Unit
Mass (without hydrogen tank)	270 kg
Maximum speed	20 km h^{-1}
Characteristics of the ReliOn E-1100™ power-plant [21]	
Maximum net power output (electrical)	1.1 kW
Output tension	48 V
Rated current at 48 V DC	28 A
Hydrogen consumption at 1000 W output	13 slpm
Characteristics of the LEM-130/95 permanent magnet traction motor [23]	
Peak current	100 A
Rated tension	36 V
Continuous traction motor power	2.2 kW
Rated torque	4.35 Nm
Number of motors	2
Characteristics of the EXV90 Enduroline calcium leisure battery 90 Ah [22]	
Tension	12 V
Capacity (one battery)	90 Ah
Battery-pack capacity (four batteries)	4.3 kWh
DC-bus electrical tension	48 V
Tractive effort (with compressed hydrogen tank)	645 N
Maximum acceleration with a 600 kg trailing load	0.8 m s^{-2}
Hydrogen-gas storage pressure	200 bar
Gross mass of hydrogen tank	16 kg

[23] Lynch Motor Company. (2013). LMC Motors: LEM-130. Honiton: Author.
[21] ReliOn. (2011). E-1100TM Fuel Cell System: Operator's Manual. Spokane, WA: Author.
[22] Tayna Ltd. (2013). EXV90 Enduroline Calcium Leisure Battery 90 Ah. Retrieved from http://www.tayna.co.uk/EXV90-Enduroline-Calcium-Leisure-Battery-P8281.html.

or a combination of both. The power output of the DC bus is used to drive the traction motors, supply power to auxiliaries and, depending on the operating conditions, to charge the battery-pack. The parameters of the locomotive are presented in Table 1 and the drive-system is illustrated in Fig. 1.

The evaluation consisted of (a) the Run-Down Experiment, to determine the resistance to motion, and (b) the Locomotive Operation Experiment, to establish the drive-train efficiency in operating conditions.

An on-board National Instruments CompactRIO computer system was used to control the locomotive and collect the measured data, which were stored for later processing and analysis. This data acquisition system is able to measure and record the following properties:

- Hydrogen consumed by the fuel cell, measured using a mass flow meter.
- Electrical current output of the fuel cell.
- Electrical voltage across each battery and current flow through all batteries, and thus the DC traction bus voltage whilst in operation.
- Electrical current draw of the traction motor controller.
- Speed of the locomotive, measured using a tachometer on one axle.

Only data relevant to each experiment were collected and analysed as described in more detail below. All tests were conducted without a trailing load, therefore, resembling light running on a full-scale operational railway.

2. Locomotive characteristics

The resistance to motion for railway vehicles is often described through the Davis equation [24,25]:

$$R = A + Bv + Cv^2 \tag{1}$$

where: resistance term A is independent of speed and mainly influenced by the mass of the vehicle, accounting for rolling resistance, track resistance, and friction in bearings. Resistance term Bv increases proportionally with speed and accounts for flange friction, swaying, and oscillation. Resistance term Cv^2 increases with the square of the speed and accounts for aerodynamic drag [24]. Traditionally, the Davis parameters, A, B, and C, are determined through analysis of railway vehicle run-down tests [25] and this was the approach taken to determine resistance to motion of the Hydrogen Pioneer. Test track was installed in the laboratory and the locomotive was accelerated to the maximum safe speed, after which propulsion was stopped and the vehicle decelerated to a halt due to the resistance to motion. The collected speed and deceleration data were tabulated and a function derived to fit the experimental data while conforming to the general Davis equation. Computational modelling of the braking performance of the Hydrogen Pioneer was employed to establish its resistance to motion function, which is as follows:

$$R = 0.051626 + 0.018131v \tag{2}$$

Giving the Davis parameter A as 0.052 kN and B as 0.018 kN when rounded. A coefficient C is not present, and Davis [24] explains that an equation without an exponential term is to be anticipated for light vehicles that travel at low speeds and have a small cross section. The Hydrogen Pioneer conforms to these conditions.

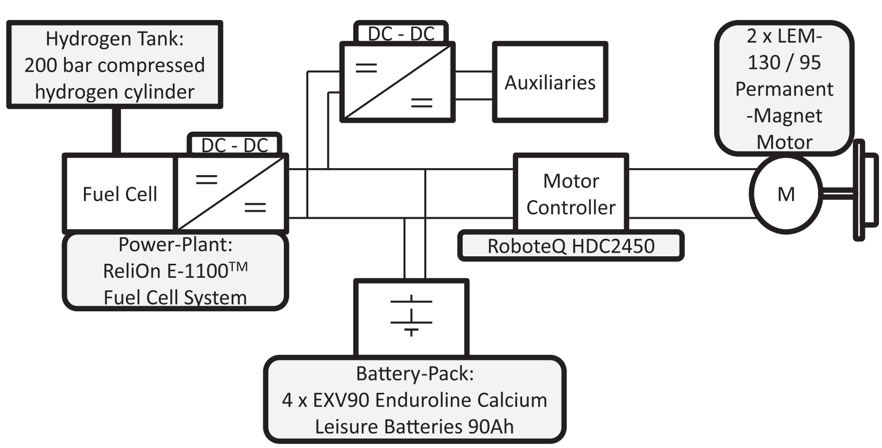

Fig. 1. Drive-train of the Hydrogen Pioneer.