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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.

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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]:

$$R = A + Bv + Cv^2 \quad (1)$$

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:

$$R = 0.051626 + 0.018131v \quad (2)$$

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.

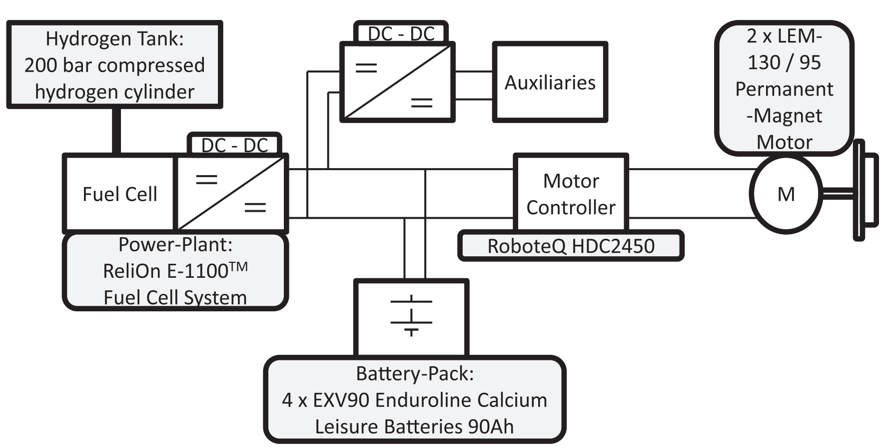

Fig. 1. Drive-train of the Hydrogen Pioneer.

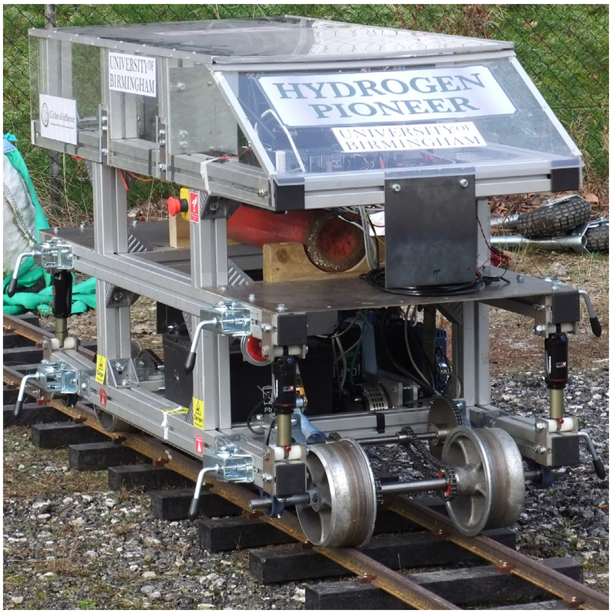

Fig. 2. Hydrogen Pioneer on 30 m test track.

3. Locomotive Operation Experiment

Tests at various selected maximum speeds of the locomotive were conducted to show the respective energy contribution of the power-plant and battery-pack. Test speeds of 6 km h^{-1} and 7 km h^{-1} showed negligible battery-pack charging, thus allowing comparison with other non-hybrid railway traction technologies.

Further tests at two representative speeds were also undertaken: at 2 km h^{-1} the power-plant charges the battery-pack as well as drives the vehicle, and at 10 km h^{-1} the batteries contribute energy to meet the higher traction power demand.

All tests were conducted outdoors on a 30 m long test track, with a 5 m safety distance at each end to ensure safe stopping of the locomotive before the end of the line. The track only included straight alignment and a reasonably level right of way, but a small gradient, due to the gravel subgrade, was present. The Hydrogen Pioneer was operated with a pressurised 200 bar gas cylinder, which had a mass of 16 kg.

The locomotive was placed on the test track and operated in the forward and reverse directions. Fig. 2 shows the locomotive on the test track prior to the start of the experiment.

Each speed test consisted of five forward and five reverse movements, covering a distance in each move of between 20 and 25 m. The vehicle was accelerated as fast as possible to the selected maximum speed and, once the marker point for the experiment distance was reached, slowed as quickly as possible, utilising the regenerative service brake. After a brief stop, the run was repeated in the opposite direction. This procedure continued until five laps were completed, as illustrated in Fig. 3, and is the modelled duty cycle of the locomotive including acceleration and deceleration. In contrast, the steady state operation analysis shown below only includes a subset of the data: the time when the vehicle is operating at its target speed.

All the results, data analysis, and data presentation conform to the law of conversion of energy, and the term *loss* is used in this context to refer to energy that could not be utilised for a useful purpose but led to non-recoverable heat generation. The lower heating value of hydrogen, at 120.21 MJ kg^{-1}, has been applied to all relevant calculations.

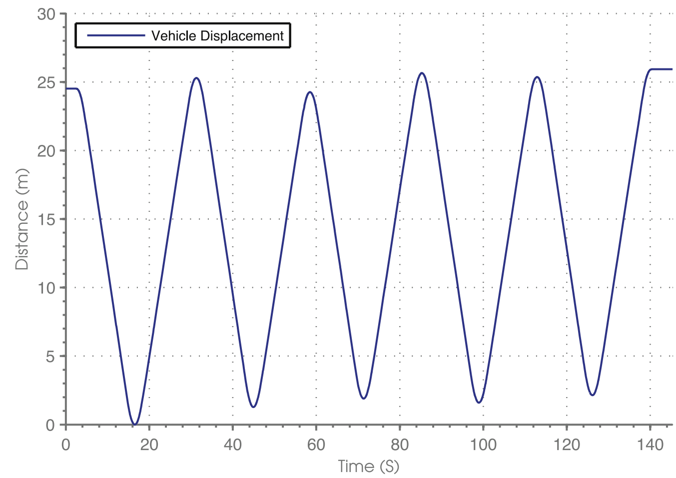

Fig. 3. Distance covered during 7 km h^{-1} duty cycle test.

The auxiliary power value was not measured but was determined through calculation: From the power-plant output, the motor controller power and the battery charge power were subtracted to give the value for power consumed by the auxiliaries. Losses are also included in this calculation, but are considered negligible due to the short cable length. Auxiliaries are all the components that are not directly necessary for the drive-train but are necessary for vehicle operation; they include: the CompactRIO control computer and associated instrumentation, the traction motor controller, and the vehicle's emergency stop and mechanical brake systems.

3.1. Results and discussion

Detailed results are presented for the 7 km h^{-1} test, which was closest to hydrogen-only operation over the whole duty cycle. To avoid repetition, the results for the other speeds are summarised and shown after the 7 km h^{-1} test, which is followed by a discussion.

3.1.1. 7 km h^{-1} maximum speed test

In this test the target line-speed of the locomotive was 7 km h^{-1} (1.94 m s^{-1}), and each run was approximately 25 m long, as shown in Fig. 3. In this figure, the brief stops of the locomotive are

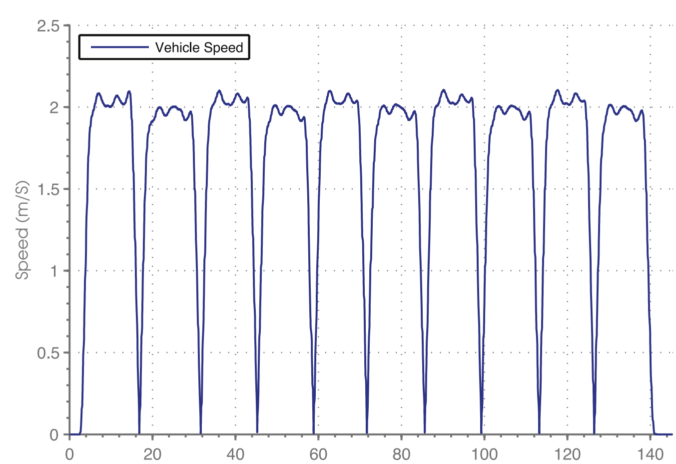

Fig. 4. Measured locomotive speed for 7 km h^{-1} duty cycle test.

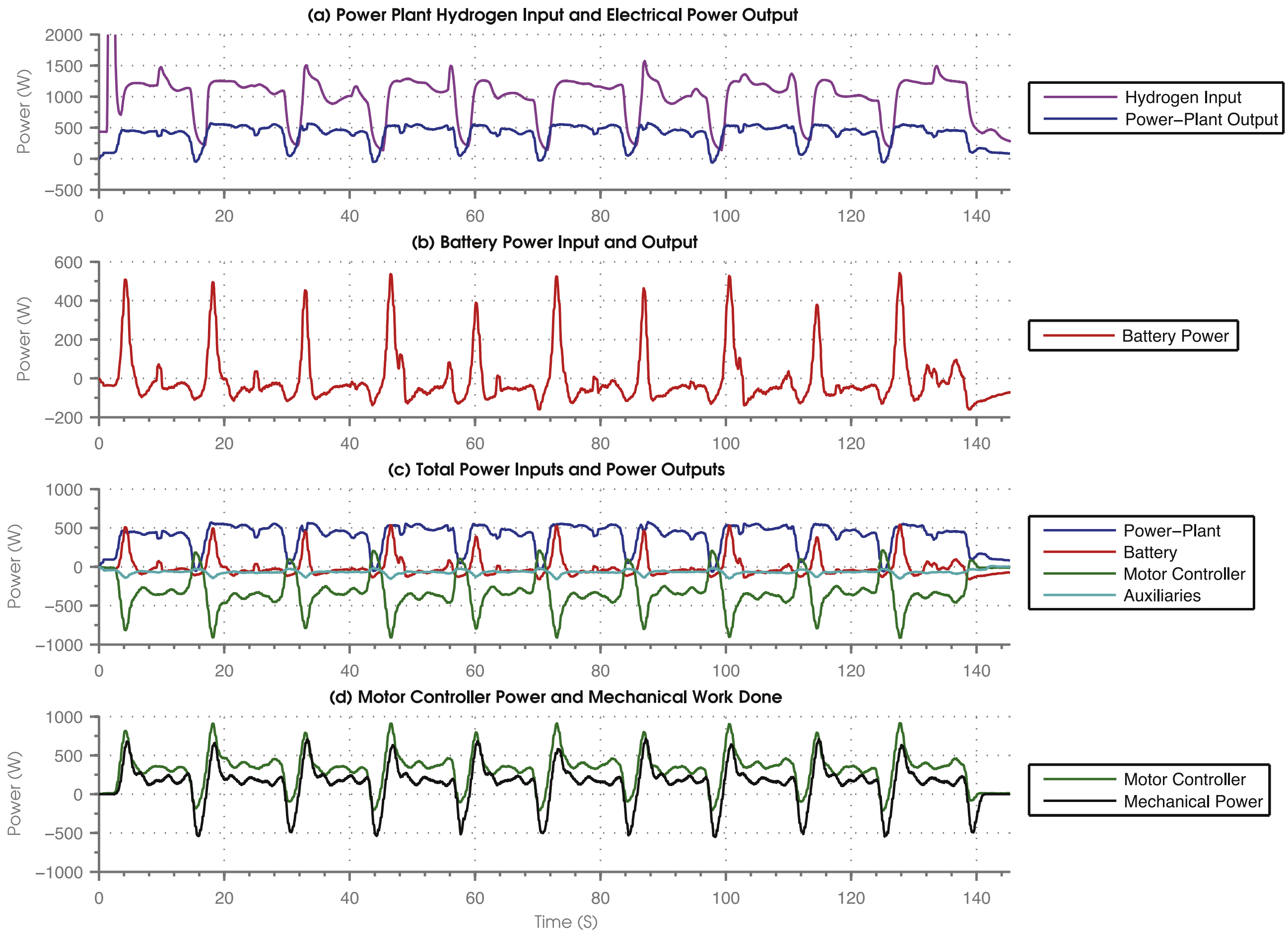

Fig. 5. Drive system performance for 7 km h^{-1} duty cycle test.

indicated by the peaks and troughs. The target speed was maintained for the majority of the running time, illustrated in Fig. 4, and the stops are indicated by the troughs. A slight variation in the actual speed can be observed between forward and reverse runs, indicating the gradient in the alignment. The gradient does not have a large effect on the other results as the slightly higher energy consumption during the uphill run is balanced by the lower energy consumption during the downhill run.

The power that was necessary to complete the duty cycle is presented in Fig. 5.

Graph (a) in Fig. 5 shows the hydrogen input into the power-plant and the corresponding electrical-power output of the plant. The large peaks in the hydrogen consumption are due to power-plant maintenance, where the fuel cells are purged with additional hydrogen to remove excess water that is produced when in operation. The hydrogen used for purging is not converted to energy but ensures the reliable operation of the fuel cells.

Graph (b) shows the power contribution of the battery-pack, and it can be seen that the batteries are being charged for the majority of the duty cycle. The battery-pack provides power in high power demand situations, such as during acceleration, which is illustrated by the positive peak values. Energy recovered through regenerative braking is shown at the negative peak power values in this graph.

Graph (c) shows the DC bus power inputs and consumption. Power consumption is shown as negative values while input power is shown as positive. The auxiliary power consumption remains relatively constant throughout the duty cycle, and the majority of the input-power is transferred to the traction motor controller and consequently to the traction motors.

Graph (d) shows the power consumption by the traction motors and the power required to overcome the resistance to motion. This value is based on the Davis equation determined earlier, combined with the power necessary or gained during acceleration of the vehicle; its kinetic power.

The cumulative integration of the power of each main component over time, or the cumulative energy distribution during the duty cycle, is visually presented in Fig. 6. The Hydrogen designation in the graph's legend refers to hydrogen input into the power-plant. The depletion of hydrogen in the pressurised tank is not shown.

In Fig. 6 it can be seen that the overall energy consumption rises over the time of operation, as expected. Further, it is shown that the battery-pack state of charge increases slightly over time. Therefore, the power-plant provides the energy necessary to move the vehicle as well as to charge the battery-pack. The lower plot in the figure is a more detailed view of the kinetic energy stored through the motion of the locomotive. It drops to zero whenever the vehicle is stationary, at the end of each run.

The 'work done' plot accounts for the energy that was required to overcome the resistance to motion during the duty cycle. The values at the end of the duty cycle as well as during steady state operation are shown in Table 2. The account shows: in the first column, energy that is not used for the motion of the vehicle; in the second column, energy that is available for the motion of the vehicle, both columns designated in joules; in the third column, the drive-train component loss or energy available at the component in

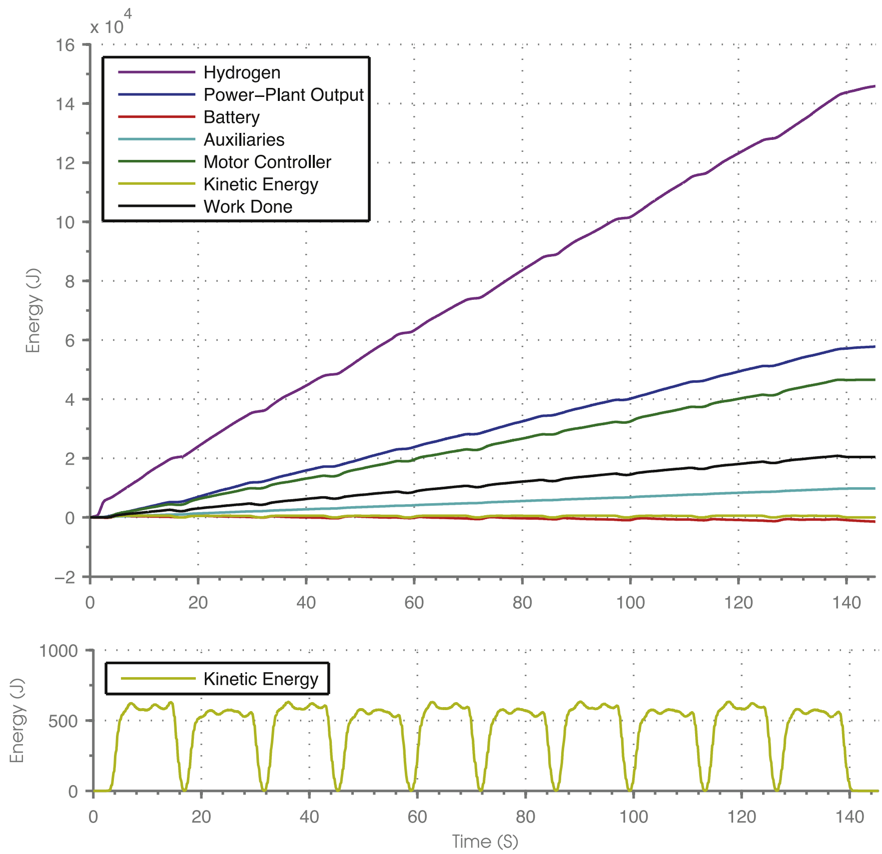

Fig. 6. Vehicle energy contributions for 7 km h^{-1} duty cycle test.

percentages; and in the fourth column, the cumulative tank-to-wheel efficiency chain in percentage. All the values presented in percentages have been rounded to the closest integer.

From the energy accounts it can be seen that overall efficiency is higher in steady state operation compared to the overall duty cycle. This is expected, as the plant can operate in a continuous state rather than having to react to changes in energy demand, and is consistent with full scale experiments of electric traction vehicles [26]. However, in our experiment the variation between the steady state and the duty cycle efficiency is low, which suggests a quick, reactive response to the change in demand. In Fig. 7 the energy input share and the energy consumption distribution respective to the total energy input is presented for all tests. In the 7 km h^{-1} test, overall vehicle efficiency is 14% during the duty cycle and 15% in the steady state. The efficiency is lower than anticipated, mainly due to the relatively low efficiency of the traction motors at these speeds, but the power-plant performs as expected. This suggests that traction motor changes or modifications to the mechanical drive-train may be necessary to increase the vehicle efficiency.

The Hydrogen Pioneer completed all the tests without difficulty, establishing that a hydrogen-hybrid locomotive can perform various duty cycles effectively. The development of the locomotive was, therefore, a success and demonstrated the proof-of-concept of such a vehicle.

Effects of the short length and straight alignment of the test track, as well as the light running operating mode of the locomotive, were observed in all test results. These are primarily shown in short steady state operation and in the relatively low vehicle efficiencies, as no useful work, such as moving passengers or goods, was undertaken.

3.1.2. Power-plant

The power-plant performed as expected and provided an efficient prime-mover in all cases but the lowest speed test at 2 km h^{-1}. A hydrogen-to-electrical power conversion efficiency of around 40% was achieved, with a peak efficiency of 43%, which matches the manufacturers specifications [21].

The lowest efficiency was recorded at the 2 km h^{-1} test when only a fraction of the maximum power output was needed. This is expected, as with any chemical energy conversion device, low efficiencies are common at partial loading.

All the tests indicate a quick response of the power-plant to changes in power requirements. Further, little difference between the duty cycle and steady state performance is observed. This is in contrast to many combustion engine operated railway vehicles where the peak efficiency is often considerably different from the duty cycle efficiency [27]. An improved power management of the hybrid drive-train could lead to cases where the power-plant is operating close to its maximum efficiency for the majority of the time.

The performance of the power-plant, established by the tests, suggests that a hydrogen fuel cell based prime-mover is suitable for railway applications; the small scale of the Hydrogen Pioneer having little effect on the functionality of the fuel cell stack. A more powerful fuel cell system that is suitable for standard gauge railway vehicles could have a higher efficiency, of around 50%, as full-scale tests have demonstrated [13,15].

3.1.3. Hybrid drive-train

In all tests the hybrid function of the locomotive was apparent: During high power demands, in the test cases during acceleration, the battery-pack contributed a significant proportion of the

Table 2
Energy Account for 7 km h^{-1} locomotive test.

Energy source or consumer	Energy not used for motion	Energy available for motion		
	J	J	%	%
Duty cycle energy account				
Energy source				
Hydrogen		145867		100
Power-plant	88101		60	
Electrical energy input		57766	40	40
Non-traction consumption				
Battery-pack charge	1390		2	
Auxiliary and electrical drive-train losses	9813		17	
Total non-traction consumption	11203		19	
Traction consumption				
Energy available at traction motor controller		46563	81	32
Traction motors and mechanical drive-train	26129		56	
Energy consumed to overcome resistance to motion		20434	44	14
Vehicle efficiency				14
Steady state energy account				
Energy source				
Primary energy input as hydrogen		1189		100
Power-plant	680		57	
Electrical energy input		509	43	43
Non-traction consumption				
Battery-pack charge	52		10	
Auxiliary and electrical drive-train losses	70		14	
Total non-traction consumption	122		40	
Traction consumption				
Energy available at traction motor controller		387	76	33
Traction motors and mechanical drive-train	214		55	
Energy consumed to overcome resistance to motion		173	45	15
Vehicle efficiency				15

traction power. During the regenerative service brake application the batteries were recharged, recovering some of the braking energy. In steady state operation the power-plant charged the battery-pack in all but the highest speed test, as per locomotive design.

The power-plant provided, in the three lower-speed cases, all the energy required during the duty cycle, and the average electrical power output was around 500 W for all but the 10 km h^{-1} test case. If the lower speed cases were the standard operating conditions, then the power-plant could be down-sized to an output of slightly more than the average power requirement, approximately 600 W. This would not affect the performance of the locomotive but conserve energy.

The hybrid design shown can also be applied to full scale vehicles, allowing autonomous railway vehicles to utilise regenerative braking and offers the potential to down-size the prime-mover, both modifications lowering overall primary energy consumption. The tests have demonstrated that this is a feasible option without compromising on performance. Autonomous hybrid railway vehicles have already been introduced on some railway services [28,29], albeit not hydrogen-powered. The authors suggest, based on the test results and implementation of the hybrid drive system, that hydrogen-hybrid traction systems can be successfully implemented in full-scale railway traction vehicles.

3.1.4. Auxiliaries

Behaviour of the auxiliary load is similar throughout all tests in proportion to total energy consumption, with a small difference in power draw between duty cycle and steady state operation. This can be observed during acceleration, where a high power demand is present and the auxiliary load increases respectively.

The largest energy consumers are the control computer and the emergency brake hold-off, which both have relatively stable power requirements. The overall auxiliary power share is not excessive and the total consumption is reasonable for the locomotive operation.

3.1.5. Traction motors and mechanical drive-train

The traction motors and the mechanical drive-train perform poorly in all experiments in energy consumption terms, with a peak efficiency of 43% in the 10 km h^{-1} test. The majority of the energy usage is most likely due to sub-optimum operation of the traction motors, as the losses in the mechanical drive train are likely to stay practically constant, independent of speed.

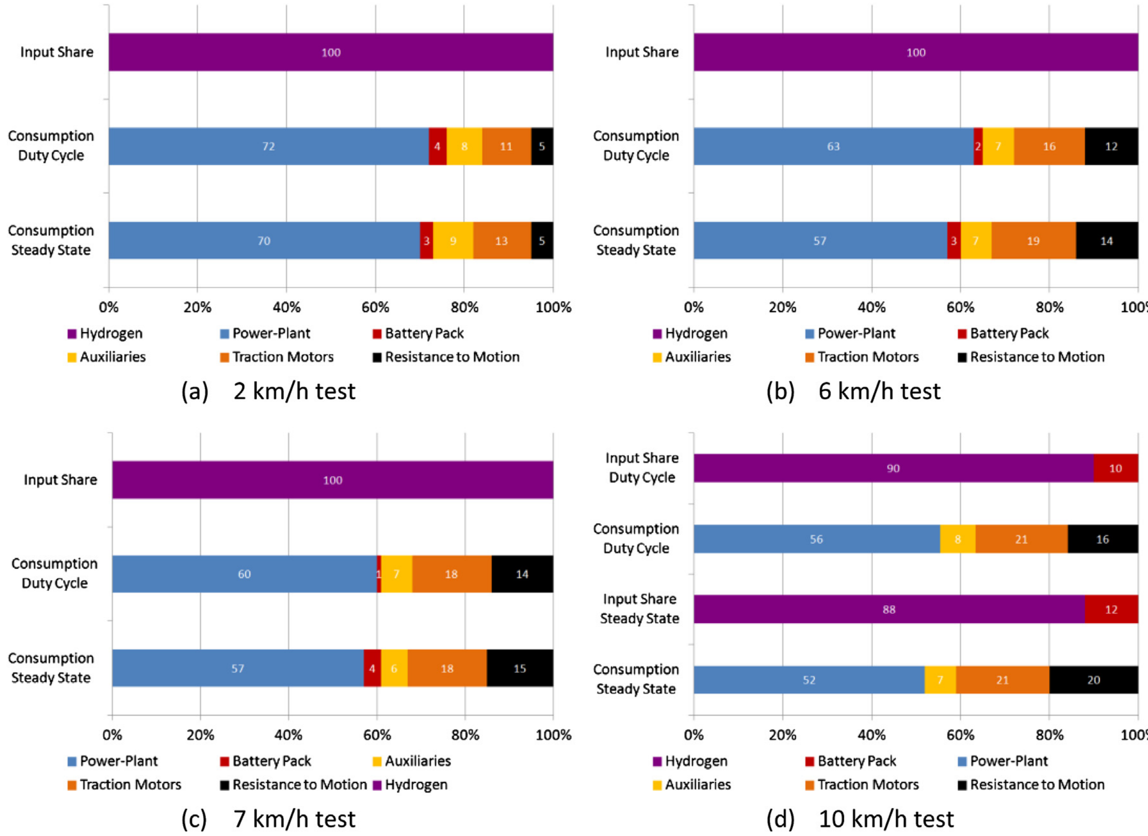

Fig. 7. Energy input share and energy distribution for locomotive speed tests.

Given the current design, the traction motors operate with maximum efficiency at vehicle speed of approximately 25 km h^{-1}, rather than lower speeds used in these tests. Higher speeds were not possible due to the short track length.

The normal operating speed of the locomotive is within the range represented by the tests, and vehicle efficiency could be improved by altering the mechanical drive-train design. Increasing the gearing ratio between motor and driven wheelset would reduce maximum vehicle speed but allow the motor to operate in its most efficient region.

3.1.6. General performance

In general, the Hydrogen Pioneer performed better in steady state operation than in the overall duty cycle, as illustrated in Fig. 8. This is usual for any type of railway vehicle [26], but the difference in performance seen in the conducted tests is small.

In the steady state, components such as the power-plant, battery-pack, and traction motors do not have to react to changes, which positively affect their performance. Total duty cycle efficiency would increase with extended periods of steady state operation, and such periods would be typical of usual railway operation.

At low speeds, the vehicle's performance was poor, owing to the minimal utilisation and loading of all components. This was to be expected, as the vehicle was not designed to operate at such speeds for extended periods of time. Once the normal operating speed is reached, between 5 km h^{-1} and 10 km h^{-1}, the efficiency of the power-plant and the vehicle stabilise at around 40% and 15%, respectively. A higher vehicle efficiency in the operating speed range is desirable, and this may be achieved through mechanical alterations as described above. When evaluating the performance of the locomotive, the original design objective must be considered: demonstration of proof-of-concept for hydrogen-powered railway traction vehicles. Rather than optimising overall efficiency, the original design effort for the Hydrogen Pioneer was focused on novel fuel and power-plant integration.

The performance of the vehicle is expected to improve with higher operating loads, as work done would increase proportionally more compared to energy consumption. The tests establish that a hydrogen-hybrid locomotive can perform a duty cycle in an effective and efficient manner.

The Hydrogen Pioneer energy storage and drive-train design, supported by the strong performance of the power-plant, will

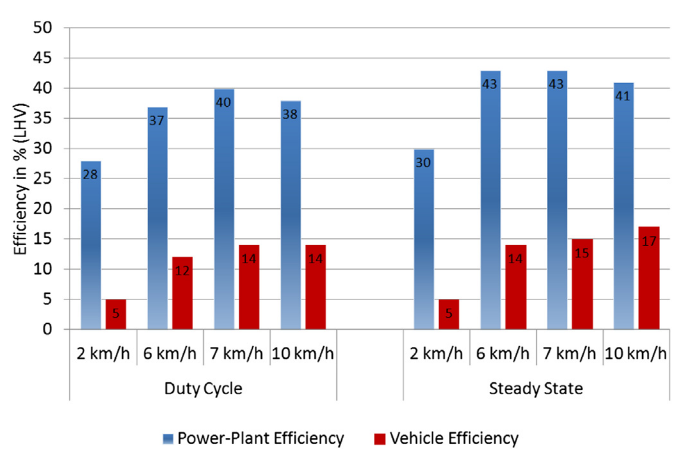

Fig. 8. Power-plant and vehicle efficiencies of the Hydrogen Pioneer for tests at various speeds.

provide a valuable contribution towards a full-scale concept design. In such a design the main drive-train components, such as compressed-gas hydrogen storage, PEM fuel cell based power-plant, and a hybrid system utilising batteries as energy storage devices will be retained. Computer modelling of such a concept railway vehicle that includes data collected from this evaluation, such as duty cycle power-plant efficiency, will allow fact based suitability evaluation. Further, a comparison with a conventional simulated vehicle is possible and, therefore, performance characteristics, energy consumption, and carbon impact can be contrasted.

4. Conclusion

The narrow-gauge hydrogen-hybrid locomotive Hydrogen Pioneer was utilised for an empirical performance evaluation. It was established that the fuel cell power-plant operated as expected, at an efficiency of around 40%, and the hybrid drive-train performed as designed: the battery-pack provided peak power and was re-charged during steady-state operation and service braking. Overall, the evaluation showed a strong performance of the power-plant and hybrid-system, and established the suitability of both for railway traction purposes. A gaseous hydrogen on-board power supply system with a fuel cell based power-plant is demonstrated to be suitable for railway traction vehicles and the potential for a high vehicle efficiency shown.

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References

[1] IEA, Transport, Energy and CO_2, IEA, Paris, 2009.
[2] C.-J. Winter, Int. J. Hydrogen Energy 34 (2009) S1–S52.
[3] S. Hillmansen, Proc. Inst. Mech. Eng., Part F J. Rail Rapid Transit. 217 (2003) 291–298.
[4] Y. Haseli, G.F. Naterer, I. Dincer, Int. J. Hydrogen Energy 33 (2008) 1788–1796.
[5] G.D. Marin, G.F. Naterer, K. Gabriel, Int. J. Hydrogen Energy 35 (2010) 6084–6096.
[6] G.D. Marin, G.F. Naterer, K. Gabriel, Int. J. Hydrogen Energy 35 (2010) 6097–6107.
[7] A. Hoffrichter, Hydrogen as an Energy Carrier for Railway Traction (PhD thesis), University of Birmingham, Birmingham, 2013. Retrieved from, http://etheses.bham.ac.uk/4345/.
[8] L.M. Fernandez, P. Garcia, C.A. Garcia, F. Jurado, Energy Convers. Manag. 52 (2011) 2183–2192.
[9] L. Guo, K. Yedavalli, D. Zinger, Energy Convers. Manag. 52 (2011) 1406–1413.
[10] D.J. Schroeder, P. Majumdar, Int. J. Hydrogen Energy 35 (2010) 11308–11314.
[11] A.S. Martinez, J. Brouwer, G.S. Samuelsen, J. Power Sources 213 (2012) 203–217.
[12] A.S. Martinez, J. Brouwer, G.S. Samuelsen, J. Power Sources 213 (2012) 358–374.
[13] A.R. Miller, T.L. Erickson, J.L. Dippo, R.I. Eisele, M.D. Johnson, T. Lambrecht, in: 9th World Congress on Railway Research (WCRR), Lille, 2011.
[14] J. Kawasaki, S. Takeda, R. Furuta, Jpn. Railw. Eng. 160 (2008) 6–8.
[15] T. Yamamoto, H. Hasegawa, T. Furuya, K. Ogawa, Q. Rep. RTRI 51 (2010) 115–121.
[16] W. Chen, in: 8th International Hydrail Conference, Toronto, 2013.
[17] A.R. Miller, M.D. Johnson, K.S. Hess, T.L. Erickson, J.L. Dippo, T. Lambrecht, in: The Fuel Cell Seminar, Palm, Springs, CA, 2009.
[18] Railway Gazette International, Hydrogen Fuel Cell Tram Unveiled, Sutton, 2011. Retrieved from, http://www.railwaygazette.com/news/single-view/view/hydrogen-fuel-cell-tram-unveiled/archiv/2011/10.html.
[19] A.R. Miller, A. Hoffrichter, S. Hillmansen, C. Roberts, in: 19th World Hydrogen Energy Conference 2012, Toronto, 2012.
[20] TIG/m Modern Street Railways, TIGm Modern Street Railways Sends World's Greenest Streetcars to Aruba Toward 100% Sustainability, 2012. Chatsworth, CA.
[21] ReliOn, E-1100TM Fuel Cell System: Operator's Manual, ReliOn, Spokane, WA, 2011.
[22] Tayna Ltd, EXV90 Enduroline Calcim Leisure Battery 90Ah, Tayna Batteries, Abergele, 2013.
[23] Lynch Motor Company, LMC Motors: LEM-130, Lynch Motor Company, Honiton, 2013.
[24] W.J. Davis, Gen. Electric Rev. 29 (1926) 685–707.
[25] B.P. Rochard, F. Schmid, Proc. Inst. Mech. Eng. Part F 214 (2000) 185–199.
[26] UIC, Evaluation of Energy Efficiency Technologies for Rolling Stock and Train Operation of Railways (EVENT), 2003. Paris.
[27] S. Lu, S. Hillmansen, C. Roberts, IEEE Trans. Veh. Technol. 60 (2011) 406–420.
[28] R. Cousineau, Instrum. Meas. Mag. IEEE 9 (2006) 25–29.
[29] N. Shiraki, H. Satou, S. Arai, in: 2010 International Power Electronics Conference (IPEC), 2010, pp. 2853–2858.