The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 33.4
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.33.4
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Estimation of the Hydrogen Consumption of an Intermodal Freight Locomotive

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Abstract

This work offers an insight into both the theoretical possibility and practical challenges surrounding the use of hydrogen fuel cells to power the Class 66 , one of the most popular intermodal freight locomotives. Results are presented for a test route constructed out of the most challenging sections of the West Highland line in Scotland, where hydrogen powered trains are most likely to operate. The forward model of the Class 66 models the dynamics effectively. The data from the inverse model is then used in Inverse Simulations, where many different methods are trialled. All methods reproduced the tractive force time history from the forward model effectively. Powertrain components were then chosen on the basis of the inverse simulation results, in particular the high gain method. It was found for a hypothetical 14km test route that a hydrogen fuel cell system containing 14 200kW fuel cells would be able to cover the power requirements of the locomotive and consume 39.942 kg of hydrogen. Alternatively, a hybrid configuration with 8 fuel cells and 5 60 kWh batteries would also cover the power levels, with the added benefit of using comparatively less hydrogen at 22.824 kg. The mass of the fuel cell only powertrain and the hybrid powertrain would be 12.25 and 16.25 tonnes, respectively, with the omission of power electronics. The final conclusion is that it is most certainly possible

to power the locomotive with fuel cells and batteries, and the problem lies in the general arrangement of the locomotive and the infrastructure surrounding hydrogen.

Keywords: hydrogen, battery, hybrid, inverse, simulation, modelling

1 Introduction

The exploration of carbon neutral forms of traction for rolling stock is attracting increased attention. The Scottish Government's long term plan for the full decarbonisation of the railway network involves significant extensions of overhead electrical infrastructure, along with the use of alternative traction technologies involving use of hydrogen fuel cells and traction batteries for routes having traffic levels that do not justify conventional electrification [1]. Such routes are the primary focus in this work. Current developments include the conversion of a retired Class 314 three-coach electric multiple unit, led by Ballard Motive Solutions [2] and preliminary simulation work has indicated significant potential for hydrogen in passenger rail vehicle applications. This involves simulations of a Class 156 diesel multiple unit [3,4]

This work attempts to build on the previous modelling and simulation work described for passenger rolling stock [3,4] and adapts the modelling approach to consideration of a typical intermodal freight locomotive. The chosen reference power unit is the British Rail Class 66, the most numerous freight locomotive in the UK, with a load of 5 fully laden KTA 'pocket' wagons. The development of a suitable forward model of the train will allow the implementation of a hybrid powertrain involving hydrogen fuel cells and battery packs.

Traditional forward models of trains involve the application of a tractive force in order to induce movement. In contrast, an inverse simulation may be developed, where a given schedule for a specific route (in terms of distance or speed versus time) forms the input to the model, producing an estimate of the required tractive force or power. Inverse modelling provides a powerful alternative to conventional simulation methods in the context of this application, in that any route may be defined, and the inverse model allows direct estimation of the amount of hydrogen required from the energy time history found from integration of the power output. Design options and trade-offs can then be considered from the data acquired.

2 Methods

This work is based on computer simulations using the MATLAB/Simulink environment, where well-established and validated train performance and hybrid powertrain models were implemented. A distributed mass model in which the train is represented by a one dimensional chain of point masses, with the vehicle connections involving springs with damping [5]. As an example, the locomotive equation is given by Equation (1).

$$M_1\ddot{x}_1 = F_T(t) - k_1\big(x_1(t) - x_2(t)\big) - d_1\big(\dot{x}_1(t) - \dot{x}_2(t)\big)$$
$$-(1587.352 + 11.662\dot{x}_1(t) + 0.462\dot{x}_1(t)^2)$$
$$-M_1 g \sin\theta - 0.004C_1\,(t)M_1 \tag{1}$$

Where $F_T(t)$ is the tractive force (N), $\ddot{x}_1(t), \dot{x}_1(t)$ and x_1 are the locomotive acceleration (ms^{-2}), velocity (ms^{-1}) and displacement (m), respectively. Table 1 details the parameters used within the model with numerical values.

Parameter	**Symbol**	**Numerical Value (with units)**
Locomotive mass	M_1	129600 kg
Spring coefficient	k_1	121×10^6 N m^{-1}
Damping coefficient	d_1	121×10^4 N sm^{-1}
Gravitational constant	g	9.81 ms^{-1}

Table 1: Model parameters.

The powertrain is modelled using a very simple form of energy management, similar to the approach used in previous work [2]. The fuel cells and batteries are modelled as ideal power sources, meaning that the dynamic effects associated with rapid changes in fuel cell power levels, typically of the order of 10 seconds, are neglected. Battery power is only employed when the hydrogen fuel cell configuration is incapable of covering the demanded power at the rail from the locomotive.

Hydrogen consumption can be estimated from the parameters relevant to the hydrogen fuel cell and the molecular mass of hydrogen, taken to be 2.02 x 10^{-3} kg/mole [6]. The fuel cell parameters of interest are the power levels throughout operation, the voltage of a single cell (0.6-0.7V) and the operational time period, which is the length of time required for the route.

The inverse simulation model can be generated in several ways using differential, integral and feedback principles:

- Differential methods involve defining a distance schedule and obtaining velocity and acceleration via differentiation and obtaining control inputs via a Newton-Raphson iterative scheme [7]

- Integration methods involve working from accelerations and obtaining control inputs via a Newton-Raphson iterative scheme [8]

- For the feedback method, a comparison is made between the distance or speed record from the inverse model and the reference input. This error is multiplied by a large gain factor and provides the input to the model of longitudinal dynamics of the train. A velocity compensation pathway can be introduced to damp possible high frequency oscillations within the feedback structure [3,4].

In this particular application, all inverse simulation methods produced similar responses.

3 Results

The test route considered is described in Table 2.

Track Section	**Gradient (deg)**	**Curve (m)**	**Speed Restriction (km/h)**	**Length (km)**
1	0.282	0	64.3738	4
2	0.955	200	64.3738	0.3
3	0.955	0	64.3738	3.7
4	-0.556	300	48.2803	0.3
5	-0.556	400	48.2803	0.2
6	-0.556	0	48.2803	3.5
7	0.115	0	64.3738	2

Table 2: Test route.

The velocity profile in Figure 1 shows strict adherence to speed restrictions. The displacement of the locomotive, shown in Figure 2, confirms that the locomotive reaches the quoted test route length of 14km.

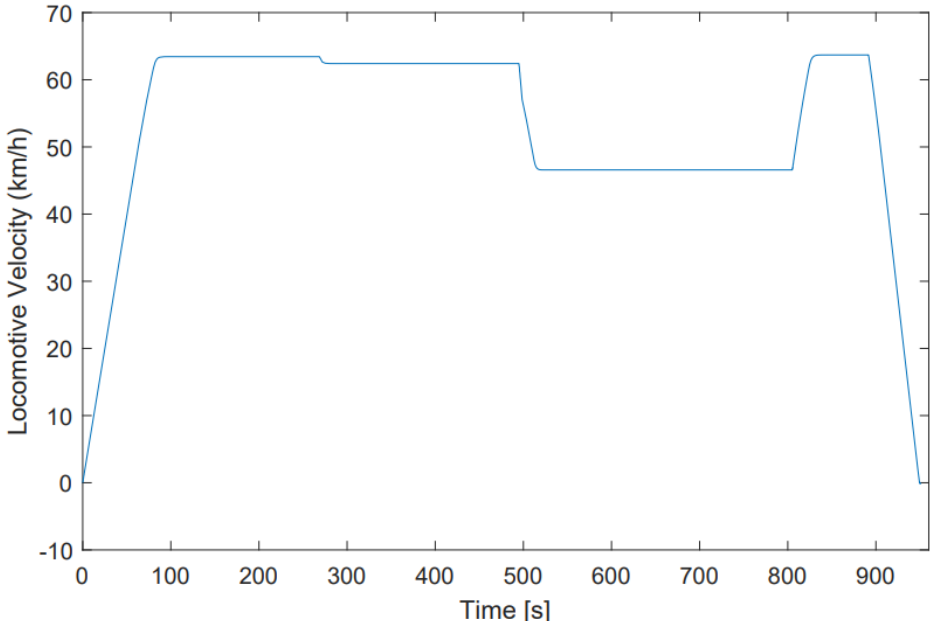

Figure 1: Velocity time history.

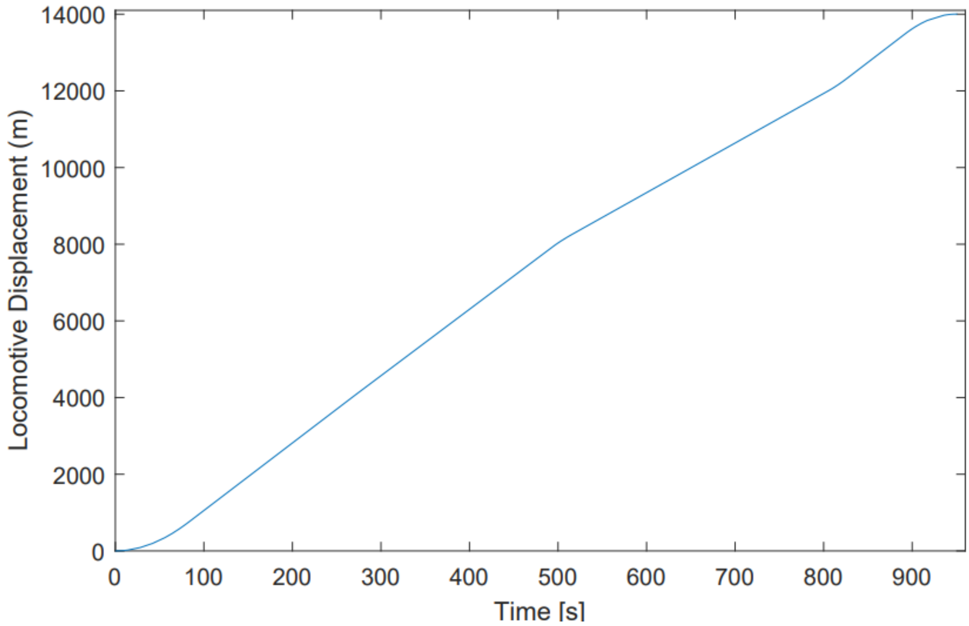

Figure 2: Displacement time history.

The displacement and velocity time histories both indicate a travel time of approximately 950s, which is typical of a typical Class 66 over a 14km journey. The displacement time history forms the input to the inverse simulation, which produces an estimate of tractive force. The tractive force trend of the locomotive from inverse simulation can be seen in Figure 3. The numbers on the plot are indicative of the route section and the tractive force response. The product of tractive force and velocity renders the power trend of the locomotive, which can be seen in Figure 4.

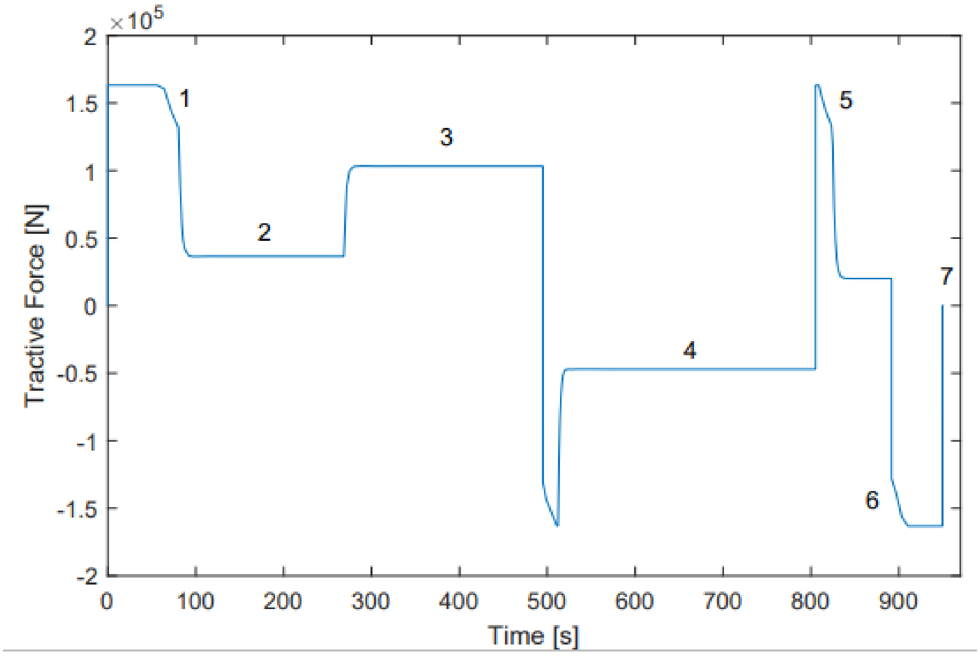

Figure 3: Tractive force time history.

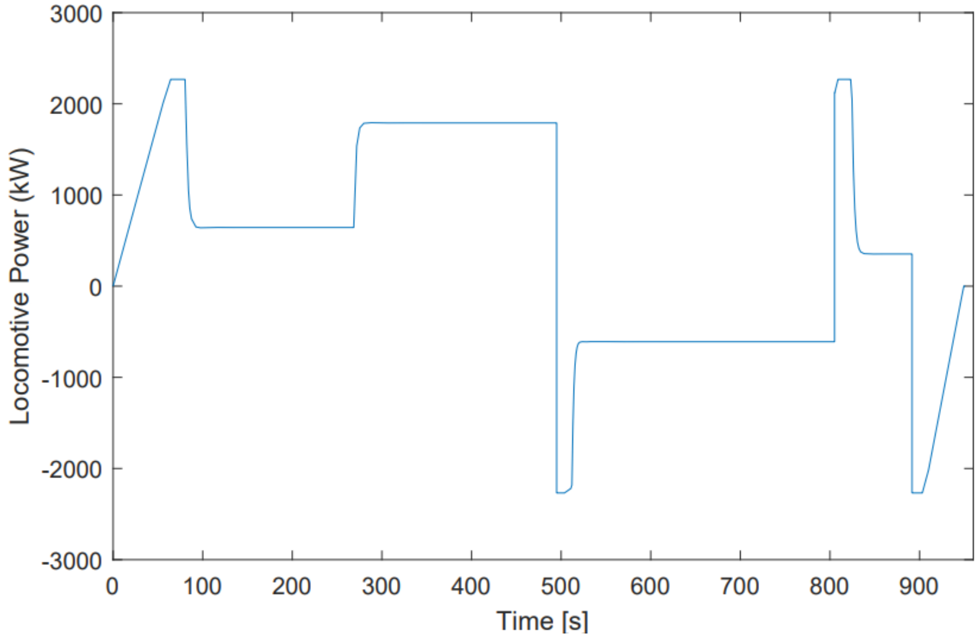

Figure 4: Power at the rail time history.

The tractive force and power at the rail records reflect the nature of the test route, as shown by the sharp rise in tractive force during the 1 in 60 climb. The powertrain configuration involves eight 200 kW output fuel cells and five 60 kWh traction battery systems. The fuel cell and battery power time histories obtained from the inverse simulation can be seen in Figures 5 and 6, respectively.

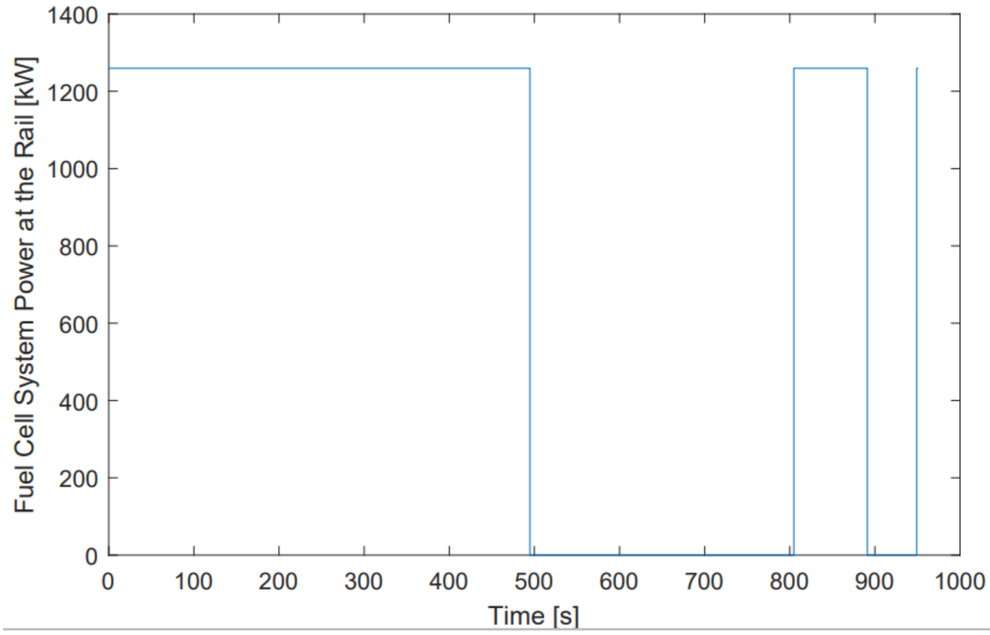

Figure 5: Fuel cell power at the rail.

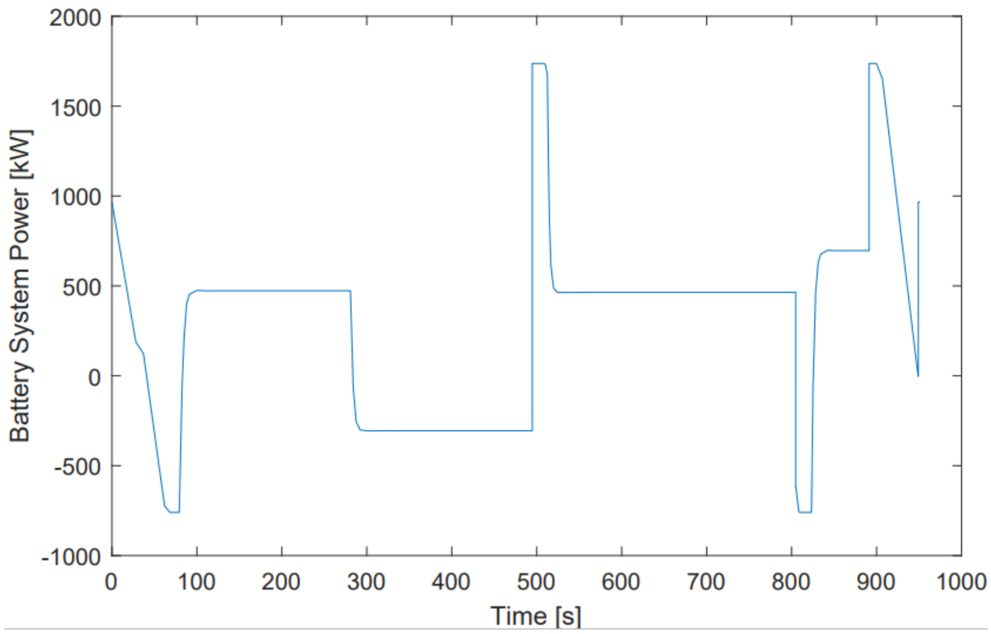

Figure 6: Battery power at the rail.

Fuel cell power at the rail and hydrogen usage falls to zero when regenerative braking is applied since the fuel cells are then powering only the auxiliary components. This is reflected in Figure 6, where positive values of battery power indicate that there is power available for charging. Negative power values indicate that battery power is being employed to cover excess power at the rail demands. The hydrogen consumption can be seen in Figure 7.

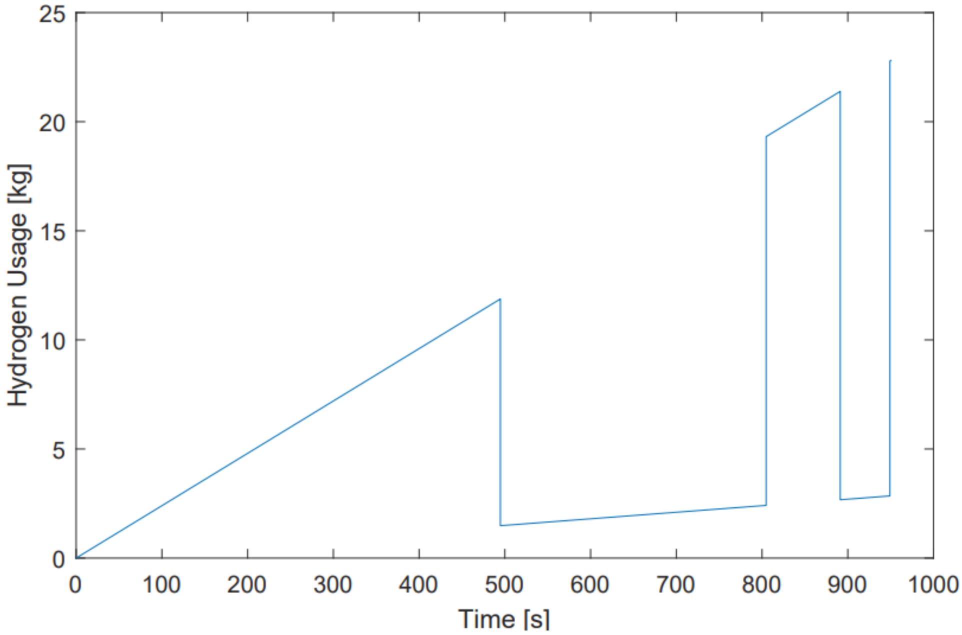

Figure 7: Hydrogen consumption time history.

The final value of hydrogen consumed for the case considered was 22.824 kg. Extension of the work to allow for longer trains and longer route sections increases the hydrogen consumption significantly.

4 Conclusions and Contributions

Results presented here indicate the value of simulation methods in addressing problems of design and optimisation of hybrid powertrains for railway applications. More specifically, they emphasise the importance of inverse simulation methods in tackling problems of this kind. This work has shown that hydrogen fuel cells and batteries provide a possible way forward in finding replacements for traditional diesel engines in some freight applications. Additional problems lie in the infrastructural requirements surrounding hydrogen over longer routes and the simulation results suggest that frequent refuelling would be necessary. There is the possibility of storing hydrogen in hydrogen wagons, however there may be some issues with channelling the hydrogen from an external wagon to fuel cells in the locomotive. Ultimately, the deadline for full decarbonisation of Scotland's railway network is 2035, allowing a window for the exploration, assessment and implementation of the issues.

References

[1] Anonymous, "Rail Services Decarbonisation Action Plan," Transport Scotland, 2020.

[2] D. J. Murray-Smith, P. Fisher, "Hybrid trains for the Highlands? Computer Simulations of Fuel-cell/Battery-electric Trains on Secondary Routes in Scotland," University of Glasgow, Glasgow, Technical Report, 2021.

[3] D. J. Murray-Smith, “Modelling and Simulation of Hybrid Electric Trains Powered by Hydrogen Fuel Cells and Batteries for Routes in the Highlands of Scotland,” University of Glasgow, Glasgow, Technical Report for the Scottish Association for Public Transport,, 2020.

[4] D. J. Murray-Smith, “Design Options for Hybrid Trains Powered by Hydrogen Fuel Cells and Batteries for Routes in the HIghlands of Scotland,” University of Glasgow, Glasgow, Technical Report for the Scottish Association for Public Transport, 2020.

[5] M. Chou, X. Xia, C. Kayser, “Modelling and model validation of heavy-haul trains equipped with electronically controlled pnuematic brake systems,” Control Engineering Practice, pp. 501-509, 2006.

[6] J. Larminie, A. Dicks, “Appendix 2 - Useful Fuel Cell Equations,” in Fuel Cell Systems Explained, Second Edition, John Wiley & Sons, Ltd, pp. 395-400, 2003.

[7] D. G. Thomson, “The Helinv Numerical Algorithm,” Department of Aerospace Engineering, University of Glasgow, Glasgow, 1994.

[8] M. Ireland, K. J. Worrall, R. Mackenzie, T. Flessa, E. McGookin, D. Thomson, “A Comparison of Inverse Simulation-Based Fault Detection in a Simple Robotic Rover with a Traditional Model-Based Method,” in 19th International Conference on Autonomous Robots and Agents (ICARA 2017), Madrid, 2017.