Hybrid trains for the Highlands?

Computer Simulations of Fuel-cell/Battery-electric Trains on Secondary Routes in Scotland

A Progress Report on an Industry and University Collaboration*

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Abstract: Although electrification is the preferred choice in the decarbonisation of railways in the United Kingdom there are important secondary routes where the business case for electrification is not strong. Examples include the lines north and west of Inverness and the West Highland lines linking central Scotland to Oban, Fort William and Mallaig. These routes all involve relatively long journeys, with few intermediate stations, prolonged gradients and many speed restrictions. Hydrogen fuel-cell/battery-electric hybrid units offer a possible solution for de-carbonisation of passenger services on lines such as these and, early in 2020, Transport Scotland and Scottish Enterprise announced financial support for development of a hydrogen fuel-cell/battery-electric multiple unit for trials in Scotland. The Hydrogen Accelerator group at St Andrews University is involved in management of the project and a contract for converting a former ScotRail Class 314 three-coach electric multiple unit to a hybrid configuration has been awarded to a group of companies led by Arcola Energy Ltd. This project forms part of a more broadly-based move to strengthen relevant industrial and business supply chains within the rail transport sector in Scotland and help promote new industrial/academic collaborations.

Hydrogen fuel-cell stacks are characterised by a sluggish response to demanded power-level changes and their efficiency depends on the operating condition. Powertrain control strategies may therefore involve fuel-cell stack operation with slow rates of change that capture power demand, with fast dynamic changes and peak loads being supplied by the battery pack. The battery pack recharges through regenerative braking or from available power from the fuel-cell stack. Optimal powertrain component sizes depend on route characteristics, with relatively flat routes and operation at constant speed favouring large fuel-cells, while routes with prolonged and steep gradients or larger accelerations require larger batteries. Specifications for lengthy routes involving steep and prolonged gradients such as those encountered in the Scottish Highlands present significant difficulties.

Mathematical models for longitudinal train motion involving second-order nonlinear ordinary differential equations, derived using Newton's second law, provide a basis for conventional forward simulation of a train. Power or tractive force variables are applied as an input, with acceleration, speed and distance travelled being defined as outputs. In contrast, the analysis of road-vehicle powertrains often involves a reverse procedure which starts from a duty cycle based on a record of speed versus time with static or quasi-static models being used to estimate steady-state power and energy demands, However, although also involving an inverse type of approach, the simulation methods applied in this paper are based on dynamic models which allow transient power requirements to be understood more fully. These methods have been applied to the assessment of hydrogen train designs for some specific routes and also for test routes having profiles that are chosen to be typical of the routes of interest, but with simplified profiles. It is believed that use of these simplified test routes provides useful physical insight regarding the effect of train characteristics on the specifications for fuel cell stacks, battery packs and other powertrain components. Use of inverse modelling techniques has been found to allow straightforward investigation of performance sensitivities, not only in terms of the longitudinal train dynamics but also the powertrain parameters and route characteristics. Trade-off investigations using these inverse simulation models can be used to reduce the weight and volume of powertrain components and the cost of the train. Fuel-cell efficiency can also be considered, as larger cells allow operation over a wider range of conditions. Findings from the test routes considered allow estimation of powertrain ratings and storage requirements for operation of a three-coach hybrid hydrogen fuel-cell/battery electric train on the Glasgow to Fort William line.

Keywords: hydrogen fuel cell; battery; powertrain; train performance; simulation; inverse; Scotland.

1. Introduction

Transport Scotland has recently proposed major investments in railway electrification, with the replacement of diesel multiple units being a priority. Considerable interest is being shown in the potential of hydrogen fuel-cell and battery-electric trains for secondary routes where the business case for electrification is not strong. The West Highland lines linking central Scotland to Oban, Fort William and Mallaig are a prime example, involving relatively long journeys, with few intermediate stations, prolonged gradients and many speed restrictions. Early in 2020 Transport Scotland and Scottish Enterprise announced support for development of a hydrogen fuel-cell/battery-electric multiple unit for trials in Scotland, with the Hydrogen Accelerator group at St Andrews University involved in management of the project. A contract for converting a former ScotRail Class 314 three-coach electric multiple unit (Figure 1) to a hybrid configuration was awarded in December 2020 to a group of companies led by Arcola Energy Ltd. This project is also intended to help promote new industrial/academic collaborations, with the link between Arcola and a group at Glasgow University being an early example. This report provides a very brief overview of some aspects of the modelling and simulation work carried out jointly during the first half of 2021.

Figure 1: The former ScotRail Class 314 unit to be converted to hydrogen fuel-cell hybrid.

2. The powertrain

Hydrogen fuel-cell stacks are characterised by a sluggish response to demanded power-level changes and their efficiency depends on the operating condition. Powertrain control strategies may therefore involve fuel-cell stack operation with slow rates of change that capture power demand, with fast dynamic changes and peak loads being supplied by the battery pack. The battery pack recharges through regenerative braking or from available power from the fuel-cell stack.

Figure 2 shows typical powertrain components and interconnections. The stack has a unidirectional link but connections to the inverter and batteries are bi-directional.

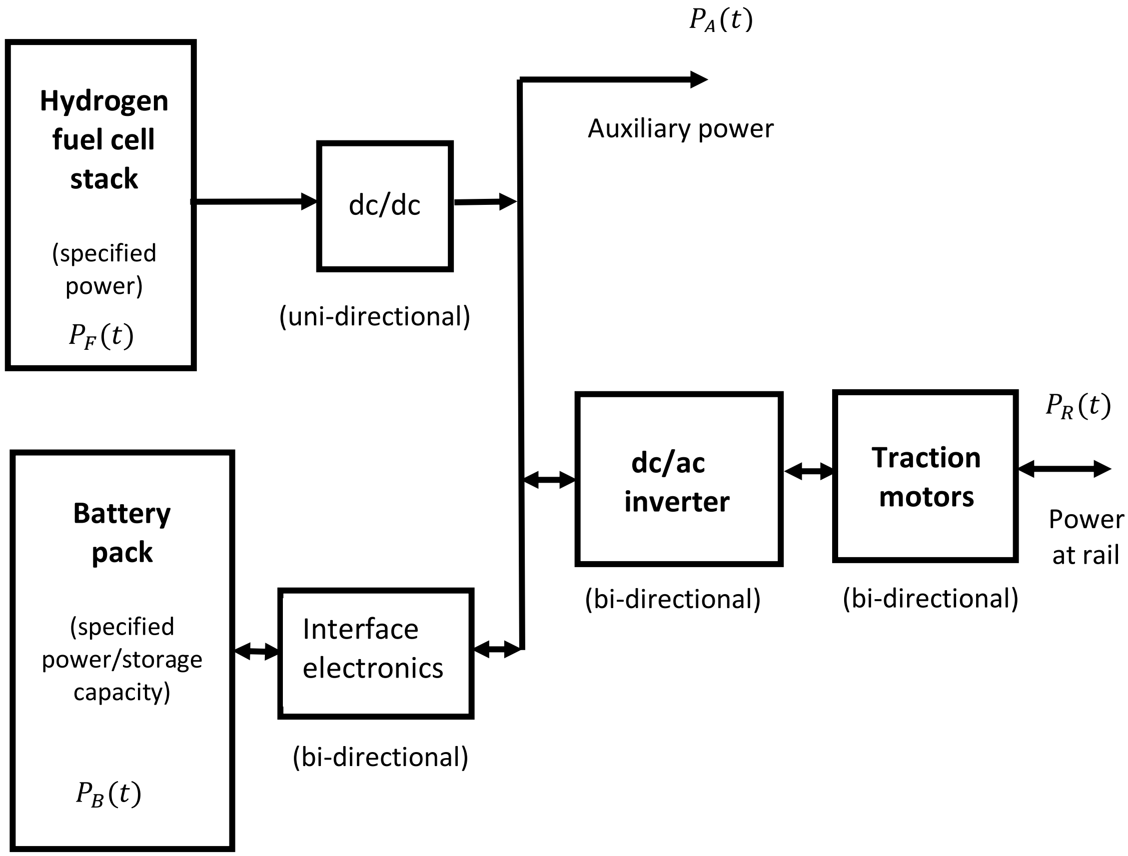

Figure 2. Powertrain block diagram.

3. Computer simulation models

Mathematical models for longitudinal train motion are well established[1-3] and most involve second-order nonlinear ordinary differential equations, derived using Newton's second law:

$$\text{Mass} \times \text{Acceleration} = \text{Tractive force at the rail} - \text{Sum of all resistive forces} \tag{1}$$

Acceleration can be found directly from (1) and train speed and distance travelled can then be determined by integration.

It is also possible to work backwards from a given speed or distance schedule to the tractive force using "inverse simulation". Analysis of road-vehicle powertrains is often approached this way using static or quasi-static models [4]. In the simplest ("direct") method (1) is rearranged as follows:

$$\text{Tractive force at the rail} = \text{Mass} \times \text{Acceleration} + \text{Sum of all resistive forces} \tag{2}$$

The tractive force $T(t)$ is then multiplied by the velocity to give the required power at the rail, $P_R(t)$, and this allows consideration of options for fuel-cell power and battery power (Figure 3).

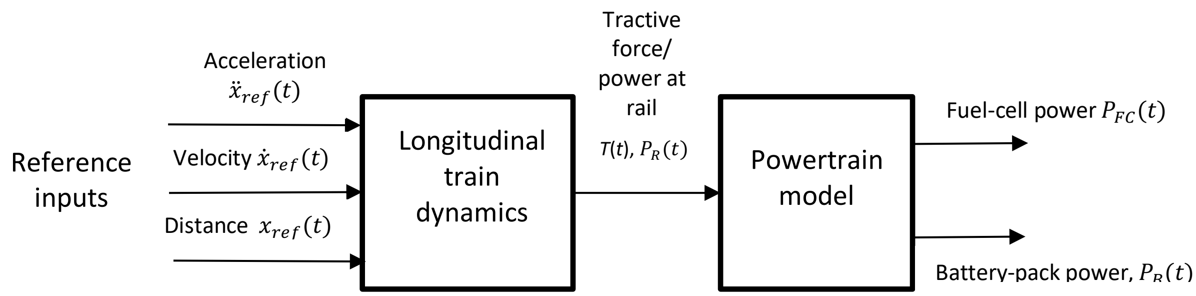

Figure 3: Direct inverse simulation block diagram.

Another approach[1] involves high-gain feedback in which the reference input is compared with the corresponding model variable to determine the tractive force $T(t)$ and power at the rail $P_R(t)$. Powertrain analysis is then possible, as in the direct approach.

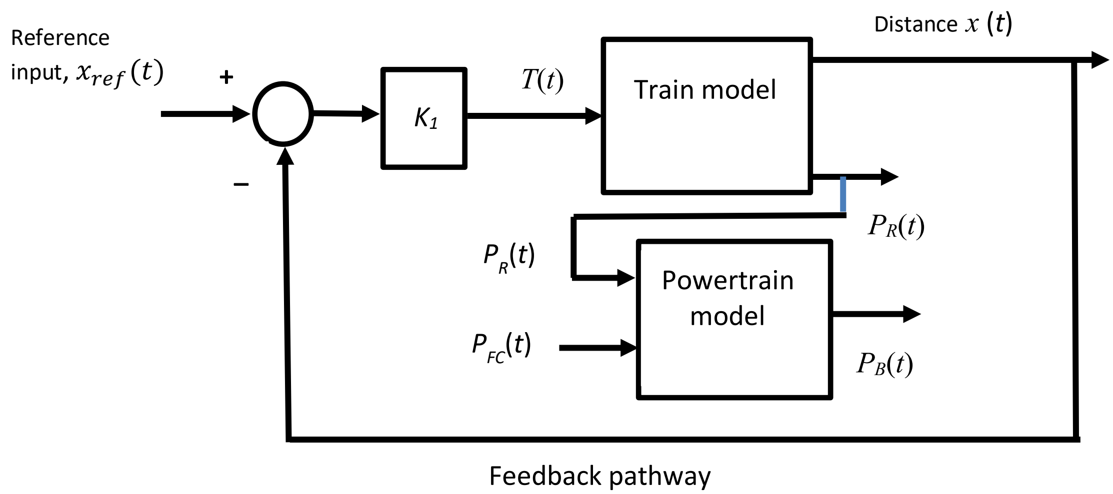

Figure 4: Block diagram - feedback approach.

4. Modelling and simulation of powertrain components

In the Glasgow University investigations, the fuel-cell stack and battery-pack have been represented by ideal sources with specified power and battery energy-storage levels. A battery efficiency factor accounts for energy losses between charge and discharge and efficiency factors are included for power electronic sub-systems and motors. The tractive force is subject to an adhesion limit and this is applied during braking as well as during acceleration.

Initial estimates of component sizes can be found from steady-state analysis. For example, for a given fuel-cell power level, an increase in power demanded at the rail is met by increased power from the battery pack (Figure 5). The battery pack also switches from discharge to charge mode when power at the rail falls below critical levels. The storage capacity needed to meet transient demands can be established through dynamic analysis.

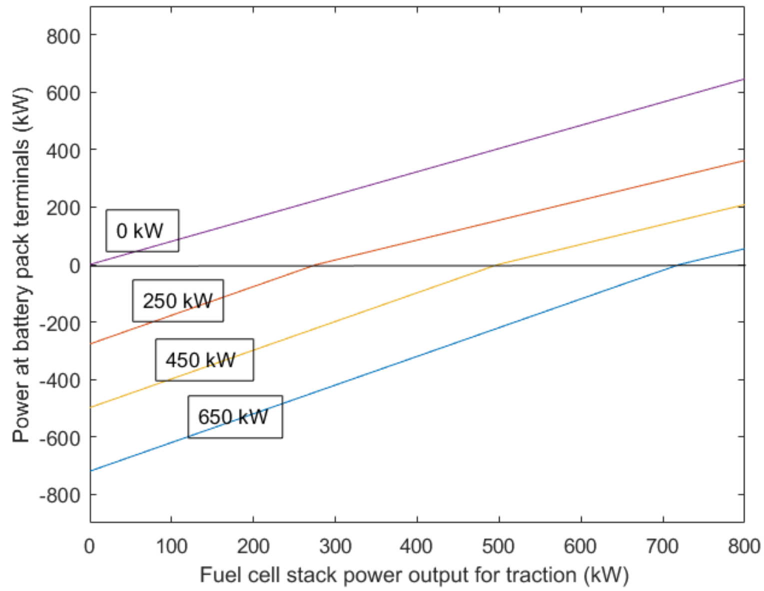

Figure 5. Steady-state conditions for four values of required power at the rail. Positive values of battery power indicate charging.

5. Route modelling, driver actions and reference data

Route modelling is based on gradient profiles or elevation information, together with speed limits. Global positioning system (GPS) information can give speed and elevation from on-train measurements, thus providing both a speed reference and gradient information. However, care is required in the application of appropriate GPS data corrections, especially for elevation. Published gradient information, available for most routes, provides a good alternative. Reference schedules may also be based on quasi-steady straight-line segments for speed or distance, or derived using forward simulation.

6. Inverse simulation results

6.1 Direct approach

Arcola engineers have used a direct inverse simulation approach for a model of the hybrid Class 314 on two routes. One is the Bo'ness and Kinneil heritage line where some sections involve gradients as steep as 1 in 58, with an overall speed limit of 20 mph and some more severe local restrictions. The speed schedule used involves straight line segments representing phases of constant acceleration and phases involving constant speed. Such quasi-static approximations can provide good estimates of power and energy requirements. Reference time histories obtained from a forward simulation model of an existing diesel multiple unit have potential advantages by allowing for train dynamics and thus avoiding physically implausible transients that can arise in the quasi-static approach.

6.2 Using the feedback approach

The University group has applied the feedback approach to a Class 314 train model on the Bo'ness and Kinneil route using speed profiles and elevation data provided by Arcola Energy. Gradient information was derived from the elevation data. Results matched those found using the direct method very closely.

Further work is under way at Glasgow using the feedback approach for the Kilmarnock to Dumfries route to obtain results to compare with those found by Arcola engineers using their direct approach. The train model within the feedback loop represents the hybrid Class 314 with a reference input from a three-coach Class 159/1 diesel multiple unit simulation[3]. Gradient profiles and speed restriction data are from publicly available sources.

The current work differs from the approach used previously for the West Highland lines[2,3] where special route sections were defined to provide typical (but simplified) profiles. One such section was approximately 15 km long with a line speed limit of 96 km/hr, involving five phases as follows: a) an initial length of 4 km on level track, b) a section with a gradient of 1 in 60, c) a further section of level track continuing to the destination, d) a coasting phase starting at 11.3 km and e) a final braking phase starting at 14.3 km to bring the train to rest. The reference input was generated from the forward simulation model for the Class 159/1 three-coach unit[3] That reference model was based on (1), involving a simplified representation of the diesel engines and transmission.

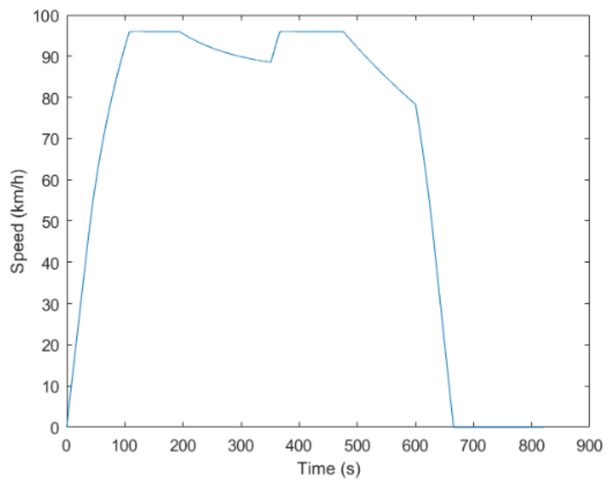

Figure 6. Speed versus time record from Class 159/1 dmu simulation for the test route.

Figure 6 shows the speed versus time plot from the Class 159/1 simulation. This record gave a journey time of just over 11 minutes and this, or the corresponding distance time history, provided the reference used for inverse simulations of the hybrid unit[3]. Figure 7 shows the time history of power at the rail found using the feedback method to meet this schedule with the hybrid unit. This is influenced, very strongly, by the nature of the route and is subject to a tractive force adhesion limit of 50 kN. During acceleration from rest, the transition from the adhesion-limited condition to the constant power condition occurs at a speed of 12 m/s and the tractive force then falls inversely with the speed. During regenerative braking the speed drops until it reaches the 12 m/s threshold when frictional braking is applied, with a negative force at the rail equal to the adhesion limit.

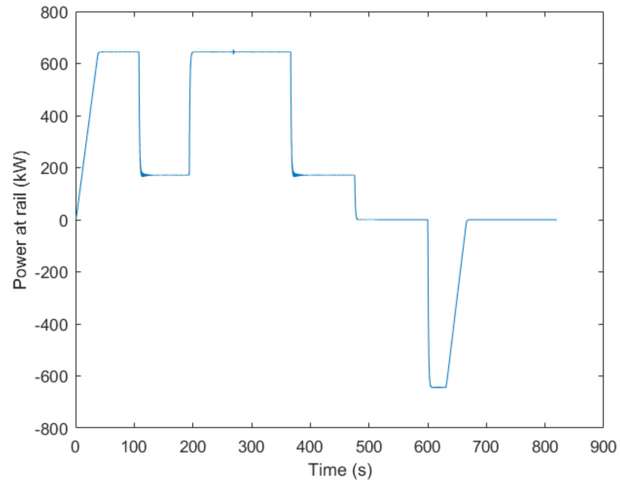

Figure 7. Power at the rail from inverse simulation. Braking involves negative power values.

7. Powertrain component sizing

Inverse simulation results (Figure 7) show a maximum power at the rail ($P_R(t)$) of about 650 kW and this establishes ratings for the traction motors. Figure 5 suggests that, with a fuel-cell stack supplying 500 kW, the battery pack power output must be about 220 kW. Although such steady-state analysis provides a first estimate of powertrain component ratings, dynamic investigations can provide more insight about stored-energy requirements of the battery. Figure 8 provides relevant simulation results showing a maximum rate of change of stored energy for the test route of - 6.1 kWh/min and an average recharging rate of 4.9 kWh/min during coasting, braking and stationary periods. The battery is fully recharged about one minute after the train comes to a halt. Findings like this from the test route have been used to estimate powertrain ratings for the Fort William line[3].

Increasing the fuel-cell stack power rating to 600 kW reduces the battery discharge to -4.5 kWh/min while the re-charge rate is increased to about 6 kWh/min, thus allowing possible use of a smaller battery pack. Trade-off investigations like this can be used to try to reduce the weight, volume and cost of the train. Fuel-cell efficiency is another issue, as larger cells allow operation at points lower down on the polarisation curve, but such investigations are only possible using more detailed physically-based fuel-cell models.

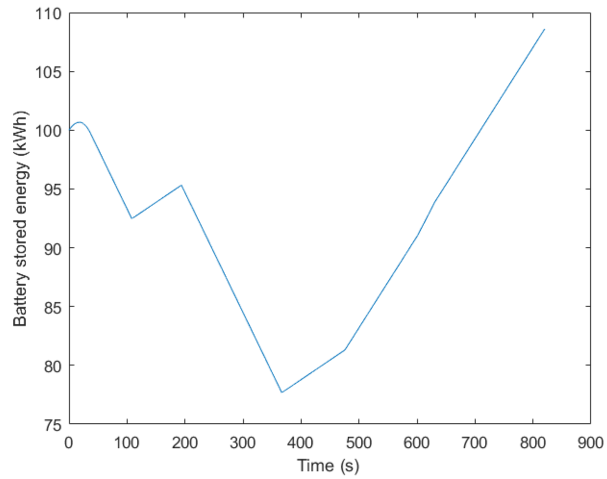

Figure 8. Battery stored energy time-history from inverse simulation.

The inverse approach allows sensitivity analysis for other model parameters, since each simulation run uses the same reference schedule. For example, simulation shows that reduction of the train mass by 15 tonnes reduces the maximum power drawn from the battery by about 25 kW. Effects of journey time changes can also be found through time-scaling of the reference input and this is described in reports of the earlier work[1-3].

8. Discussion and conclusions

Hydrogen fuel-cell electric powertrains provide a route to decarbonising rail on lines where electrification is difficult to achieve. Optimal powertrain component sizes depend on route characteristics, with relatively flat routes and operation at constant speed favouring large fuel-cells, while routes with prolonged and steep gradients or larger accelerations require larger batteries. Specifications for lengthy routes involving steep and prolonged gradients such as those encountered in the Scottish Highlands present significant difficulties.

This sensitivity to route characteristics highlights the benefit of using inverse modelling techniques as a straightforward way to define powertrain characteristics. Research on modelling and simulation techniques provides opportunities for further collaboration between academic research groups and industrial design and development teams.

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