



# Redesign of a Non-electrified Urban Railway Line with Hydrogen-Fuelled Trains

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**Abstract.** The passenger rail transportation system is of strategic importance to the decarbonization of the transportation sector. The use of green hydrogen is an environmentally sustainable option where highly polluting diesel trains currently operate on non-electrified rail lines. This paper proposes a novel adaptive power flow management strategy for urban railway trains powered by a hydrogen fuel cell stack and electrochemical batteries. The fuel cell stack is not dynamically controlled as usual, but it operates in on-off conditions to improve its overall efficiency. It always operates at the maximum efficiency operating point when it provides electrical power (on state) without following the load power variations. Furthermore, the state of the fuel cell stack depends on the state of charge of the electrochemical batteries which is the controlled quantity. As a case study, it is proposed a simulation of a suitably redesigned hydrogen-fuelled railway train operating, over an existing non-electrified line, for the L'Aquila (Italy) urban transportation service. The main components of the railway line and vehicle powertrain are designed, and the hydrogen consumption for railway operation is estimated.

**Keywords:** Railway Transport · Hydrogen Fuelled-Rail Train · Fuel Cell · Decarbonization

## 1 Introduction

Transport systems currently are responsible for a quarter of the greenhouse gas (GHG) emissions in Europe.

The European Commission has adopted a set of proposals to make EU climate, energy, and transport policies aligned with the community's purposes of reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels, and then achieving climate neutrality in 2050 [1].

The European rail industry is implementing and financing research activities to achieve the sustainable performance target set up by the European Commission. The goal is to perform the widest research activities in the rail sector, to get the greatest enhancements, able to introduce operative and technological changes in the railway system, which enable it to meet the Sustainable Development Goals (SDG).

The use of alternative fuels, such as hydrogen, rather than fossil ones offers further potential in reducing emissions in railway transport [2]. However, nowadays the production and refuelling hydrogen chain has not been fully developed. To substitute diesel traction vehicles running in secondary railways there would be necessary high infrastructural investments, which now are economically justified only in the so-called “primary” lines and high speed/high-capacity service that have significant operative frequencies and flows (for passengers and goods).

Therefore, highly polluting diesel trains operate on secondary lines, which range from 30% to 70% of the extension of European national railway networks [3], due to low traffic density and high electrification costs.

Undoubtedly, the transition to electric mobility is a fundamental step towards cutting direct environmental emissions but will be not fully effective if the energy used is from fossil combustibles. At the same time, change in the rail sector requires the full use of energy carriers produced from renewable sources.

In addition, the development of innovative technologies that can reduce the motion resistance of vehicles makes it possible to increase their operational efficiency and, consequently, reduce energy consumption. [4–6].

For railway applications on non-electrified lines, one of the most environmentally friendly technology options involves the use of hydrogen as a fuel in vehicle traction. This has zero greenhouse gas emissions, can be produced from renewable energy sources, and overcomes the need for infrastructure electrification [7].

Operational examples on this topic have been realized, in the international context, both urban and extra-urban environments [8–10].

Most of the above applications use technological solutions in which the hydrogen FC is hybridized with energy storage systems (ESSs), that usually are electrochemical batteries [11]. As an alternative for electrochemical batteries’ usage, such as ESS, to support FCs, some authors have investigated more environmentally sustainable technological options based on the Flywheel Energy Storage System (FESS) [12–18].

The work aims to simulate the dynamic behaviour of a hydrogen-powered railway train traveling along an existing non-electrified line, suitably redesigned for urban transportation service in L’Aquila City (Italy).

## 2 Vehicle Design Method

The scheme of the proposed railway train is shown in the Fig. 1. The traction motors are placed in the two end side trolleys; FCs and the hydrogen vessels are distributed on the roof of the rail train. The proposed powertrain uses electric traction motors (EM), fed by the hybrid power unit (HPU), for each rail car. The HPU consists of FC stacks operating in on-off conditions and ESS electrochemical battery-based. The traction motor and the FC are connected to the DC power bus (continuous red line) by converters, respectively (CM and CFC), to manage the power flows, as required by the master control system (CS) via a communication bus (green line).

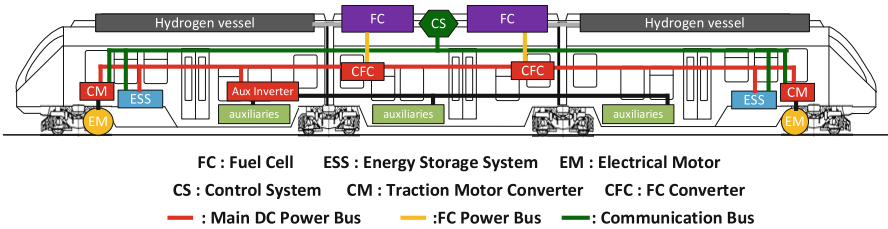


Fig. 1. Sketch of the vehicle system architecture

The control strategy of the HPU is based on the ESS state of charge. Due to the FC’s slow dynamic response and to improve the FC’s overall efficiency, the master controller imposes a constant operating point for the FC stack. In this way, the ESS handles the load variations with the purpose of:

- a) providing power when the load power is higher than the FC power
- b) recovering power when the FC power is higher than the load power and during the regenerative electrical braking.

### 2.1 Model-Based Approach

The vehicle’s powertrain is described by using a model-based approach [19]. A parametric dynamic simulator has been developed, by the authors, in a MATLAB-Simulink environment. It consists of interconnected analytical-numerical sub-models and allows to simulate the travel of a given vehicle along a path and evaluate the performance of each component. The submodule interconnection is illustrated in the block diagram in Fig. 2.

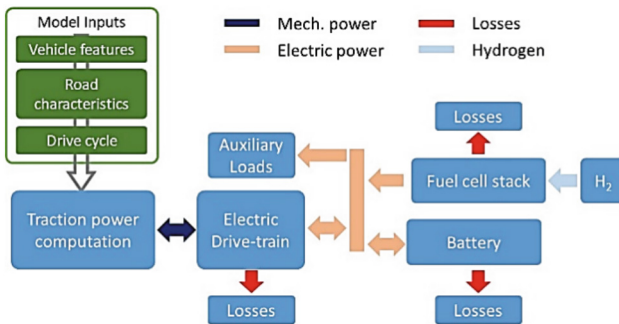


Fig. 2. Block diagram of the system simulator

The implemented software calculates the power flows and energy consumption starting from the definition of the inputs concerning the following three blocks:

- “Vehicle”, addressing the vehicle (mass, dimensions, mechanics, efficiency, payload, etc.);
- “Railway path”, concerning the topography characteristics;
- “Drive cycle”, describing the vehicle mission’s driving profile by specifying the speed vs. time;
- “Traction power” block computes the mechanical power needed to drive over the input path at the specified speed profile.

The vehicle simulation software, developed by the authors, was used for the investigations presented in this paper. The simulator solves the following vehicle equations of motion utilizing numeric integration:

$$T(v(t)) - m \cdot a \cdot \frac{dv}{dt} = \sum R(v(t)) = R_W(v(t)) \mp R_S + R_W(v(t)) + R_A(v(t)) \quad (1)$$

where  $R_W$  is the rolling resistance,  $R_S$  is the slope resistance,  $R_A$  is the air resistance,  $m_{ax}$  is the average mass vehicle per axle,  $m$  is the gross mass,  $v$  is the speed of the train, respectively,  $g$  is the acceleration of gravity,  $\beta$  is the angle of the track slope,  $C_A$  is the drag coefficient,  $S$  is the vehicle frontal area,  $n_c$  is the number of coaches, and  $\alpha$  is the rotational mass inertial coefficient. Through the traction thrust  $T(v(t))$  the mechanical power of the traction motors  $P_M$  can be evaluated as:

$$P_M(t) = \frac{1}{\eta_t} T(v(t)) \cdot v(t) = \frac{1}{\eta_t} \sum R(v(t)) \cdot v(t) \quad (2)$$

where  $\eta_t$  is the transmission efficiency. In regenerative braking  $1/\eta_t$  becomes  $\eta_t$ . Considering regenerative electrical braking, the electrical traction power  $P_U$  is:

$$P_U(t) = \begin{cases} \frac{P_M(t)}{\eta_M} & \text{if } P_M(t) > 0 \\ \eta_M \cdot P_M(t) & \text{if } P_M(t) < 0 \end{cases} \quad (3)$$

where  $\eta_M$  is the electromechanical conversion efficiency of the EM and CM. The energy recovered during braking is stored according to the ESS stack’s State of Charge (SOC). Moreover, the use of on-board auxiliary devices is considered, whose operation requires energy  $E_{aux}(t)$  that is calculated taking in consideration the absorbed power  $P_{aux}(t)$ . The electric traction motor is simply modeled using its torque and power capability, i.e., the torque/speed and power/speed limit curves. The FC is assumed to be a non-linear voltage generator modeled by its voltage-current static characteristic, neglecting its dynamic behavior and any time delay. Since the FC works at constant power, the maximum output power is chosen as the operating point to minimize the rating of the whole FC stack. This choice has been possible because the efficiency value does not differ too much from the maximum one. Therefore, an FC constant efficiency ( $\eta_{fc}$ ) is assumed in the model. The fuel consumption is calculated using relation (4):

$$m_{Fuel} = \frac{E_o}{\eta_{fc} \cdot H_i} \quad (4)$$

where  $E_o$  is the output energy,  $m_{Fuel}$  (kg) is the mass of fuel and  $H_i$  (MJ/kg) is the fuel lower heating coefficient.

### 3 Case Study

To validate the proposed vehicle performance, a real urban path with four stations was identified. L'Aquila City's (Italy) railway has been selected for application study. This is an existing non-electrified single-track line where diesel trains currently operate. The railway line has been redesigned, introducing further 8 stations, to increase the line accessibility. Figure 3 shows the map of the selected railway line on which the round-trip route (47.2 km long) is simulated.

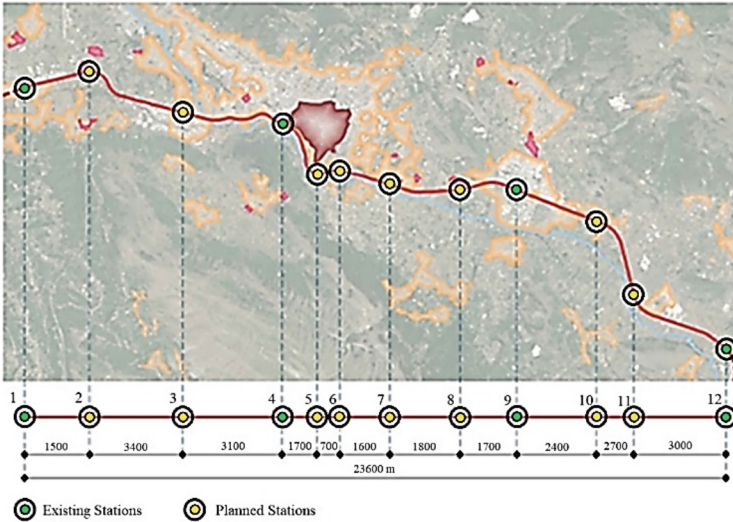


Fig. 3. Case study railway line section.

The calculated driving cycle is illustrated in Fig. 4.

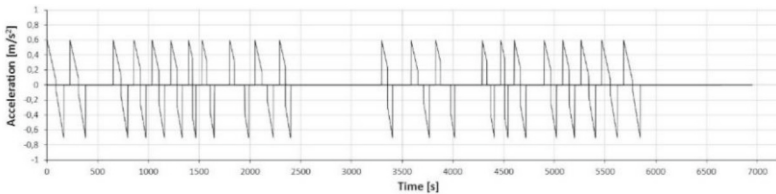


Fig. 4. Driving cycle

Vehicle mission requires an overall time of 115 min, dwell time included, to cover a 47.2 km distance. A maximum speed of 80 km/h is reached during the mission with corresponding peaks, of positive and negative acceleration, of 0.6 m/s<sup>2</sup>. Logged peaks and grade average are, respectively, of 13‰ and 3.38‰. The cycle time is calculated by including an average dwell time per station of 60 s and railhead turn-around times of,

respectively, 25 min and 15 min. The overall roundtrip time is about 115 min, including dwell times on terminals. An urban rail train topology, carrying a full load capacity of 300 passengers, was considered to run along the selected railway line shown above. The main characteristics of the baseline vehicle are listed in Table 1.

**Table 1.** Main rail vehicle data.

Parameters	Symbol	Unit	Value
Number of coaches per train	$n_c$	-	3
Carrying capacity (passengers)	$n_p$	-	300
Gross mass	$m$	t	104
Auxiliaries Power (peak)	$P_{aux}$	kW	114
Fuel Cells Power	$P_{fc}$	kW	250
Fuel Cells Efficiency	$\eta_{fc}$	-	0.55
DC/DC Efficiency	$\eta_{DC/DC}$	-	0.91
Fuel Cell Stacks	$k$	-	1
Vehicle Front Area	$S$	m <sup>2</sup>	9.8
Drag coefficient	$C_A$	-	0.45
Motors power for traction (total, peak)	$P_M$	kW	1200
ESS Energy	$E_{ESS}$	kWh	100
ESS Power (peak)	$P_{ESS}$	kW	1400
ESS Efficiency	$\eta_{ESS}$	-	0.9
Maximum efficiency of traction motor/generator	$\eta_M$	-	0.94
Transmission efficiency	$\eta_t$	-	0.92
Inertia coefficient of rotating masses	$\alpha$	-	1.18
Radius of wheel	$r_W$	m	0.425

### 3.1 Simulation and Results

A simulation of the rail train based on the adaptive control logic have been carried out on the selected rail path whose features are described above.

Each single block of the whole system's power flow has been evaluated by using the developed dynamic model to simulate the vehicle mission in the application case.

The electrical power is provided by the FC and ESS, managed by the control strategy, and is based on the ESS SOC reference value. The FC behaviour, in terms of output power and of the ESS SOC over the vehicle mission, is reported in Fig. 5.

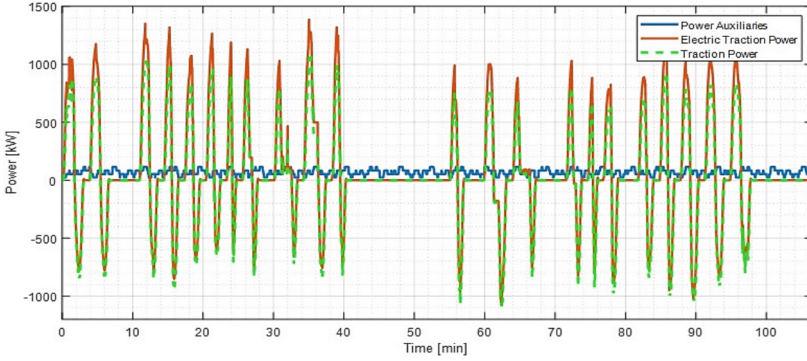


Fig. 5. Power profiles of traction, electric traction and Auxiliaries.

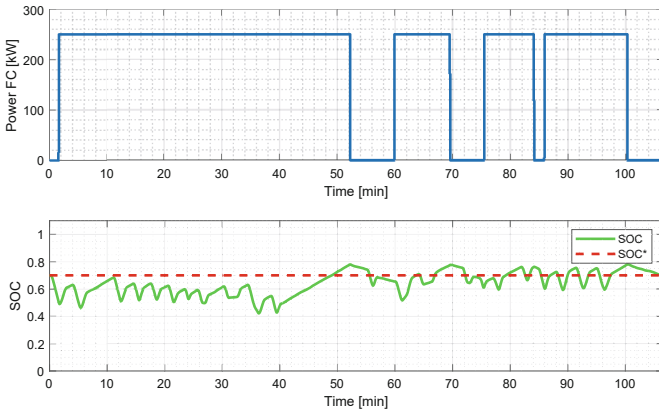
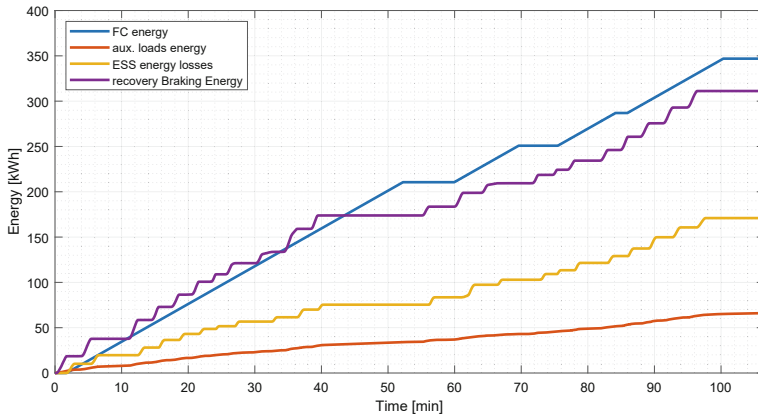


Fig. 6. FC output power (top), reference and actual FESS SOC (bottom).

Figure 6 shows the most significant energy values during the mission cycle. Given that the ESS SOC value at the end of the cycle is equal to the initial one and it can be neglected, the following energy balance considerations can be drawn. The electric recovery braking energy is almost 310 kWh, the useful energy recovered is about 170 kWh and the amount of energy generated by FC is about 350 kWh. Those results demonstrate the ESS bank’s significant braking energy recovery capabilities, while the FC control appears to be well suited to respond to the energy output variations that occur during driving.

The effect of the auxiliary loads is significant in terms of energy consumption; nevertheless, their energy absorption during braking operation or driving downhill helps to keep the ESS SOC within its boundaries. The results show a railway train fuel consumption of 0.4 kg H<sub>2</sub>/km (Fig. 7).



**Fig. 7.** Vehicle cycle: energy count of FC stack, electric drivetrain (losses included), auxiliary loads and the energy losses in the ESS.

## 4 Conclusion

This paper provided a novel adaptive energy flow management strategy for an urban railway electric train powered by a hydrogen fuel cell stack and electrochemical batteries.

An existing non-electrified single-track railway for the urban transport service in the L'Aquila city (Italy) has been properly redesigned and considered as case study.

The main components of the railway and the vehicle drive train were designed and the hydrogen consumption for railway operation was estimated. The results show a rail train fuel consumption of 0.4 kg H<sub>2</sub>/km. Moreover, the results prove that the new control strategy of the fuel cell stack is suitable for urban applications. This is relevant result because the proposed control strategy increases the system efficiency while reduces the energy consumption and traction costs.

Future research will be focused on the development of a fully predictive control strategy aiming to reduce railway train fuel consumption, by knowing the actual passenger's load, and to minimize the power unit.

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