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Performance simulation of hydrogen-electric transit bus running in a mountain environment

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Abstract

As is well known, the transport sector accounts for a third of all final energy consumption in the EU and is responsible for more than a quarter of total greenhouse gas emissions, making it one of the main contributors to climate change. Reducing the negative effects of transport is a strategic objective of the EU, which has put in place a series of actions to promote cleaner and more efficient transport modes, using more sustainable technologies, fuels, and infrastructure.

The development of more sustainable and zero-emission collective transport solutions implies the use of novel propulsion systems capable of using energy carriers produced from renewable energy sources.

This article deals with the preliminary design and performance analysis of a hydrogen hybrid passenger bus to be used in a mountainous area characterized by mainly curvilinear routes with high gradients both uphill and downhill, within an experimental context of technological-energy innovation.

The study is part of a wider project (LIFE3H) co-funded by the European Union, which, among other objectives, intends to lay the bases for the development of a Hydrogen Valley (integrated hydrogen production, storage, and use site), through public hydrogen transport and refueling stations in the mountain area of “Altopiano delle Rocche” in Abruzzo (Italy).

The studied vehicle power-train configuration is based on an electric motor fed by a hybrid power unit consisting of a hydrogen fuel cell functionally coupled with an electrochemical battery.

A minibus configuration run over a round trip path according to the real traffic conditions is simulated and main vehicle powertrain components are sized. Finally, hydrogen consumption for traction is estimated.

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1. Introduction

The EU policies on energy transition and sustainable development, aimed at mitigating global warming, provide for a 90% reduction in direct greenhouse gases emissions (GHG) from transportation by 2050, compared to 1990 levels, as envisaged in the European Green Deal (EC, 2019). Achieving the EU objectives requires limiting the impact per unit of transport service satisfied, which can be obtained both shifting towards more sustainable transport modes and using technological solutions that are able to increase the efficiency of vehicles, thus limiting GHG emissions per unit of energy (MIMS, 2022). Hydrogen Fuel Cell (HFC) technologies have been identified as an interesting solution as they allow not only to reduce energy consumption, but also to curb the use of fossil fuels in favor of national renewable sources (Bucci et al., 2004; EC, 2020). In a fuel cell vehicle (FCV), the propulsion system is an electric motor powered by energy produced on board by electrochemical fuel cells, that transform the chemical energy of the hydrogen vector combined with atmospheric oxygen, directly into electricity. Hydrogen is stored in pressurized tanks, while an electric energy storage system (ESS), namely a chemical battery (BES) or a flywheel (FESS), is always present on-board (Ciancetta et al., 2016b, 2016a, 2010; D'Ovidio et al., 2020a, 2020b, 2014). The technology is already commercially available for both road and railway transport systems (D'Ovidio et al., 2017), but there are still economic and environmental barriers linked to their spread, including the absence of a hydrogen distribution, and refueling network, high purchase costs, low technology readiness level (TRL) and high cost of hydrogen vector - linked to its limited demand (Ajanovic et al., 2021). Therefore, it is essential to promote pilot projects aimed at stimulating the diffusion of FC technologies and increasing the hydrogen demand (Bucci et al., 2007).

Furthermore, the performances of FCVs are strictly connected to the operation conditions (e.g., air temperature and pressure) and to the mission profile required for the vehicle, which in turn affect the dimensions of the FC stacks and the energy and power requirements for the on-board ESS. For this, the estimation of the dynamic performance of FCVs in real driving conditions is essential for a preliminary feasibility assessment of the given technological solution.

De Lorenzo et al. have proposed a calculation tool developed in Matlab and Simulink environments for estimating mechanical power and torque of the electric motor and energy requirements of FC stack and ESS for a FC city bus, once defined bus characteristics and mission profiles (De Lorenzo et al., 2014). The simulation tool allows for simulating different traffic conditions (by increasing and decreasing bus stops number) for obtaining an estimation of the hydrogen consumption and the batteries State of Charge (SOC). Alfonsin et al. have developed a simulation Matlab/Octave toolbox for the preliminary calculation of motor and battery power requirements of FC buses (Alfonsin et al., 2018). The toolbox allows the importation of GPS data thus considering the real orography of different routes. Both previous studies focused on urban buses, which normally run on fixed and low energy-demanding routes. Recently, Sparber et al. have developed and tested a simulation model based on vehicle's energy balance for evaluating the energy consumption of both battery electric buses and FC buses and assessing their capabilities for replacing diesel buses in inter-urban bus services in an Alpine Italian region (Sparber et al., 2022). The complex orography of this region involves differences in altitude of up to 1700 meters for a single ride, making mission profiles particularly challenging. However, the calculations were based on the specific energy consumption of commercially available buses and no data on their actual operation were used.

This work aims to fill the above research gap, through the proposal of a proper developed simulation model, tested on an extremely energy demanding mission profile, acquired in real driving conditions via GPS. The study has been carried out within the LIFE 3H project aiming at exploit three Hydrogen Valleys (integrated system of hydrogen production, storage, distribution and use for application in transport) in three different areas each with different peculiarities: city, port, and mountain areas. Specifically, the work is part of the activity of defining the technical requirements of two FCBs, eight meters in length, serving the mountain area of Altopiano delle Rocche in Abruzzo (Italy).

The mission profile is characterized by long route length, high altitudes, and severe slopes. In fact, to date, there are no FCB manufacturers providing a suitable solution for operating such demanding route, especially with reference to minibuses. Due to the lack of market solutions for the proposed scenario, it becomes essential to know how such a challenging mission profile can affect vehicle specifications. This information will be essential for the development of suitable solutions by interested manufacturers.

The objective of the present work is to simulate the dynamical behavior of a minibus traveling along the route envisaged by the project. The kinematic profile of the mission has been measured by acquiring data in real traffic

condition, travelling on a small sized diesel-bus. A proper developed simulation model has been used to identify the main operative parameters which may be used to characterize vehicle overall energy consumption, and therefore to size the powertrain components.

2. Methodological approach

The methodological approach consists of the following steps: i) vehicle model construction; ii) identification of the route and typology of transit bus; iii) acquisition of the topographical characteristics of the route and of the kinematic profile in real traffic condition; iv) simulation of the run of the bus on the chosen path; v) definition of powertrain characteristics and vi) consumption analysis.

2.1. Vehicle architecture

The architecture of the vehicle has been developed with the aim of designing a powertrain capable of operating in a mountain environment characterized by steep slopes and long daily range. For these reasons a hybrid hydrogen fuel cell – battery vehicle has been taking into consideration. The main purposes aim to: i) increase efficiency of the vehicle by a new hybrid propulsion system; ii) avoid energy dissipation; iii) limit the installation of chemical batteries for traction; iv) use a green fuel that can be generated from renewable energies.

A scheme of the proposed vehicle architecture is shown in Fig. 1. The proposed power plant uses an electric traction motor (EM) fed by a hybrid power unit consisting of a hydrogen Fuel Cell (FC) and a battery pack system.

The traction motor, the FC and the battery pack system are connected to the DC power bus (continuous red line) by means of converters: Converter Electric Drivetrain (CED) and a Battery Management System (BMS). To manage the power flows required, a master control system (CS) communicates with the FC control system (CFC) and the driving control (DC) via a communication bus (green line).

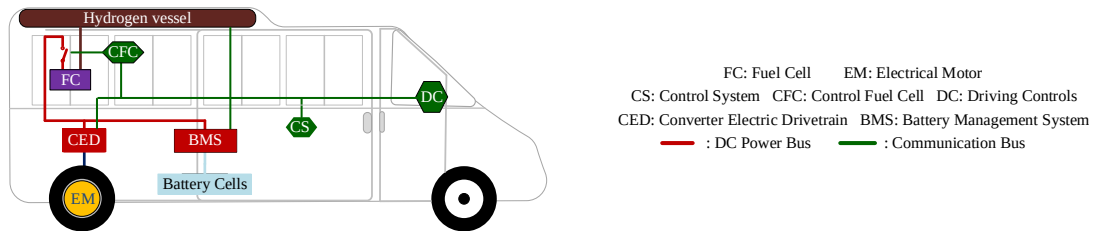


Fig. 1. Scheme of the zero-emission bus

2.2. Vehicle model

The dynamic model of the FC bus has been developed for evaluating the performance of the vehicle and its components while moving on the investigated route. Here, the mathematical model is only briefly described and further details can be found in (Di Battista et al., 2015; Villante, 2015).

Based on the cinematic profile of the mission and vehicle parameters, the traction power requirement has been calculated starting from the differential equation of motion, splitting the external forces in traction thrust, $T(v(t))$, and summation of the resistances to the vehicle motion, $\Sigma R(v(t))$. The latter can be expressed as the summation of rolling, R_w , slope, R_s , and air, R_A , resistances. Thus, the traction thrust is given by:

$$T(v(t)) = m\alpha \frac{dv}{dt} - [R_w(v(t)) + R_s(\beta) + R_A(v(t))] \quad (1)$$

where, m is the gross mass of the vehicle, α is the inertial rotational mass coefficient, v is the vehicle speed, and

β is the angle of the road slope.

The electrical traction power, P_{el} , has been calculated considering also the regenerative electrical braking, as:

$$P_{el} = T(v(t))v(t)/(\eta_t\eta_D) \text{ for } T(v(t))v(t) > 0 \quad (2)$$

$$P_{el} = T(v(t))v(t)\eta_t\eta_D \text{ for } T(v(t))v(t) < 0 \quad (3)$$

with η_t and η_D the transmission and electrical traction drive (namely, converter plus electrical motor) efficiency respectively. For properly simulate the breaking phase, limiting the maximum applicable breaking power, a weight distribution on the vehicle axles has been assumed. Finally, the model considers that no energy is recovered if the SOC of the battery is full.

The sketch of the model implementation in the simulation software showed in Fig. 2a has been implemented on MatLAB by the authors. The model calculates the power flows and the energy consumption (traction and auxiliary systems) starting from the definition of the inputs concerning the following three blocks:

- “Vehicle features” addressing the characteristics of the vehicle (mass, dimensions, mechanics, efficiency, payload, etc.).
- “Road characteristics” concerning the topography of the path and the road surface features.
- “Drive cycle” describing the driving profile by specifying the speed versus time.

The “Traction power” block computes the mechanical power needed to drive over the input path with the selected vehicle at the specified speed profile.

The “Electric Drivetrain” block computes the electrical power needed for the traction, accounting for the energy losses of the gear, motor, and power converter. The computation of the drivetrain losses is based on look-up tables validated by means of experimental data and by literature. The torque-speed working point of the electric drivetrain is the input of the look-up table; power losses are the output. The losses produced by the fuel cell stack and the battery are evaluated by considering their system efficiency. The model allows to compute the total energy required (including auxiliary loads) and the hydrogen consumption in the given track with the envisioned driving cycle.

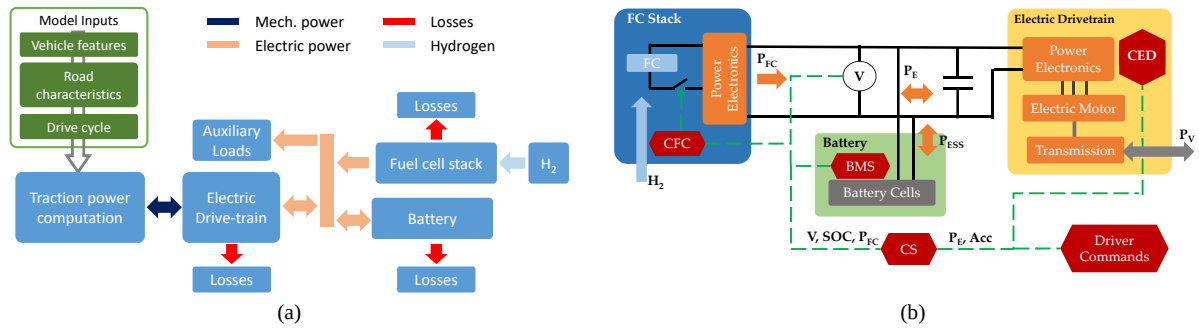


Fig. 2. a) Sketch of the vehicle simulator (left); b) block diagram of the electric power system (right)

2.3. Electric power system and control strategy

The block diagram of the envisioned electric power system is shown in Fig. 2b where the power and control lines are detailed. It is based on an FC stack controlled by its Fuel Cell Controller (CFC) and equipped with a DC/DC converter to ensure the proper energy transfer from the FC to the DC bus. The Energy Storage System (ESS) configured as a Lithium-ion battery is directly connected to the DC bus and managed by the Battery Manager System BMS. The traction electric motor, the vehicle single gear transmission, and the related power electronics is referred as the Electric Drivetrain and is managed by the Electric Drivetrain Controller (CED). The Electric Drivetrain is directly connected to the DC bus by mean of a bulk capacitor.

In terms of power, the proposed configuration requires the battery to be sized to provide the peak power of the Electric Drivetrain, while the FC is envisioned as a range extender, and it is managed to work at a fixed power level where maximum efficiency is achieved.

To this extent, the BMS monitors the DC bus voltage and exchanges its level to the other controllers through the communication bus along with the SOC of the battery. When the SOC decreases below a proper threshold the main control system (CS) demands the FC to be powered on and inject power in the DC bus to avoid that the battery is fully discharged. Depending on the road grade and on the vehicle dynamics the fuel cell provided energy is used directly by the electric drivetrain or to refill the battery.

3. Case Study

An Italian area of high environmental value located in the National Park of Abruzzo, Lazio and Molise in which there are also two ski areas (Campo Felice and Ovindoli), trekking and cycling trails etc. was chosen as a case study.

The environmental and morphological features of the case study affect the design of the components of the bus kinematic chain since this depends both on the characteristics of the vehicle itself (mass, shape and transported load) and on the characteristics of the route and speed profile.

3.1. Description of the vehicle

The main features of the selected zero-emission hybrid vehicle, with a carrying capacity of 25 passengers, are shown in the Table 1. The mass of this vehicle is increased by approximately 1000 kg compared to that of a similar diesel vehicle.

Table 1: Main vehicle data used in the simulations

Parameter	Symbol	Unit	Value
Length		m	7.76
Width		m	2.4
Height		m	3.05
Passengers seats			25
Full load vehicle mass	m	kg	8700
Frontal section		m ²	7.32
Aerodynamic coefficient	c_x		0.380
Tires type			225/75 R-16

3.2. Description of the path

A round trip path (161 km long) in the extra-urban of L'Aquila country has been selected for study application (Fig. 3a). This route is a part of the actual regional bus line that connects the cities of Avezzano and L'Aquila via the Altopiano delle Rocche. The bus route is currently served by the regional public transport company TUA (Trasporto Unico Abruzzese).

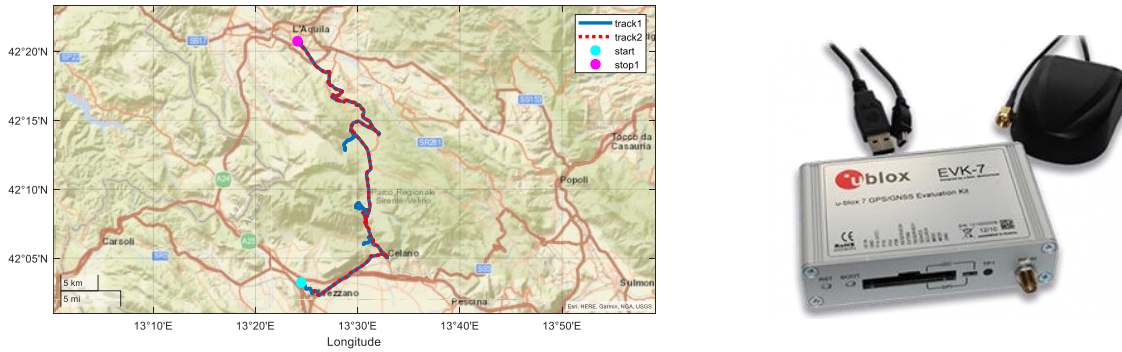


Fig. 3. a) View of the selected route for the case study (left); b) the U-blox7 high precision Global Navigation Satellite System (GNSS) evaluation kit adopted for the vehicle tracking (right).

To acquire the topography features of the route and the drive cycle of vehicle mission, a measurement station based on acquisition system including GPS device has been mounted on diesel bus with performance characteristics similar to those of the project. The measurement station adopts a u-blox 7 Evaluation Kit with Precise Point Positioning system which supports the NEO-7P module. The module, reported in Fig. 3b, is a high precision Global Navigation Satellite System (GNSS) with the following characteristics: i) 56 channels for GPS (L1C/A), SBAS (L1C/A), QZSS (L1C/A), GALILEO (E1B/C); ii) horizontal position accuracy: 2.5 m (in autonomous mode), 2.0 m (in SBAS) and <1.0 m (in PPP); iii) velocity accuracy: 0.1 m/s; iv) data rate acquisition: 1 Hz to 10 Hz. The module has been configured to acquire the roundtrip route with a data rate of 5 Hz in order to mean the measured data and to increase the accuracy.

The results of acquisition show that: i) the maximum altitude is between 600 m and 1500 m asl; ii) the maximum and the average slope are 15% and 4.5%, respectively; iii) the maximum and the average speed are 20.98 m/s and 9.63 m/s, respectively. Fig. 4a illustrates the altitude profile, while the Fig. 4b shows the speed profile.

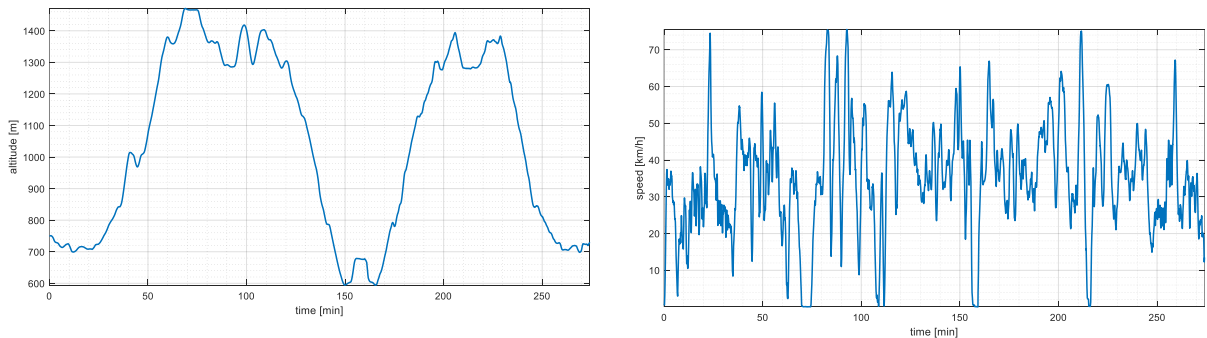


Fig. 4. Description of the round-trip mission profile: a) path altitude vs. time; b) vehicle speed vs. time.

4. Simulation results

The run of the above-described vehicle has been simulated according to the acquired data of the driving cycle and the path to size the powertrain components.

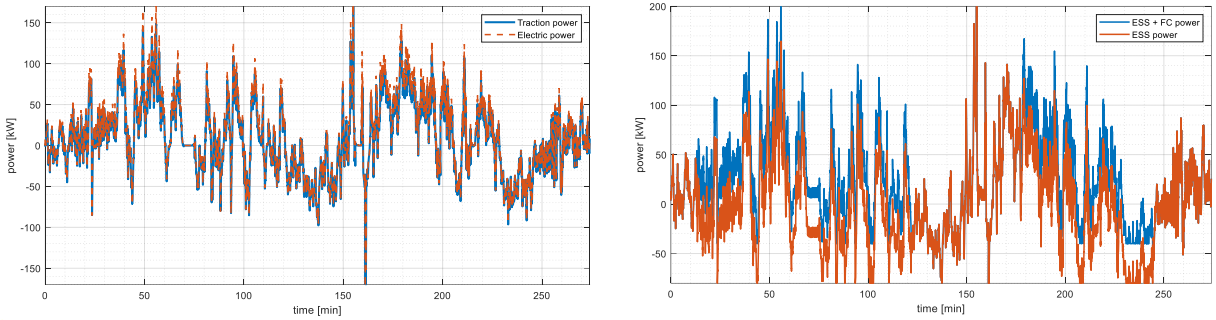


Fig. 5. Description of the mission profile: a) Traction (top) and power (bottom) profiles. b) ESS and power units profiles

In Fig. 5a the traction and electric power profiles have been reported. Fig. 5b illustrates the ESS power and the power unit (ESS and FC power) profiles, respectively. The results show that the electric peak power is 160 kW and the ESS peak power is 200 kW in discharge and 80 kW in charge. Then a 150 kW peak power traction motor has been chosen.

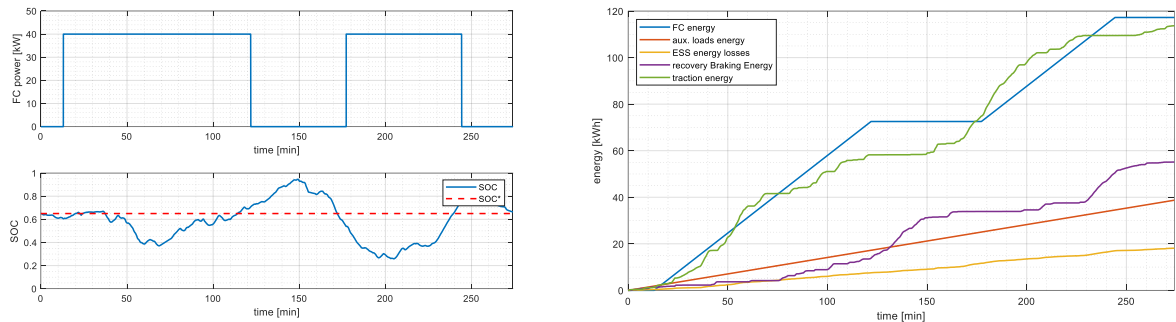


Fig. 6. Description of mission profile: a) FC (top) and ESS (bottom) power requirements. b) Energy profile of main component of the system.

Fig. 6a shows how the FC and ESS manage the power requirement of the vehicle. It can be noted that a FC power of 40 kW and a battery energy of 50 kWh are able to supply the electric power required avoiding overcharge and undercharge battery conditions. The energy profiles of the main components of the system are reported in Fig. 6b. The H₂ estimated consumption is 6.4 kg (about 0.039 kg/km) for the considered roundtrip. However, it should be noted that some uncertainty parameters can influence the simulation results. Among the others, those that can have the greatest influence are errors associated with the accuracy of the sensors, possible loss of the GPS signal, also due to the presence of long tunnels, and the effective electrical energy that can be recovered both downhill and during the regenerative braking in the deceleration phases. Therefore, rather than considering a single average consumption per kilometer, it is more appropriate to assume a range of values which, for the present study, is between 20/25 km/kg_{H₂}, with the first the most realistic one.

5. Conclusions

In this paper the zero-emission technological aspects, sizing and performance of a hydrogen hybrid passenger bus to be operated in a high environmental value mountainous area have been analyzed and presented. The study is part of a wider project (LIFE3H) co-funded by the European Union, which, among other aims, intends to lay the bases for the development of a Hydrogen Valley (integrated hydrogen production, storage, and use site), through public hydrogen transport and refueling stations in the mountain area of Altopiano delle Rocche in Abruzzo (Italy). The results show the feasibility of adopting hydrogen hybrid passenger buses even in mountainous areas on high gradient routes. For the considered round trip path, a 150 kW peak power traction motor, an ESS peak power of 200 kW and a

FC power of 40 kW are able to manage both power and energy requirements with a H₂ consumption of 6.4 kg. Net of all the uncertainty parameters that can influence the simulation results, it is however more appropriate to consider a range of values for the average consumption which, in this study, is between 20/25 km/kg_{H₂}. Further work will focus to develop a measurement system on-board in order to validate the theoretical results.

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