Citation:

Yulianto, A, Simic, M, Taylor, D and Trivailo, P 2017, 'Modelling of full electric and hybrid electric fuel cells buses', Procedia Computer Science, vol. 112, pp. 1916-1925.

See this record in the RMIT Research Repository at:

https://researchbank.rmit.edu.au/view/rmit:45221

Version: Published Version

Link to Published Version:

https://dx.doi.org/10.1016/j.procs.2017.08.036

Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 112 (2017) 1916–1925

Procedia Computer Science

www.elsevier.com/locate/procedia

International Conference on Knowledge Based and Intelligent Information and Engineering Systems, KES2017, 6-8 September 2017, Marseille, France

Modelling of full electric and hybrid electric fuel cells buses

Ahmad Yulianto*, Milan Simic, David Taylor, Pavel Trivailo

School of Engineering, RMIT University, Melbourne 3053, Australia

---

Abstract

Future road transports will increasingly move towards zero emissions. Although electric bus technology is available today, low energy density of lithium-ion (li-ion) batteries is a major drawback, leading to higher vehicle mass and range limitations. Hybrid buses, with more energy dense storage, appear as an easier transition from fossil fuels towards zero local emissions. Main objective of the research is drive systems' modelling and calculating energy consumption for public buses. Simulations were conducted in MATLAB/Simulink by modelling fuel cells and li-ion batteries where power consumption is driven by the instantaneous power demand of a bus on a given route. The simulation output includes the output power, energy consumption, efficiency, energy storage system requirements and refuelling times. The model can iterate energy storage options, to determine effects on system efficiency. Simulation results show that hybrid fuel cells buses offer up to 75% mass reduction, up to 43% volume reduction, with faster refuelling time, over battery only systems. This study provides a tool that allows comparison of multiple bus configuration for any route, on the path of viable, efficient and environmentally friendly transport system.

Peer-review under responsibility of KES International

Keywords: Fuel cells; Hybrid buses; Electric buses; Vehicle dynamics; Simulation modelling;

---

1. Introduction

Transport sector generated approximately 23% of global greenhouse gases in 2013, with road transport the dominant category producing 5,547 million tonnes of CO_2[1]. If current regulatory and technology trends continue, the future road transport, including public buses, will move towards zero emissions. The problem lies in the fact that today's public buses, which generally use diesel engines, cannot simply be converted to battery based energy storage. Li-ion batteries used in Electric Vehicles (EVs) have an energy density of 0.94-2.63 MJ/L, much lower than

---

* Corresponding author. Tel.: +6285859220267.
E-mail address: yulian.prof@gmail.com (Ahmad Yulianto)

Peer-review under responsibility of KES International
10.1016/j.procs.2017.08.036

diesel fuel with 35.8 MJ/L[2, 3]. In order to maintain the same power storage level, the fully-electric buses would need dramatically more space for batteries, with a corresponding higher mass. While electric motors are more efficient at producing tractive power from stored energy, the challenge remains. Simply reducing the battery size directly affects the operating range, and changes the business model of today's urban bus. Hybrid electric vehicles, which combine electric motors with another power sources, such as fuel cells, offer longer operating range and faster refuelling time than EVs; higher performance, better fuel economy and lower emission than vehicles using internal combustion engines[4, 5]. Therefore, bus hybridization offers an attractive solution for a public transport system.

Public buses transport passengers from point A to B, and so it is important to maximise the passenger carrying capacity while minimising the need for dedicated infrastructure. Buses travel many varied routes, geographies, and so the ability to carry sufficient energy is not always a simple calculation. This research is aimed at calculating the energy consumption of a bus travelling on a given route using MATLAB/ Simulink. The research focuses on the application of Proton Exchange Member Fuel Cells (PEMFC) and li-ion batteries for urban buses.

2. Drive system model

The simulations were conducted using two different models: buses with hybrid fuel cells and fully electric. They share the same driveline but differ in the provision and storage of energy. The PEMFC model is developed based on the generic fuel stack Simulink block. The input data for the fuel stack Simulink block refers to the PEMFC developed by Tremblay and Dessaint[6]. Resulting power is 100 kW. A plot of voltage vs current characteristics is shown in Fig. 1. Starting from the characteristics of voltage vs current, the rest of the input variables can be determined based on a commonly used general fuel stack datasheet. The number of cells (N) can be calculated using equation (1), based on the nominal voltage (V_{nom}) and nominal stack efficiency (η_{nom}), while nominal air flow rate ($V_{lpm(air)}$) can be calculated using equation (2) based on the ideal gas constant 8.3145 J/mol K (R), temperature of operation (T_{nom}), number of cells (N), nominal current (i_{nom}), number of moving electrons (z), Faraday constant 96485 A s/mol (F), and percentage of oxidant ($y\%$). The air and fuel control are given by equation (3) and (4) by considering the supply pressure of fuel (P_{H2}) and air (P_{air}), also the utilization of hydrogen (U_{fH2}) and oxygen (U_{fO2}).

$$N = \frac{2 \cdot 96485 \cdot V_{nom}}{241.83 \cdot 10^3 \cdot \eta_{nom}} \tag{1}$$

$$V_{lpm(air)_{nom}} = \frac{60000 \cdot R \cdot T_{nom} \cdot N \cdot i_{nom}}{2z \cdot F \cdot P_{air} \cdot \eta_{nom} \cdot y\%} \tag{2}$$

$$V_{H_2} = \frac{6000 \cdot R \cdot T \cdot N \cdot i_{fc}}{z \cdot F \cdot P_{H_2} \cdot U_{fH_2} \cdot x\%} \tag{3}$$

$$V_{air} = \frac{6000 \cdot R \cdot T \cdot N \cdot i_{fc}}{2z \cdot F \cdot P_{air} \cdot U_{fO_2} \cdot y\%} \tag{4}$$

The DC/DC boost converter model used in this research is developed from based model created by Motapon, Tremblay[7]. The power balance defines that the product of the input voltage (V_{in}) and input current (I_{in}) is equal to the output power given as product of (V_{out}), (I_{out}) as written in equation (5). Based on the charge balance, the input current (I_{in}) can only provide the charge to output side when the switch is open for the time $(1-d)$ in T period. This relationship is written in equation (6). Based on equation (5) and (6), the new relationship of input voltage (V_{in}) and output voltage (V_{out}) including the duty cycle (d) is given by equation (7). Therefore, interface between the PEMFC and DC/DC boost converter is shown in Fig. 2

$$V_{in} \cdot I_{in} = V_{out} \cdot I_{out} \tag{5}$$

$$I_{in}(1-d) = I_{out} \cdot T \tag{6}$$

$$V_{out} = \frac{V_{in}}{1-d} \tag{7}$$

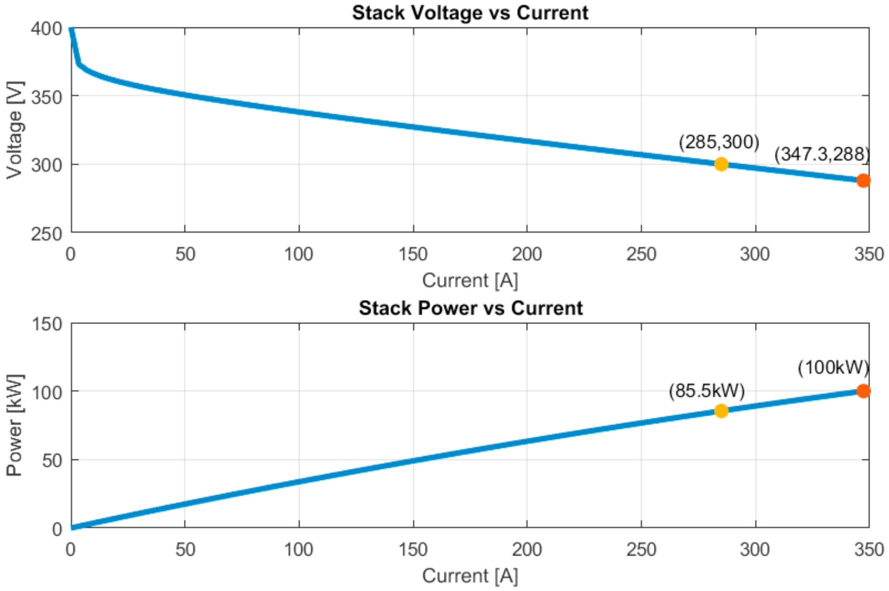

Fig. 1. Voltage and power vs current characteristics of 100kW PEMFC.

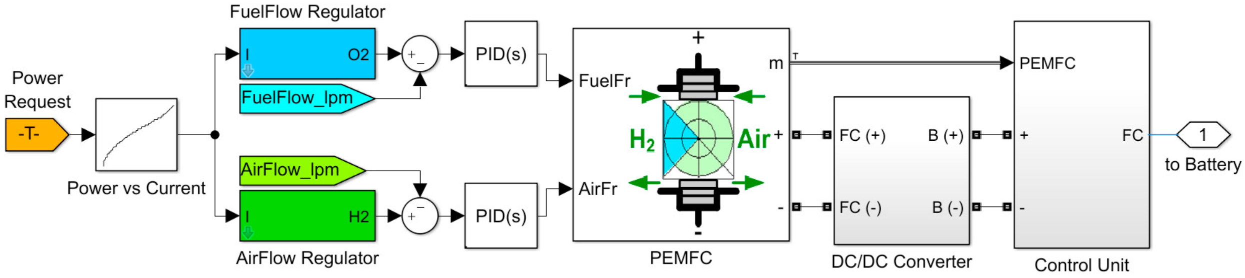

Fig. 2. 100kW PEMFC model.

The total hydrogen required for a given time period is measured in the defined supply pressure of fuel (P_{H2}). Fuel storage is set at 350 bar, so that the simulation model is equipped with the volume conversion based on the ideal gas law. The fuel mass (m_{350}) is calculated based on hydrogen density at respective pressure (ρ_{350}), which is $0.02365\ kg/dm^3$. The fuel tank shape is defined to be cylinder which is calculated based on the given input diameter (D_{tank}) and the number of tanks (N_{tank}) to ensure that all fuel tanks have the same length (L_{tank}) and are less than the bus width with the calculation described in equation (8). The fuel tank for the bus is assumed to be made of carbon fibre reinforced shell which have material density of $0.67402\ kg/dm^3$. The total mass of the fuel tank (m_{total}) is sum of the fuel tank mass (m_{tank}) and the fuel mass (m_{fuel}) as described in equation (9).

$$L_{tank} = \frac{V_{350}}{0.25 \cdot \pi \cdot D_{tank}{}^{2} \cdot N_{tank}} \tag{8}$$

$$m_{total} = (\rho_{350} \cdot V_{350}) + (\rho_{tank} \cdot V_{350}) \tag{9}$$

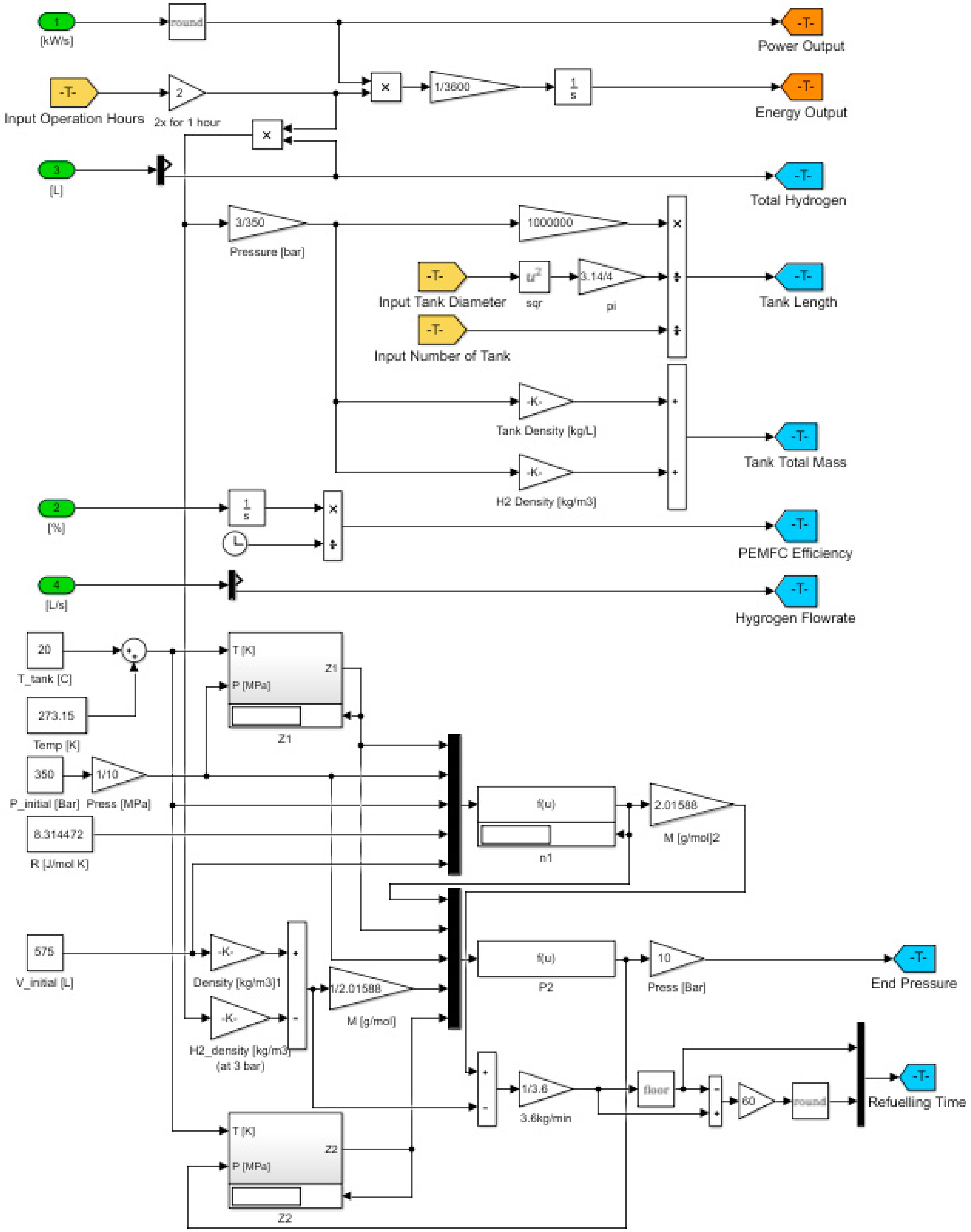

Fig. 3. Hydrogen tank calculation model.

Table 1. Constants for calculating compressibility[8]

i	ai	bi	ci
1	0.05888460	1.325	1.00
2	–0.06136111	1.870	1.00
3	–0.002650473	2.500	2.00
4	0.002731125	2.800	2.00
5	0.001802374	2.938	2.42
6	–0.001150707	3.140	2.63
7	0.9588528×10^{-4}	3.370	3.00
8	$-0.1109040 \times 10^{-6}$	3.750	4.00
9	0.1264403×10^{-9}	4.000	5.00

The pressure change inside the tank can be described using the ideal gas equation by looking at pressure (P), volume (V), number of molecule (n_{mol}), ideal gas constant 8.3145 J/mol K (R) and temperature (T). Due to the fact that the initial pressure (P_1) is relatively high (350bar), the ideal gas equation also needs to consider the compressibility factors of the hydrogen (Z). Therefore, the ideal gas equation can be written in equation (10). The compressibility factor for hydrogen (Z) for a given pressure and temperature can be calculated using equation (11) and given constant values as presented in Table 1. The nominal fuelling rate follows the standard SAE J2601-2, which defines the normal fuelling rate $(\dot{m}_{refuelling})$ as $\leq 60\ gr/s$[9]. The refuelling time $(t_{refuelling})$ is calculated based on the total fuel consumption in terms of mass (m_{H2}). The fuel tank calculation model in respect to the volume, mass and pressure is presented in Fig. 3.

$$P \cdot V = Z \cdot n_{mol} \cdot R \cdot T \tag{10}$$

$$Z(P,T) = \frac{P}{\rho \cdot R \cdot T} = 1 + \sum_{i=1}^{9} ai \left(\frac{100}{T}\right)^{bi} \cdot (P)^{ci} \tag{11}$$

Models for electric motors are built based on motor equations where the input variable is torque. Energy requested from the battery is calculated, as well as, the actual power given to the tires based on motor efficiency. In addition, the motor acts as a generator during deceleration by changing the torque request into negative value (required braking effort). The electric motor model is presented in Fig. 4.

The battery model is built based on the Simulink generic block. Calculations of parameters needed such as voltage, current, charge of the battery, electric power loss, volume and total mass are made. The battery model and its connection to the electric motors and the PEMFC is illustrated in Fig. 4.

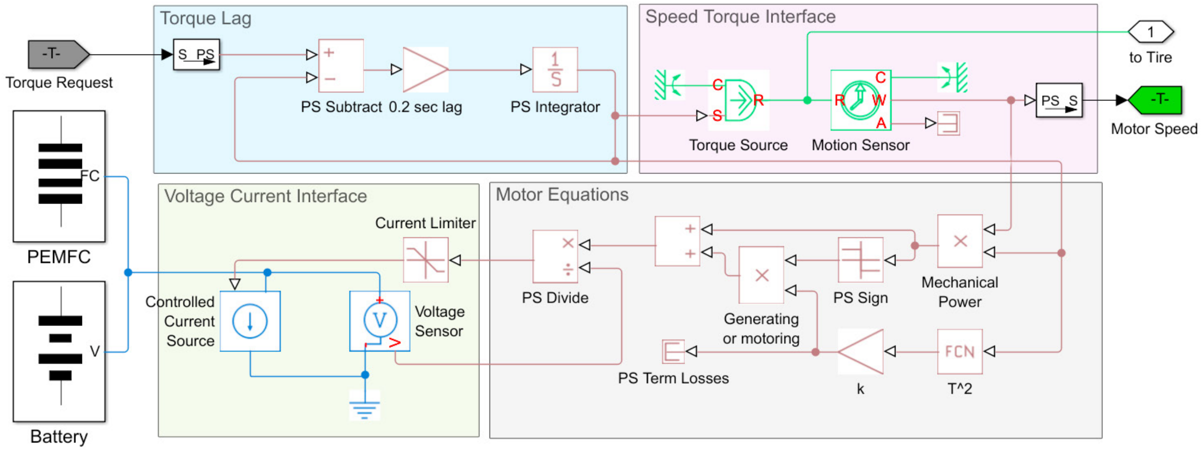

Fig. 4. Electric motor, batteries and PEMFC model.

3. Vehicle dynamics and driving simulation

The vehicle model is built without considering the normal force (F_z) experienced by the tires. It is assumed no tire slip occurs to simplify the bus model. This assumption is applicable to the vast majority of operating scenarios a bus will experience in the real world. Therefore, the equilibrium equation of the vehicle is based on the translational force (F_{xr}) and aerodynamic force (F_D) as presented in equation (10) and (11) respectively. Through these forces, the model is considering the number of the wheels (n_{wheel}), bus mass (m_{bus}), bus frontal area (A), bus drag coefficient (C_d), acceleration (a), bus speed (V_x), wind speed (V_{wind}), air density (ρ), and road inclination (β). The bus model uses the Simulink generic block with given mass 14,000 kg, drag coefficient 0.7 and frontal area 8.75 m^2.

$$F_{xr} = n_{wheel} \left(\frac{1}{2}\, m_{bus}\, a \,\sin\beta \right) \tag{10}$$

$$F_D = \frac{1}{2}\, \rho\, C_d\, A\, (V_x - V_{wind})^2 \tag{11}$$

The bus route captured is route *101* in Perth, Australia, *12,326 m* is shown for a complete round trip. According to the publicly available timetable, this trip takes approximately *30* minutes[10]. The route is made in Google Maps by plotting the actual route of the bus. The selected route is then extracted to a **.gpx* file containing data of latitude (La), longitude (Lo) and altitude (Al) of each point along the route. The resulted data are used to calculate the distance (D) and road inclination (β) by using equation (10) and (11) respectively in order to build look-up tables for the route environments in the Simulink model. The look up tables become the reference of empirical ceiling speed relative to distance and provides road inclination.

$$D = \cos^{-1}[\cos(90 - La_2)\cdot\cos(90 - La_1) + \sin(90 - La_2)\cdot\sin(90 - La1)\cdot\cos(Lo_2 - Lo_1)]\cdot 6371 \tag{10}$$

$$\beta = \sin^{-1}\left[\frac{Al}{D}\right] \tag{11}$$

The driver is designed to follow the given route represented by look-up tables of ceiling speed relative to distance and road inclination. Sufficient acceleration and/or deceleration is requested of the bus based on maintaining ceiling speed as illustrated in Fig. 5. The driver model works based on PID controls representing throttle and brake pedals as shown in Fig. 6. Actual vehicle speed is compared to ceiling speed calculating torque required for acceleration; or total brake force. Braking forces are provided by a negative torque (regenerative brakes) until the allowable energy storage rate is met, at which point thermal brakes are added to satisfy the required total brake force.

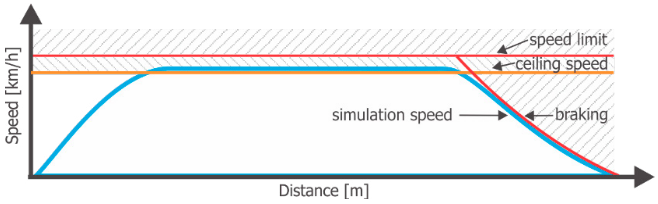

Fig. 5. Ceiling speed and simulation speed.

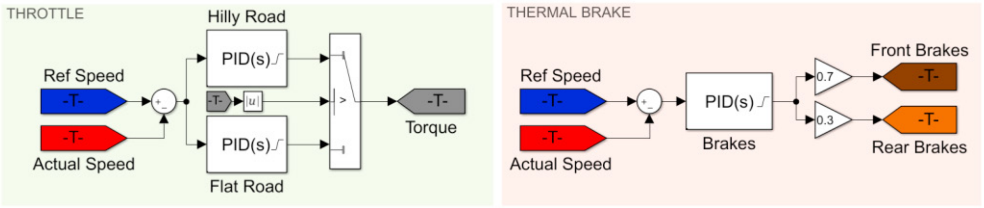

Fig. 6. Throttle and brake of driver model.

4. Results

The hybrid electric bus with PEMFC model, with all subcomponent blocks attached, is illustrated in Fig. 7. The fully-electric bus has the same simulation model and properties as seen in Fig. 7, except without the additional power generation of the PEMFC. Energy consumption for a fully-electric bus is solely calculated from the li-ion batteries, while the hybrid electric bus is also calculated from the PEMFC.

The simulation was done for a single round trip in route *101*. A stop time of 60 seconds is added at the end of each one way journey for both fully-electric bus and hybrid electric buses with PEMFC. The simulation results were extrapolated out to run 8 hours (representing a full day) of operation. This simplification of actual bus operation, purely to show the estimate energy consumption for an 8 hour day. The energy consumption calculated is limited to the energy required for powertrain. Other systems such as air conditioning, cooling system, etc. are not considered in this research.

The vehicle speeds, for both models, are the same as both have the same driveline and route environment. This is to be expected as both have the same driveline torque availability and route environment. The bus speed on route *101* is presented in Fig. 8. The bus model is able to follow the ceiling speed at respective distance points by providing appropriate acceleration and deceleration. The bus model's speed also can drop to *1 km/h* at every bus stop as it is assumed that there is no waiting time, except in the final stop before the return trip. This simplification is due to the model considering driveline energy consumption, not what are referred to as 'hotel' loads. These loads would accumulate energy consumption during a stop, however these loads are not large when compared to drive system loads, hence the simplification for this iteration of model.

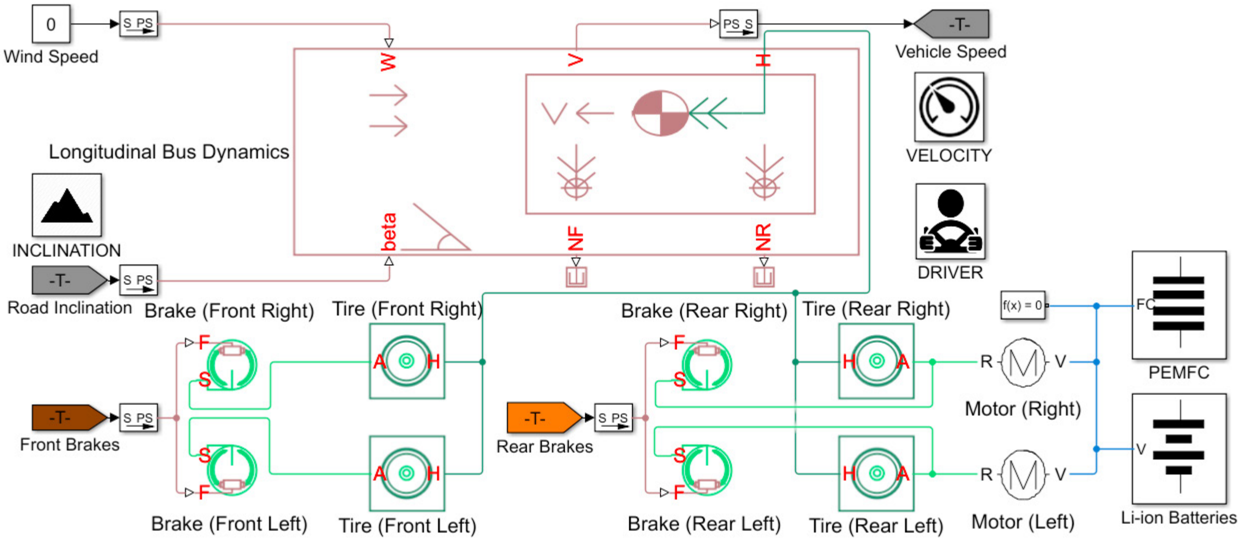

Fig. 7. Hybrid electric bus with PEMFC model.

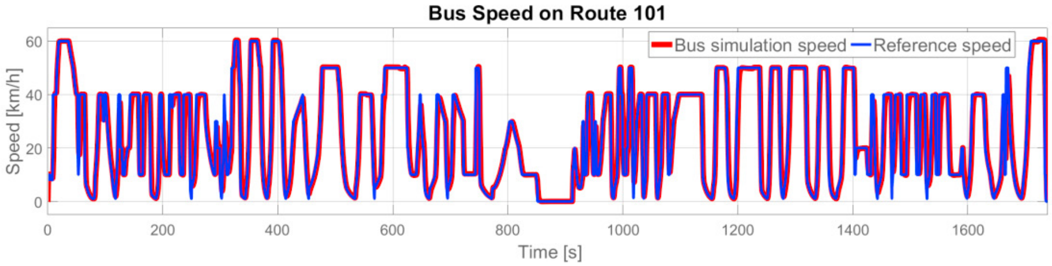

Fig. 8. Bus speed on route 101.

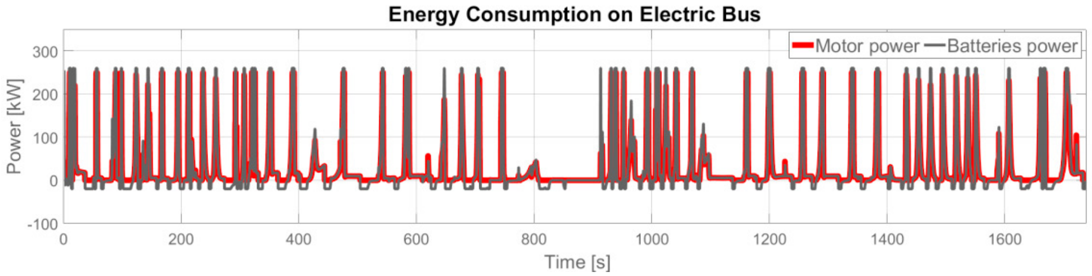

Fig. 9. Fully-electric bus energy consumption.

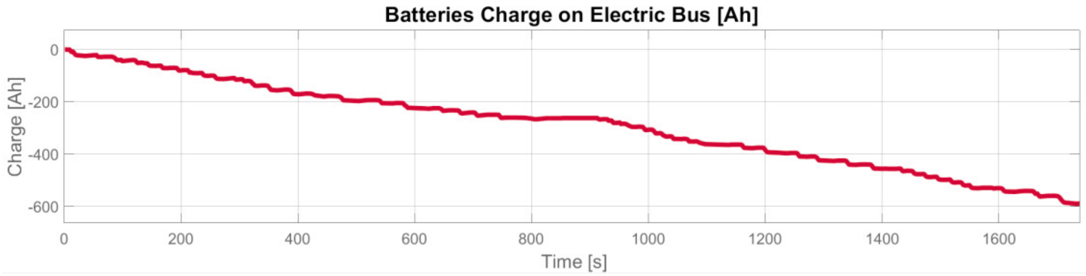

Fig. 10. Fully-electric bus batteries charge.

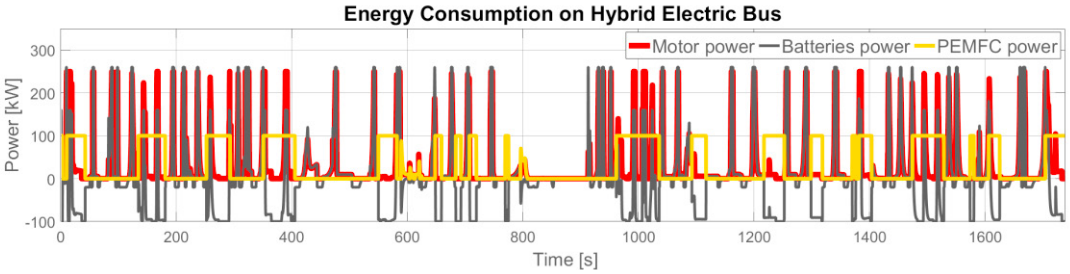

Fig. 11. Hybrid electric bus with PEMFC energy consumption.

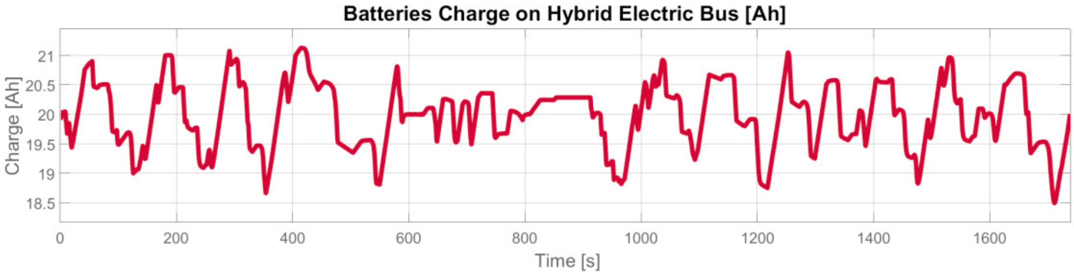

Fig. 12. Hybrid electric bus batteries charge.

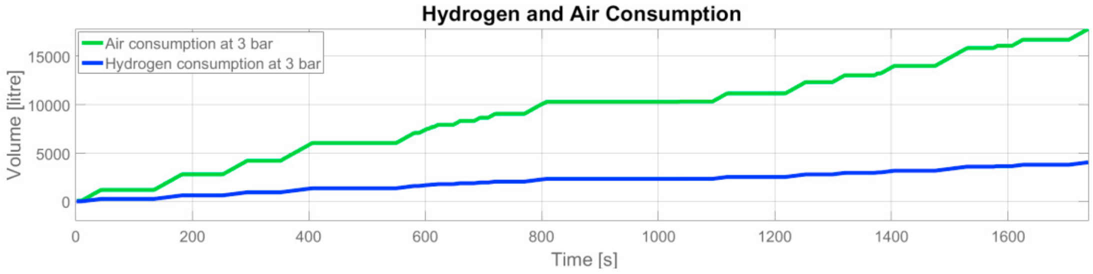

Fig. 13. Hydrogen and air consumption on the 100kW PEMFC.

For the full day of operation, the model demonstrates a total energy consumption of 235.9 kWh for the electric bus. Recovered energy during all bus decelerations is 35.27 kWh. The regenerative braking current is nominally limited to 50 A to satisfy motors and batteries characteristics in terms of quick charging. Energy consumption of the bus is illustrated in Fig. 9, while the batteries charge trend is presented in Fig. 10. In order to meet the 8 hours of energy demand in a single charge while maintaining a 20% reserve, a fully-electric bus requires 400 V li-ion batteries with capacity of 710 Ah. This represents an approximate battery volume of 1597 litres and the battery mass of 2964 kg. This assumes premium li-ion batteries. Lower class batteries will require a larger volume and mass.

The hybrid bus with 100 kW PEMFC and a system efficiency of 65.26% requires 575 litres of hydrogen (at 350 bar), which equals 13.598 kg in mass. 10 fuel tanks, each 300 mm in diameter and length of 813.871 mm are required to contain the hydrogen. This provides an overall mass of tank and fuel at 401.16 kg. In addition, the 100 kW PEMFC has an approximate volume 250 litre and mass 200 kg. Once the fuel tank pressure drops to 4.5 bar, approximately 3 minutes 45 seconds is required to refill the tanks to capacity. The PEMFC provides a total energy of 235.9 kWh in maintaining the charge of the li-ion batteries above 20 Ah. The required li-ion batteries is an approximate volume of 74.717 litres and mass 148.5 kg. The energy consumption and batteries charge of hybrid electric bus on route 101 are shown in Fig. 11 and 12 respectively, while the hydrogen and air consumption is illustrated in Fig. 13. The results of both simulation models are presented in Table 2.

Table 2. Simulation results comparison.

Drive System	Mass [kg]	Volume [litre]
Fully-electric bus		
Li-ion batteries	2964.00	1597.00
Total mass	2964.00	1597.00
Hybrid electric bus		
PEMFC	200.00	250.00
Fuel tank	401.16	575.00
Li-ion batteries	148.50	74.72
Total mass	749.66	899.72

5. Discussions

This simulation demonstrates configurations of two different buses run over an identical route. Both buses use the same electric motors, but the energy supply systems are different. Bus powertrain design, based on battery storage subsystem only, was compared with the hybrid design that included fuel cells subsystem as a support to battery storage. Hybridization shows a 75% mass reduction and 43% volume reduction, yet faster refuelling time, compared to the fully-electric bus. Both solutions are advantageous, compared to current diesel technology, in terms of bus operational efficiency and environment protection, i.e. there is no CO_2 emission.

Further work is required to refine the model to fully correlate real world conditions and environments. The model presently assumes no tyre slip, allowing the bus to always have the required grip for acceleration and deceleration. In actual driving conditions, the bus wheels may have certain level of wheel slip during acceleration but more likely during braking. As the braking force is used to recover energy through regenerative braking, a more sophisticated brake control model needs to be built. The rolling resistance and tyre inertia are small losses compared to aerodynamic load and gravitational forces, however as the tyre elements are refined then the rolling resistances can be added. These changes will have a small influence over the energy consumption calculations. Furthermore, the actual bus mass varies from time to time due to changes in passenger numbers. This was not considered in the simulation model. Further work will be undertaken to model in passenger masses, embarkation and disembarkation times, door open times, all of which have an effect on total energy consumption.

The prime purpose of the simulation models is to estimate the energy consumption of given drive system on a given route considering the actual geographical conditions without the need to visit a study site. The numerical models also offer a tool that allows comparison of multiple bus configurations, observing implications of energy consumption such as overall mass, or range.

6. Conclusions

The comparative results show that hybrid fuel cells buses offer up to 75% mass reduction, up to 43% volume reduction and faster refuelling time, over battery only systems. Performance comparison between both drive systems depends on the route taken and the bus properties. Of course, simulations are limited by accepted assumptions. The simulation model offers a valuable method of investigating the application of given drive systems for any given routes considering its actual geographical conditions, distance and time travelled. Overall, the simulation model provides a reliable tool with numerical calculation that allows comparison of multiple bus configurations for any given route providing the approximate prediction of viable, efficient and environmentally friendly alternatives.

Acknowledgement

The first author would like to express sincere appreciation to the Ministry of Finance of the Republic of Indonesia for providing the scholarship of Indonesia endowment fund for education (LPDP) for studying at RMIT University.

References

1. IEA, *CO2 Emissions from Fuel Combustion*, in *Secure Sustainable Together*. 2015, International Energy Agency: Paris. p. 1-152.
2. Hagenow, G., et al., *Fuels*, in *Handbook of Diesel Engines*, K. Mollenhauer and H. Tschöke, Editors. 2010, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 77-125.
3. Zhang, C., et al., *Microporous Organic Polymer-Based Lithium Ion Batteries with Improved Rate Performance and Energy Density.* Journal of Power Sources, 2016. **317**: p. 49-56.
4. Ehsani, M., Y. Gao, and J.M. Miller, *Hybrid Electric Vehicles: Architecture and Motor Drives.* Proceedings of the IEEE, 2007. **95**(4): p. 719-728.
5. Kellaway, M.J., *Hybrid Buses—What Their Batteries Really Need To Do.* Journal of Power Sources, 2007. **168**(1): p. 95-98.
6. Tremblay, O. and L.-A. Dessaint. *A Generic Fuel Cell Model for The Simulation of Fuel Cell Vehicles*. in *2009 IEEE Vehicle Power and Propulsion Conference*. 2009. IEEE.
7. Motapon, S.N., O. Tremblay, and L.-A. Dessaint, *Development of a generic fuel cell model: application to a fuel cell vehicle simulation.* International Journal of Power Electronics, 2012. **4**(6): p. 505-522.
8. Lemmon, E.W., M.L. Huber, and J.W. Leachman, *Revised standardized equation for hydrogen gas densities for fuel consumption applications.* Journal of research of the National Institute of Standards and Technology, 2008. **113**(6): p. 341.
9. SAE, *Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles*, in *SAE International*. 2014, SAE International: United States.
10. Transperth. *Bus Route 101 Timetable*. 2017 [cited 2017 1 March]; Available from: http://www.transperth.wa.gov.au/timetables/details?Bus=101.