



Reducing Hydrogen Consumption by Using Regenerative Braking Energy for Hydrogen Fuel-Cell Electric Bus Vehicles

Aekkasit Kingmaneerat,^{1,#} Tosaphol Ratniyomchai,^{2,#} Waiard Saikong,³ Chanchai Techawatcharapaikul^{4,#} and Thanatchai Kulworawanichpong^{2,*}

Abstract

The application of regenerative braking energy for water electrolysis is discussed in this work. Fuel savings can be achieved by using the hydrogen produced by this method to offset the quantity of hydrogen fuel required. Hydrogen can also be produced by reusing the by-product water. In addition to conserving fuel, the extra weight of the vehicle due to the by-product water is also greatly decreased. The amount of time spent using the brakes is the primary factor that determines how much hydrogen fuel is consumed during a journey. Significant braking reduces the quantity of hydrogen fuel utilized. The greatest reduction in hydrogen fuel use from the seven typical driving test cycles is 21.33%. When the driver of the SUT campus bus service stepped on the brakes, it was pretty hard. This enables the reproduction of hydrogen using braking energy, resulting in a 46.61% reduction in the amount of hydrogen used.

Keywords: Hydrogen fuel-cell vehicle; Regenerative braking; Water electrolysis; Hydrogen consumption.

Received: 22 August 2024; Revised: 07 November 2024; Accepted: 21 November 2024.

Article type: Research article.

1. Introduction

The engine that powers buses or coaches is usually an internal combustion engine, especially powered by a diesel engine. These buses are called diesel buses. Because diesel is safe, dependable, and efficient, it is the energy source most frequently utilized for public transportation, intercity travel, schools, and other business uses. Diesel engines are utilized in nearly all buses and large, heavy-duty trucks due to their remarkable ability to generate high levels of torque. If the engine has adequate torque, the car can lift a significant amount of weight. Diesel is one of the fuels available today that has the highest energy density and efficiency.^[1] Due to its higher energy density compared to gasoline, it provides

superior fuel efficiency. Diesel engines need regular maintenance to remain in operating condition, even though diesel fuel is believed to be more efficient than gasoline.

Electric bus vehicles have been introduced and are undergoing testing in certain city bus routes to replace traditional diesel buses within the last 10 years.^[2] The electric motor in the bus not only improves its environmental friendliness but also enhances its overall performance, resulting in a higher-quality vehicle. The electric bus has gained popularity due to its exceptional ability to navigate steep inclines. Electric transportation has proven to be effective in reducing air pollution due to its emission-free nature.^[3] Everyone on board enjoys a more comfortable ride thanks to the electric engine's substantial reduction in vibration throughout the bus, which gets rid of the occasional "rattling" sound that occurs while a bus is stopping or waiting for a signal. The bus is an economical choice for operators due to its extended lifespan and decreased maintenance needs resulting from reduced vibration. Despite the high initial installation costs, electric buses prove to be cost-effective in terms of their lifespan and maintenance. An often-cited advantage of the electric bus is its lack of noise. Electric buses are significantly quieter, reduce noise pollution, and enhance passenger comfort.^[4] When regenerative braking is applied, the electric bus's motor also functions as a generator, returning excess energy to the battery.^[5,6] Electric buses save over 30%

¹ Institute of Research and Development, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand

² School of Electrical Engineering, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand

³ College of Industrial Technology, King Mongkut's University of Technology North Bangkok, Bangkok, 10800, Thailand

⁴ Department of Electrical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, 10140, Thailand

[#] These authors contributed to this work equally

*Email: thanatchai@gmail.com (T. Kulworawanichpong)

of energy just by this difference, whereas diesel buses lose this energy through friction when they stop.

A fuel cell bus is an electric vehicle that utilizes a hydrogen fuel cell to propel its wheels as a component of its electrical powertrain. In a hybrid setup, batteries or a supercapacitor are sometimes incorporated into the fuel cell system.^[7] As an experimental measure in Beijing, fuel-cell buses fueled by hydrogen were put into operation in 2006. The inaugural deployment of fuel cell buses in China consisted of three Daimler buses, which were financed by the United Nations Development Program. Fuel cells' efficiency and operating life were lowered by air pollution, which hindered the technology's wider application in urban areas.^[8] The Aberdeen Hydrogen Bus Project operates a fleet of ten single-decker buses powered by hydrogen fuel cells, forming one of the biggest fleets of its kind in Europe. The project is based in Aberdeen, Scotland. Starting in 2020, routes implemented the use of double-decker buses. Three-bus demonstration projects lasted two years in Vancouver and Chicago.^[9,10] A total of 200,000 passengers covered a distance of over 118,000 kilometers during the testing phase, utilizing the six buses. Instead of utilizing the New Flyer Industries 40-foot low floor F40LF bodywork (with a mileage of 73,000), the Fuel Cell Bus Club opted for an earlier model of Ballard fuel cell. Following their shutdown, the three units in Vancouver underwent conversion into diesel-electric hybrids before being dismantled. A portion of these units were subsequently sold back to Ballard, the manufacturer of fuel cells.^[11] With the present goal of lowering greenhouse gas (GHG) emissions to address the effects of climate change, there has been a push to investigate alternate fuels in addition to natural gas. The idea of employing fuel cells in public transportation, such as buses, has been tested under the Fuel Cell Bus Program, a group of projects funded by the DOE's Fuel Cell Technologies Office (FCBP).^[12] Their goal is to promote the use of fuel-cell buses by increasing their affordability, durability, and accessibility.^[13] When it comes to public transportation, buses have become the mainstay for both intercity travel and travel within the city in many nations these days. This is because buses are more adaptable and require less infrastructure to be built than train systems. In the long run, a hydrogen fuel cell is a good substitute to decarbonize this portion of transportation. This is due to the fact that pure battery electric vehicles are less appealing for long-distance driving since they primarily necessitate rapid refueling times and constant high speeds.^[14,15] Energy storage systems can support fuel cells by providing high power for acceleration as well as deceleration, while also allowing for power disengagement during constant speed driving. However, these systems should have a relatively small amount of energy available for regenerative braking and high-speed cruising. It is clear that some test-driving cycles are required to study the effectiveness of the energy-saving enhancement paradigm. As mentioned previously, hydrogen fuel-cell vehicles are able to be potential alternatives for modern public bus vehicle technology in the near future. In

this paper, the energy consumption of the hydrogen fuel-cell vehicle is investigated to find their energy saving by recuperating regenerative braking to produce hydrogen from by-product water in hydrogen fuel-cell electric bus vehicles. The main elements that affect the rates at which hydrogen is produced during electrolysis will be discussed, along with pertinent references for each. As an illustration, important elements affecting the rates of hydrogen production in water electrolysis can be briefed. Since increasing current density speeds up the electrode reaction, it can increase the rates at which hydrogen is produced. But, as explained in Ref. [16], larger current densities can lower overall system efficiency since they result in higher ohmic losses and more heat production. Production rates are directly impacted by conductivity, which is influenced by the composition of the electrolyte (potassium hydroxide for alkaline water electrolysis, alkaline electrolysis (AEL), or sulfuric acid in some proton exchange membrane (PEM), applications. Ionic transport is often enhanced by higher electrolyte concentrations, but over time, as in Ref. [17], this can result in greater resistance. Higher temperatures typically speed up reaction kinetics, which increases the rate of hydrogen production. This is especially advantageous in high-temperature electrolysis, such as SOEC (Solid Oxide Electrolysis Cell). Higher temperatures, as explained in Ref. [18], can also cause materials to wear down more quickly, which could lower long-term efficiency. Higher operating pressures increase the efficiency of hydrogen production and make direct hydrogen compression easier, which lessens the requirement for post-production compression. However, as explained in Ref. [19], pressurization might call for stronger materials and system engineering. Consistent production rates are supported by high water purity because impurities are prevented from harming electrodes and membranes. In PEM and AEL systems, as in Ref. [20], effective ion movement across the electrolyte is particularly crucial, and this is ensured by optimizing the water flow rate. In reaction kinetics, catalyst materials are essential. PEM cells frequently contain platinum and iridium, which have high activity but can raise expenses. As in Ref. [21], developments in substitute catalysts, including those based on ruthenium or nickel, aim to strike a compromise between cost and efficiency.

2. Methods and materials

2.1 Bus vehicle movement and performance calculation

A bus's movement is primarily determined by three dynamic variables: position, velocity, and acceleration rate. The relationships between these variables in single-vehicle motion are only affected by the basic kinematic equation, in accordance with Newton's second law of motion.^[8] Examine Fig. 1, where a bus is traveling over an incline. The motion can be quantitatively demonstrated in equation (1) by utilizing a free-body diagram that illustrates all the forces exerted on the bus vehicle.^[8]

$$F_T - F_R = M_{eff}a \tag{1}$$

$$F_R = F_{RR} + F_{drag} + F_{grad} \tag{2}$$

where F_T denotes the tractive effort of the bus vehicle, F_R denotes the rolling resistance force of the bus vehicle, F_{RR} denotes the resistance force of the bus vehicle, M_{eff} denotes the total mass of the bus vehicle, a denotes the bus vehicle acceleration, F_{grad} denotes the gravitational force (gradient force) of the bus vehicle, and F_{drag} denotes the aerodynamic drag force of the bus vehicle.

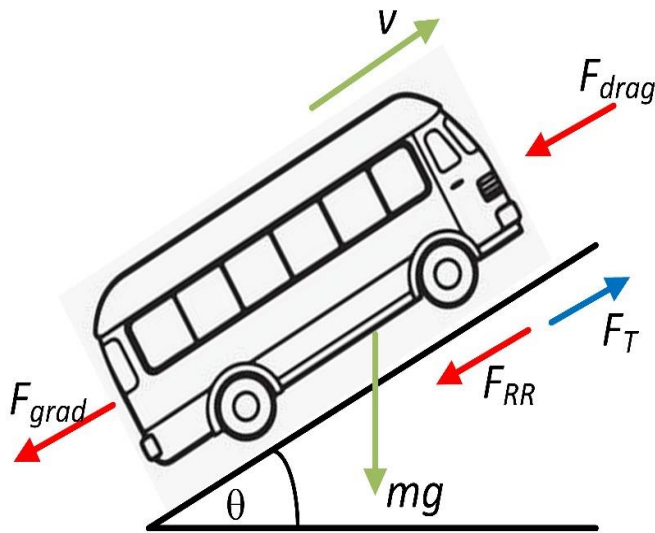


Fig. 1 Free body diagram of bus vehicle movement.

2.1.1 Tractive effort

The tire-road interface generates tractive force or effort. This occurs when the torque from the traction motor causes the wheel to slip at the point of contact area of the wheel axis. It signifies that if the applied force (F_T) is less than the maximum force (F_{max}), the wheel will experience slipping rather than rotating. Tractive forces are exerted on the bus vehicle to propel it forward. The electric motor or diesel engine is the propulsion system responsible for generating traction forces in electric and diesel vehicles, respectively. The diagram in Fig. 2 illustrates the traction forces generated by both an electric

traction motor and a diesel engine.^[22]

Diesel engines generally operate at elevated levels of torque and moderate velocities. A single gear significantly decreases the tractive force while maintaining a broad range of operating speeds. At every gear, it is evident that the tractive force varies in accordance with the speed of the vehicle. When the vehicle is in a lower gear, the greater tractive force results in enhanced acceleration. The irregular tractive force produced by the gears of a diesel engine can be observed in Fig. 2a. Traction motors for mid- and heavy-duty electric vehicles are frequently constructed using AC motors, which can be either permanent magnet synchronous or induction motors. One of the core features of electric motors is their capacity to generate torque at zero speed. Power electronic inverters are required to regulate the torque-speed properties of the traction motors. Fig. 2b illustrates the controlled characteristics of the electric traction motor's tractive effort. The tractive effort of the electric bus vehicle can be represented by equation (3).^[8]

$$F_T = \frac{\eta_T \tau_m \omega_m}{v} \tag{3}$$

where F_T is the tractive effort, τ_m is the torque produced by the traction motor, η_T is the overall power transmission system efficiency, v is the longitudinal speed of the bus vehicle, and ω_m is the rotational speed of the traction motor's shaft.

2.1.2 Vehicle resistance forces

The bus vehicle experiences opposition to its motion from resistance forces, also known as F_R . Resistance forces can be classified into three main types: gravity or gradient forces, denoted as F_{grad} , air resistance, also known as dynamic drag forces, denoted as F_{drag} , and frictional forces, also known as rolling resistance, denoted as F_{RR} . Rolling resistance refers to the resistance encountered by rotating components when in motion. The rolling resistance can be classified into two distinct categories: bearing torques, which refer to the friction between gear teeth, and the friction that occurs between brake pads. Equation (4) presents a mathematical depiction of the rolling resistance.

$$F_{RR} = f_R W \approx (f_0 + f_1 v) W \tag{4}$$

where f_R is the rolling resistance coefficient, W is the wheel or

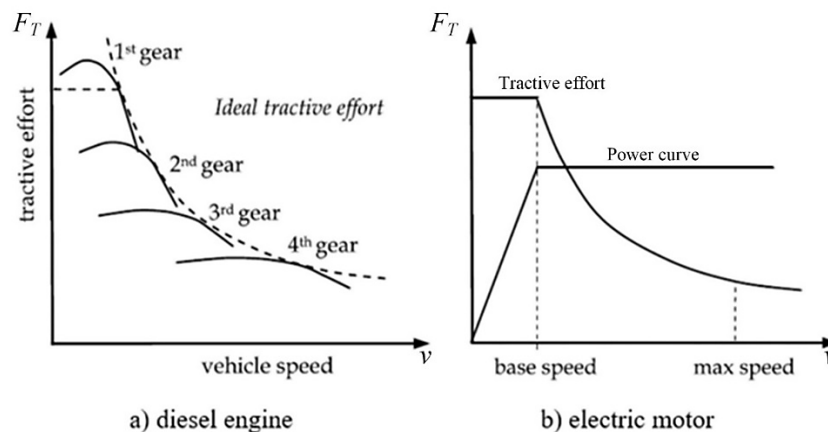


Fig. 2 Tractive effort of a bus vehicle.

axle load, $f_{\theta} = 0.005 - 0.010$ (buses and trucks traveling on concrete or asphalt roads), f_{θ} and f_i are two constants (for simplification, f_i is neglected).

2.1.3 Aerodynamic drag forces

The aerodynamic force that the air exerts when a vehicle is moving affects its velocity. The force of aerodynamic resistance is produced by, i) The pressure differential between the bus's front and back, which results from airflow splitting and creating a vortex behind the vehicle, ii) The amount of roughness on the vehicle's body surface is referred to as skin friction., iii) The movement of air entering the car's interior is referred to as internal airflow. Equation (5) represents the fundamental form of the aerodynamic resistance force.^[8]

$$F_{drag} = \frac{1}{2}\rho_{air}C_dA_Fv_{air}^2 \quad (5)$$

where A_F is the projected frontal area of the moving vehicle, C_d is an aerodynamic drag coefficient, ρ_{air} is air density (kg/m^3), and v_{air} is the speed of air relative to the moving vehicle body

2.1.4 Gradient forces

The gravitational force opposes the motion of a vehicle, regardless of whether it is moving uphill or downhill. For motions that are ascending or descending, there are favorable and unfavorable indicators, respectively. The gravitational force is a continuous force as long as the slope remains constant. Equation (6) presents a mathematical depiction of the gradient force.^[8]

$$F_{grad} = \pm M_{eff}g \sin \theta \quad (6)$$

where M_{eff} is the vehicle's effective mass (kg), θ is the slope angle, and g is the gravitational constant (9.81 m/s^2).

2.1.5 Newton's equation of motion

The relationship between velocity and time becomes apparent when traveling in a linear path with a constant acceleration. Constant acceleration refers to a steady and uninterrupted alteration in velocity. Greater acceleration results in a larger magnitude of velocity change. The velocity's rate of change is directly proportional to the duration of time during which the acceleration remains constant. The final velocity of an object would be equal to its initial velocity plus any adjustment, if applicable. Among the three options, the formal derivation of this equation is the most direct and uncomplicated. By considering acceleration as the rate of change of velocity, we establish the relationship between velocity and time. Equation (7) defines the correlation between velocity and time.^[8] The displacement of a moving object is inversely proportional to the product of its speed and time. This type of problem becomes increasingly difficult when acceleration is taken into account. Displacement exhibits a direct correlation with both time and velocity, whereas time exhibits a direct correlation solely with velocity. The relationship between displacement and time is a quadratic function, meaning that displacement is directly proportional to the square of time. This relationship is

due to the combined effect of time. Equation (8) represents the correlation between displacement and time in the second motion equation.^[8] An additional equation is derived by merging the initial two equations (9).^[8] Hence, displacement is directly proportional to the square of velocity, while acceleration remains constant.

$$v(t + \Delta t) = v(t) + a\Delta t \quad (7)$$

$$x(t + \Delta t) = x(t) + v(t)\Delta t + \frac{1}{2}a(\Delta t)^2 \quad (8)$$

$$v(t + \Delta t)^2 = v(t)^2 + 2a\{x(t + \Delta t) - x(t)\} \quad (9)$$

where Δt is the time step, a is the acceleration rate of motion, $v(t)$ is the velocity or speed at time t , and $x(t)$ is the displacement at time t .

2.2 Hydrogen fuel-cell for electric bus vehicles

Fuel-cell bus vehicles will be a big part of public transportation's transition to an emissions-free economy in the near future. Such hybrid vehicles, which run on hydrogen instead of diesel and are emission-free, have the potential to completely transform the public transportation industry. Hydrogen fuel-cell vehicles use electric traction motors, batteries, and hybrid fuel cells. The fuel in question is hydrogen. The fuel cells convert hydrogen into electricity, and the batteries store this energy temporarily to run the traction motors in a dependable manner. By storing any excess energy for later use, the vehicle's brakes recharge the batteries, further enhancing fuel efficiency. To improve overall energy conversion efficiency, a water electrolysis module can also break down fuel-cell reaction by-product water using regenerative braking power as the module input. The parts of the hydrogen fuel-cell bus vehicles are displayed in Fig. 3. The primary fuel supplied from the storage tank is hydrogen. Hydrogen and oxygen gasses are combined in the fuel cell reaction to create energy and water as a by-product. Air pumps can be used to supply oxygen gasses. As illustrated in Fig. 4, the primary battery for the onboard energy buffer can store electric energy from the fuel cells. The amount of hydrogen used by heavy-duty fuel cell cars is shown in Refs. [23,24]. A hydrogen flow rate of 20 kg/h is needed to provide 300 kW of output electric power (see Fig. 5). These two quantities may have a linear or quadratic connection. The expression of (10) can be obtained by applying the linear function.

$$P_{fc} = 15 \times h_{in} \quad (10)$$

$$W = 9 \times h_{in} \quad (11)$$

where P_{fc} is the output power of the fuel-cell module in kW, h_{in} is the hydrogen flow rate in kg/h, and W is the water production rate of the fuel-cell module in kg/h. There are three primary categories of electrolysis technologies to take into account, each with unique benefits and drawbacks. 1) Alkaline Water Electrolysis (AWE or AEL): This well-known technique uses potassium hydroxide (KOH) or another aqueous alkaline solution as the electrolyte. Features include great efficiency, comparatively inexpensive investment costs, and good long-term stability. It is appropriate for industrial-scale applications. Usually, efficiency falls between 60% and

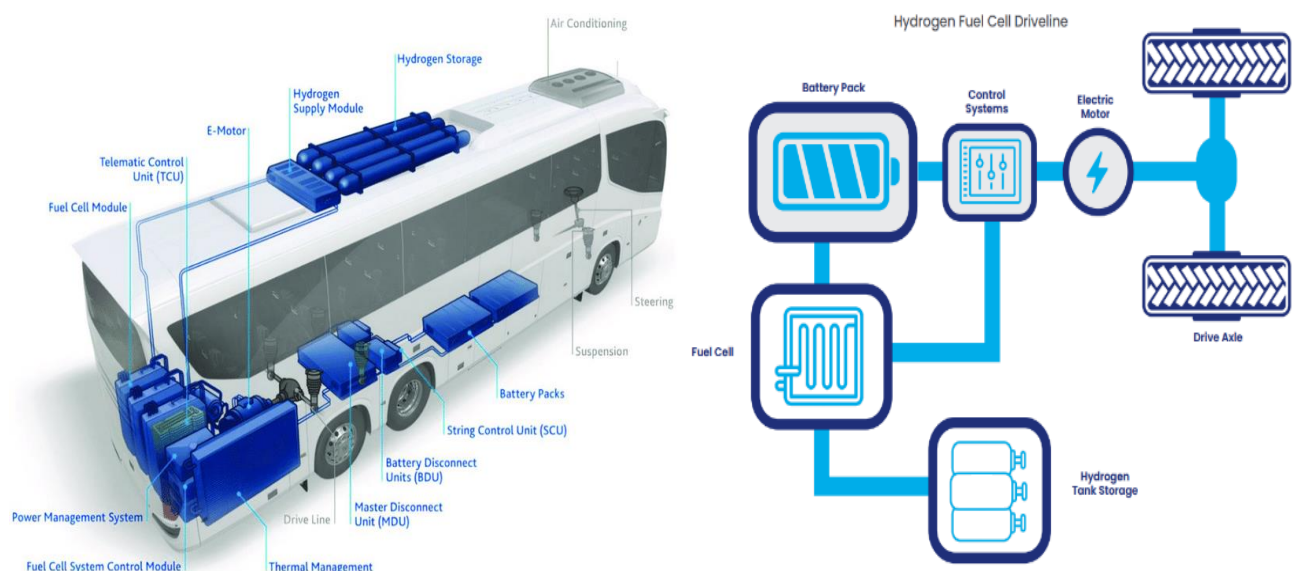


Fig. 3 Structure of a hydrogen fuel-cell bus vehicle.

80%. Although AEL is renowned for its affordability and longevity, it requires pure water and runs at lower current densities, necessitating a purification procedure. 2) PEM Electrolysis separates hydrogen and oxygen by passing only protons across a solid polymer electrolyte membrane. Uses a solid proton-conducting membrane that is acidic rather than a liquid electrolyte. The anode receives water and oxidizes it to produce hydrogen and oxygen protons. It functions at high pressures and low temperatures. Currently being scaled up for industrial applications, it is well-known for its excellent efficiency. It has a 70% to 85% efficiency rate. PEM electrolysis is appropriate for varying energy inputs due to its high efficiency and quick response time. However, because platinum-based catalysts and membranes are needed, the costs are higher. 3) A solid ceramic electrolyte, usually yttrium-stabilized zirconia, is used in Solid Oxide Electrolysis Cells (SOECs). It converts water vapor to hydrogen and oxygen ions at extremely high temperatures (500 °C to 1,000 °C). Because of the high operating temperatures, it often runs efficiently, although it is sensitive to temperature changes. For industrial applications, it is now in the demonstration stage. When waste heat is present, its efficiency can increase to 90%. Although SOEC is very efficient, maintaining the operating temperature necessitates a significant energy input. With issues relating to material deterioration over time, it is still mostly in the experimental stage. Additionally, the anode and cathode are separated by an anion exchange membrane in the Anion Exchange Membrane (AEM) Electrolysis. Water separates into hydrogen and hydroxide ions as it passes through the membrane. Although it is still in the research and development phase, it has the potential to be very efficient and current-dense. Under ideal circumstances, AEM electrolysis can reach efficiencies of up to 90%, while it usually reaches 60–70%. The cost-effectiveness of non-precious metal catalysts and environmental advantages are its primary advantages, yet it has drawbacks, such as lesser efficiency and durability

difficulties when compared to PEM electrolysis. Furthermore, it might generate less pure hydrogen and react to power changes more slowly. The efficiency of the water electrolysis depends on the applied voltage, electrode material, electrolyte type, operating temperature, and system pressure. PEM electrolysis, for instance, pairs well with renewable sources due to its adaptability to intermittent energy supplies, while SOEC can integrate industrial waste heat to boost efficiency. For Alkaline Electrolysis, it typically achieves efficiencies around 65-85%. PEM Electrolysis is a current commercial system that has efficiencies ranging from 65% to 77%, with ongoing research aiming to improve this. SOEC can achieve efficiencies up to 92% due to high operating temperatures. AEM Electrolysis’s efficiency data is still emerging as the technology is developing. Factors influencing hydrogen production rates consist of electrolyte concentration, temperature, pressure, electrode materials, and current density. The electrolyte concentration is higher, concentrations can improve conductivity and efficiency but may also increase corrosion rates. Higher temperatures generally increase reaction rates and efficiency, especially in SOEC systems. Elevated pressures can enhance hydrogen production rates but require more robust system designs. The choice of materials affects the efficiency and durability of the electrolyzer. For example, platinum and iridium are commonly used in PEM electrolyzers for their catalytic properties. Higher current densities can increase production rates but may also lead to higher energy consumption and reduced efficiency. Regenerative braking energy can be recovered and transformed into electric power. This electric power can then be utilized to either store the energy directly in the storage battery or power the onboard water electrolysis module, which creates hydrogen. These two choices are shown in Fig. 6. The primary focus of this paper is water electrolysis. The electrolysis module uses the regenerated braking power to break down the by-product water of the fuel cell and then

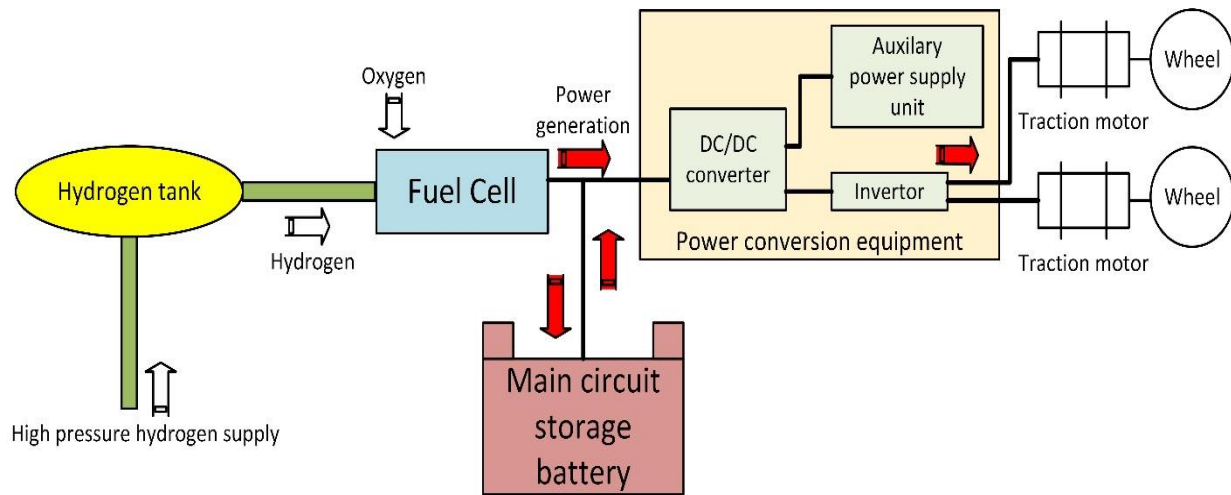


Fig. 4 Fuel cell working diagram for hydrogen bus vehicles.

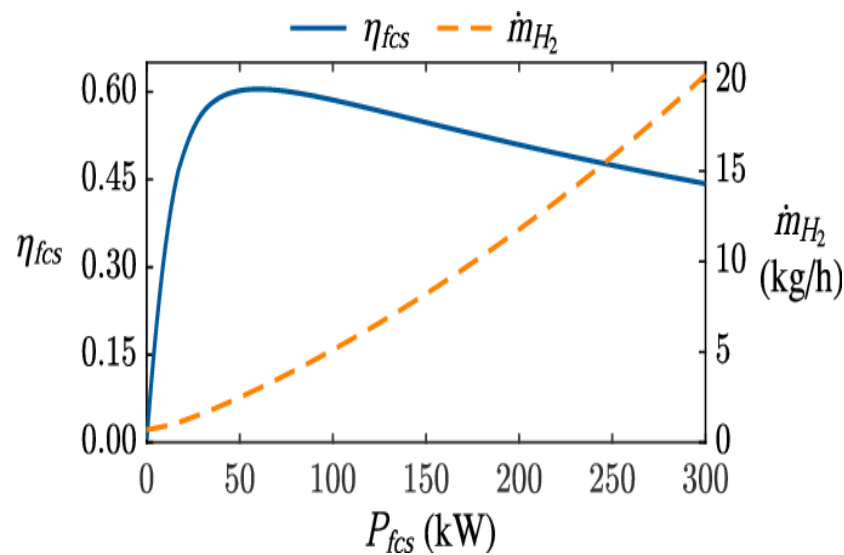


Fig. 5 Fuel cell hydrogen consumption vs output power.^[24]

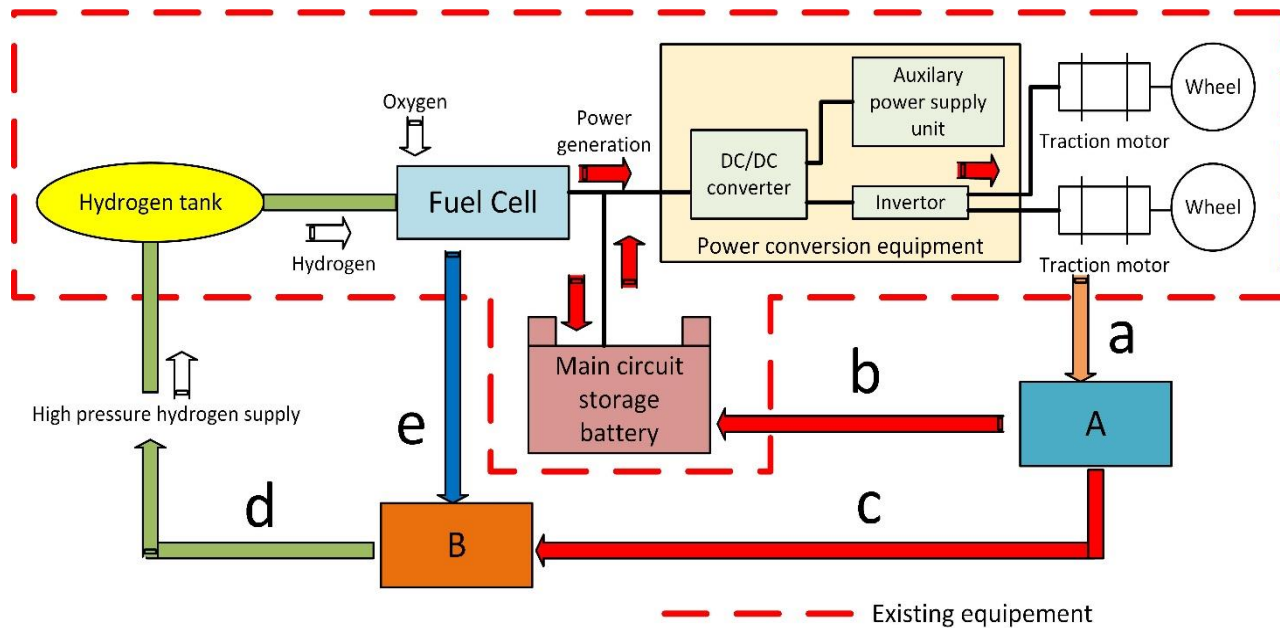


Fig. 6 Electrolysis module working diagram for hydrogen fuel-cell bus vehicles. A: Braking energy controller, B: Water electrolysis module, a: regenerative braking energy, b: battery charging energy c: electrolysis module input energy, d: produced hydrogen, e: fuel-cell's by-product water, f: refilling hydrogen.

create hydrogen. This procedure recycles unused water while also reducing fuel consumption. Fig. 7 illustrates the almost linear relationship between the rate of hydrogen production and the electrolysis's power input.^[25] 45 kW of input power is required to produce 1.7 Kg/h of hydrogen. Its linear expression for this relation is given in equation (12). Furthermore, equation (13) shows how much water is required to generate the same quantity of hydrogen as in equation (12).

$$h_{we} = 0.038 \times P_{in} \tag{12}$$

$$W_E = 0.342 \times P_{in} \tag{13}$$

where P_{in} is the input power of the electrolysis module in W or kW, h_{we} is the hydrogen production rate in g/h or kg/h, and W_E is the water used by the electrolysis cell in g/h or kg/h.

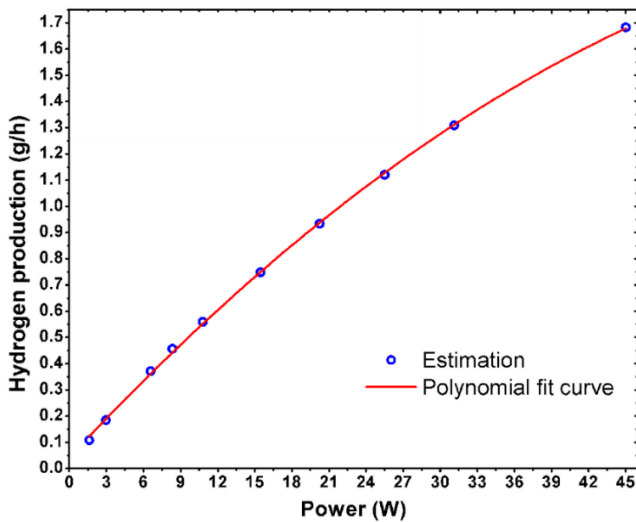


Fig. 7 Water electrolysis cell hydrogen production rate vs input power.

2.3 Simulation programming

This study entails the simulation of the motion of a bus vehicle. The power propulsion system is anticipated to comprise inverters, either battery or hydrogen fuel-cell systems, and traction motors. However, it disregards any complex depictions of this device. The battery buffer functions as an exemplary energy source. The efficiency of the on-board inverter and traction motors is generally advantageous for this specific application. Consequently, a comprehensive metric that encompasses all of these factors can be employed to define the overall power-conversion efficiency. Fig. 8 provides an overview of the structure of the simulation software. This analysis incorporates an already existing bus. It is widely believed that each bus under investigation is equipped with a GPS tracking device or a comparable alternative. To run this simulation, the data for road elevation and the vehicle's speed-time curves must be obtained through some means.

3. Results and discussion

The vehicle driving schedules and shift patterns for the chassis dynamometer, which are employed by the United States Environmental Protection Agency for assessing car emissions

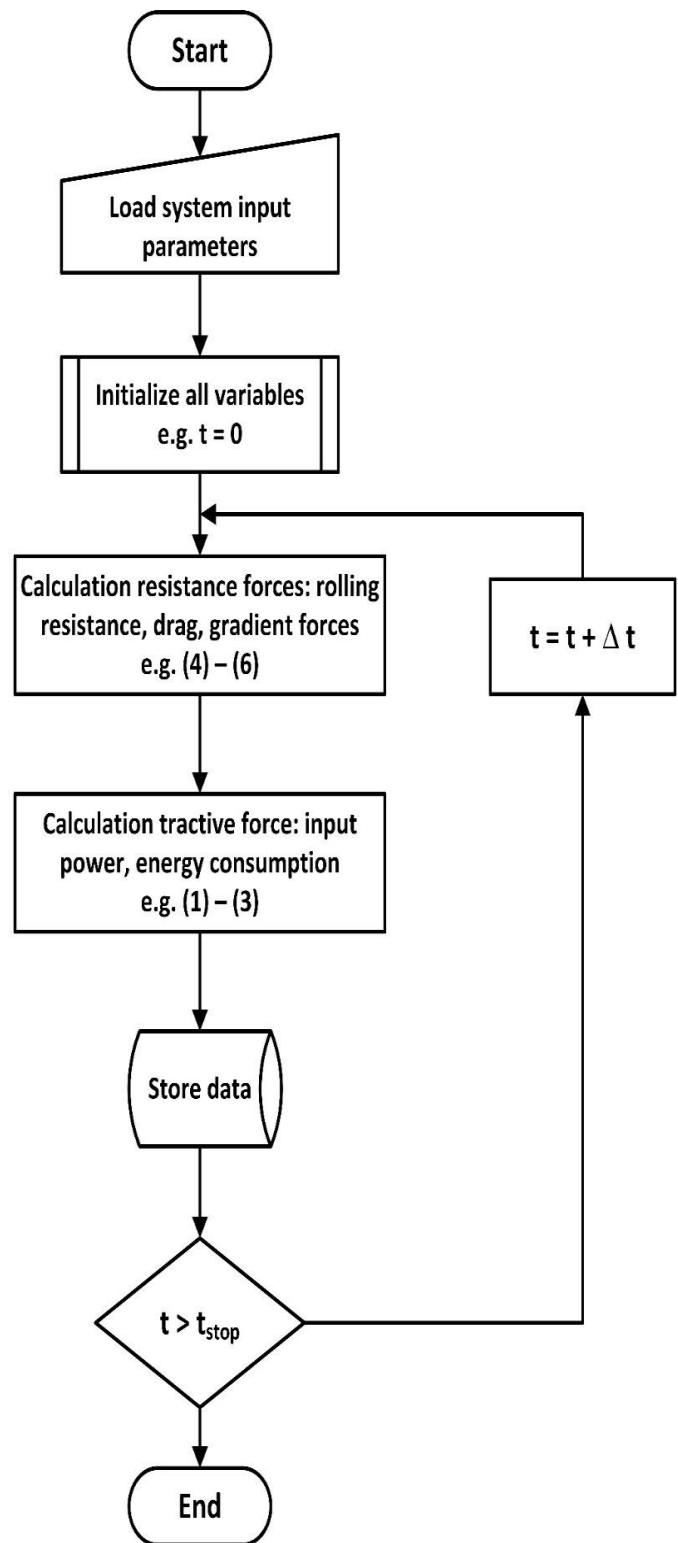


Fig. 8 Flow chart of the simulation program.

and fuel efficiency,^[26] have been selected for investigation. In order to conduct these tests, it is anticipated that the bus vehicle has an onboard hydrogen fuel cell engine. MATLAB software was utilized to conduct the test on an Intel(R) Core (TM) i7-1065G7 CPU running at 1.30GHz. This study employs seven driving schedules for testing purposes: 1. Fig. 9 shows the velocity pattern of the FTP-75 urban driving cycle (FTP-75). The EPA Urban Dynamometer Driving Schedule

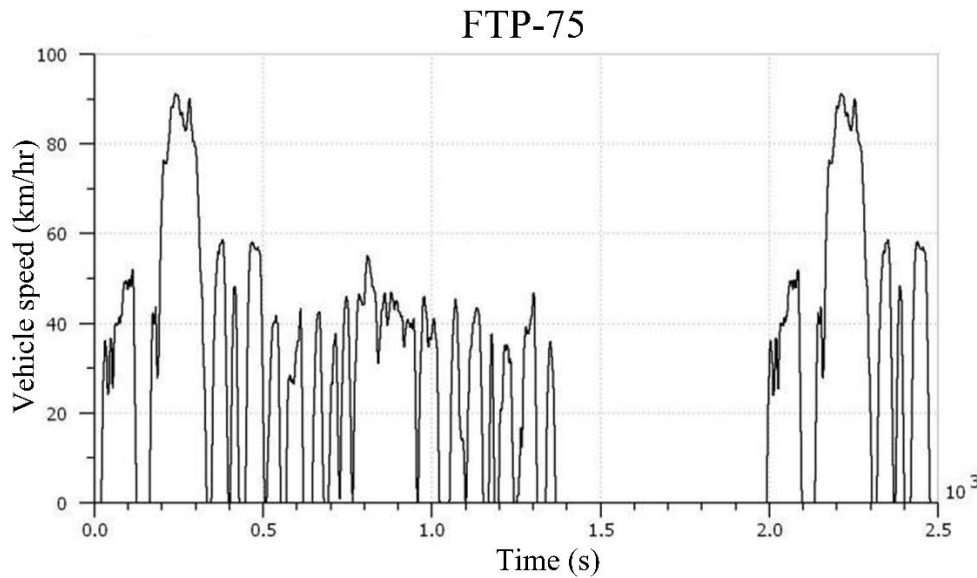


Fig. 9 FTP-75 speed-time profiles.

(UDDS) as in Fig. 10, also referred to as LA4, comprises the following driving schedules: The following driving schedules are used for testing fuel economy and emissions: 3. The Highway Fuel Economy Driving Schedule (HWFET) shown in Fig. 11; 4. The New York City Cycle (NYCC) as in Fig. 12; 5. The US06 Supplemental FTP driving schedule as in Fig. 13; 6. The SC03 Supplemental FTP driving schedule as in Fig. 14; and 7. The LA-92 for Class 3 Heavy-Duty Vehicles as in Fig. 15. The bus vehicle used for test has parameters as shown in Table 1.

The seven driving cycles are the chassis dynamometer, which are utilized herein for assessing vehicle fuel efficiency. A hydrogen fuel-cell bus vehicle equipped with traction motors and their controllers are employed for all seven driving cycles. The simulation conducted incorporating with the vehicle parameters as given in Table 1. All the running tests are operated with the regenerative braking to resume the

wasted braking energy. The energy saving is evaluated by using the reduction of hydrogen consumption. As a result, 19 – 20% of the hydrogen consumption for a trip can be reduced when the regenerative braking is applied to the water electrolysis module. Table 2 describes the test results obtained from the seven driving test cycles. All the braking energy was used to decompose by-product water into hydrogen gas. The average reduction in hydrogen fuel consumption considering all driving cycles was 19.74%.

Table 1. Parameters for a tested bus vehicle.

Parameters	Value
Tare mass (ton)	16.5
Frontal Area (m ²)	10.5
Vehicle drag coefficient	0.65
Rolling resistance coefficient, f_0	0.01

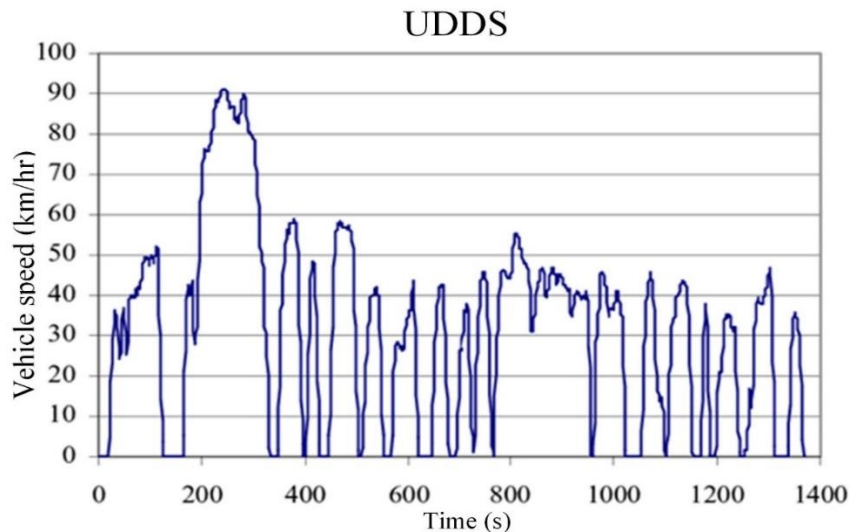


Fig. 10 UDDS or LA4 speed-time profiles.

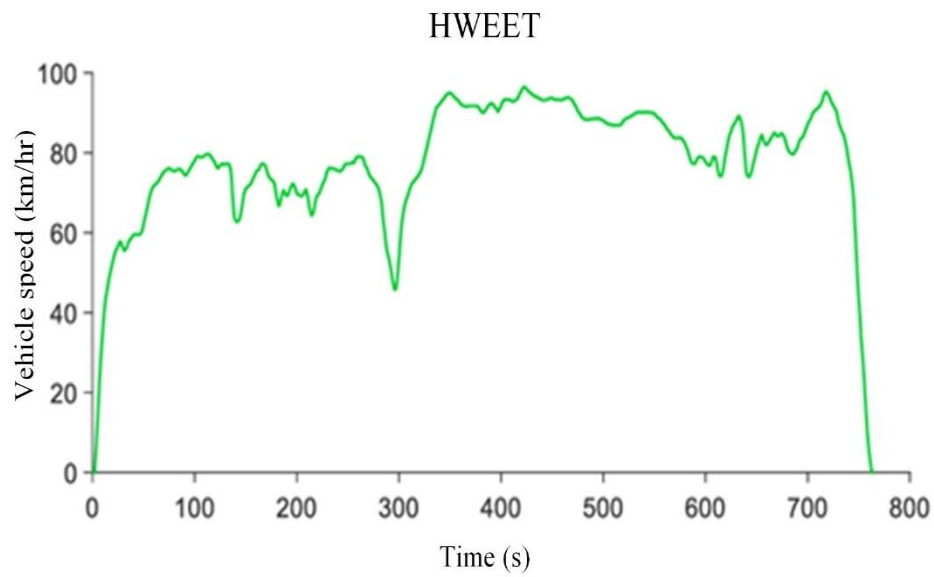


Fig. 11 HWEET speed-time profiles.

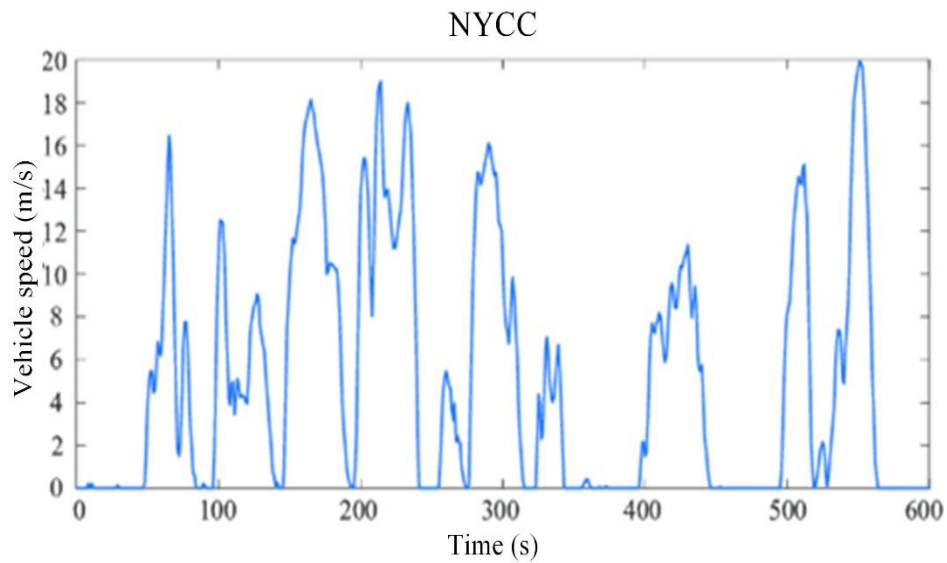


Fig. 12 NYCC speed-time profiles.

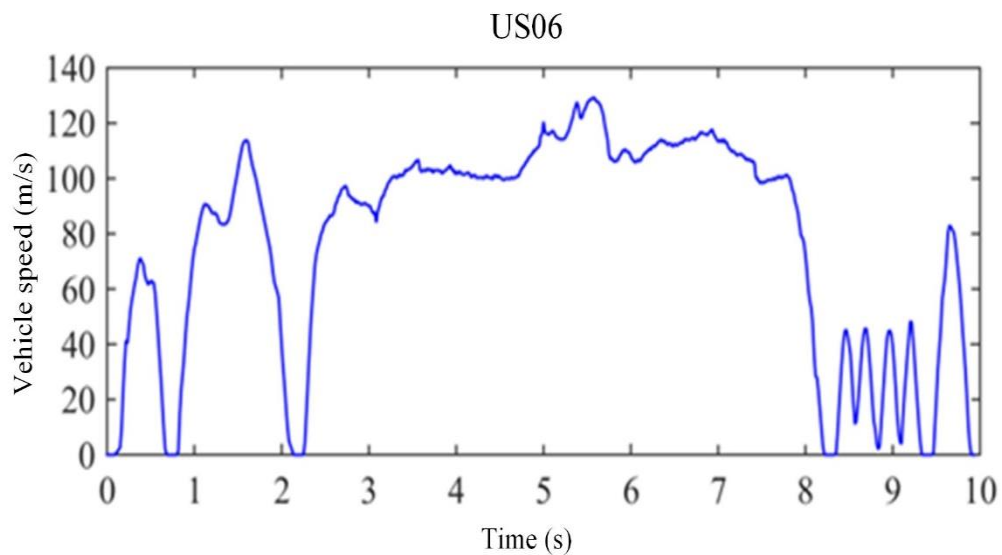


Fig. 13 US06 speed-time profiles.

Table 2. Results of a hydrogen fuel-cell vehicle test running.

Driving Cycle	FTP-75	UDDS	HWEET	NYCC	US06	SC03	LA-92
Hydrogen consumption (kg)	2.0864	1.4245	2.4535	0.4074	1.745	1.745	2.5905
Water production (kg)	18.7779	12.8207	22.0814	3.6661	15.70	15.70	23.3144
Hydrogen production (kg)	0.39944	0.26784	0.46137	0.0766	0.372	0.372	0.51632
Water usage (kg)	3.5950	2.4106	4.1523	0.6897	3.350	3.350	4.6469
% Hydrogen reduction	19.1447	18.8023	18.8045	18.813	21.33	21.33	19.9313

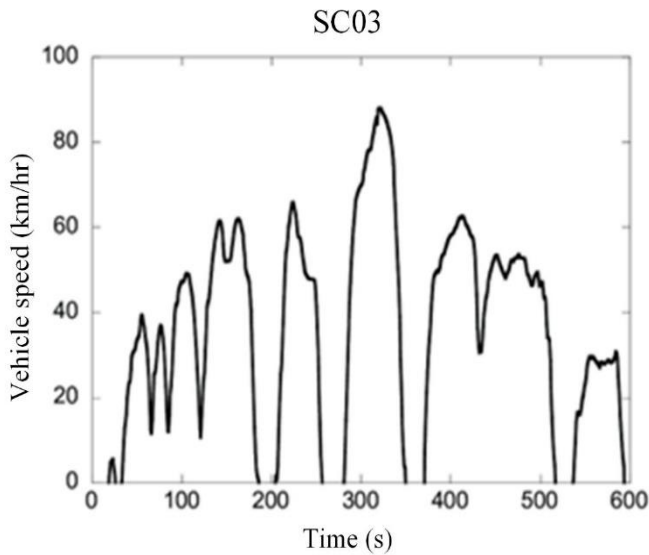


Fig. 14 SC03 speed-time profiles.

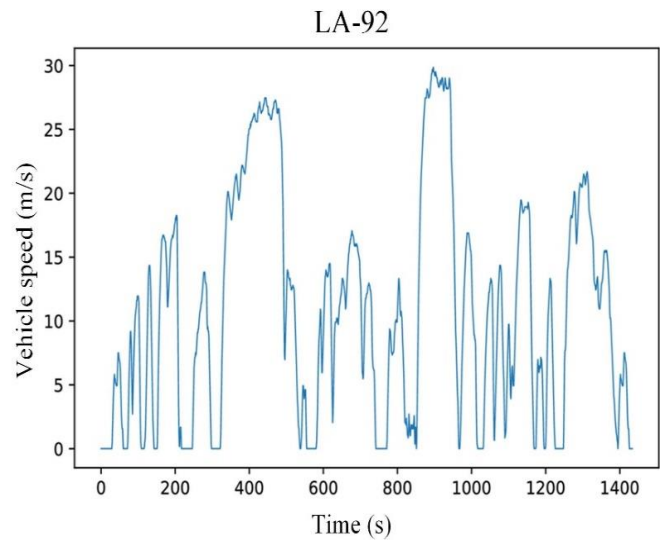


Fig. 15 LA-92 speed-time profiles.

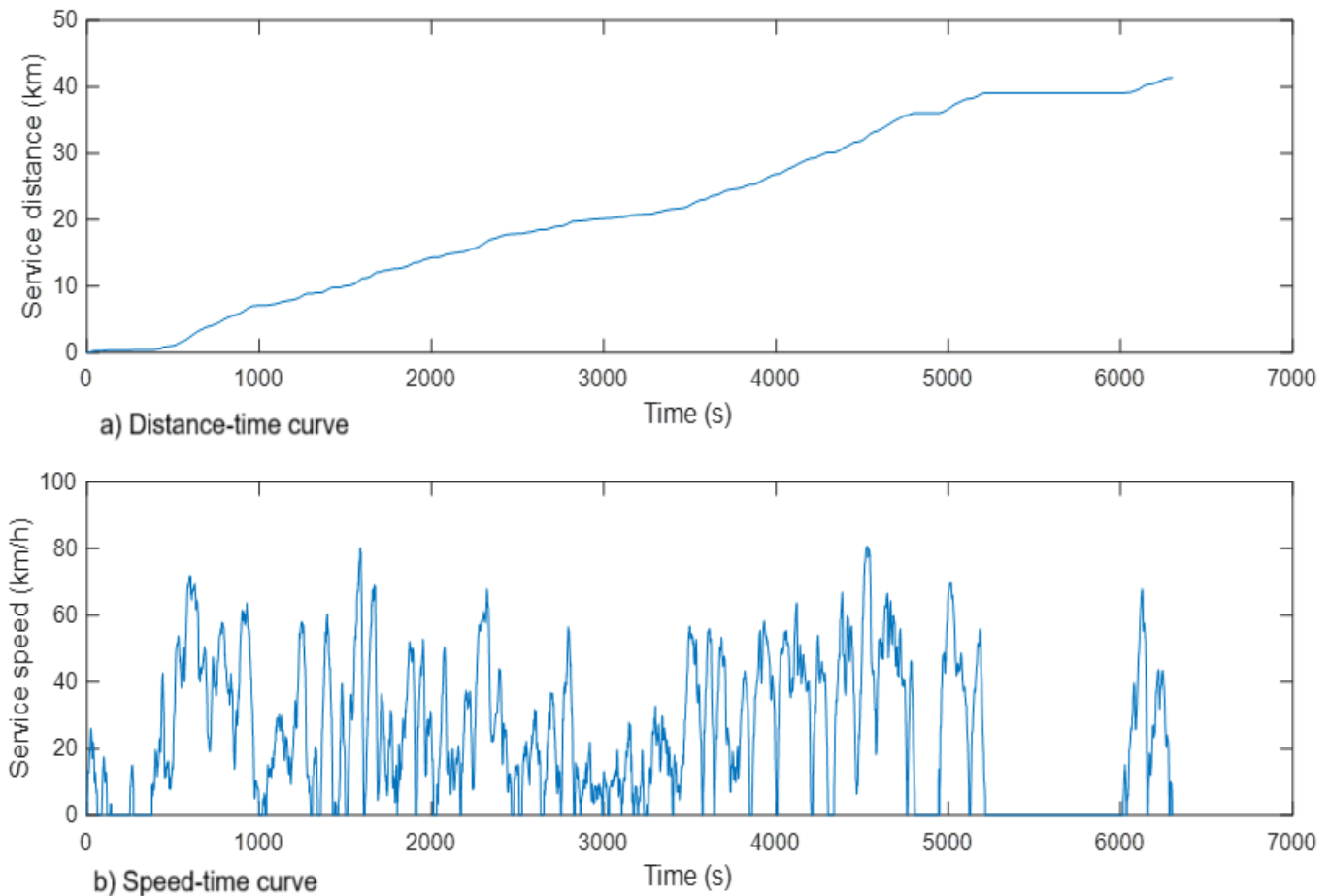


Fig. 16 SUT campus mini-bus service speed-time profiles.

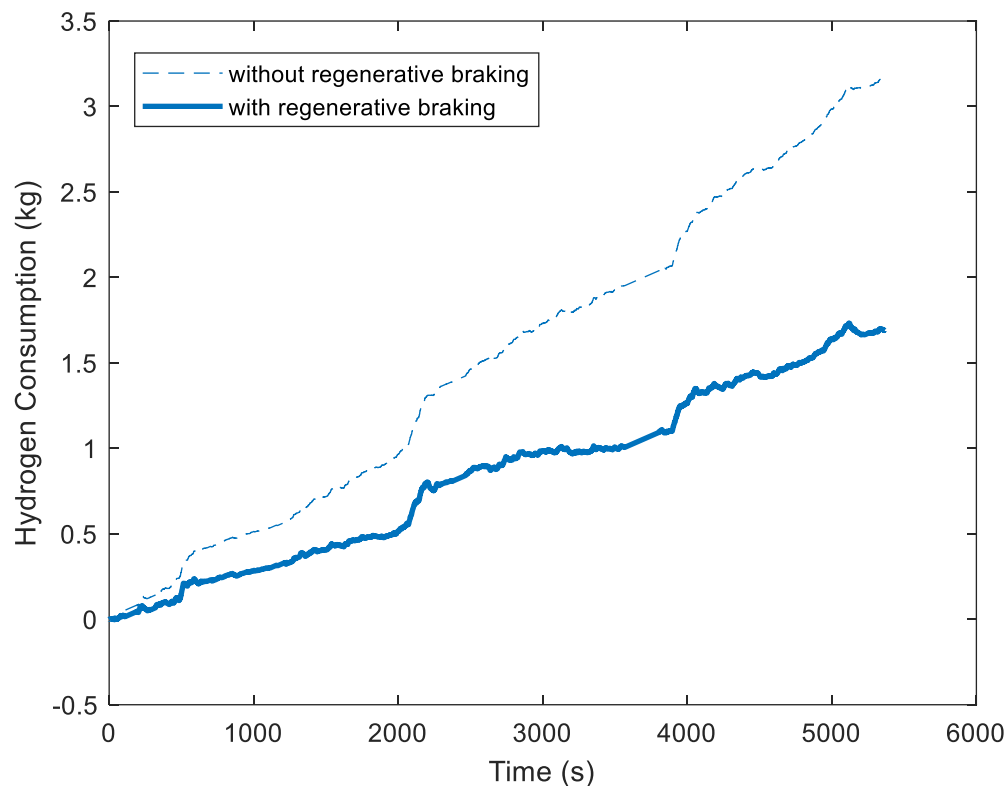


Fig. 17 Hydrogen consumption of the SUT campus mini-bus service.

In addition to the standard driving cycles, practical bus driving routes are also utilized. The initial driving route is a mini-bus service within the campus of SUT (Suranaree University of Technology, located in Nakhon Ratchasima, Thailand). The service covers a total distance of 25.054 km during its trial journey. Its service distance and speed profile acquired from a GPS module installed on-board the moving vehicle of a selected driving cycle are shown in Fig. 16. The hydrogen fuel consumption of the fuel-cell bus vehicle for this driving route is 3.1652 kg and produced 28.5237 kg of by-product water. During the vehicle braking, 13.277 kg of water is decomposed to generate 1.4752 kg of hydrogen. This hydrogen reproduction can help reduce the overall hydrogen usage for this driving trip around 46.61%. the reduction is considerably greater than the seven standard driving test cycles due to a driving's behavior of a driver. The SUT campus service bus vehicle takes more frequent braking implying that more braking energy can be utilized to the electrolysis module for hydrogen reproduction. The key factor that gives the most influence impact on the hydrogen fuel reduction is how frequent the braking is applied during the trip. High amounts of braking have the effect of reducing hydrogen fuel consumption. Fig. 17 illustrates how difference the hydrogen consumed during the trip. The hydrogen consumption (in kilos) and time (in seconds) for the two scenarios—with and without regenerative braking—are contrasted in this picture. Without regenerative braking, the dashed line shows a continuously increased rate of hydrogen consumption. The efficiency obtained from recovering energy during braking is highlighted by the solid line, which represents consumption with

regenerative braking and shows a reduced rate of hydrogen utilization. Overall, within the recorded time period, regenerative braking considerably lowers hydrogen usage. The use of regenerative braking reduces hydrogen consumption by approximately 36.4%, demonstrating its effectiveness in improving energy efficiency for the system.

4. Conclusions

This paper presents the use of regenerative braking energy for water electrolysis. The hydrogen produced by this process can be used to compensate for the amount of hydrogen fuel used, resulting in fuel savings. In addition, water from the electrolysis process can be reused to create hydrogen. The additional weight of the vehicle from the by-product water is also reduced significantly in addition to fuel savings. The main variable that has the biggest impact on the reduction of hydrogen fuel throughout a trip is how frequently the brakes are used. Significant braking has the effect of lowering the amount of hydrogen fuel used. From the seven standard driving test cycles, the maximum reduction of hydrogen fuel consumption is at 21.33%. In the SUT campus bus service where the driver's behavior in stepping on the brakes was quite harsh. This allows the use of braking energy to reproduce hydrogen, resulting in a reduction in hydrogen use of up to 46.61%.

Acknowledgements

This research has received funding support from (i) Suranaree University of Technology (SUT) , (ii) the NSRF via the Program Management Unit for Human Resources &

Institutional Development, Research and Innovation (PMU-B) (grant number B13F660067) and (iii) King Mongkut's University of Technology Thonburi (KMUTT), Thailand Science Research and Innovation (TSRI), and National Science, Research and Innovation Fund (NSRF) Fiscal year 2023 Grant number FRB660073/0164.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

References

- [1] A. Lozanovski, N. Whitehouse, N. Ko, S. Whitehouse, Sustainability assessment of fuel cell buses in public transport, *Sustainability*, 2018, **10**, 1480, doi: 10.3390/su10051480.
- [2] G. J. Offer, D. Howey, M. Contestabile, R. Clague, N. P. Brandon, Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system, *Energy Policy*, 2010, **38**, 24-29, doi: 10.1016/j.enpol.2009.08.040.
- [3] A. Ajanovic, A. Glatt, R. Haas, Prospects and impediments for hydrogen fuel cell buses, *Energy*, 2021, **235**, 121340, doi: 10.1016/j.energy.2021.121340.
- [4] A. Estrada Poggio, J. Balest, A. Zubaryeva, W. Sparber, Monitored data and social perceptions analysis of battery electric and hydrogen fuelled buses in urban and suburban areas, *Journal of Energy Storage*, 2023, **72**, 108411, doi: 10.1016/j.est.2023.108411.
- [5] G. Leoutsakos, A. Deloukas, K. Sarris, I. Apostolopoulos, C. Mamaloukakis, D. Kyriazidis, A. Bensmann, R. Hanke-Rauschenbach, Metro traction power measurements sizing a hybrid energy storage system utilizing trains regenerative braking, *Journal of Energy Storage*, 2023, **57**, 106115, doi: 10.1016/j.est.2022.106115.
- [6] A. T. Hamada, M. F. Orhan, An overview of regenerative braking systems, *Journal of Energy Storage*, 2022, **52**, 105033, doi: 10.1016/j.est.2022.105033.
- [7] S. C. A. de Almeida, R. Kruczan, Effects of drivetrain hybridization on fuel economy, performance and costs of a fuel cell hybrid electric vehicle, *International Journal of Hydrogen Energy*, 2021, **46**, 39404-39414, doi: 10.1016/j.ijhydene.2021.09.144.
- [8] K. Mongkoldee, E. Sukjit, T. Kulworawanichpong, Optimal on-board energy buffer design for fuel-cell hybrid intercity vehicles, *Journal of Energy Storage*, 2022, **46**, 103820, doi: 10.1016/j.est.2021.103820.
- [9] J. Bamford, Aberdeen gets first fuel cell double-decker bus, order for Birmingham, *Fuel Cells Bulletin*, 2020, **2020**, 2, doi:10.1016.s1464-2859(20)30492-2.
- [10] M. Sayer, A. Ajanovic, and R. Haas, On the economics of a hydrogen bus fleet powered by a wind park—A case study for Austria, *International Journal of Hydrogen Energy*, 2022, **47**, 33153-33166, doi.org:10.1016/j.ijhydene.2022.07.195.
- [11] P. Thounthong, V. Chunkag, P. Sethakul, B. Davat, M. Hinaje, Comparative study of fuel-cell vehicle hybridization with battery or supercapacitor storage device, *IEEE Transactions on Vehicular Technology*, 2009, **58**, 3892-3904, doi: 10.1109/TVT.2009.2028571.
- [12] D. Feroldi, M. Serra, J. Riera, Design and analysis of fuel-cell hybrid systems oriented to automotive applications, *IEEE Transactions on Vehicular Technology*, 2009, **58**, 4720-4729, doi: 10.1109/TVT.2009.2027241.
- [13] Q. Li, T. Wang, S. Li, W. Chen, H. Liu, E. Breaz, F. Gao, Online extremum seeking-based optimized energy management strategy for hybrid electric tram considering fuel cell degradation, *Applied Energy*, 2021, **285**, 116505, doi: 10.1016/j.apenergy.2021.116505.
- [14] H. Kim, N. Hartmann, M. Zeller, R. Luise, T. Soyly, Comparative TCO analysis of battery electric and hydrogen fuel cell buses for public transport system in small to midsize cities, *Energies*, 2021, **14**, 4384, doi: 10.3390/en14144384.
- [15] R. Caponi, A. Monforti Ferrario, L. Del Zotto, E. Bocci, Hydrogen refueling stations and fuel cell buses four year operational analysis under real-world conditions, *International Journal of Hydrogen Energy*, 2023, **48**, 20957-20970, doi: 10.1016/j.ijhydene.2022.10.093.
- [16] A. Buttler, H. Spliethoff, Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: a review, *Renewable and Sustainable Energy Reviews*, 2018, **82**, 2440-2454, doi: 10.1016/j.rser.2017.09.003.
- [17] M. Carmo, D. L. Fritz, J. Mergel, D. Stolten, A comprehensive review on PEM water electrolysis, *International Journal of Hydrogen Energy*, 2013, **38**, 4901-4934, doi: 10.1016/j.ijhydene.2013.01.151.
- [18] S. D. Ebbesen, S. H. Jensen, A. Hauch, M. B. Mogensen, High temperature electrolysis in alkaline cells, solid proton conducting cells, and solid oxide cells, *Chemical Reviews*, 2014, **114**, 10697-10734, doi: 10.1021/cr5000865.
- [19] S. A. Grigoriev, V. I. Porembskiy, S. V. Korobtsev, V. N. Fateev, F. Auprêtre, P. Millet, High-pressure PEM water electrolysis and corresponding safety issues, *International Journal of Hydrogen Energy*, 2011, **36**, 2721-2728, doi: 10.1016/j.ijhydene.2010.03.058.
- [20] K. E. Ayers, E. B. Anderson, C. Capuano, B. Carter, L. Dalton, G. Hanlon, J. Manco, M. Niedzwiecki, Research advances towards low cost, high efficiency PEM electrolysis, *ECS Transactions*, 2010, **33**, 3-15, doi: 10.1149/1.3484496.
- [21] E. Fabbri, T. J. Schmidt, Oxygen evolution reaction—the enigma in water electrolysis, *ACS Catalysis*, 2018, **8**, 9765-9774, doi: 10.1021/acscatal.8b02712.
- [22] S. Punpaisarn, T. Kulworawanichpong, Development of electric bus transportation challenge in Thailand, *Interciencia Journal*, 2018, **43**, 145-161.
- [23] M. Ehsani, Y. Gao, A. Emadi, Modern electric, hybrid electric, and fuel cell vehicles - fundamentals, theory, and design, 2004.

- [24] A. Ferrara, S. Jakubek, C. Hametner, Energy management of heavy-duty fuel cell vehicles in real-world driving scenarios: robust design of strategies to maximize the hydrogen economy and system lifetime, *Energy Conversion and Management*, 2021, **232**, 113795, doi: 10.1016/j.enconman.2020.113795.
- [25] H. Tebibel, R. Medjebour, Comparative performance analysis of a grid connected PV system for hydrogen production using PEM water, methanol and hybrid sulfur electrolysis, *International Journal of Hydrogen Energy*, 2018, **43**, 3482-3498, doi: 10.1016/j.ijhydene.2017.12.084.
- [26] W. Pacura, K. Szramowiat-Sala, J. Gołaś, Emissions from Light-Duty Vehicles—From Statistics to Emission Regulations and Vehicle Testing in the European Union, *Energies*, 2023, **17**, 209, doi: 10.3390/en17010209.

Publisher's Note: Engineered Science Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits the use, sharing, adaptation, distribution and reproduction in any medium or format, as long as appropriate credit to the original author(s) and the source is given by providing a link to the Creative Commons licence and changes need to be indicated if there are any. The images or other third-party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

©The Author(s) 2025