A NOVEL CONCEPT OF HYBRID ELECTRIC PUBLIC BUS WITH POWER MANAGEMENT SYSTEM IN VIETNAM'S CONDITION

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ABSTRACT: Environmental concerns such as environmental pollution and unnatural climates are drawing the increasing interest of people around the world and being encountered by people in many different countries, especially in the transportation area. In response to this situation, the automotive manufacturing industry is conducting initial research focusing on environmentally friendly vehicles due to the policies and restrictions that are placed in each country. The public bus system is one of the most important solutions for commuting and community building in the inner city to diminish productive air waste of engines. This research implemented a supercapacitor-coupled internal combustion engine power management system in traditional vehicles to tackle the challenges created by output efficiency of existing Vietnam conventional buses. This allowed for the proportion of exhaust released into the environment to be evaluated in conditions that were not optimal, such as when temperature in surrounding area was low. With the use of AMESim platform, it was determined that there is a potential for actual vehicle application in Vietnam with a fuel economy of 33.10%.

KEYWORDS: *Hybrid Electric Vehicle; Energy Management; Real-Time Simulation; Emission Reduction.*

1.0 INTRODUCTION

1.1 Environmental problem and passenger bus market

Concerns over fuel depletion and global warming led to the introduction of limitations on greenhouse gases. In the United States, typical government rules such as the Air Pollution Control Act, the Clean Air Act, and the Clean Air Act Amendments in 1955, 1963, and 1990 respectively, regulate vehicle emissions. National and international accords limit greenhouse gas emissions. The recent Leaders' Summit on Climate in 2021 aims to reduce US greenhouse gas emissions by 50% by 2030 [1]. The 2030 goal for Japan is a 46% reduction from 2013 levels. China intends to reduce and eliminate coal use to achieve carbon neutrality by 2060. The Climate Law of the EU sets a reduction target of 55% between 1990 and 2030 [2-3]. Twelve states, led by California, participate in the ZEV credit in the United States. Through this regulation, manufacturers get credits depending on the electric range of a vehicle, while automobile manufacturers will be punished for exceeding regulations [4]. Companies with insufficient sales of eco-friendly automobiles struggle to increase sales and must pay a premium for credit from other manufacturers to make up the difference. By 2030, Korea should reduce average passenger vehicle emissions by 30% or improve fuel efficiency by 36% [5-6].

Up to 2017, forty partners presented the Zero Emission Urban Bus System project in eight European cities with 35 electric buses. It sought to develop the total electric and include unique electric bus options with different electric powertrain technologies (including next-to-battery electric vehicles - BEV also hybrids and electric trolleys with batteries - HEV). In 2020, the total bus stock was approximately 18 million units, including nearly 300,000 large transit buses [7]. As of May 2022, the total number of BEV and HEV buses in the European Union is 7,356 and 656 segments, respectively. By 2030, the overall bus fleet is projected to reach around 20 million units, including nearly 300,000 big transit buses in China, and South Korea is anticipated to have the most prominent bus inventories. The expansion of the worldwide electric bus market is propelled by introduction of autonomous and semi-autonomous transportation systems, as well as the expanding manufacturing of inexpensive secondary energy storage systems. The market share of battery-electric buses is anticipated to reach 95.3% by 2028. On the basis of the hybrid powertrain, the market for electric buses is divided into series-parallel hybrid, parallel hybrid, and series-hybrid segments. In 2020, parallel hybrid category dominated the electric bus market with

64,3% dominance and was anticipated to account for 63.6% of the market by 2028 [7-8].

Over the years, the amount of public bus lines in Hanoi has increased by a factor of three, going from 31 to 92 routes; the fleet of vehicle has increased by nearly 4.5 times and the number of passengers has increased by a factor of 28.5% [9]. The Vietnamese government has begun deploying electric buses in an effort to reduce the amount of pollution that is caused by vehicles as a response to the alarmingly high levels of pollution that have been measured in major cities such as Hanoi and Ho Chi Minh [10]. This is being done as a response to the fact that the levels of pollution that have been measured have reached dangerously high levels. It is anticipated that the growth of the electric bus market in Vietnam would be stimulated as a result of this action. During the timeframe of the projection, the market for electric buses in Vietnam is anticipated to expand due to the high demand for HEV brought about by favorable government policies encouraging the use of emission-free public transport in the country as well as continuous advancements in battery/ultracapacitor technology. Additionally, rapid urbanization, shifting oil prices, and declining energy storage system prices are encouraging the adoption of HEV across the country, which is positively affecting the growth of the HEV market in Vietnam. According to information that was made public the year before, Vin Bus anticipates operating somewhere between 150 and 200 electric buses in the cities of Hanoi, Ho Chi Minh City, and Phu Quoc, and the company expects a very large number of 3,000 electric buses for the market in Vietnam [11-12]. However, so far these statistics are still open about the exact numbers.

1.2 Related work

The comparison of the trip and daily average fuel consumption of transit buses are the primary emphases of the models, which are based on either actual or simulated data. Using portable emission monitoring equipment, researchers evaluated a variety of buses powered by hybrid diesel, natural gas, and conventional diesel in Beijing and Macao[13], and their findings revealed that hybrid diesel buses can reduce fuel usage by 18–29%. Few studies compared the fuel consumption of a hybrid electric passenger vehicle to that of an Internal Combustion Engine (ICE) vehicle with the same chassis under real-world driving conditions [14]. Wang and Rakha [15] created quadratic format models for calculating the amount of fuel used by diesel and hybrid buses. Buses in their research have the most efficient fuel consumption rate while traveling at cruising speeds of between 39 and 47 kilometers per hour on gradients ranging from 0 to 8% [15-16]. The gradient and load of the train both have an impact on the rate of fuel consumption. Thanks to the multi-objective battery SoH sensitive control strategy, the battery pack in research [17] was downsized by 35% with no influence on battery lifetime, while fuel consumption increased by 1.1%. The energy audit (equivalent consumption reduction technique) uses system-level coordinated control to simulate the multi-mode powertrain's mode scheduling. Computation results indicate coordinated control's influence on equivalent consumption reduction techniques in creating optimum operating schedules [18]. When determining UDDS driving cycle, researchers in [19] evolve a model predictive multi-objective management system for HEVs in vehicle-following circumstances to examine the interaction between fuel economy, vehicle exhaust emissions, and inter-vehicle safety by reducing fuel consumption by 10.49%, CO by 48.02%, HC by 55.38%, and NOx by 22.79%. The great majority of chemical energy that is not transformed into usable work is squandered as heat through hot exhaust gases and coolant [20]. Recovering engine excess heat may result in large advancements in engine performance and hence has the potential to advance engine technology significantly. The investigation of pollution emissions of electric, conventional, and hybrid automobiles operating on Poland's congested roads [21] depicts a strong overview of the gradual transition of vehicles to electrification and their benefits. Environmental problems in Hong Kong, and how new energy alternatives and cars contribute to the city's 2050 Carbon Neutral Plan. When conducting a case study in Hong Kong, the researchers offered valuable insights into the sustainability and environmental advantages of adopting electric vehicles, specifically PHEVs, in urban environments with critical concerns about air quality and transportation emissions, making its findings relevant and applicable to similar urban areas confronting comparable environmental challenges [22]. There have been a few studies that have focused on hybrid buses, but the majority of research has been done on diesel buses because advanced prediction methods, such as neural networks or support vector machines, have been used in the past to predict the fuel and emissions of diesel buses inspire of time-consuming [23]–[25]. To the best of our knowledge, no such statistics for evaluating automobiles in Vietnam conditions have been openly or publicly disclosed.

To complete the empty space, this study goes beyond the previously conducted research to design an optimal Energy Management Strategy

(EMS) and suggests a solution to a real-time EMS that previous studies have not solved. There are dual objectives within this study: Firstly, to develop an optimal EMS for a promise-type hybrid electric bus that integrates an ICE and an ultracapacitor pack, which enhances efficiency of hybrid bus by intelligently allocating power between the two energy sources that optimize performance. Secondly, evaluating a real-time adaptive EMS that dynamically responds to varying operational conditions in Vietnam, which considers traffic patterns, road terrain, and driving behavior to ensure efficient energy utilization and improved performance throughout the vehicle's operation. The AMESim software is utilized as a platform to simulate and calculate the performance of the hybrid electric bus system. This simulation assesses the proposed EMS's efficacy, specifically focusing on its ability to increase the ICE's operating efficiency, reduce fuel consumption, and mitigate CO, NOx, and HC emissions from the exhaust gases. This article is structured as follows: Section 2 describes the dynamic model, which is the basis of vehicle simulation, and explains the powertrain characteristics of the HEV and each part that composes the powertrain. Section 3 presents the powertrain structure of HEV and their working process, as well as the energy arrangement of each component for optimizing and improving fuel efficiency. The simulation results are performed and evaluated in Section 4. Section 5 presents the conclusions, presenting some fruitful models and future work.

2.0 HYBRID ELECTRIC BUS MODELLING

2.1 Vehicle Dynamic Model

Equations provide methods for calculating the total HEV tractive force. During the trajectory of the driving cycle, it is the accumulation of all of the different sorts of forces that are operating on the HEV [26], [27].

$$F_{Tractive} = F_{Rolling} + F_{GRF} + F_a + F_{ADR} \tag{1}$$

Substituting (1) with rolling resistance $F_{Rolling}$, grading resistance F_{GRF}, acceleration forces F_a and aerodynamic drag F_{ADR} as (2). In (2), C_R is rolling coefficient; W_{HEV} is total weight; θ means surface angle; a represents acceleration; v is HEV speed; ρ denotes air density, C_D is drag coefficient, and $Area_F$ is vehicle frontal area of the HEV.

$$F_{Tractive} = W_{HEV}C_R + W_{HEV}sin\theta + W_{HEV}a + \frac{1}{2}\rho v^2 C_D Area_F \qquad (2)$$

2.2 Internal Combustion Engine

The engine under consideration in HEV was a six-cylinder unit with a displacement of 10420cc and a capacity of 10.6 liters with idle speed at hot condition of 600rpm. The size of the rod was 142 millimeters, while the diameter and stroke of the engine were 110 millimeters and 135 millimeters, respectively. Some particulars of the engine are detailed in Table 1.

Table 1: Characteristics of ICE

Name	Dimension	Unit
Engine type	10.6L 6-cylinder	-
Displaced volume	10420	cc
Compression ratio	14.4:1	-
Bore × Stroke	110 × 135	mm×mm
Weight of the HEV	15000	kg
Rolling coefficient	0.007	-
Air density	1.226	kg/m^3
Drag coefficient	0.5	-
Vehicle frontal area	7.6	m^2

2.3 Ultra-Capacitor

The Ultra-Capacitor (UC) has the ability to discharge and charge large amounts of energy [28]. By adding UC to the current engine, this technology improves the efficiency of high energy usage. Because the efficiency of a battery is reduced during high-output charging and discharging, it is helpful to subsidize the high-output operating section with UC [29], [30]. Furthermore, unlike batteries, UC does not have a reduction in life-time due to charging and discharging; therefore, it may be utilized semi-permanently with no need for subsequent replacement. The SoC affects the voltage of UC in the same way as the battery does, and the output in the low condition of the SoC is significantly reduced. As a result, the UC SoC was set to 50÷100 %. The equivalent circuit formula of UC is as (3)-(7), where Q_{init}, $Q_{\max}$ denotes the initial and maximum charge [C], C_{UC} is rated capacitance [F]; $R_{UC,\mathrm{i}}$ is internal resistance of the UC. The characteristics of UC for referred HEV model are presented in Table 2. The SoC of UC can be calculated:

$$SoC_{UC} = \frac{Q_{init} - \int I_{UC}}{Q_{\max}} \qquad (3)$$

Open circuit voltage of UC:

$$V_{UC,OC} = \frac{Q_{init} - \int I_{UC}}{C_{UC}} \tag{4}$$

Terminal voltage of UC:

$$V_{UC} = V_{UC,OC} - I_{UC} R_{UC,\mathrm{i}} \tag{5}$$

Power of the UC:

$$P_{UC} = I_{UC} V_{UC} \tag{6}$$

Current of the UC:

$$I_{UC} = \frac{V_{UC,OC} \pm \sqrt{V_{UC,OC}^2 - 4\left(\mathrm{R}_{UC,i} + \frac{1}{C_{UC}}\right) P_{UC}}}{2\left(\mathrm{R}_{UC,i} + \frac{1}{C_{UC}}\right)} \tag{7}$$

Table 2: Characteristics of UC in HEV

Name	Dimension	Unit
Capacitance	315	F
Initial charge	36879	C
Maximum charge	39375	C
Voltage time constant	0.01	s

2.4 Drivetrain on Hybrid Electric Bus

The arrangement seen in Figure 1 is what is often referred to as a parallel hybrid drivetrain setup. The combination of two separate mechanical powers in a single mechanical coupler is the essential component of this design. The ICE is the most important power plant, while the energy bumper comprises the supercapacitor and the electric motor drive. Only the power plants, which consist of an ICE and an electric motor, are capable of controlling the flow of power [26]. The powertrain incorporates UC in combination with the existing ICE system, creating what is known as a Hybrid Energy Storage System (HESS). A powertrain can have high energy efficiency in a variety of driving circumstances if it is equipped with some different energy storage systems.

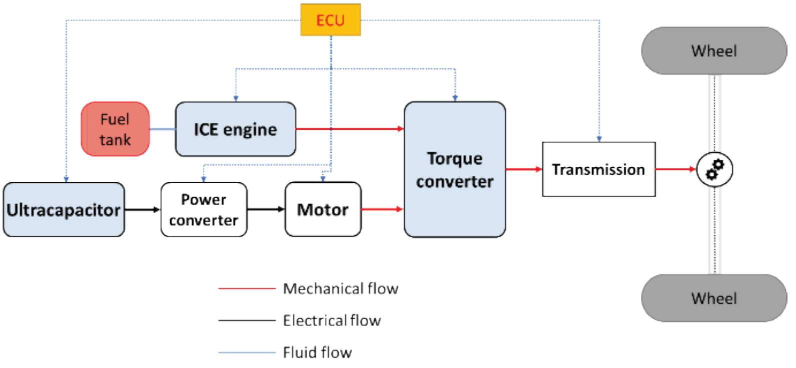

Figure 1: Construction of proposed HEV

When driving, the driver may dispatch traction or brake torque command to the vehicle Electric Controller Unit (ECU) through accelerator or brake pedals, as well as additional operational data, incorporating the ultracapacitor's SoC and vehicle velocity. Real-time information and ECU control logic are used to create reference signals that are sent to the engine throttle actuators, traction motor controllers, clutch, and lock actuators in order to regulate various vehicle systems which include the engine and traction motor.

This advanced configuration executed using the AMESim version 2020.1 software and computing on Intel i7-10750H CPU @ 2.6GHz 16Gb DDRAM, leading to reduced total fuel consumption, enhances the efficiency of the ICE in comparison to conventional counterparts and reducing CO, NOx and HC emissions in vehicle exhaust. In the meanwhile, along with ensuring the stability of the supercapacitor through the SoC characteristic within Vietnamese condition.

3.0 RESULTS AND DISCUSSION

In Figure 2, the dashed red line represents the comparison of the simulated road surface to the real circumstances in Hanoi. This is Vietnam's first ever bus-specific driving cycle, and it was developed exclusively for use on public transportation. For the purpose of determining the extent to which the simulated driving cycle effectively represented real-world driving patterns of 13.2% in order to adopt standard bus driving cycle in intra-city bus criteria, the speed-acceleration frequency distribution was utilized [31]. However, the instantaneous speed error value at this wheel is within the allowable limit, so the system's characteristics are still guaranteed with the requirements of the model.

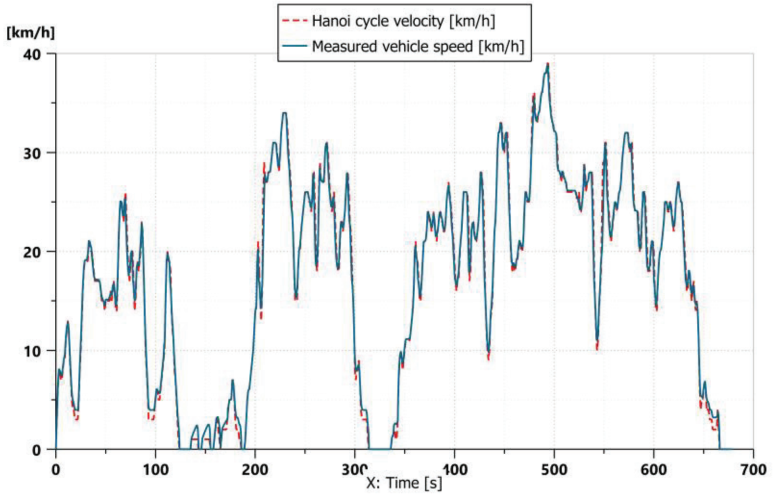

Figure 2: Hanoi driving cycle condition [31]

The connection between the amount of torque produced by the engine and the selected gear ratio are shown in Figure 3(a) and Figure 3(b), respectively, for the Hanoi driving situation. This study explores a transmission strategy that optimizes gear selection using an automatic control mode, considering engine speed, vehicle speed, engaged gear, and driver acceleration. Transitioning between strategies is challenging due to the unique parameter sets associated with each strategy. The strategy's main objective is to compute two values: the vehicle speed required for downshifting and upshifting. An initial gear ratio parameter allows for selecting a specific gear ratio at the simulation's outset, while a fixed delay of ΔT=0.5 seconds is imposed between consecutive gearshifts which suitable for clutchless-automatic–manual transmission [32-33]. When the engine speed falls below the first computed value, the control strategy seeks to engage the previous gear; conversely, when the engine speed exceeds the second calculated value, the strategy aims to engage the subsequent gear. The control strategy begins by establishing the proportion of the gearboxes at 3.3 and 3.4, respectively, as the starting gear ratio for the HEV type of bus and the traditional type of bus, respectively. The speed of the cycle can be seen to change as a result of the shifting gear ratios, and the control system makes extensive use of the gear ratio of the gearbox. This results in the gearbox rapidly reaching a higher gear or the greatest possible gear during the exponential growth phase in terms of making use of the driving torque in order to satisfy the speed demand while still meeting the goal of fuel economy. On the other hand, when it comes to the HEV model, the engine contributes positively to the total tractive effort and torque that the vehicle has. The importance of the aforementioned two components cannot be overstated when it comes to enhancing the transmission shift strategy.

Figures 3(c) and 3(d) illustrate the temporal responses of the electric motor torque and UC SoC in the HEV model throughout a range of 200-450 seconds of simulation time. Figure 3(c) presents the traction distribution of ICEs and electric motors for vehicles operating at different speeds. The conventional ICE only provides positive traction to the vehicle, with occasional negative drag during engine braking when the vehicle slows down, resulting in wasted brake energy. To address this, the proposed model incorporates an additional electric motor in powertrain. This electric motor serves dual roles: generating traction to the tractive wheels during acceleration, maintaining a stable speed, and regenerating energy during deceleration (electric motor braking). Figure 3(d) demonstrates the stable state of the energy supply and storage system, with the UC's state of charge maintained within the 50-100% permissible limit. The supercapacitor charges from the regenerative energy produced by the electric motor during braking, as transmitted through the current/voltage converter.

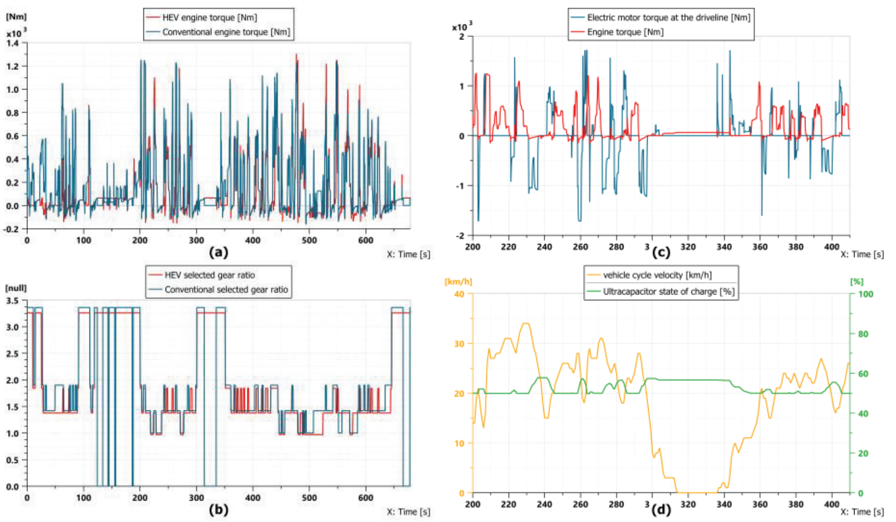

Figure 3: Comparison of: (a) Engine torque; (b) Selected gear ratio; (c) Electric motor torque; (d) UC SoC

With the proposed model, the supply of usable traction power to the passenger vehicle's transmission is divided between the engine and the traction motor, as shown in Figure 4. The vehicle's ability to pull a trailer or other trailered load has been dramatically increased as a result of the installation of a supercapacitor on the vehicle. This decreases stress being placed only onto the ICE when opposed to the traditional concept. Not only that but moving a vehicle at the speed of driving conditions in Hanoi usually involves a quick deceleration, which means that the vehicle has to be able to handle the braking process at this time. With the conventional model, this braking energy is not used until, otherwise, at this time, the ICE is still emitted into the environment. As a result, the model suggests using a supercapacitor in conjunction with a motor that is able to recycle any surplus energy produced by HEV during braking as well as traction in order to charge the UC hence contributing to the increased driving range of vehicle.

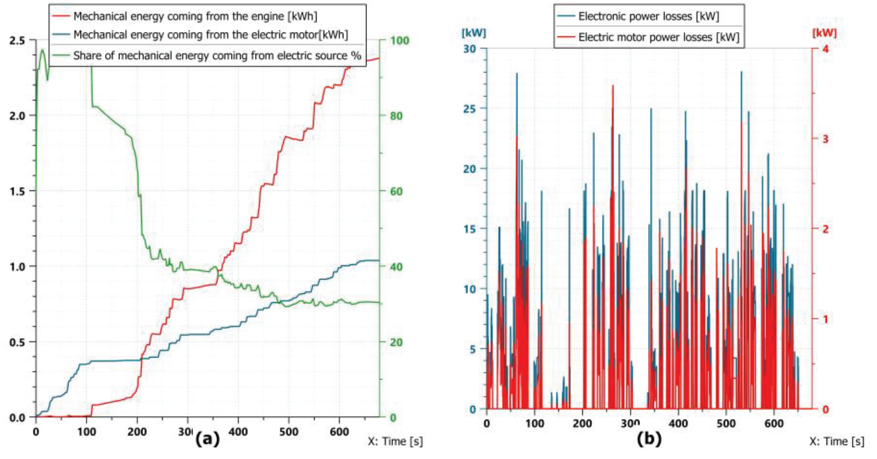

Figure 4: (a) Energy distribution from powertrain; (b) Power electronics and electric motor losses in HEV

Figure 4(a) presents the contribution of the two power sources in HEV and their proportion due to the time simulation. The HEV accelerated from 0 to 40km/h in first-50 seconds, and as a result, the share of mechanical energy rapidly cached up to 100%. It means that the motor plays an influential role in the acceleration stage, which demands high power in a short time. As explained in the velocity graph of Figure 2 above, the time delay phenomenon is the leading cause of the discrepancy between the theoretically calculated power amount and the direct measurement of the system's output. Meanwhile, the power converter, which converts the voltage for the supercapacitor and the traction motor, which transforms the pulling torque for the powertrain, requires a small amount of energy with the advent of the auxiliary for cooling and lubrication systems. These energy losses are illustrated in Figure 4(b).

The fuel economy of the proposed model is shown visually in Figure 5. Here, the red lines represent the total amount of fuel consumed by the engine during the simulation. In addition, the green line depicts the model's average fuel consumption over a distance of 100km. In the integrated resulting image, the dashed line represents the HEV model, while the solid line represents the traditional model. With the proposed model, the fuel consumption is significantly reduced in the simulated distance with a number of 31.10%, showing its superiority and suitability to meet Asian's ambition of reducing vehicle emissions, particularly in Vietnam in the 2030s [12]. At the optimum period, the traditional model consumes 36.15L/100km while the HEV model requires only 13.53L/100km. With this criterion, the model achieves an impressive result at the 87th second of simulation process with 11.26L/100km. Figure 5(b) displays the efficiency of the ICE in the two models. It can be clearly seen that the proposal HEV has an effect on the engine efficiency in the acceleration zone. Using UC has contributed to the instantaneous power supply when the towing motor requires high productivity for acceleration. Thanks to the superior characteristics of UC, the process of providing traction to the gearbox reduces latency while ensuring fuel economy for the vehicle. When the passenger vehicle runs at high speed, the efficiency of the ICE is also much higher than that of the traditional model, which signals that the engine life in the proposed model is more optimal.

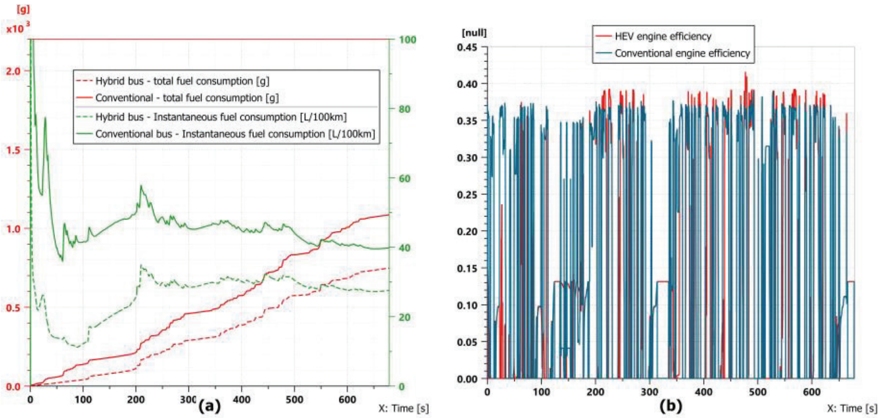

Figure 5: Comparison of: (a) Fuel consumption of the proposal models; (b) ICE operating efficiency

Figure 6 presents a comparison of the total emissions produced by the engine to those produced to environment based on four parameters according to amount of fuel consumption, including CO, NOx, HC, and soot. In general, each of these four metrics for ICE seen in HEVs is much lower than what is shown in conventional model. In particular, the decrease of NOx was the most successful, coming in at 33.39%, followed by the reduction of soot, which came in at 28.18% and is more outstanding than ones in [19]. CO emissions decreased by 24.71%, while HC emissions decreased by 80.71 grams, which is equivalent to a 2.23% decrease.

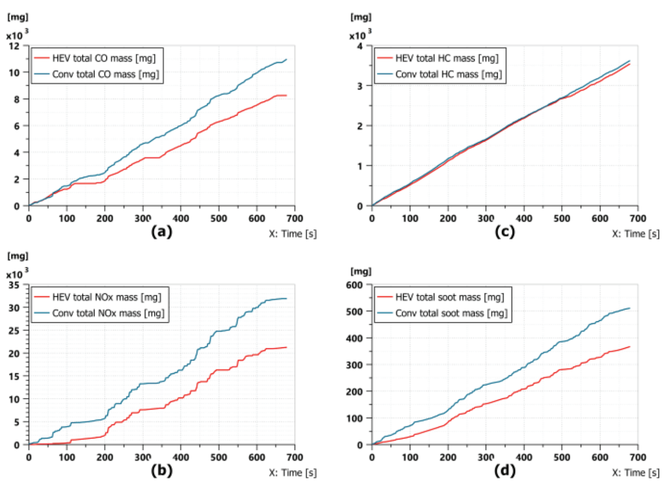

Figure 6: Comparison of the productive exhaust of engine due to simulation: (a) Total CO mass; (b) Total NOx mass; (c) Total HC mass; (d) Total soot mass

4.0 CONCLUSION

This study accomplished building a standard passenger bus which assessed under less-than-ideal circumstances, such as low ambient temperature and high air density, relevant to the driving conditions and driver behavior; specifically, the research was carried out for Vietnam. Utilizing a series hybrid electric bus model with UC enhanced the fuel economy of the traditional powertrain vehicle and tackled the limitations in real driving situations. Compared to the conventional model, the recently suggested one successfully achieved a 31.10% reduction in fuel consumption, and fuel efficiency has also been greatly improved, reaching 12L/100Km. In addition, a deliberate effort has been made to unload the possible proportion of backward products from engines, such as CO, NOx, and HC by 24.74%, 33.39%, and 2.23%, respectively, which are harmful to both the natural environment and human health not only in Vietnamese but also globalization. The design of this hybrid vehicle electric system between ICE and UC is a premise for developing other hybrid systems such as ICE-battery or ICE-battery-UC with advanced EMS. Besides, experimental models such as Hardware-in-loop simulation (HIL) or Software-in-loop simulation (SIL) need to be conducted, and further term would be validation on real vehicle models.

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AUTHOR CONTRIBUTIONS

Do Trong Tu: Conceptualization, Methodology, Software, Data Curation, Validation, Writing-Reviewing and Editing.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. The author declares no conflicts of interest concerning this research.

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