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Comparative study of fuel economy and emissions for plug-in hybrid electric Payang Water Taxi on different driving cycles using ADVISOR

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ABSTRACT

A new conceptual series-parallel plug-in hybrid vehicle for water transportation, known as the plug-in hybrid electric Payang Water Taxi (PHEPWT), is designed to improve vehicle fuel economy and significantly lower boat emissions. This article aims to analyze the fuel economy and emissions of PHEPWT, which are Hydrocarbons (HC), Carbon Monoxide (CO), and Nitrogen Oxides (NOx), with 6 driving cycles including Pulau Warisan river route, Kuala Terengganu river route, Kampung Laut river route, Seberang Takir river route, Pulau Kapas river route, and Tasik Kenyir river route. The analysis of the PHEPWT model will be compared with the existing powertrain architectures using water drive cycles by using the advanced vehicle simulator (ADVISOR). The results will be expected based on the fuel economy and emissions analysis that will show about 30–50% improvement in driving cycle for each driving cycle, and the fuel economy of the PHEPWT will indicate about 15-20% higher than that of the ADVISOR model. Also, for emission, the PHEPWT and ADVISOR models are based on the result of three-type emission such as HC, CO, and NOx, and show that the PHEPWT model has a lower emission compared to the ADVISOR model.

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1. INTRODUCTION

Fuel economy and emissions become the main concerns of civilization nowadays, as well as global warming and pollution, which have led many automotive manufacturers to produce vehicles utilizing alternative energies such as electric vehicles (EV), hybrid electric vehicles (HEV), and plug-in hybrid electric vehicles (PHEV) [1], [2]. Such vehicles are more fuel efficient and environmentally friendly without sacrificing the comfort and driving performance offered by Internal Combustion Engine (ICE) powered vehicles [3]. As the world moves towards a more sustainable and environmentally friendly energy source, understanding the importance of PHEV is essential [2]. PHEVs are becoming increasingly popular due to their ability to reduce fuel consumption and carbon dioxide emissions while also providing an affordable alternative to traditional petrol and diesel vehicles [4], [5].

PHEVs are a type of HEV that integrates an internal combustion engine, typically powered by gasoline or diesel, with an electric motor and a rechargeable battery pack. What sets PHEVs apart from conventional hybrid vehicles is their ability to recharge the battery from an external power source, usually the electrical grid [6]. This feature enables PHEV to operate in electric-only mode for a certain distance before the ICE is utilized. The electric motor, powered by the battery, works in tandem with the ICE to provide efficient and flexible powertrain options [7].

This paper begins by analyzing the power requirements of the plug-in hybrid electric Payang Water Taxi (PHEPWT) based on key vehicle parameters. Using vehicle dynamics equations, the required power for the boat is determined. The sizing of critical components, including the electric machine (EM), energy storage system (ESS), and ICE, is conducted based on these power requirements [8], [9]. The selected components are then evaluated using a water-based driving cycle [10]. The accuracy of the developed model is validated by comparing its results with simulations from the advanced vehicle simulator (ADVISOR) under standard driving cycles [11]. Additionally, the PHEPWT model estimates emissions, including hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx), across six different driving cycles [12].

2. METHOD

At the initial stage of this research, it is essential to identify and define the parameters of the PHEPWT in order to determine appropriate sizing for its powertrain components. Using vehicle power requirements under steady-state velocity conditions, the sizing of key components (EM, ESS, and ICE) is carried out [13]. These components are then evaluated and compared using a representative water-based driving cycle to ensure optimal performance [14].

The research methodology centers on the systematic development of a simulation model for the PHEPWT, guided by the defined parameters. This model is then used to analyze fuel economy and emission performance through the application of the ADVISOR [15]. The integration of ADVISOR enables a detailed assessment of the PHEPWT's operational efficiency and environmental impact under various driving conditions [16]. The overall methodology conducted throughout this study is as follows in Figure 1.

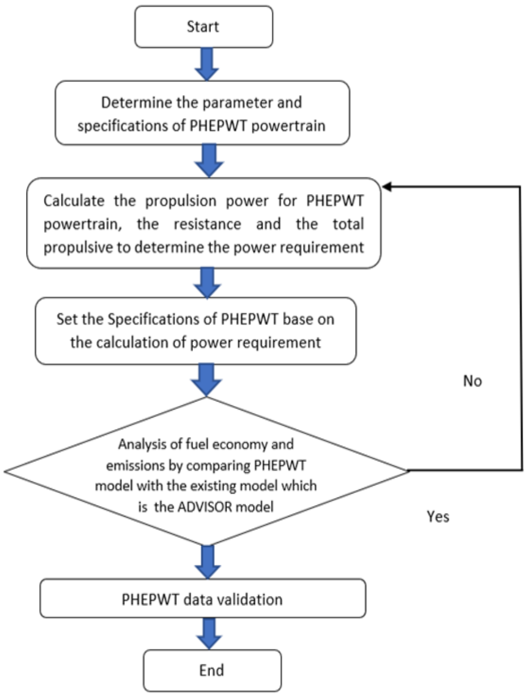


Figure 1. The research flow chart

2.1. Model development

Payang Water Taxi (PWT) service operating in Pulau Warisan, Kuala Terengganu involves the Pulau Warisan route using a recreational boat propelled by a dual petrol engine that can support about 40 passengers at a time [17]. The physical layout and design of the boat are crucial for understanding its dynamic performance and component sizing in the simulation model [18]. This boat was modelled into a new conceptual series-parallel plug-in hybrid vehicle for water transportation. The PHEPWT powertrain model is modelled in the MATLAB/Simulink environment based on the PHEPWT powertrain design requirement [19].

The parameters for the plug-in hybrid electric Payang Water Taxi (PHEPWT) have been collected and are presented in Table 1 to determine the power requirements of the vessel. These parameters, along with the specifications of each powertrain component, are used in a power flow analysis to identify suitable configurations for the EM, ESS, and ICE [20].

Table 1. PHEPWT parameters, specifications, and performance requirements

Parameter		Performance requirements	
Description	Dimension	Description	Dimension
Length between perpendicular, L_{PP}	12.2 m	Maximum Speed	50 kmh^{-1}
Length at waterline, L_{WL}	12.5 m	EV range	9000 m
Length overall, L_{OA}	13 m		
Breadth on waterline, B_{WL}	3 m		
Draught, D	0.46 m		
Density of water, $\boldsymbol{\rho}$	1026 kgm^{-3}		
Displacement, W	12080 kg		

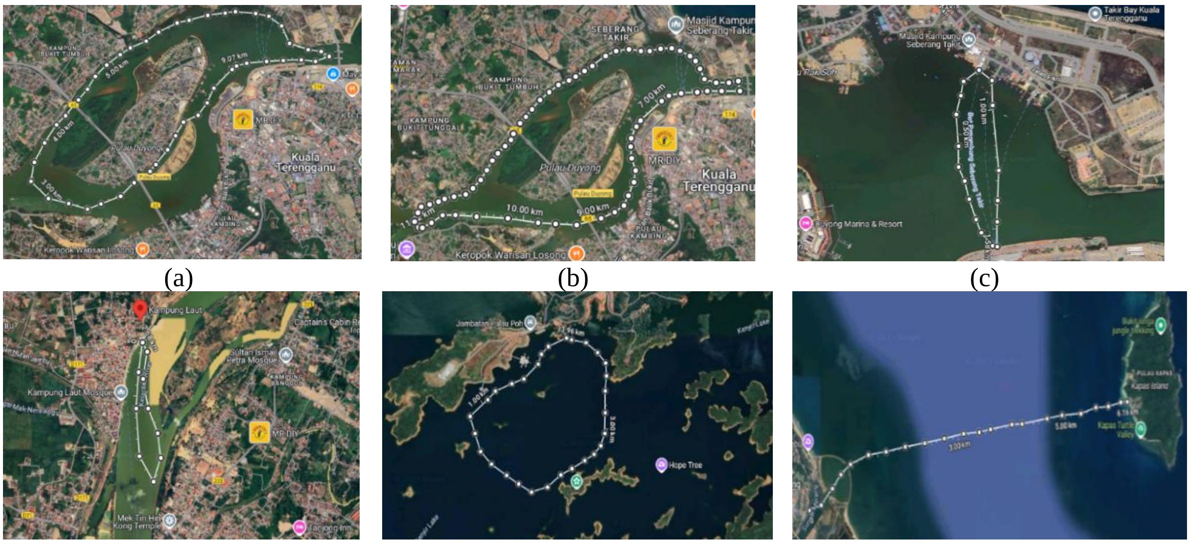
To ensure a realistic representation of actual operations, the PHEPWT driving cycles are developed to reflect these real-world conditions [21]. This enables a more accurate performance assessment of the PHEPWT model using the Advanced Vehicle Simulator (ADVISOR) [22]. Table 2 summarizes the six driving cycles developed for this study, each corresponding to a specific operational route. Figure 2 illustrates the actual routes used, derived from the driving cycle data outlined in Table 3. These driving cycles were generated based on empirical data collected from each route, capturing diverse travel and operational conditions [23]. The resulting driving cycles were implemented into the PHEPWT model within the MATLAB/Simulink environment using ADVISOR software, enabling detailed evaluation of fuel economy and emission performance [24].

Table 2. Driving cycle used and its abbreviation

Driving cycle	Route name
PW	Pulau Warisan route
KT	Kuala Terengganu route
ST	Seberang Takir route
KL	Kampung Laut route
TK	Tasik Kenyir route
PK	Pulau Kapas route

Table 3. The driving cycle parameter

Driving cycle	Duration (s)	Distance (km)
PW	1124	9.07 km
KT	2057	11.42 km
ST	787	1.58 km
KL	1360	2.68 km
TK	2293	3.96 km
PK	655	6.16 km



(a) (b) (c)

(d) (e) (f)

Figure 2. Real route for each driving cycle: (a) Pulau Warisan, (b) Kuala Terengganu, (c) Seberang Takir, (d) Kampung Laut, (e) Tasik Kenyir, and (f) Pulau Kapas

2.2. Calculation of parameters and specification for PHEPWT

The power requirements for the PHEPWT powertrain are determined by calculating the required propulsion power. In this process, it is essential to evaluate the resistance forces acting on the boat and accurately determine the overall propulsive efficiency. Since empirical methods are commonly used in these calculations, it is critical to understand the accuracy of each element involved to make a better estimation of the propulsion power and the uncertainty in the results [5]-[7]. Once all calculations are completed, the most suitable specifications for the ICE, EM, and ESS will be determined to achieve an optimal balance between performance and energy efficiency.

By using an equation that has been defined [5] to find the total resistance coefficient.

$$C_T = C_F + C_A + C_{AA} + C_R = \frac{R_T}{\frac{1}{2} p V^2 S} \quad (1)$$

Where C_F = frictional resistance, C_A = incremental resistance, C_{AA} = air resistance, C_R = residual resistance, and C_T = total resistance coefficient.

Value of wetted surface, S can be estimated with different methods and formulas exist based on only the boat's main dimensions.

$$S = 1.025 \times L_{pp}(C_B B + 1.7D) \quad (2)$$

The value of frictional resistance, C_F can be obtained by using (3).

$$C_F = \frac{0.075}{(log R_n - 2)^2} = \frac{R_F}{\frac{1}{2} p V^2 S} \quad (3)$$

The value of total resistance, $R_{TT,}$ can be defined as (4).

$$R_{TT} = \frac{1}{2} \rho C_T V^2 S \quad (4)$$

Total propulsive efficiency can be defined as (5).

$$\eta_T = \eta_H + \eta_O + \eta_R + \eta_S \quad (5)$$

Where η_H = hull efficiency, η_o = propeller in open water condition, η_R = relative rotative efficiency, and η_s = transmission efficiency.

The propulsion power PE, the effective power can be calculated using (6) [5]-[7].

$$P_E = R_T \times V \quad (6)$$

Where R_T = total resistance and V = boat velocity. Power requirement for propulsion can be estimated, P_P using (7).

$$P_p = P_E \times \eta_T \quad (7)$$

Where P_E = effective power and η_T = total propulsive efficiency. Figure 3 illustrates the power requirement of the PHEPWT at steady-state speeds. This relationship is crucial for determining appropriate component sizing and system optimization [25]. Based on the power requirement of PHEPWT for steady state, the main components such as EM, ESS, and ICE are selected.

2.2.1. Electric machine

The power requirement of the electric machine propulsion (P_{EM}) is determined by the maximum speed of the boat. The designed maximum speed is assumed to be 50 km/h (red circle). All calculations are undertaken with maximum mass. To achieve 50 km/h, the P_{EM} is:

$$P_{EM}(50 \text{ km/h}) = 14.78 \text{ kW} \quad (8)$$

If the speed requirement is relaxed, the motor size and cost can be reduced. To give an example, one could design the boat to run at a cruising speed of 35 km/h (as indicated by the red circle), which would still meet undertaking requirements, and you’d be able to use a smaller (cheaper) propulsion motor.

$$P_{EM,}\text{ continuous} = P_{EM}(40 \text{ km/h}) = 7.75 \text{ kW} \quad (9)$$

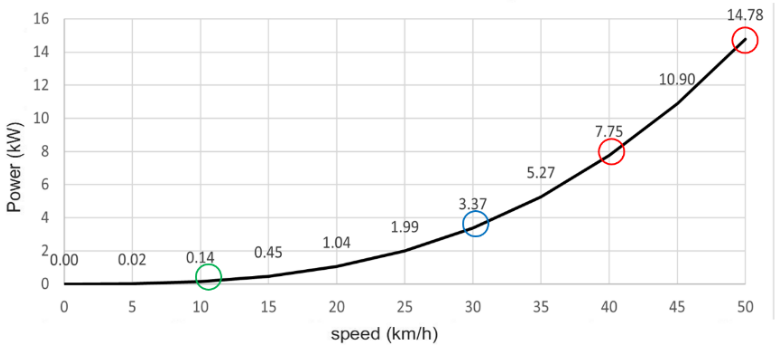


Figure 3. PHEPWT power requirement for steady state velocity

2.2.2. Energy storage system

There are two primary energy storage needs: maximum power and available energy. From Figure 3, the provided energy is expected to be enough for 10 km (green circle) in pure electric and driving mode. Its average velocity is of the order of 10 km/h, and for a simplified calculation, a speed of 10 km/h is assumed. This is because the average speed depends on a higher plateau speed behavior with a high number of starts and stops. The P_{EM} required to drive the boat at a speed of 10 km/h is as follows:

$$P_{EM}\,(10\ \text{km/h}) = 0.14\ \text{kW} \quad (10)$$

Based on the reading, the overall efficiency of the drivetrain is about 84.1 %. Assuming the overall efficiency of the drivetrain is 80%.

$$\text{Ess, min}\ (20\ \text{km} / 20\ \text{km/h}) \times (0.14\ \text{kW}/0.8) = 0.2\ \text{kWh} \quad (11)$$

The battery power (P_{ESS}) should be sufficient to boost the propulsion motor to its highest power. Maximum motor power is 1.5 times the continuous motor power.

$$P_{ESS,}\ \text{max} = 1.5 \times P_{EM,}\ \text{continuous} - P_{ICE,}\ \text{continuous}$$
$$1.5 \times 7.75\ \text{kW} - 7\ \text{kW} = 4.6\ \text{kW} \quad (12)$$

In order to achieve full performance, a maximum discharge of 3C (3 times the rated capacity) was assumed.

$$E_{ESS,}\ \text{max} = P_{ESS,}\ \text{max} / 3\text{xh} = 1.54\ \text{kW}$$

2.2.3. Internal combustion engine

The ICE demands are based on the average power demands for the series PHEPWT powertrain concept as shown in Figure 3. The maximum speed is assumed to determine the average power at optimal case, cruising at 30km/h (blue circle). The output power requirement for the ICE (P_{ICE}) is given by:

$$P_{ICE,}\ \text{continuous} = P_{EM}\,(30\ \text{km/h}) = 3.37\ \text{kW}$$

The electric output power is 4 kW, with an estimated efficiency of 85%. The mechanical input power has to be 7 kW. This is the minimum P_{ICE} requirement:

$$P_{ICE,}\ \text{continuous} = 7\ \text{kW}$$

Table 4 lists the estimated main components of the PHEPWT powertrain, which are EM, ICE, and ESS, based on each component's specifications and requirements during the sizing process. The value is estimated to be around 15 kW for ICE, 30 kW for EM, and 7 kW for ESS.

2.3. Advanced vehicle simulator (ADVISOR) software

Simulation tools are critical for the implementation and verification of these strategies ahead of real applications. Hence, in this section, the vehicle simulators that were used in the initial phase for the strategy development of vehicles are introduced. Effective and reliable software tools play a critical role in the optimization of vehicle structure and the verification of control strategies. The simulation tools that have been used for advanced hybrid electric powertrain research are ADVISOR [9].

ADVISOR, an abbreviation of Advanced Vehicle Simulator, was developed by the United States National Renewable Energy Laboratory. It was developed for the analysis of performance, fuel economy, and emissions of conventional, electric, hybrid electric, and fuel cell vehicles [12]. The specifications of the PHEPWT's ICE, EM, and ESS were first modelled and simulated in MATLAB/Simulink to verify the compatibility and performance of the system. These validated designs were then incorporated into the ADVISOR simulation tool for further optimized performance. Figure 4 illustrates the implementation of the PHEPWT configuration within the ADVISOR simulation environment. Based on the previously defined powertrain setup, the model was simulated to analyze system performance under realistic operating conditions. The ADVISOR platform was then used to compare the fuel consumption and emission performance between the PHEPWT model and the ADVISOR model.

Table 4. Selected component parameters and specification

Component	Specifications
ICE	15 kW @ 3000 rpm
	Compression-Ignition mode
EM	30 kW 3-phase motor
	Torque: 49 Nm
ESS	Lithium metal battery
	7 kW, 3 kWh

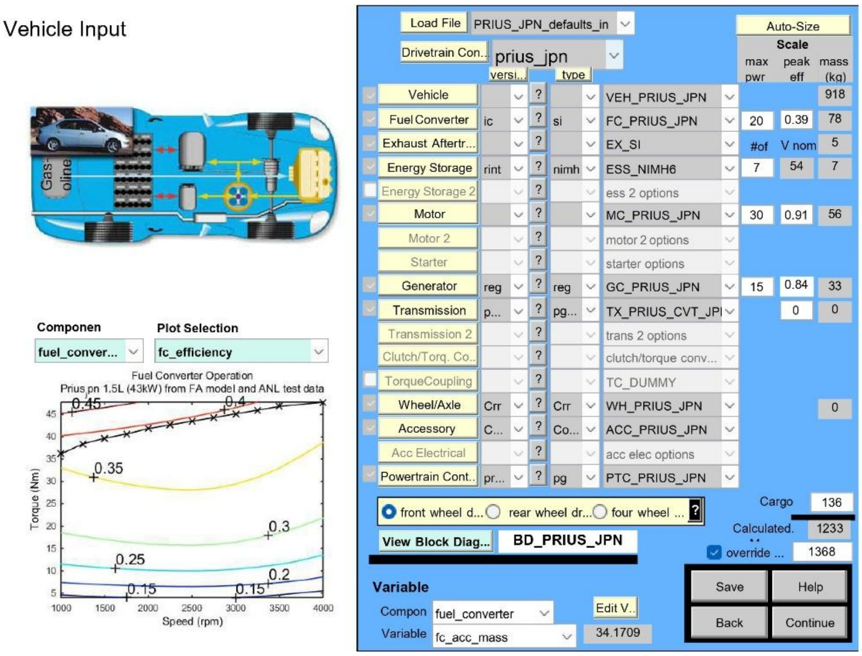


Figure 4. ADVISOR front display for PHEPWT configuration

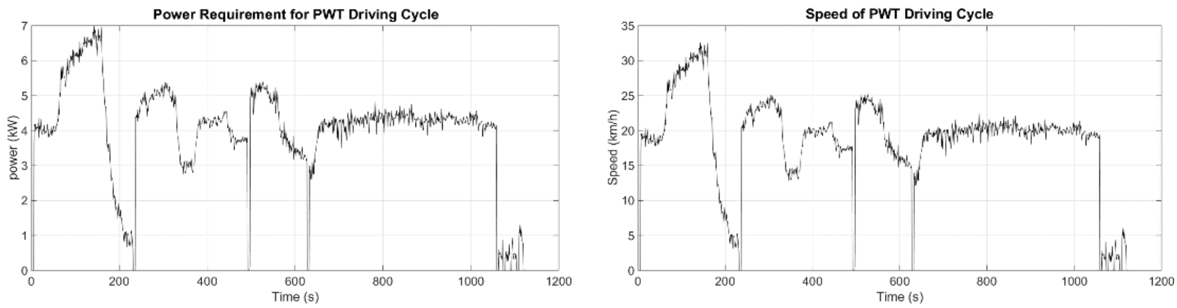
3. RESULTS AND DISCUSSION

This section touched on the discussion about the power requirement and speed graph of 6 driving cycles and the component sizing for the river driving cycle. Next, a simulation was conducted using ADVISOR to see whether the PHEPWT model or the ADVISOR model is more efficient in terms of fuel economy and emissions.

3.1. Power requirement for each driving cycle

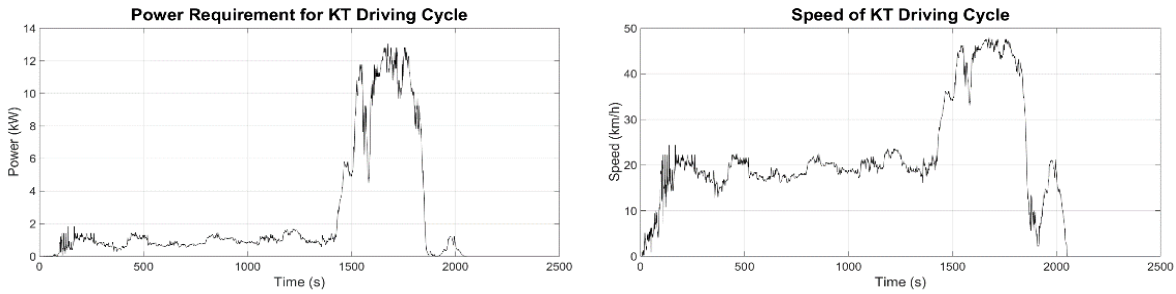
To evaluate the suitability and efficiency of the PHEPWT powertrain, it is essential to analyze the power requirements across various real-world operating routes. Each driving cycle in this study reflects different navigational conditions, such as cruising speed, passenger activity, and route characteristics, which directly influence the propulsion power demand. This section presents the power and speed profiles for six selected driving cycles, highlighting the variations in power requirements and their implications for component sizing, particularly for the EM, ICE, and ESS, as shown in Figures 5-10.

From Figure 5, the highest power needed to propel the boat is about 6.9 kW with the maximum speed of 33 km/h for the Pulau Warisan driving cycle. During the voyage, the power requirement graph plunges to a value of 0 kW because the boat stops at several checkpoints that have been set for tourists to take pictures and see the architecture and scenery at that checkpoint. The maximum power requirement of the boat in Figure 6 is 13.4 kW with a maximum speed of 46 km/h. Next, Figure 7 shows the Seberang Takir driving cycle. The maximum power that takes to propel the boat is 1.1 kW, which is the lowest power needed compared to the other driving cycles due to the boat sailing through the route, only driving at a speed of 20.6 km/h. From Figure 8, the maximum power requirement for the Kampung Laut driving cycle is 16 kW with the maximum speed of 51 km/h. Other than in Figure 9, the power requirement to propel the boat is 19.7 kW with a maximum speed of 55 km/h. Lastly, as shown in Figure 10, different from other driving cycles, the voyage through the Pulau Kapas route used speedboat, while on the other route, a recreational boat. In addition, to reach the destination quickly, the boat used high power, which is 43 kW, with a maximum speed of 72 km/h.



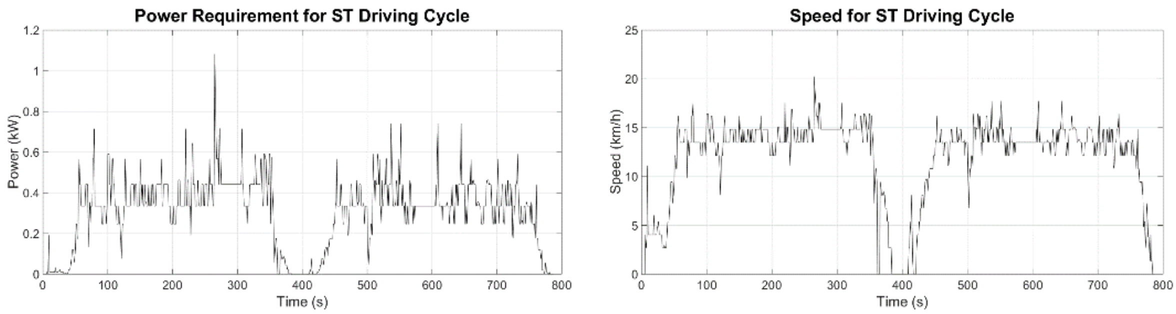
(a) (b)

Figure 5. Power requirement and boat speed for the Pulau Warisan driving cycle: (a) power requirement and (b) boat speed



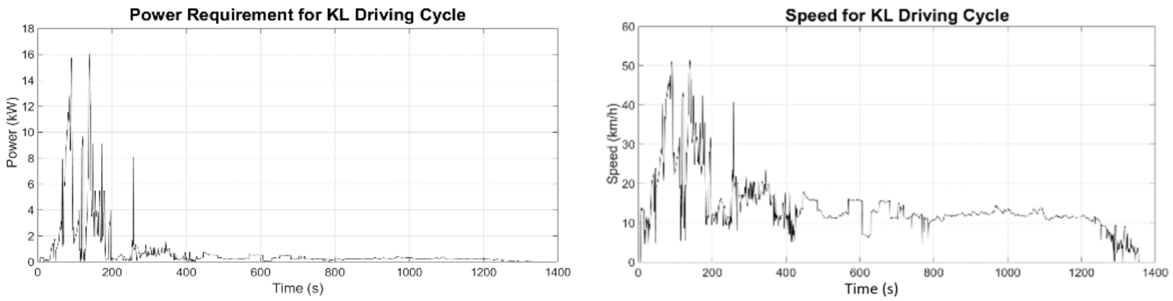
(a) (b)

Figure 6. Power requirement and boat speed for the Kuala Terengganu driving cycle: (a) power requirement and (b) boat speed



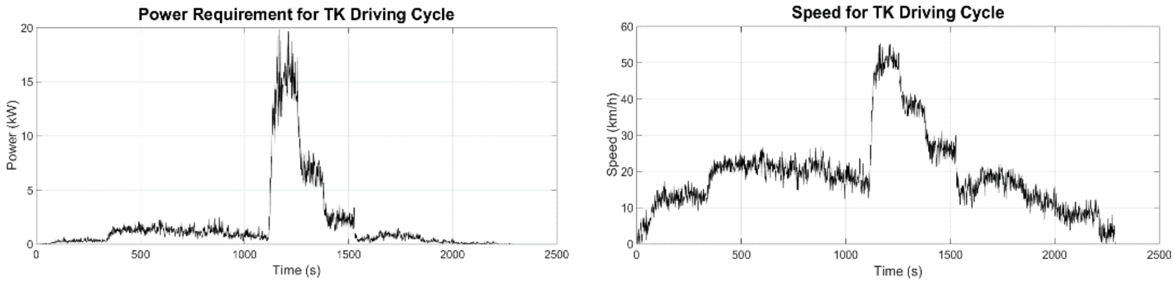
(a) (b)

Figure 7. Power requirement and boat speed for the Seberang Takir driving cycle: (a) power requirement and (b) boat speed



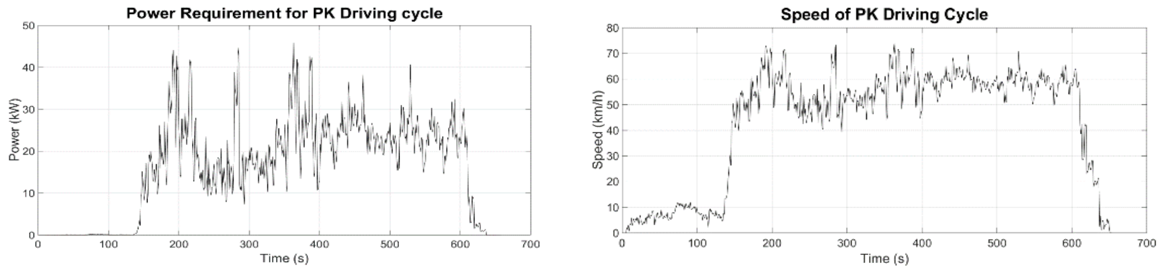
(a) (b)

Figure 8. Power requirement and boat speed for the Kampung Laut driving cycle: (a) power requirement and (b) boat speed



(a) (b)

Figure 9. Power requirement and boat speed for the Tasik Kenyir driving cycle: (a) power requirement and (b) boat speed



(a) (b)

Figure 10. Power requirement and boat speed for the Pulau Kapas driving cycle: (a) power requirement and (b) boat speed

From the power requirement, the component sizing based on the water driving cycle can be estimated using power flow analysis from the power requirement graph for each driving cycle. The power requirement for EM, ICE, and ESS for each driving cycle is stated in Table 5. The overall structure of PHEPWT is relevant and fits the purpose. From the selected component, the specification of PHEPWT is suitable and in the expected range for every driving cycle except the Pulau Kapas driving route due to the high power needed to meet the speed requirement for a speedboat.

Table 5. Component sizing for river driving cycle

	Driving cycle	PW	KT	ST	KL	TK	PK
EM	P_{EM} (kW)	9.72	13.05	1.30	17.09	19.68	45.81
	P_{EM}, continuous = P_{EM} (kW)	5.59	8.02	0.92	8.60	11.01	38.34
ICE	P_{ICE}, continuous = P_{EM} (kW)	1.50	1.19	0.34	3.98	5.29	20.62
	P_{ICE}, continuous (kW)	3.00	2.50	0.70	8.00	10.00	35.00
ESS	P_{EM} (kW)	0.10	0.20	0.18	0.19	0.50	10.36
	E_{ESS}, min (kWh)	0.13	0.35	0.23	0.24	0.63	12.95
	P_{ESS}, max (kW)	3.38	9.53	0.16	4.90	6.52	17.51
	E_{ESS} (kWh)	1.13	3.18	0.1	1.70	2.20	9.17

3.2. Analysis of fuel economy and emissions

A series of simulations was conducted using six driving cycles: PW river driving cycle, KT river driving cycle, ST river driving cycle, KL river driving cycle, TK river driving cycle, and PK river driving cycle. The purpose of this analysis is to compare the fuel economy and emissions, including HC, CO, and NO_X, for various vehicle powertrains among the PHEPWT and ADVISOR models. Table 6 lists the characteristics of the PHEPWT model and the ADVISOR model.

Table 6. The powertrain specifications

Component	PHEPWT Specifications	ADVISOR Specifications
ICE	20 kW @ 3000 rpm Compression-Ignition mode	20 kW @ 3000 rpm
EM	15 kW 3-phase motor Torque: 49Nm	15 kW AC Induction motor
ESS	Lithium Metal Battery 7 kW, 3 kWh	Li, 7kW, 3 kWh

The fuel economy of the PHEPWT model is calculated as (13),

$$Fuel\ Economy = \frac{D}{Vfuel} \tag{13}$$

where D is the test distance in miles, and $Vfuel$ is the volume of fuel consumed in gallons. The FE of the PHEPWT is calculated by (14).

$$Fuel\ Economy = \frac{D}{Vfuel + \frac{E\ charge}{E\ gasoline}} \tag{14}$$

Where $E\ gasoline$ is a conversion factor equal to 79.25 kWh/gallon, indicating the energy equivalent of petrol and electricity, and $E\ charge$ is the necessary electrical recharge energy (in kWh). To calculate this value, the energy content of a gallon of petrol is expressed in terms of electrical energy, which is 79.25 kWh per gallon.

$$Percentage\ of\ FE\ improvement\ = \left| \frac{before\frac{ADVISOR}{PHEPWT} - After\ PHEPWT}{before\frac{ADVISOR}{PHEPWT}} \right| \times\ 100 \tag{15}$$

The fuel economy of the PHEPWT powertrain for the Pulau Warisan river drive cycle is improved by about 47.3 mpg compared to the ADVISOR model, which is 31.13 mpg, showing PHEPWT is more efficient by 34.2%. Then, the improvement by 67.5 mpg from PHEPWT and 54.49 mpg from the ADVISOR model for the KT river drive cycle shows an FE improvement by 19.3%. For the ST drive cycle, 43.3 mpg from PHEPWT and 33.1 mpg from the ADVISOR model. The percentage of FE improvement for the ST driving cycle is 12.7%. The increasing of fuel economy was also recorded for the Kampung Laut river drive cycle, which is 23.3% more than the ADVISOR model, while for the TK drive cycle, the improvement was from 47.2 mpg for the PHEPWT model and 32.93% for the ADVISOR model. Lastly, for the Pulau Kapas drive cycle, the fuel economy from the PHEPWT model was 41.4 mpg, while from the ADVISOR model was 30.43 mpg. Most of the fuel economy for the PHEPWT powertrain is reduced compared to the ADVISOR model, up to 12.7% to 34.2%. Table 7 shows the fuel economy for 6 driving cycles.

Table 7. Fuel economy for 6 driving cycles

Driving cycle	Fuel economy (mpg)	
	PHEPWT	ADVISOR
PW	47.3	31.13
KT	67.5	54.49
ST	43.3	37.79
KL	44.6	34.23
TK	47.2	32.93
PK	41.4	30.43

The criteria pollutant emissions generated from fuel combustion by ICE include HC, CO, and NO_x. The analysis of emissions was carried out using the PHEPWT model and the ADVISOR model. The PHEPWT and ADVISOR model is based on the simulation results of emissions such as HC, CO, and NO_x.

These graphs show the emissions of these pollutants for the driving cycle, including PW river route, KT river route, KL river route, ST river route, PK river route, and TK river route.

The emissions of the PHEPWT were based on the real-time data recorded during the voyage. During the voyage, the speed of the boat was not consistent; thus, the emission level was irregular. The graph shows another pollutant emissions which is particulate matter (PM). Particulate matter is not considered in this paper. That is the reason why the level of PM remains at the lowest level in the graph.

The Seberang Takir driving cycle released the highest emission of HC, which is 2.628 g/m. Pulau Kapas driving cycle released the CO as much as 5.624 g/m, which is the highest compared to the other driving cycles. The PK driving cycle also released the highest NO_x as much as 0.466 g/m. The factor that causes the PK driving cycle is the highest driving cycle that releases CO and NO_x because of the usage of the highest power to propel the boat. Table 8 shows the overall emissions for 6 driving cycles.

Table 8. Emissions for the six driving cycles

Driving cycle	Emissions (grams/mile)					
	HC		CO		NOx	
	PHEPWT	ADVISOR	PHEPWT	ADVISOR	PHEPWT	ADVISOR
PW	1.156	1.846	1.009	1.592	0.108	0.128
KT	0.676	1.14	0.688	1.056	0.116	0.105
ST	2.628	4.687	2.581	3.977	0.235	0.081
KL	0.838	1.497	1.269	2.119	0.377	0.552
TK	0.632	1.311	2.467	1.221	0.250	0.185
PK	1.281	1.624	5.624	1.857	0.466	0.478

By inserting the specification of PHEPWT, like the value of ICE, EM, and ESS, the analysis of fuel economy and emission for each driving cycle was defined. From the analysis of results shown in Tables 7 and 8, the different driving cycles showed different results of fuel economy and emissions due to the power used during the voyage. From the result, an improvement was achieved by the PHEPWT model compared to the ADVISOR model because it was able to get a good fuel economy, which was up to 30% and, on average, 10% higher than ADVISOR.

For emission, the PHEPWT model shows the result of three-type emission, such as HC, CO, and NO_x. The results showed that the PHEPWT model has a lower emission, not more than 2 grams/mile, except for the emission of CO from Pulau Kapas (PK) driving cycle, because the TK and PK were using a speedboat, which causes more power to be used compared to the other driving cycles that used a recreational boat. The emission of regulated pollutants from the ADVISOR model is much higher than the PHEPWT model that causes even higher pollution rates to occur.

4. CONCLUSION

In the present time, commercial recreational boats use fuel and ICE as their main energy sources in order to drive the boat; however, this is harmful and dangerous to the environment. Looking towards the future, research on the development of technologies that can improve the efficiency of PHEPWT such as better battery management systems and optimized powertrain design. Additionally, research should be done to explore the potential of PHEV to improve the utilization of renewable energy sources and reduce emissions. This paper has shown that the PHEPWT model successfully improves the vehicle fuel economy and lowers the boat emission by designing a specific powertrain environmentally friendly compared to the ADVISOR model. The model was built based on the parameters, specification, and requirements appropriate to the PHEPWT condition. The analysis for the fuel economy and emissions has been done in ADVISOR shows that the PHEPWT model released a small percentage of emissions and has high fuel economy in all 6-driving cycles. Finally, future research should be focused on the economic feasibility of PHEV and their potential to reduce the cost of transportation. Overall, this paper provides valuable insights into the potential of PHEV to reduce emissions and fuel consumption.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data supporting the findings of this study are available within the article.

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