Journal of Engineering Science and Technology
Vol. 16, No. 3 (2021) 2067 - 2079

ANALYSIS OF COST OPERATION, FUEL ECONOMY, ELECTRICAL CONSUMPTION AND ALL ELECTRIC RANGE FOR PHERB POWERTRAIN

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Abstract

Plug-In Hybrid Electric Recreational Boat (PHERB) is a new innovation conventional boat with special energy management strategy has provided higher fuel efficiency and lower emissions through the combination of the conventional internal combustion engine with electric machines. This paper analyses and compares between PHERB, conventional hybrid electric boat (CHEB) and conventional boat (CB) in daily operation cost, fuel economy, electrical consumption and all electric range. So, The PHERB and comparative powertrains are studied through numerical simulations to determine fuel consumption for water drive cycles. Suitable results are achieved in terms of fuel economy and the all-electric range for the PHERB powertrain, providing significant improvement over the alternative powertrains. The analysis of these boats is extended to include cost-based analysis of each powertrain in order to estimate the daily operation cost at different fuel prices using different water driving cycle. The results obtained from this analysis show that PHERB daily cost operation is less 50 % compared to CB and CHEB. PHERB powertrain is more suitable and lower operation cost for water driving cycle for recreational.

Keywords: Electric vehicles, Energy management strategy, Fuel economy, Hybrid electric vehicles, Operation cost.

1. Introduction

One of the problems that must be faced by the ship/boat owner is to determine the amount of the cost of fuel. The biggest operational cost in ship is the cost of fuel. Due to the costs incurred for fuel, the question arises how to reduce the cost of bunker to the ship so the expenditure for fuel can be reduced. For such a system, something related to energy use must be environmentally friendly and low maintenance. Similar results were reported recently [1]. Reducing operating cost, fuel consumption and emission remains a major problem that must be facing by a company [2]. Both shipping companies and other public companies [3. 4]. Gusti and Semi [5] stated that the reducing of fuel costs can provide higher savings on the total cost of the ship. Many methods are taken by shipping companies to reduce fuel consumption. One of the alternatives is sailing at low speeds.

To solve several issue surrounding conventional boat, a new conceptual series-parallel plug-in hybrid vehicle for water transportation known as plug in hybrid electric recreational boat (PHERB) is introduced in this research. The PHERB powertrain has a unique energy management strategy (EMS) which contains only one electric machine, operated as either an electric motor (EM) or a generator during different time intervals as specified by the EMS is displayed in Fig. 1. PHERB consists of one EM which functions as either a motor or generator at one time while in the ESS there is ultracapacitor (UC) bank for fast charging and discharging during the regenerative braking and fast acceleration. A special EMS for the PHERB is needed to save the weight, space and cost plus improve the fuel economy. A special EMS were built to focus on developing the UC characteristic and increasing the battery lifetime and system efficiency. This paper presents a comparative analysis between the PHERB, a conventional hybrid boat and conventional boat powertrains using different water drive cycles. It studies the fuel economy, all electric range, and operation daily cost under a range of fuel prices for each vehicle.

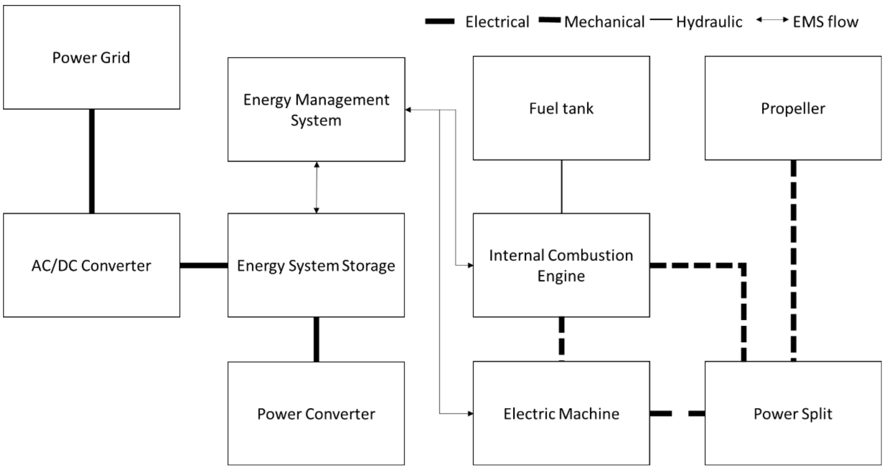


Fig. 1. Block diagram of the PHERB powertrain [2].

2. PHERB Configuration and Parameters

Design specifications, requirements, sizing and selection for EM, ICE and ESS are carried out, in order to identify the main components of PHERB powertrain. The

EM, ICE and ESS are sized according to boat parameter, specifications and performance requirements listed in Table 1, based on the boat power requirement for steady state velocity using dynamic equation boat [6-10]. The power required, Preq for a boat as shown in Fig. 2, is calculated using equation (1) where PE is an effective power and ηT is the total propulsive efficiency. After the sizing process, main components are selected based on the parameters and specifications.

$$Preq = PE \; x \; \eta T \tag{1}$$

Table 1. PHERB parameters, specifications and performance requirements.

Parameter and Specifications	
Configuration	Series-Parallel
Length overall, L	12.4 m
Length at waterline, LWT	11.0 m
Breath, B	1.8 m
Draught, T	0.64 m
Length between perpendicular, LPP	10.67 m
Density of water, ρ	1000 kgm^3
Total propulsive efficiencies, ηT	0.9
Performance Requirement	
Maximum speed	Over 30 km/h
EV range	10 m

2.1. Electric machine (EM)

The power requirement of the electric propulsion motor is determined by the maximum speed. The designed maximum speed is assumed as 40 km/h. All calculations are undertaken with maximum mass. To achieve 40 km/h, the propulsion motor power requirement is: PEM (40 km/h) = 17.4 kW

Motor size and cost may be reduced if the speed demand is relaxed. If the boat is designed to run at 35 km/h it will still meet the requirements, but allowing for a smaller propulsion motor: PEM, continuous = PEM (35 km/h) = 11.8 kW.

2.2. Internal combustion engine (ICE)

The ICE requirements are determined by the average power requirements in the series PHERB powertrain concept. Cruising at 30 km/h, the maximum velocity is assumed to define the average power in the worst-case scenario. The continuous ICE output power requirement is: PICE, continuous = PEM (30 km/h) = 7.6 kW

The electric output power is 8 kW with an estimated efficiency of 85 %, the mechanical input power has to be 10 kW. This is the minimum continuous ICE power requirement: PICE, continuous = 10 kW

2.3. Energy storage system (ESS)

There are two main energy storage requirements, which are an available energy and a maximum power. The available energy should be sufficient for 10 km in pure electric driving mode. The average velocity is about 10 km/h. In a simplified calculation, an average of 10 km/h is assumed. This is to take into account that the average speed is based on a higher speed plateau but with frequent starts and stops. The motor power to propel the boat at 10 km/h is: PEM (10 km/h) = 0.4 kW.

Assuming an overall drivetrain efficiency of about 60 %,the required battery storage capacity is at least:

EESS, min (10 km / 10 km/h) × (0.4 kW / 0.6) = 0.7 kWh

The battery power should be sufficient to boost the propulsion motor to its highest power. Maximum motor power is 1.5 times continuous motor power.

$P_{ESS}, max = 1.5 \times P_{EM}$, continuous – P_{ICE}, continuous = 6 kW

In order to achieve full performance, a maximum discharge of 3C (3 times the rated capacity) was assumed. The battery storage capacity is determined by the requirement, provided it also meets the criteria for pure electric range

$E_{ESS} = P_{ESS}$, max / 3 × h = 2 kWh

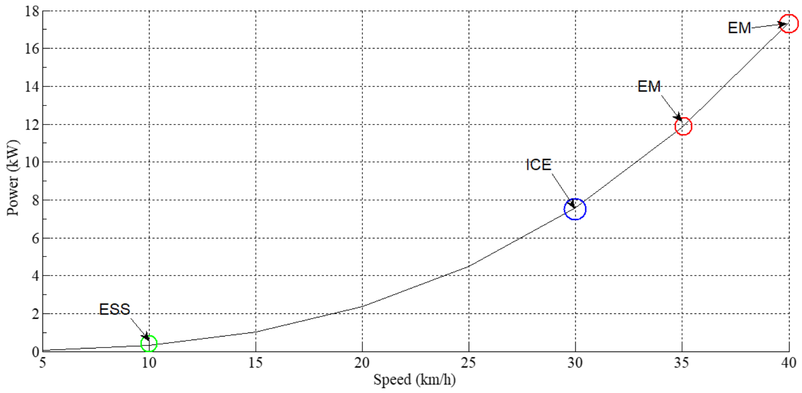


Fig. 2. Vehicle power requirements for steady state.

Based on the boat power requirements for steady state velocity, the main components of the PHERB powertrain were sized.

2.4. Selected components parameters and specifications

Based on the boat power requirements for steady state velocity, the main components such as electric machine, energy system storage and internal combustion engine of the PHERB powertrain were sized [11, 12]. Table 2 lists the estimated main component of PHERB powertrain, which are EM, ICE and ESS based on each component specifications and requirements during the sizing process. The value is estimated around to 20 kW for ICE, 30 kW for EM and 7 kW for ESS. Figure 3 shows the overall structure of the PHERB powertrain model.

Table 1. Main component of the PHERB powertrain.

Component	**Specifications**
ICE	20 kW @ 3000 rpm
EM	30 kW AC induction motor
ESS	Li, 7 kW, 3kWh

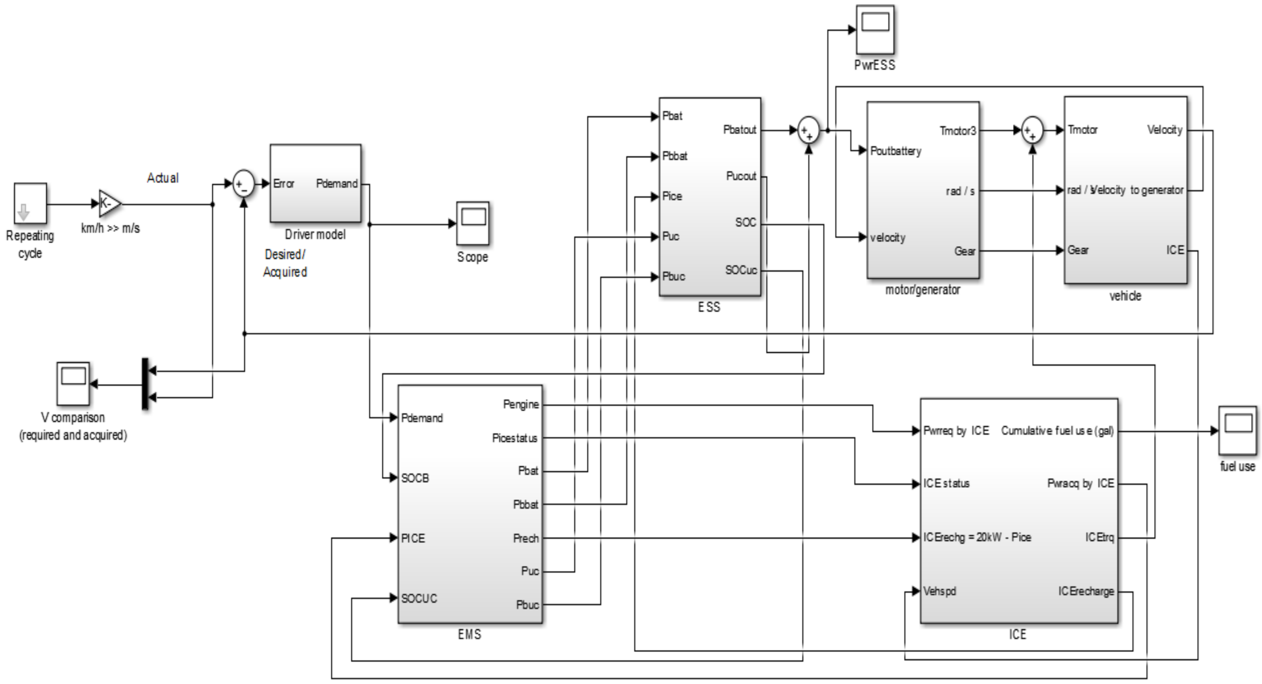


Fig. 3. The overall structure of the PHERB powertrain model.

3. PHERB EMS Development

In PHERB study, EMS has two main conditions which are reverse and forward condition. There are six operation modes which are mechanical reverse, regenerative reverse, EM only, EM and ICE combined, ICE only and ICE recharged. All six operation modes are operated based on the vehicle power demand in forward or reverse and level SOC in ESS. Three level of ESS SOC are low, moderate and high. In water vehicle, another name for cruising is forward mode and braking mode is also known as reverse mode. Figure 4 shows various operation modes of the proposed EMS for PHERB to control the distribution of power among the components according to the vehicle power demand in forward and reverse, as well as the SOC level of the ESS.

In PHERB EMS, there are two conditions for PHERB drive which are forward mode and reverse mode. The forward mode and reverse mode are determined by power demand flow. When the power demand is greater than zero it is considered as forward mode, and vice versa as reverse mode. Figure 5 shows the overall six operations in forward mode and reverse mode. In forward mode, there are four operations involved which are ICE mode (when ICE used only to drive the boat), ICE recharged mode (when ICE used to recharge ESS), ICE or EM mode (when the boat can choose used ICE or EM to drive the boat) and EM mode only. Thus, reverse mode involves two operations consisting of regenerative reverse mode and mechanical reverse mode, respectively.

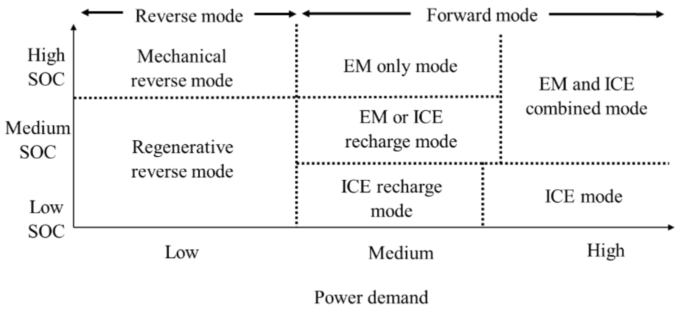


Fig. 4. EMS for PHERB.

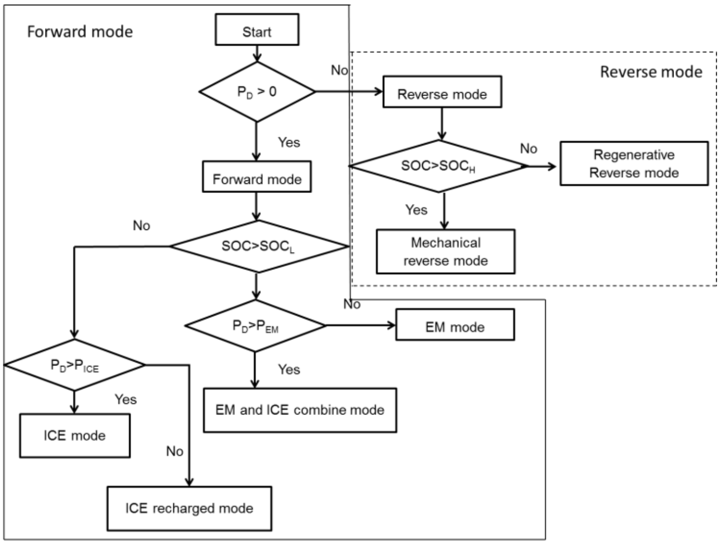


Fig. 5. Flow chart of PHERB EMS.

4. Drive Cycles

The water drive cycle used were Pulau Kapas (PK) driving cycle, Tasik Kenyir (TK) driving cycle, Kampung Laut (KL) river driving cycle, Seberang Takir (ST) river driving cycle, and KT river driving cycle. The parameters of this driving cycle are shown in Table 3. Figures 6 to 10 demonstrate the speed traces of water driving cycle used in this research.

Table 3. The driving cycle parameter.

Driving cycle	Duration (s)	Distance (km)
KT	2217	8.5
ST	505	1.7
KL	1521	3.5
TK	2467	8.1
PK	702	5.0

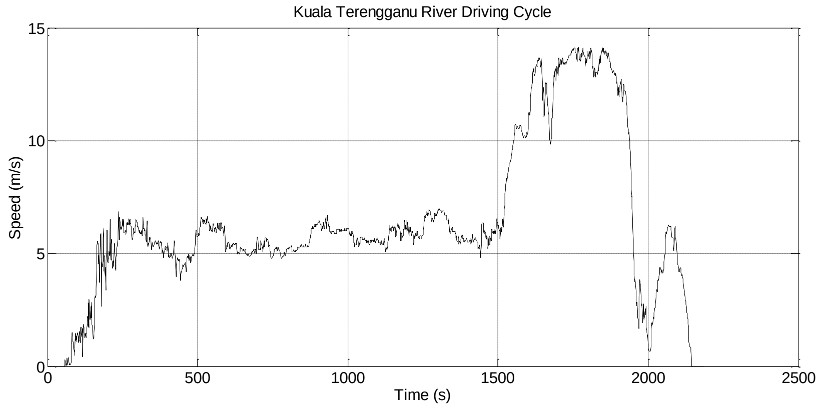


Fig. 6. The KT river driving cycle.

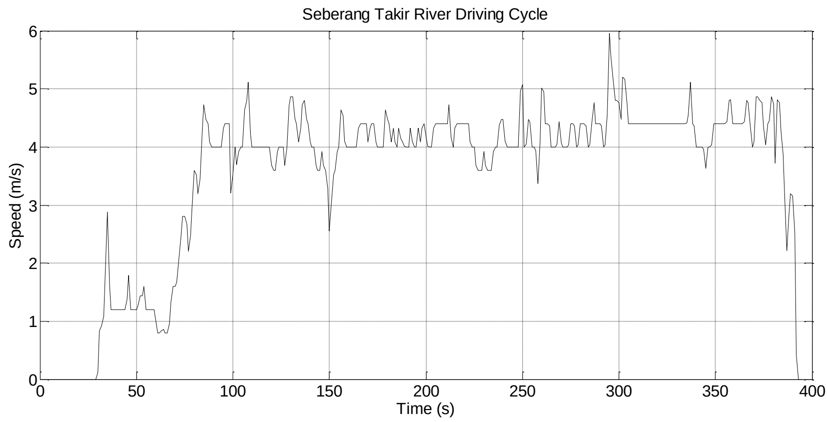


Fig. 7. The ST River driving cycle.

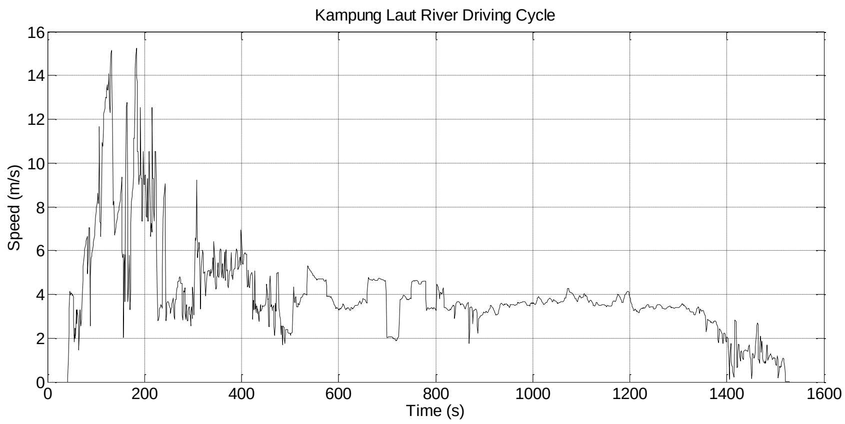


Fig. 8. The KL River driving cycle.

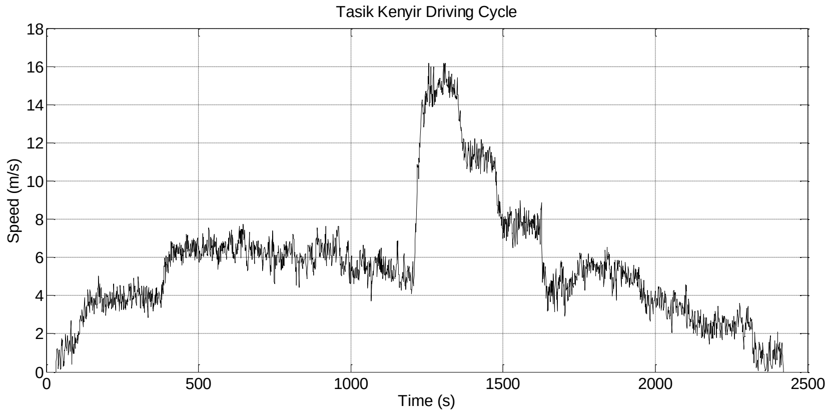


Fig. 9. The TK driving cycle.

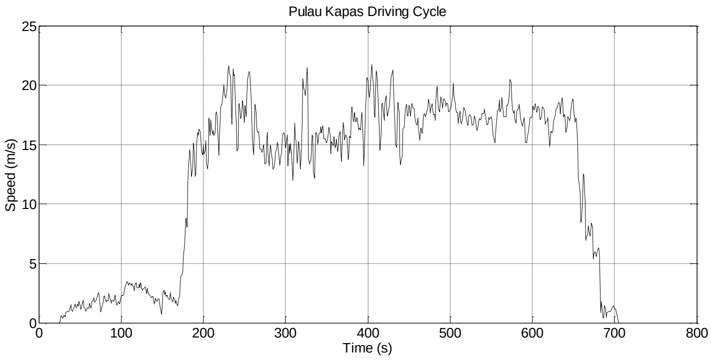
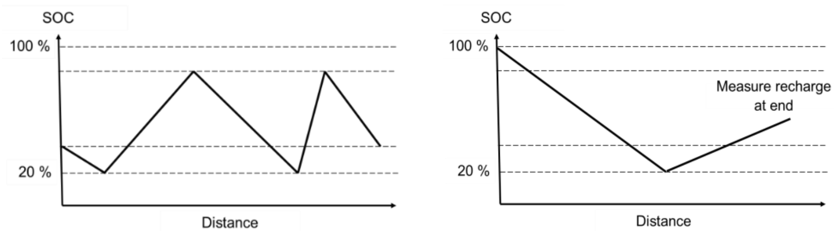


Fig. 10. The PK driving cycle.

Test Methods

For these analyses two types of fuel economy tests are employed, the partial charge test (PCT) and full charge test (FCT) [13-14]. If the ESS is fully charged, the fuel economy for a given range is calculated using the FCT method. In this method the equivalent energy stored in the battery as a volumetric ratio is considered along with the volume of fuel consumed. Figure 11 shows type of fuel economy test of the (a) PCT and (b) FCT.



(a) **(b)**

Fig. 11. Types of fuel economy test (a) PCT and (b) FCT.

The determination of the PCT is to measure the vehicle's FE in a hybrid operating mode, such as after the ESS of the PHERB is depleted to a low threshold operating level. In the PCT test, the final SOC should go back to the same level as the initial SOC at the start of the simulation. The FE of the PCT is calculated as

$$Fuel\ Economy(PCT) = D / Vfuel \tag{2}$$

where *D* is the test distance in miles, and *Vfuel* is the volume of fuel consumed in gallons.

The FCT measures the fuel economy of the PHEV when the initially fully charged ESS is permitted a net discharge over the duration of the simulation. In the FCT, the initial SOC is set at 100% and decreases as the vehicle is driven electrically. The FE of the FCT is calculated by

$$Fuel\ Economy(FCT) = D / (Vfuel + Echarge/Egasoline) \tag{3}$$

where Echarge is the required electrical recharge energy (in kWh), and Egasoline is a conversion factor equalling to 33.44 kWh/gallon, representing the energy-equivalency of gasoline and electricity. The energy content of a gallon of gasoline is expressed in terms of electrical energy at 33.44 kWh per gallon to derive this value.

5. Results and Discussion

Simulations of each powertrain were conducted in the Simulink environment of MATLAB for evaluation of the fuel economy, all electric range and operation daily cost analysis.

5.1. PHERB Fuel economy, electrical consumption and all electric range analysis

Table 4 compares the PHERB, conventional boat (CB), and convention hybrid electric boat (CHEB) fuel economy used PCT for different vehicle powertrains during different drive cycles. Based on the PCT analysis results, a significant improvement in the fuel economy and emissions is obtained from the PHERB powertrain and the following observations can be made. The percentage significant improvement in the fuel economy is calculated using equation

$$Percentage\ of\ FE\ improvement = \left|\frac{Before\ CB/CHEB - After\ PHERB}{Before\ CB/CHEB}\right| \times 100\% \tag{4}$$

The fuel economy of the PHERB powertrain is improved by about 52% from the CB and by 14% from the CHEB for the KT river drive cycle, 94% from CB and 58% from KL river drive cycle. For TK drive cycle, 94% from CB and 29% from CHEB. The increasing of FE also was recorded for ST river drive cycle which is 104% from CB and 34% from CHEB, while for PK drive cycle the improvement was from 159% for CB and 19% for CHEB. Most of the emission for the PHERB powertrain are reduced compared to the CB and CHEB.

Table 4. Fuel economy for the PCT.

Driving cycle	Powertrain	ESS	Fuel Economy (mpg)
KT	CB	-	99.5
	CHEB	Battery pack	132.5
	PHERB	Battery and UC	151.2
KL	CB	-	83.4
	CHEB	Battery pack	102.2
	PHERB	Battery and UC	161.8
TK	CB	-	65.5
	CHEB	Battery pack	98.6
	PHERB	Battery and UC	127.3
ST	CB	-	102.4
	CHEB	Battery pack	155.5
	PHERB	Battery and UC	209.2
PK	CB	-	17.7
	CHEB	Battery pack	38.7
	PHERB	Battery and UC	45.9

Table 5 shows the FCT fuel economy. The same travel distance of 5 km was used in FCT analysis for every applied drive cycle and the initial battery SOC is fully charged, which is about 100%. From the analysis results of FCT, the fuel economy of the PHERB powertrain for FCT has improved in comparison with the PCT analysis. This is because most of the energy used to drive the vehicle comes from the power grid, which is cheaper and cleaner if the electricity is generated from renewable energy sources. Since less fuel is consumed in the FCT analysis, most of the harmful emissions are also reduced.

Table 5. FCT fuel economy.

Driving Cycle	Fuel economy (mpg)
KT	184.6
KL	214.0
TK	151.9
ST	246.0
PK	51.0

For PHERB electrical consumption and AER analysis, the different initial SOC for five driving cycle was listed in Table 6. For the analysis, all electric range (AER) and electrical consumption for different initial SOC of PHERB, each test started in EM only mode with a high SOC. The high SOC was applied at 90% and the battery was allowed to discharge to a low SOC level. Before the start of the simulated boat test, the PHERB powertrain used several cycles of the different water drive cycle. The battery was charged to a high SOC level. The boat operated in the EM mode only until the ICE was on. This phenomenon is called AER where the boat used 100% EM mode only. For the different initial SOCs analysis, the boat was run with different initial SOCs from 90% to 50%, with an interval of 10%.

Tables 6 is showing that PHERB powertrain can support and be used for daily driving range about 10 km in cruising the boat by primarily using the energy from ESS in electric-only mode with the backup ICE disconnected, but if the boat travels a distance greater than 10 km, then it would then work as an HEV. Besides that, initial SOC be important role to make PHERB run in EM mode without use fuel of fuel that produces emission.

Table 6. Electrical consumption and AER for different initial SOC for water driving cycle.

Initial SOC	Electrical consumption (Wh/km)				
	KT	ST	KL	TK	PK
0.90	753.0	1057.0	2550.0	988.8	1278.0
0.80	771.0	1057.0	2568.0	1023.5	1321.4
0.70	800.0	1058.0	2632.0	1083.6	1340.7
0.60	807.0	1069.0	2751.0	1093.0	1352.8
0.50	830.0	1078.0	2785.0	1373.2	1404.9
0.40	845.0	1085.0	2795.0	1385.2	1425.5
0.30	870.0	1092.0	2800.0	1395.8	1450.2
0.20	900.0	1100.0	2815.0	1400.0	1458.1
AER (km)					
0.90	14.29	9.96	10.32	10.0	7.30
0.80	11.71	8.47	7.80	8.40	6.60
0.70	9.11	7.00	7.14	6.20	5.50
0.60	7.12	5.56	4.76	4.90	3.10
0.50	6.31	4.10	3.81	4.00	2.80
0.40	5.50	3.20	2.22	3.50	2.50
0.30	4.00	3.00	1.90	2.80	1.50
0.20	3.21	2.15	1.02	1.10	0.90

5.2. PHERB operation cost analysis

In this analysis, PHERB operation cost were calculated based on daily fuel cost, daily electricity cost, and daily operation cost for KT river, ST river, KL river, TK and PK driving cycle driving cycle based on battery characteristic (Table 6). Besides that, the comparison between PHERB, CB and CHEB powertrain daily operation cost were evaluated. The assumption used to generate the operational cost estimates were fuel RON 95 and RON 97 because this is a type used in Malaysia and electricity costs of RM2.20/litre and RM2.50/litre and RM0.22/kWh, respectively based on data from Ministry of Domestic Trade, Co-Operative and Consumerism and Tenaga Nasional Berhad. The daily fuel cost, daily electricity cost and daily operation cost is calculated using equations 5-7.

$$Daily\ fuel\ cost\ (RM)\ =\ Fuel\ used\ x\ Fuel\ price \tag{5}$$

$$Daily\ electricity\ cost\ (RM) = Electric\ energy\ used\ x\ Electricity\ price \tag{6}$$

$$Daily\ operation\ cost\ (RM)\ = Daily\ fuel\ cost +\ Daily\ electricity\ cost \tag{7}$$

From analysis of Table 6, PHERB daily cost operation is minimum compared to CB and CHEB. PHERB powertrain is more suitable for water driving cycle for recreational, where the boat is moving slowly and there are more opportunities to recover the regenerative braking energy during the stop-and-start events. Most of the energy used to move the boat comes from the power grid, which is a lot cheaper compared to the fuel price shown in Fig. 12.

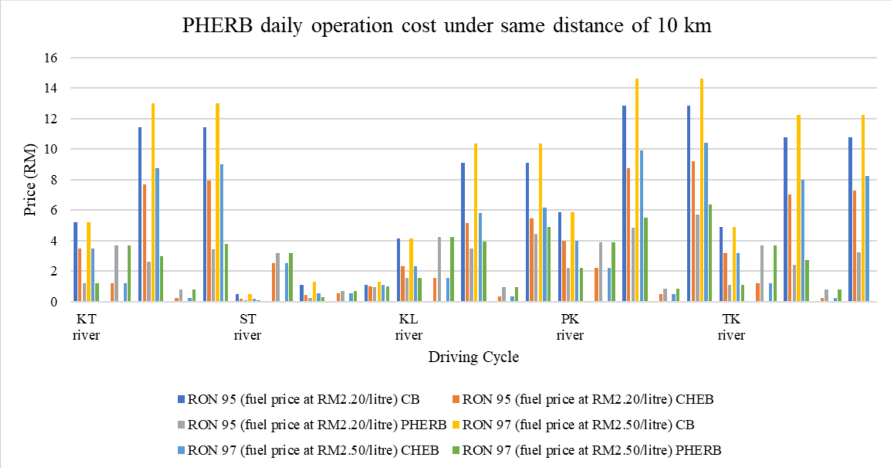


Fig 12. PHERB daily operation cost under same distance of 10 km.

From analysis of Fig. 12, PHERB daily cost operation is minimum compared to CB and CHEB. PHERB powertrain is more suitable for water driving cycle for recreational, where the boat is moving slowly and there are more opportunities to recover the regenerative braking energy during the stop-and-start events. Most of the energy used to move the boat comes from the power grid, which is a lot cheaper compared to the fuel price.

6. Conclusion

This research study the comparison between PHERB, CHEB and CB daily operation cost. From this analysis, PHERB powertrain shown that operation cost is minimum less more than 50% compared to CHEB and CB. Besides that, the lower results of fuel economy, AER, and electrical consumption PHERB comparing the simulation results between CB and CHEB were analyse. So that, PHERB powertrain is more suitable and lower operation cost for water driving cycle for recreational and this model can be referenced to build prototype boat hybrid in Malaysia environment.

Acknowledge

The authors would like to be obliged to Universiti Malaysia Terengganu (UMT) for UMT Scholarship, Ministry of Education Malaysia for providing financial assistance under FRGS (59353) grant and Faculty of Ocean Engineering Technology and Informatics, UMT for all their technical and research support for this work to be successfully complete.

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