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Research Article

Modeling and analysis of the voyage cycle for ferryboat electrification

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Abstract

Voyage cycle modeling provides an estimation of the battery energy requirements in preparation for the electrification of passenger ships. In this study, the objectives are to model the voyage cycle of a public transportation ferry and to determine the appropriate battery storage capacity in preparation for ferry electrification. Pasig River Ferry Service (PRFS), located in Metro Manila, Philippines, was used to model a voyage cycle for ferryboat electrification. Speed and route characteristic data were gathered during the operations of the ferry through a surveyor equipped with a GPS logger. The voyage characteristics gathered, ferry specifications, and diesel engine look-up table were used as inputs to develop a Simulink model that provides the estimated fuel consumption and the equivalent power consumption of the ferry in the case of electrification. The fuel consumption estimate was validated by comparing it to the fuel consumed during actual operation. Based on initial results, the fuel consumption estimates have percentage errors that vary from 2.25 to 12.94 % compared to the actual recorded fuel consumption during operations. The instantaneous power consumption from the voyage cycle Simulink model was used as an input to battery discharge simulations to evaluate the target battery design of the equivalent electric ferry system. Using the methodology of this study, the battery configuration and capacity were determined and evaluated for a single roundtrip voyage of the passenger boat.

1. Introduction and objectives

1.1 Background

The shipping industry contributes around 940 million tons of CO_2, which is at least 2.5 % of the worldwide carbon dioxide emissions (UK Research and Innovation, 2021). To support the 13th United Nations sustainable development goal, namely climate action, the International Maritime Organization (IMO), in 2018, set a target to reduce the overall marine sector emissions by 40 % in 2030, and 70 % by 2050, with reference to the 2008 emissions data. The organization calls for shipping, port, and government authorities to take part and embrace the challenge.

Aside from the negative environmental impacts that engine-based ferries cause, fossil fuel dependency has been a major problem for most of the transportation sectors among various countries, including the Philippines. Marine fleet electrification is one of the ways to minimize fuel dependency (Moussodji & Bernardinis, 2015).

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In fleet electrification, modeling and analysis of voyage cycle and ferry operations is the first step to determine energy requirements (Moussodji & Bernardinis, 2015; Mauro et al., 2020). Voyage cycle analysis is also widely accepted in the design of, and promotion of advancement in, marine transport technology (Wingrove, 2019). It can determine the fuel consumption of a trip, compare available routes, and identify potential weather hazards or other dangers throughout journeys of ships traveling in international waters or in different seas (Heaslip, 2022; Chaal, 2018).

Applying the method of voyage cycle analysis to a small body of water and a more controlled environment will determine the optimal use of a ferry, especially for public transportation (Heaslip, 2022; Chaal, 2018; Estimates of Water Flow, 2022). In this study, the body of water in focus is the Pasig River, which is an inland waterway used by commuters in the heart of Metro Manila, Philippines. The ferry fleet in this waterway is an ideal candidate for electrification, since the roundtrip distance is only 25 km, and the fleet operations adhere to a pre-determined schedule. The possibility of ferry electrification is investigated in this paper by developing an estimation methodology of the energy demand based on the nature of operations.

1.2 Objectives

This study aims to determine the battery energy requirements for electrification of an existing 55-seater ferry currently being used by the Pasig River Ferry System. In doing so, the following specific objectives are accomplished: (1) to model the voyage cycle of a public transportation ferry; and (2) to determine the appropriate battery storage capacity in preparation for ferry electrification by using the voyage cycle in the battery discharge simulations.

2. Ferry specifications

The project is implemented in the Pasig River Ferry System (PRFS), which is currently operated by the Metropolitan Manila Development Authority (MMDA). PRFS consists of 13 stations that connect 4 cities- Pasig City, Makati City, Mandaluyong City, and Manila City- as shown in **Figure 1**. Its fleet is composed of 7 units of 55-seater boats, 5 units of 36-seater boats, and 2 units of 16-seater boats. The total distance from Pinagbuhatan station to Escolta station is about 12.5 km, making a roundtrip distance from point-to-point of 25 km. The busiest stations in terms of passenger volume are the end points mentioned above; along with these is the Guadalupe station, which is the nearest one to the metro railway line.

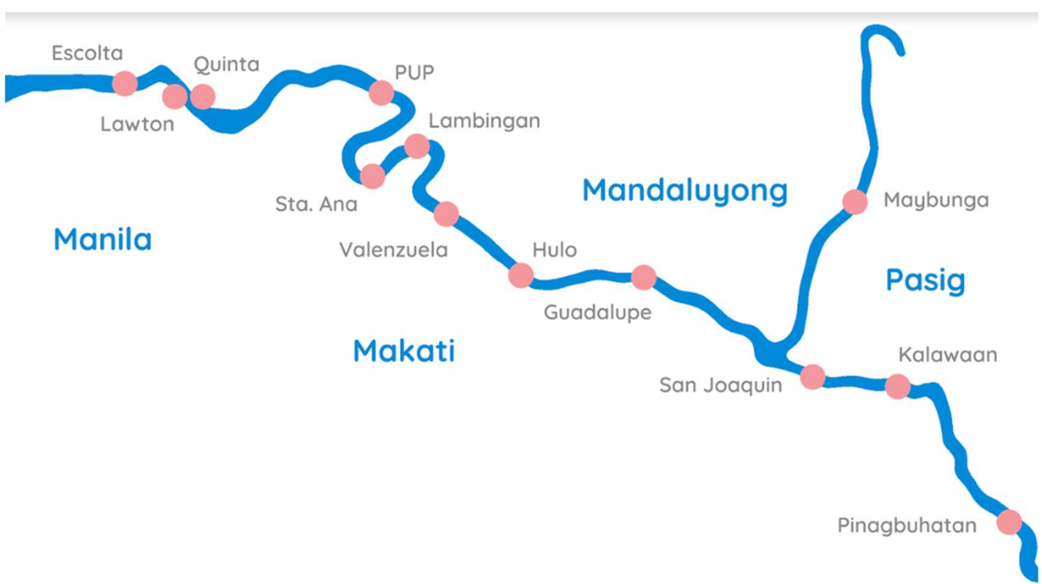

Figure 1 Pasig River Ferry System Route.

An example of a 55-seater boat is shown in **Figure 2**. This ferry model serves as the main unit used in the current operations of the PRFS. The technical specification of this model is listed in **Table 1**. The length of the ferry is 13 m, with the draft marks in full load scenario at 0.57 m. The diesel engine used for propulsion is a 376 HP Yanmar inboard engine that can produce up to 11 knots of cruising speed and 16 knots of maximum speed.

Figure 2 Phileco Boat (55-seater boat).

Table 1 55-seater boat specifications.

Length	13 m
Breadth	3.83 m
Depth	1.75 m
Draft	0.57 m
Fuel tank	600 L
Engine	376 HP inboard diesel marine engine
Cruising speed	11 knots
Max speed	16 knots
Shaft diameter	10 cm
Gear ratio	2.52
Transmission	V-drive (marine)

Four units of this passenger ferry are operational six days a week, twelve hours a day. **Table 2** shows the detailed operation profile of the Pasig River Ferry System based on the data gathered from the survey. The cruising speed on the data sheet of the ferry is 11 knots. However, the actual survey showed that the ferry only travels between 7 to 8 knots during actual operations. This results in a roundtrip travel time of between 2 to 2.75 hours.

The fleet adheres to a pre-determined schedule managed by the PRFS operators, which makes the daily route uniform. The consistency of the schedule and operations of this ferry system makes it a good candidate for electrification, as the energy requirements are also expected to be consistent on a daily basis. This operational profile will be used in determining the appropriate battery size for ferry operations.

As additional context to the current deployment of the ferries in this river system, the units have been used for several years, ranging from 5 - 6 years, and are not well-maintained. As a result, most of the instrumentation equipment of the boats were no longer functional. There were also limited documentation on the performance of the ferry. These are some limitations determined during the data gathering process of the study; thus, a more practical approach was used to determine the voyage cycle from the route survey.

Table 2 Operation profile.

Day	Weekend	Weekday
Average travel time per station	0:10:57	0:11:07
Average idle time at station	0:03:13	0:05:41
Average roundtrip travel time	02:13:45	01:53:12
Average travel speed	7.47 knots	7.02 knots
Total distance travelled	124.5 km	116.6 km

3. Methodology

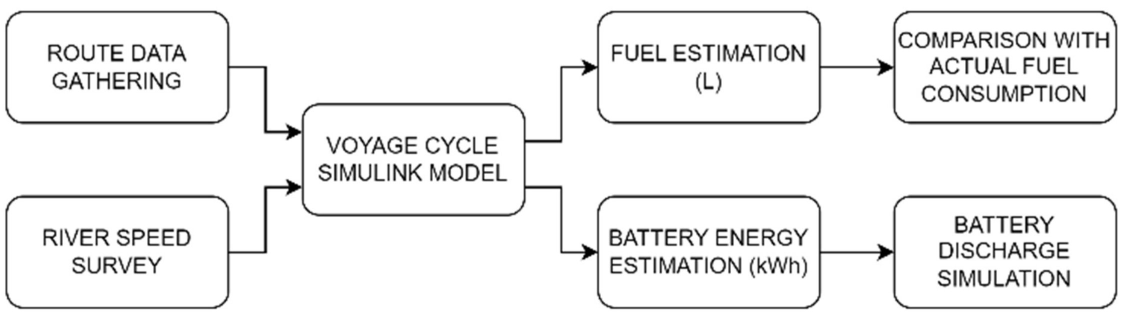

Figure 3 Research methodology.

Figure 3 summarizes the process of achieving the project objectives. The first step is data gathering by conducting route and river speed surveys. Through this step, necessary inputs from the ferry operations and external factors that may affect the voyage cycle of the ship were determined. Route characterization provides key parameters such as boat speed, ridership, distance traveled, travel time, and other operational data, while the river speed survey provides the river velocity to be incorporated in the model for both upstream and downstream cases.

After this, computations of the actual voyage cycle are done using MATLAB Simulink. Using the boat and engine specifications, and the data gathered from the first step, the voyage cycle model can provide two parameters: (1) the fuel consumption estimate, and (2) the corresponding estimated power consumption of the ferry in the context of electrification. The first output is used to validate the accuracy of the Simulink model by comparing actual fuel consumption of the ferry during the days of operations when the survey was conducted. Fuel consumption is only recorded based on the reading of the refueling station. This means that, before every survey event, the diesel tank of the ship was filled to make sure that the fuel consumed will only be for that specific period. The fuel consumed can be measured by filling the tank again after the survey activity. This method enabled the comparison of the output of the Simulink model to the actual consumption.

The second output is used to compute the battery energy requirements of the ferry should it be fully electrified. The battery discharge simulations are then done based on the energy demand computed from the model. From this stage, iterations can be made depending on the target operations of the equivalent electrified ferry and the corresponding charging system that will service the ferry.

4. Route survey data gathering

4.1 Implementation

Data gathering covers the daily route and station stops of the boat for an entire week. A surveyor was assigned to come aboard one of the ferries for the duration of the whole trip, usually lasting from 10 to 12 hours. The surveyor was equipped with a GPS logger, log sheet, and time indicator. The GPS logger captures the trip and stops made by the ferry, the daily kilometers, and the speed of travel throughout the route. The log sheet captures the ridership of the ferry, the number of people who board and alight per station, and other notable observations during the trip, such as the presence of water hyacinths, rough waters, and the effects of tides.

Figure 4 shows the screenshots of the GPS logger app. The maps show the route of the ferry system while the survey is ongoing. The GPS logger app also gives information such as distance, duration, average pace, average speed, etc. The chart tab helps visualize the ongoing data logging.

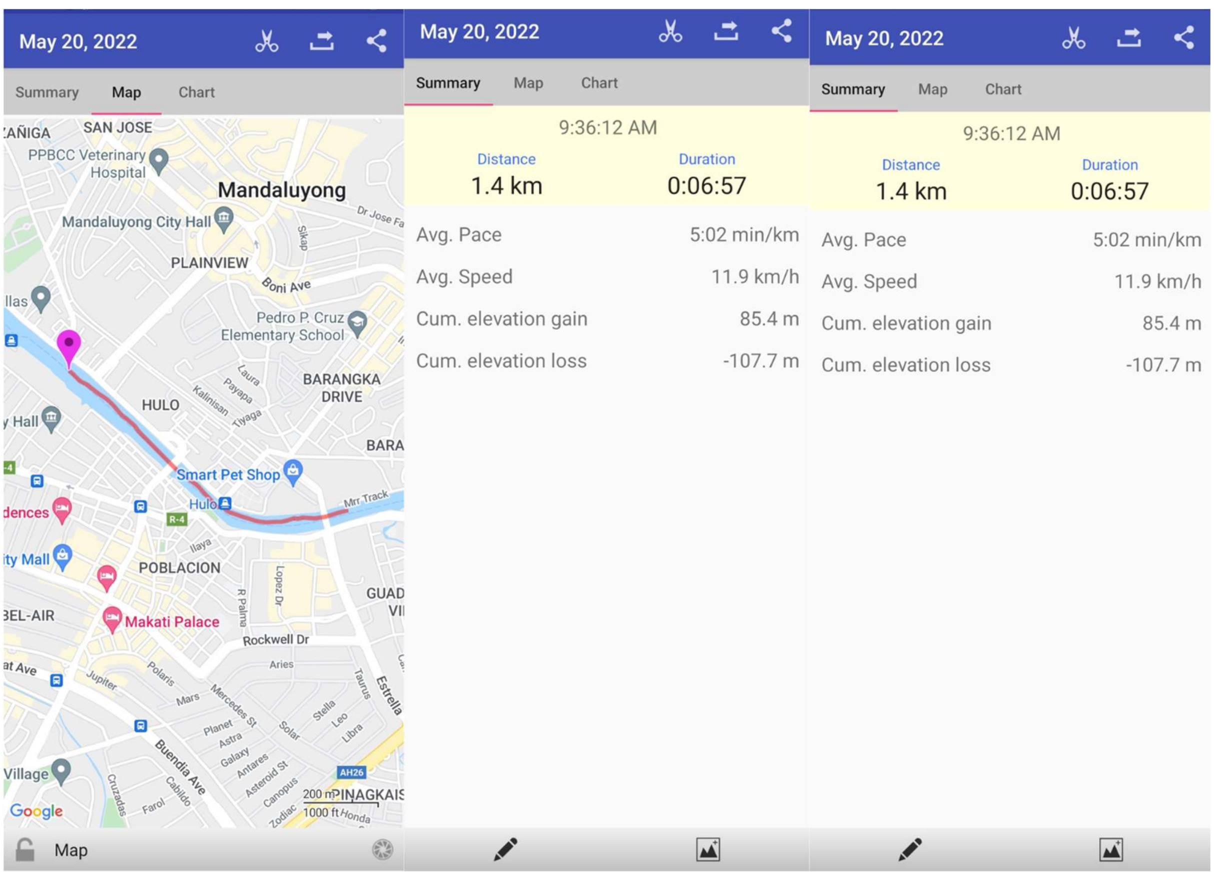

Figure 4 GPS logger data.

4.2 Results

The log sheet shown in **Table 3** is an example of the data gathered during the survey. It indicates the time of the start and end of the operation, and the intervals of the time per station of the riders. The surveyors record the boarding and alighting of the passengers in each station using this survey sheet.

The GPS logger also provides the different operational characteristics gathered from the voyage throughout the week in the form of .kml and .csv files. These data are processed and used as inputs to the MATLAB Simulink model, explained in the sections to follow.

Table 3 Sample survey log sheet.

Date	**15 Aug 22**	**Boat Name / No. of Crew**	**M/V Phileco / 4 Crews**
Time	**Station**	**Passenger Direction**	**No. of Pax**
0820 h	Escolta	Alighting	0
0902 h	Escolta	Onboarding	10
0902 h	Escolta	Onboard	10
0903 h	Lawton	Alighting	0
0905 h	Lawton	Onboarding	7
0905 h	Lawton	Onboard	17
…	…	…	…
1800 h	Escolta	Alighting	0

5. River velocity data gathering

5.1 Implementation

Aside from the GPS data, the speed of the river current in most stations of the PRFS was determined. This is an important parameter to consider, since the GPS data are only based on geolocational points and does not consider the effect of the river current on the boat speed.

The method used is the float velocity methodology. This method uses a rectangular wood, with measurements of 10 cm in length and 2.5 cm in width, as a floating device. The wood is placed in the water and allowed to float from point A until it reaches a certain distance, point B. In this case, the distance used is between 3m to 10m, depending on the available area in the station (**Figure 5**). The time traveled from point A to point B was recorded in each station. Speed is determined by dividing the distance between point A and point B by the recorded time it traversed that distance in (Estimates of Water Flow, 2022).

5.2 Results

The recorded river flow velocity data are shown in **Table 4**. A correction factor of 0.85 was applied to the data, since the river flow velocity on the surface is faster compared to the flow below the surface of the river (Estimates of Water Flow, 2022). This was used to have a more realistic value of the river flow velocity below the surface of the river, where a part of the boat is submerged.

Figure 5 River velocity survey activity.

Table 4 River velocity data.

Stations	Velocity knots	w / 0.85 correction knots
Napindan Dockyard	0.25	0.212
Pinagbuhatan	0.23	0.192
Kalawaan	0.41	0.338
San Joaquin	0.82	0.686
Guadalupe	0.21	0.183
Hulo	0.62	0.531
Santa Ana	0.39	0.329
PUP Pureza	0.60	0.519
Escolta	0.58	0.511

6. Voyage cycle model

The voyage cycle of the ferry boat was modeled using the block diagram as shown in **Figure 6**, implemented in MATLAB Simulink. The survey speed data were used as the inputs to the model to determine the equivalent instantaneous fuel consumption and energy demand.

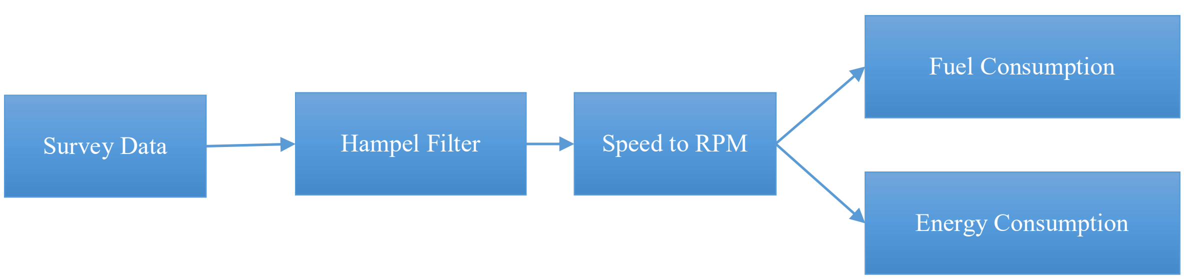

Figure 6 Simplified block diagram of the voyage cycle model.

During data review, it was observed that the raw speed data of the survey have outliers that are not within the scope of maximum rated speed of the ferry, as indicated in **Table 1**. Hence, these outliers were filtered by using the Hampel filter function in Simulink. A Hampel filter identifies outliers using the standard deviation of the data. The identified outliers are replaced by the median value of the adjacent samples of the outlier value.

Table 5 Yanmar engine specification.

RPM	Max. torque (nm)	BHP absorbed by prop	Actual L/hr
1,700	360	49.6	10
1,800	400	53.6	11
2,000	510	67	15
2,200	600	83.1	18.5
2,400	630	105.9	22
2,600	630	127.3	27
2,800	600	154.2	33
3,000	550	181	39
3,200	520	211.8	49
3,300	500	234.6	55

The engine specifications of the actual ferry engine are shown in **Table 5** (Norton, 2016). This table is used to determine the relationship between the RPM, BHP, and L/hr of the engine. To use the data in this table, the raw data in kilometers per hour must be converted to the equivalent rotational speed in RPM, as shown in **Figure 6**. The conversion of the speed data to their rotational speed equivalent is implemented in Simulink, as shown in **Figure 7**, as computed using Eqs. (1) and (2). The shaft diameter and gear ratio used for the computation are based on actual values, as specified in **Table 1**.

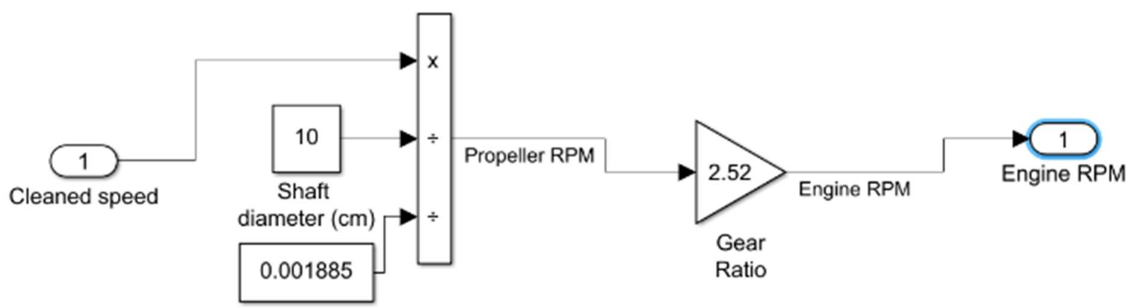

Figure 7 Speed to RPM subsystem.

$$Propeller\ RPM = \frac{Boat\ speed\ in\ kph}{Shaft\ diameter\ x\ 0.001885} \tag{1}$$

$$Engine\ RPM = Propeller\ RPM \times Gear\ Ratio \tag{2}$$

Approximation Eqs. (3) and (4) were obtained using the characteristic table of the engine, as shown in **Table 5**, through exponential and power regression curve fitting techniques. The fuel consumption Eq. (3) was obtained by using exponential regression. On the other hand, BHP Eq. (4) was obtained by using power regression. Both equations use RPM values from the conversion in Eqs. (1) and (2) as inputs to the equations. BHP is converted to kW using Eq. (5).

$$L/hr = 1.85\, e^{RPM \times 1.03 \times 10^{-3}} \tag{3}$$

$$BHP = \left(9.57 \times 10^{-7}\right) RPM^{2.83} \tag{4}$$

$$kW = BHP \times 0.7457 \tag{5}$$

Figures 8 and **9** show the implementation of these equations in Simulink. To compute for the instantaneous fuel and energy consumption, the output of each block is multiplied by the time duration, ΔT, which was obtained through the raw GPS data. The summation of the instantaneous values is equal to the total fuel and energy consumption of the ferry boat.

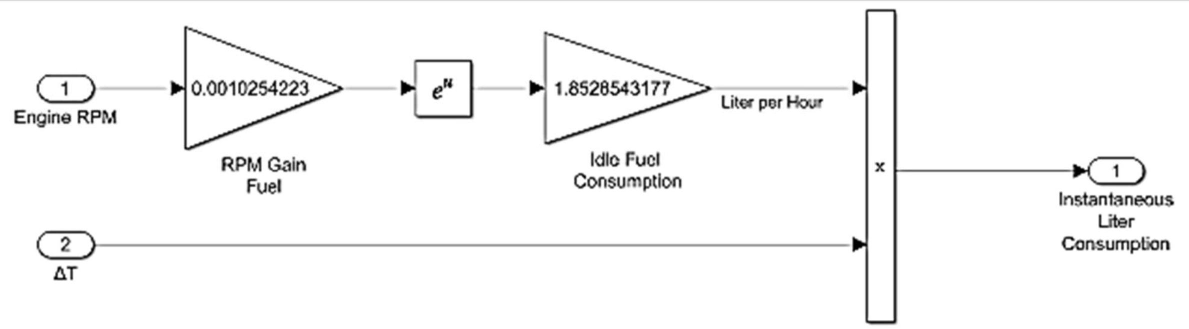

Figure 8 RPM to liter subsystem.

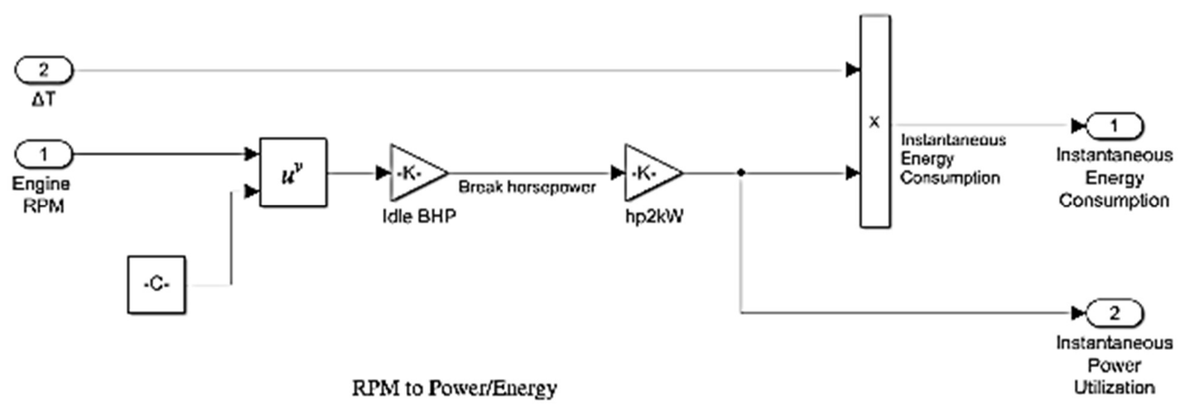

Figure 9 RPM to kWh subsystem.

Since the survey speed raw data rely only on GPS coordinates to determine the speed of the boat, the effect of the river velocity, as recorded in **Table 3**, for each station is also incorporated in the model. For the speed adjustment, the river speed is added when the boat is traveling downstream. On the other hand, the river speed is subtracted when the boat is traveling upstream.

7. Modeling results

Figures 10 and **11** show the fuel and energy consumption output of the model for a whole-day trip, based on the data gathering conducted on October 3, 2022.

It was observed that the maximum instantaneous fuel consumption of the ferry boat while cruising is 110 L/hr. The total computed fuel consumption for this sample day is 187.03 L.

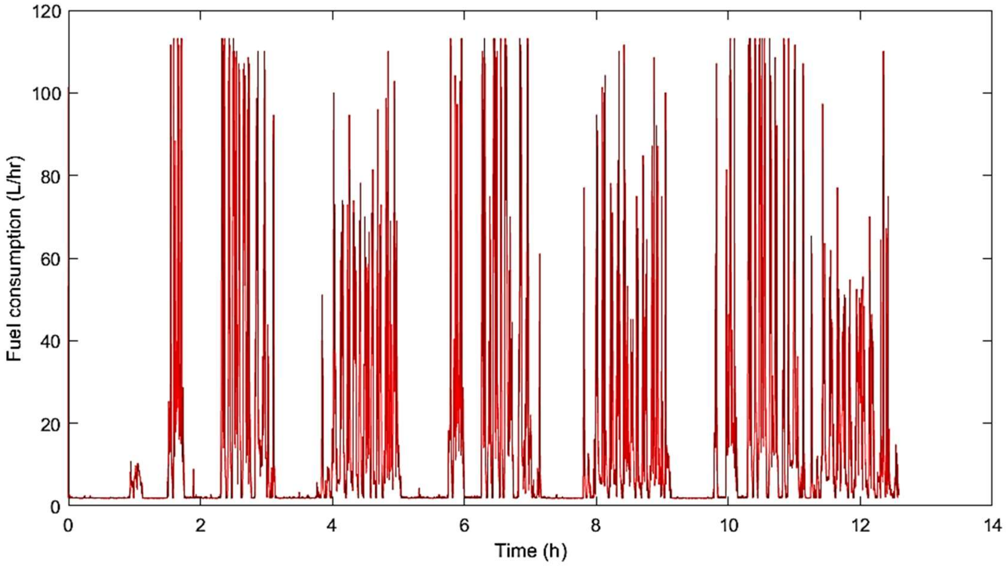

Figure 10 Fuel consumption sample output.

On the other hand, the power output reaches a peak instantaneous power of 260 kW, with an average of 165 kW, which is the cruising power of the ferry. The total energy consumption computed for October 3, 2022 is 529.4 kWh. These data were used as inputs for the battery discharge simulation.

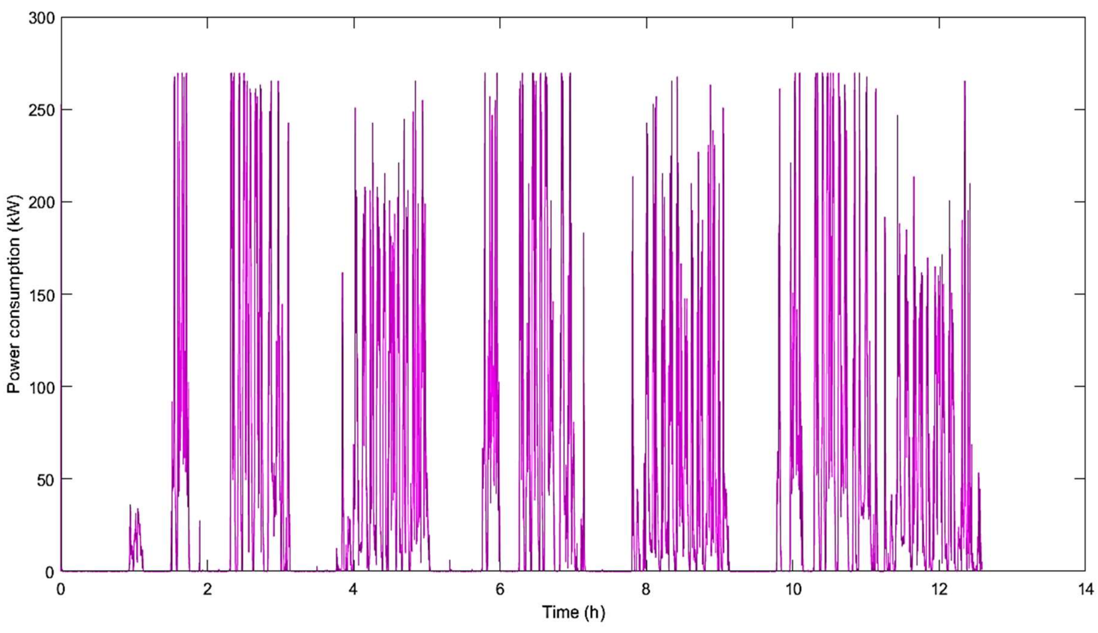

Figure 11 Power sample output.

This power estimation output is used for sizing the target electric motor for the ferry. In this case, the desired electric motor size is a 180 kW Permanent Magnet Synchronous Motor (PMSM) with a rated speed of 3100 RPM and maximum power of 300 kW. PMSM was chosen as the motor type because it is highly efficient, has a compact design, and is widely used in electric vehicle applications (Hashemnia & Asaei, 2008). This motor specification will be used for future simulations and, if validated to be sufficient, will also be used in the actual electrification.

Comparison of the actual fuel consumption of the ferry to the model output is shown in **Table 4**. The actual fuel consumption was recorded through collection of readings from the refueling station every time the diesel tank was filled up to its full capacity.

From the model, the fuel consumption output is 226.2, 203.15, and 280.15 L for the June 18, June 20, and October 3-4 data gathering, respectively. With the river speed adjustment, the model resulted in 8.96, 2.25, and 12.94 % percentage error, respectively, from the actual recorded data. These percentage errors come from the inefficiency of the engine and inaccuracy of the actual consumption reading. Percentage errors can further be improved by installing a flow meter to have more accurate data on the fuel consumption of the ferry (**Table 6**).

Table 6 Actual vs. model fuel consumption.

	Actual Fuel Consumption (L)	**Model Output (L)**	**Model Output w/ River Speed Adjustment (L)**	**%Error**
June 18	255	226.2	232.16	8.96 %
June 20	207	203.15	211.65	2.25 %
October 3 - 4	325	280.15	282.94	12.94 %

8. Battery discharge simulation

Based on the instantaneous power output of the model, the practical battery design for electrifying the boat is only limited to a single roundtrip, which is only about 25 km. It is assumed that, after a single roundtrip, a fast-charging system is available in the station to continue its operations. These assumptions were put in place to match the current nature of operations of the boats, which is around 4 - 5 roundtrips per day, with 20 - 30 minutes of downtime between roundtrips.

The initial battery energy used as an arbitrary value in the analysis is a 216 kWh battery bank based on a 100S3P configuration, with each cell having 3.2 V and 200 Ah capacity. These values are aligned with the assumptions listed in **Table 7**, and space constraints were also considered in designing the battery configuration. This battery configuration and capacity were simulated to fit the existing hull of the ferry in the event of retrofitting. This arbitrary value is used in optimizing the energy needed to satisfy the requirements of the ferry operations.

Table 7 Battery design assumptions.

Run Time	2.5 hours
Battery Voltage	320 V
Depth of Discharge (DoD)	80 %
Life Cycle	70 %

The sufficiency of the battery capacity can be verified using the battery discharge simulation. The input used for this simulation is the estimated power consumption output of the voyage cycle model as seen in **Figure 12**. It is modeled as a negative current source, which absorbs power from the battery system (Cruz et al., 2021).

Using the initial battery energy of 216 kWh and the roundtrip energy data obtained and presented in **Figure 11** as the energy demand, results show that the battery system has an 87 %

Depth of Discharge (DoD), leaving 13 % state of charge at the end of a round trip, as shown in **Figure 13**. This means that the reserve capacity is only about 28 kWh, which is not sufficient for emergency situations. Hence, the battery design must be larger than 216 kWh if 80 % DoD is the target parameter.

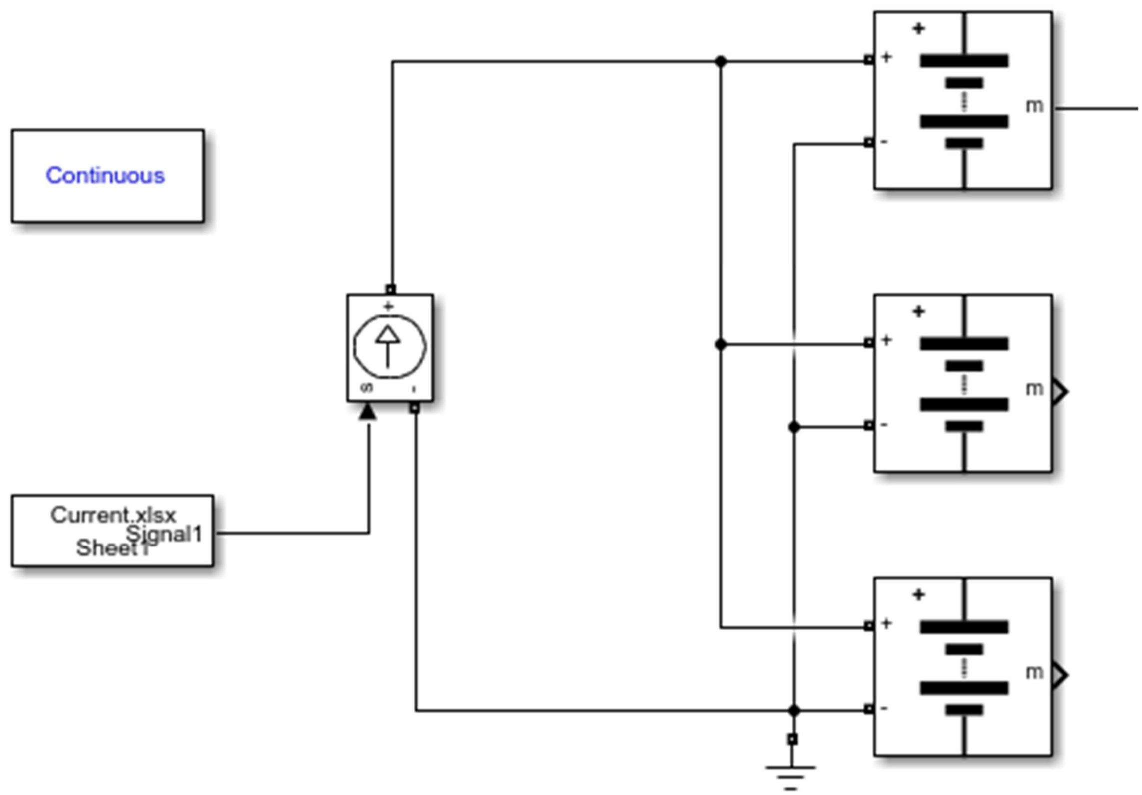

Figure 12 Battery discharge simulation.

This battery discharge simulation can be iterated to determine the optimal battery configuration for the target electrified ferry operations. However, space constraints and stability of the ferry must also be considered in the optimization.

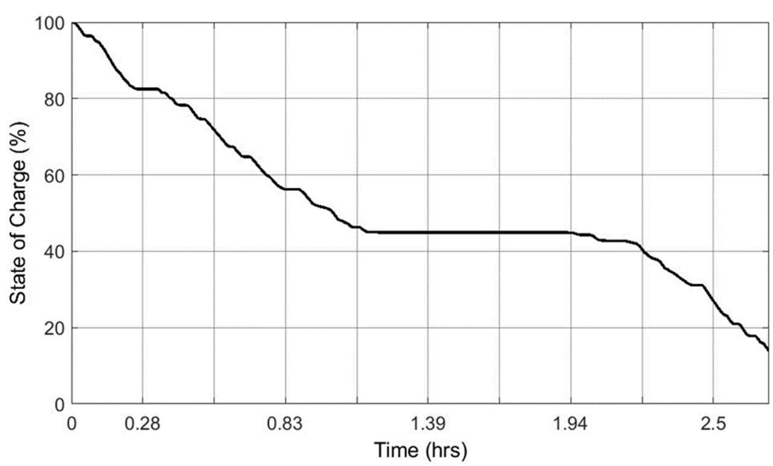

Figure 13 State of charge of the battery system.

9. Conclusions and recommendations

Based on the results, a method for fuel consumption estimation of a ferry based on its voyage cycle is presented. The GPS speed data during the survey and the engine specifications of the ferry were used as the raw inputs to the model. These data were processed using the characteristics of the existing engine to output both the fuel consumption and its equivalent in terms of instantaneous power. This work will be helpful for existing boat operators to determine the energy requirements and to forecast the performance of a boat prior to electrification. Results from this work can be the basis for battery capacity sizing, size optimization, and electric motor selection.

The model was able to reach up to 2.25 % accuracy in modeling the energy requirements, in terms of fuel consumption, of a passenger ferry compared to the actual recorded data from the operator. Engine inefficiency and inaccurate data for fuel consumption are the factors affecting these percentage errors. Further, incorporating documentation and related assumptions on the efficiency of the ferry can also improve these errors. However, for the ferry being investigated in this paper, there were limited resources and documentations on the actual performance of the boat. Hence, the sources and references were limited to the survey activity performed during the study.

The equivalent instantaneous power of the ferry operation was also produced using the model. Through this information, the proper motor size and required battery capacity can be determined. The target motor is a 180 kW PMSM, which is enough to run the ferry with its average cruising power, 165 kW, based on the simulation results.

Battery system capacity for this boat conversion was also evaluated through battery discharge simulations. These simulations use the instantaneous power produced from the model as the load of the battery system. The simulation results show the discharge behavior of the battery system. In this case, the desired system capacity is a 216 kWh battery system with 300 total battery cells. This is enough to power a roundtrip of the ferry; therefore, a fast charger is required at the end of each roundtrip to match the target nature of operations of the public passenger ferry.

Future works include improving the Simulink model by considering the low and high idling instances of the voyage cycle, since these instances are not captured through GPS coordinates. There are also plans to incorporate different segments of the voyage cycle into the data processing-set out, cruising, docking, and boarding/alighting. In this way, the general voyage cycle can be obtained based on this characterization.

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