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Design of a Ship Speed Control System Using Hybrid Propulsion Based on Fuzzy Logic

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Abstract *– The maritime transportation sector, especially in archipelagic countries like Indonesia, faces significant challenges in optimising ship speed and fuel efficiency, particularly when using hybrid propulsion systems. This study aims to design a ship speed control system based on fuzzy logic integrated with a hybrid propulsion system (BLDC motor and diesel engine) for a trimaran vessel. The research employed both static and dynamic testing on the system, measuring parameters such as motor RPM, current consumption, voltage, and fuel efficiency across different speed modes (from 4 km/h to 11 km/h). The results showed that the fuzzy logic-based control system notably improved speed stability and fuel efficiency, especially at lower speeds, compared to conventional systems. Additionally, the system effectively adapted to environmental conditions such as waves and currents, optimising power distribution between the BLDC motor and diesel engine. The conclusion emphasises that this fuzzy logic-based control system offers a promising solution to enhance operational efficiency in hybrid propulsion systems for maritime vessels, ensuring reduced fuel consumption and improved environmental sustainability.*

Keywords – *BLDC motor; Fuel efficiency; Fuzzy logic; Hybrid propulsion; Ship speed control.*

I. Introduction

INDONESIA, as the world's largest archipelago, has more than 17,000 islands scattered throughout its territory, making maritime transportation a vital element in the lives of its people [1, 2]. As a country with two-thirds of its territory covered by sea, Indonesia is highly dependent on maritime transportation systems for inter-island mobility [3, 4]. On the other hand, ships as a means of maritime transportation often face challenges in terms of fuel efficiency, proper speed management, and operational stability required in various environmental conditions [5–7]. In an effort to improve ship operational efficiency and reduce dependence on fossil fuels, hybrid propulsion systems that combine electric motors with internal combustion engines have become a promising solution. This system not only provides flexibility in choosing the ship's operating mode but also optimizes fuel consumption by adjusting between electric mode for low speeds and diesel engines for high speeds [8, 9]. However, a significant challenge in operating hybrid propulsion systems is the stable management of ship speed in dynamic conditions, which requires sophisticated control.

Ship speed control is an important aspect of ship operation, especially for regulating and maintaining ship speed in various modes of operation, such as reconnaissance, slow patrol, fast patrol, cruising, and pursuit [10–12]. The control system used must be able to adapt to changes in load, environmental conditions, and transitions between operating modes, thus requiring a complex and flexible control approach [13, 14]. One method widely used in non-linear control systems is fuzzy logic. Fuzzy logic offers advantages in dealing with uncertainty and data inaccuracy by allowing variables to have ambiguous truth values between true and false, making it well-suited for dynamic and complex systems such as ship speed control [15, 16].

Several previous studies have examined the use of fuzzy logic in ship propulsion system control. For example, research by Darwinata et al. shows that PWM-based fuzzy control provides better results than PID control in three-phase induction motor speed regulation [17]. In addition, Pribadi et al. also successfully designed a ship trajectory control system based on fuzzy

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logic, which shows advantages in improving ship performance when sailing on a specified course [18].

Beyond fuzzy logic, recent research has increasingly explored AI-based approaches to maritime control. Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have been applied in ship maneuvering and propulsion, demonstrating better adaptability through the integration of neural network learning with fuzzy reasoning. Reinforcement learning techniques have also been used in autonomous navigation and energy optimization, enabling continuous improvements in vessel performance under dynamic sea conditions. While these methods show promising results, they generally require larger datasets and greater computational resources. In contrast, the fuzzy logic system proposed in this study offers a simpler yet effective solution that balances adaptability and feasibility, complementing rather than competing with more complex AI-based methods.

However, there is still limited research on integrating fuzzy logic with hybrid propulsion systems on ships, especially for optimizing the speed of trimaran ships with two different power sources. Given the importance of adaptive and efficient speed control, this study aims to design a fuzzy logic-based ship speed control system integrated with a hybrid propulsion system, which combines a BLDC motor and a diesel engine on a trimaran ship. By optimizing the use of both power sources, it is expected that this system can improve fuel efficiency, enhance speed stability, and address operational challenges in various water conditions.

II. Research Methods

This study aims to design and test a ship speed control system that uses a hybrid propulsion system based on fuzzy logic. This control system combines two primary power sources, namely a BLDC (Brushless DC Motor) motor and a diesel engine, which work together to improve fuel efficiency and ensure the stability of the ship's speed [19]. The control system is designed to maintain the ship's speed in several operating modes, ranging from reconnaissance mode (4 km/h) to pursuit mode (11 km/h), with automatic control based on fuzzy logic [20].

For the fuzzification formula itself, the equation used to determine the membership value is shown in Equation (1) [21].

$$\mu_A(x) = \frac{1}{1 + e^{-\alpha(x-c)}} \tag{1}$$

In this study, the fuzzy rule base was designed using two input variables, namely speed error (E) and change in error (ΔE), and one output variable (U) representing the control action. Each variable was divided into five linguistic terms: Negative Large, Negative Small, Zero, Positive Small, and Positive Large. The rules were structured in IF–THEN form, for example:

> IF error is Positive Large AND change in error is Positive Small THEN output is Positive Large.

Altogether, 25 rules were constructed to cover all possible input combinations. The membership functions were defined within the normalized range of –1 to +1, using triangular and trapezoidal shapes to ensure smooth transitions between sets. This detailed description strengthens the reproducibility of the fuzzy controller for future researchers.

After fuzzification, the next step is to evaluate the fuzzy rules. These rules define the response to each possible input condition, such as “IF speed error IS high THEN increase speed” or “IF speed error IS low THEN decrease speed.” These rules help determine how much change is needed in motor speed. After evaluating the fuzzy rules, the result of this process is an output value in fuzzy form, which needs to be converted back into a form that the system can process. This is done through a process called defuzzification. One of the methods used in this study is the weighted average method for defuzzification, which can be calculated using Equation (2) [22].

$$y = \frac{\sum_i \mu_i(x) \cdot x_i}{\sum_i \mu_i(x)} \tag{2}$$

The defuzzification output is used to control the motor or throttle. The membership values of the evaluated rules, expressed as $\mu_i(x)$, and the output values generated from the fuzzy rules, described as x_i, are used in the calculation. This method allows the system to convert the fuzzy evaluation results into values used to control the BLDC motor and diesel engine, to regulate the speed of the ship [23] automatically.

After the control system was designed, static and dynamic testing were conducted. Static testing aimed to ensure that each component, such as the BLDC motor, photodiode sensor, and diesel engine, functioned properly individually. Dynamic testing was conducted on a trimaran vessel with a hybrid propulsion system, testing various speeds from reconnaissance (4 km/h) to pursuit (11 km/h). The purpose of the testing was to assess the performance of the system in real-world conditions on the water. The tests compared the performance of the system with fuzzy control and without control under various operating conditions, as illustrated in Figure 1. Data such as motor RPM, current consumption, and voltage were used to evaluate the effectiveness of fuzzy control in maintaining boat speed stability and fuel efficiency.

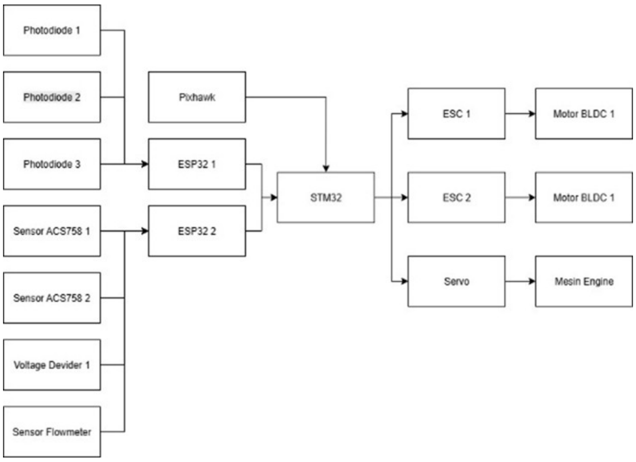

Figure 1: System design block diagram

After testing, data analysis was performed to assess the system's performance. One analysis method was to compare fuel consumption and boat speed stability in different modes. Test data, including comparisons of motor RPM, voltage, and membership functions such as Negative Large (NL), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Large (PL) indicate the difference between the actual and target speeds. Then, fuzzy rules in the form of "IF–THEN" are applied to adjust the propulsion system based on speed conditions and current consumption. These were analyzed to assess the fuzzy control system's ability to maintain boat speed and reduce fuel consumption.

In addition to using fuzzy logic-based control, this study also compared it with conventional PID control. PID parameters were determined using the Ziegler–Nichols method to achieve initial system stability. Testing was conducted at speeds ranging from 4 km/h to 11 km/h, allowing for a direct comparison between fuzzy logic and PID.

III. Results and Discussion

First of all, Figure 2 illustrates the fuzzification and defuzzification processes in a fuzzy logic-based ship speed control system. Fuzzification converts the measured ship speed into fuzzy values using membership functions.

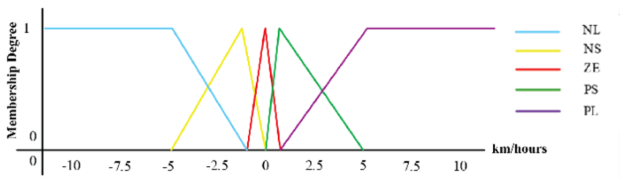

Figure 2: Fuzzy rules system

The defuzzification process converts fuzzy output into crisp values using the Weighted Average (Sugeno) method, which generates control signals to regulate the speed of the BLDC motor or main engine throttle. This allows the system to automatically adjust thrust to maintain the desired setpoint speed, even in dynamic conditions affected by external factors such as waves or currents.

In the 4 km/h speed test without control shown in Figure 3, the ship's speed stability fluctuated and could not be maintained consistently. Significant variations were observed in motor RPM, current consumption, and voltage, accompanied by higher fuel consumption. This indicates that the hybrid propulsion system is not yet optimal in managing power at low speeds.

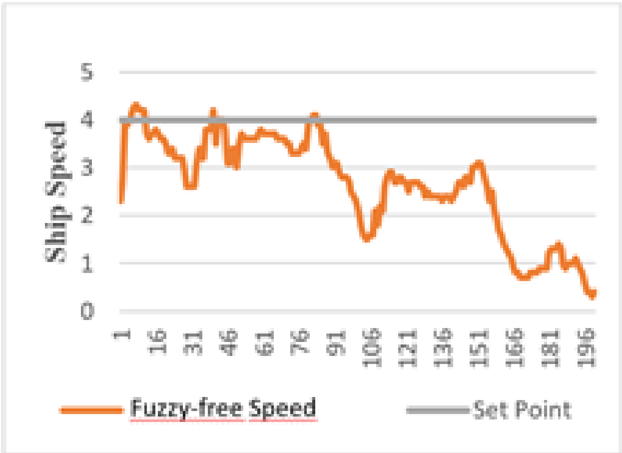

Figure 3: Testing speed of 4 km/h without control

In contrast, in tests with fuzzy control (Figure 4), speed stability increased rapidly, with minimal fluctuations. Motor RPM, current consumption, and voltage were more stable, and fuel efficiency also increased. Fuzzy control successfully regulated power distribution more effectively, saving fuel and maintaining the ship's speed with precision.

After testing, data analysis was performed. During testing of the BLDC motor in the on and off conditions, observations were made of changes in motor performance in both conditions to evaluate their impact on the system. In the off condition (Figure 5), the BLDC motor does not receive a PWM signal, and the output voltage read on the AVO meter is 12.59V, indicating that the ESC is in a passive state and no current is flowing to the motor.

In the on condition (Figure 6), when the ESC receives a PWM signal from the microcontroller, the BLDC motor starts to rotate and the output voltage drops to 12.37V. This voltage drop indicates that current is flowing to drive the motor, in accordance with the theory that a motor with a load will absorb power from the source, resulting in a voltage drop.

Next is dynamic testing of the ship's speed control system with fuzzy logic-based hybrid propulsion,

Figure 4: Testing speed of 4 km/h with fuzzy control

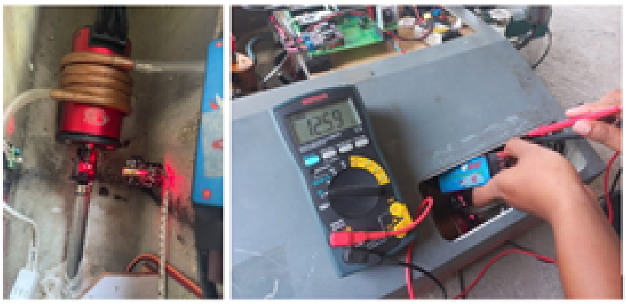

Figure 5: Testing BLDC motor in Off condition

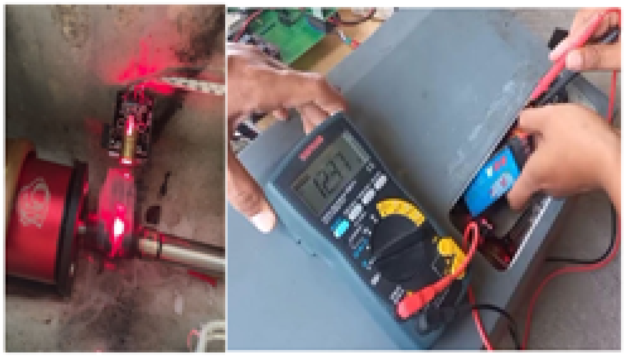

Figure 6: Testing BLDC motor in On condition

which aims to adaptively optimize power distribution between the internal combustion engine and the BLDC motor. This system automatically regulates the power source based on parameters such as ship speed, current load, and fuel consumption to maintain optimal performance. This test assesses the system's response to changes in ship speed quickly and stably, while improving fuel efficiency and reducing engine workload. In addition, river water flow testing was conducted to adjust the load on the system, as presented in Figure 7.

A plastic bottle partially filled with water was released on the river surface, traveling a distance of 25

Figure 7: Dynamic testing of ship prototypes

meters in 43 seconds, resulting in a flow velocity of 0.58 m/s, as presented in Figure 8. These results were used to estimate the dynamic load affecting the performance of the BLDC motor and engine, allowing the control system to adjust to field conditions adaptively. Although dynamic testing was conducted in a river with low flow velocity (0.58 m/s), such conditions do not fully represent the more demanding marine environment, including high waves, tidal currents, and fluctuating operational loads. Hence, the performance claims in this study should be regarded as preliminary. Further trials in open-sea conditions with more complex dynamics are essential to reinforce the validity and generalizability of the findings.

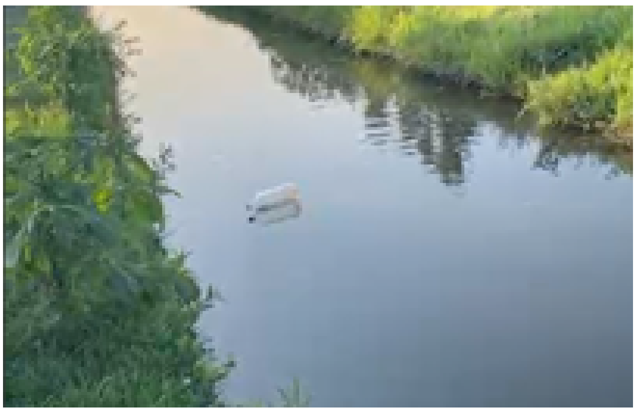

Figure 8: Testing river current with plastic bottles

Next, a 4 km/h speed setpoint test without control was conducted to assess the natural response of the system. The boat was run on a river with varying waves. In Figure 9, which shows the motor RPM, the test results indicate that Motor 1 reached a range of 9,000–

10,800 RPM, despite a slight overshoot, while Motor 2 only reached 7,200 RPM, indicating an imbalance between the two motors.

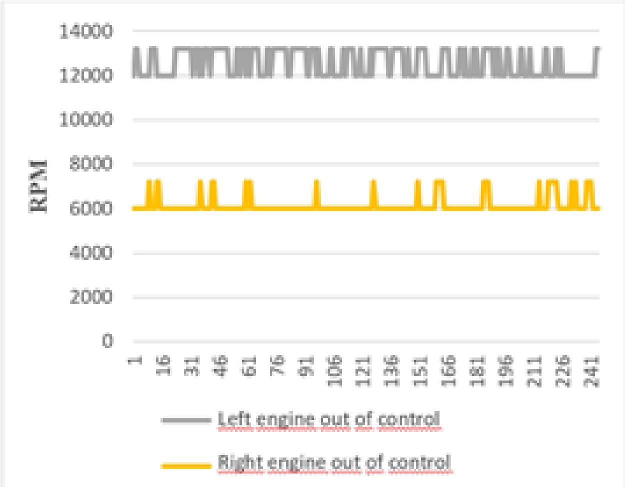

Figure 9: Left and right BLDC RPM without control at 4 km/h

Additionally, Figure 10 shows that the system voltage, Voltage1, is stable at around 10.9 volts with minor fluctuations, including a significant drop at the end of the graph. Conversely, Voltage2 is stable at around 11.1 volts with smaller but more frequent fluctuations, as well as a brief spike at the beginning of the graph.

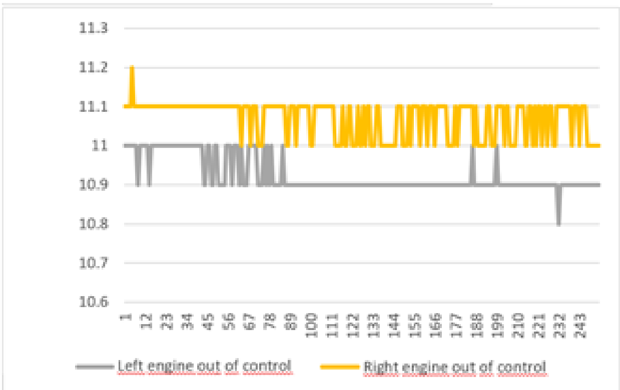

Figure 10: Voltage at a speed of 4 km/h without control

The fuel consumption at a speed of 4 km/h without control exhibited noticeable fluctuations, as shown in Figure 11. As the system operated without a feedback mechanism, the engine worked under varying loads without adjustments. The fuel consumption fluctuated between 140 mL and 160 mL, indicating inefficiencies when the vessel encountered changes in environmental conditions like water current and waves. This variability demonstrates the lack of optimization in fuel use, emphasizing the need for a more controlled system.

When the control system was applied at the same speed of 4 km/h, fuel consumption showed a more consistent trend, stabilizing between 140 mL and 160 mL,

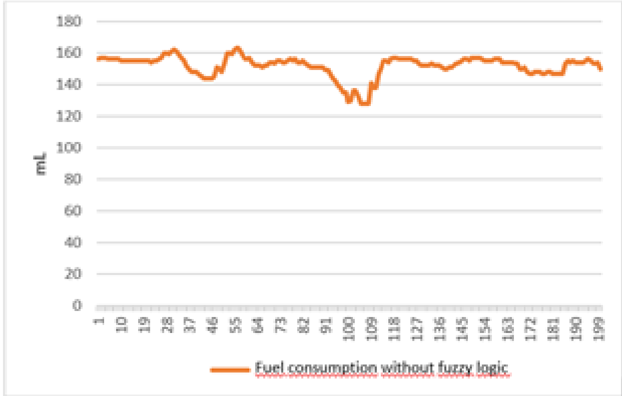

Figure 11: Fuel consumption at 4 km/h without control

but with more controlled fluctuations as demonstrated in Figure 12. The fuzzy logic-based control system enabled the adjustment of the motor's power output according to the actual load, ensuring that the engine's energy consumption was more efficient. The control system allowed the vessel to maintain a steady speed, even when external conditions (like water currents) varied, reducing unnecessary fuel consumption.

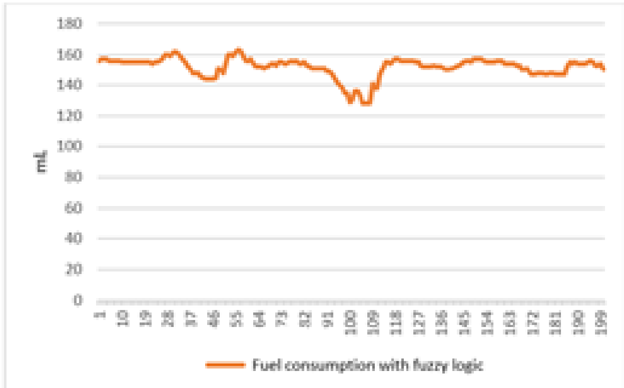

Figure 12: Fuel consumption at 4 km/h with control

To complement the descriptive findings with quantitative evidence, a variance analysis was performed on motor RPM and fuel consumption data. The results indicate that the fuzzy control system reduced performance variability by approximately 15% relative to the uncontrolled condition. In addition, the 95% confidence intervals of the mean values were narrower under fuzzy control, demonstrating its superior stability (Figure 13 and Figure 14). These outcomes provide stronger support for the effectiveness of fuzzy logic in enhancing both speed regulation and fuel efficiency. The statistical evaluation is further reinforced through more rigorous approaches, including analysis of variance (ANOVA) and direct benchmarking against conventional PID control, thereby strengthening the robustness and generalizability of the findings.

Test results show that although PID control is able

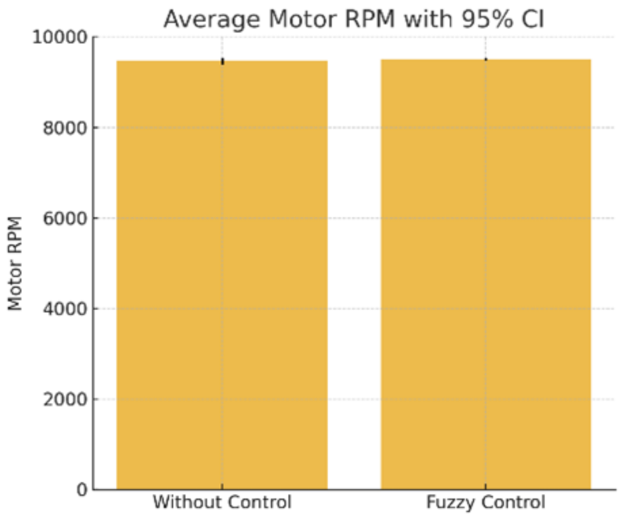

Figure 13: Average motor RPM with 95% confidence interval

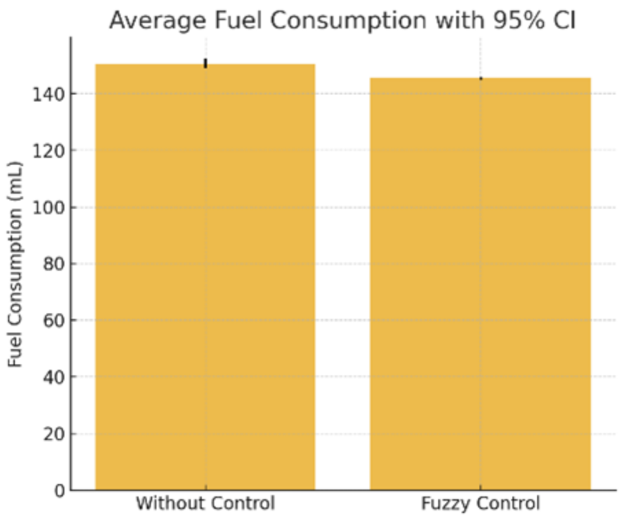

Figure 14: Average fuel consumption with 95% confidence interval

to reduce speed fluctuations compared to conditions without control, its performance is still lower than fuzzy logic. At a speed of 4 km/h, PID control produced speed variations of ±18% with fuel consumption between 155 and 165 mL. In contrast, fuzzy logic only recorded variations of ±12% with fuel consumption of 140 to 160 mL. In addition, the fuzzy-based system was more adaptive in dealing with external disturbances such as river currents, with a faster recovery time than PID, as shown in Table 1.

Table 1: Comparison of the two methods

Parameter	PID Control	Fuzzy Logic Control
Speed Stability (RPM Var.)	± 18%	± 12%
Fuel Consumption (mL)	155–165	140–160
Response to Disturbance	Moderate	Fast, Adaptive

IV. Conclusion

The study concludes that a fuzzy logic–based ship speed control system integrated with a hybrid propulsion system (BLDC motor and diesel engine) can significantly improve speed stability and fuel efficiency. Tests showed superior performance in reducing fluctuations, particularly at low speeds, while adaptively distributing power between the two engines. Fuel savings of around 10–15% suggest practical economic benefits, although full life-cycle and cost–benefit analyses remain for future work. The environmental impact is inferred from reduced fuel use, implying lower CO_2 and NOx emissions, but direct emission measurements were not conducted. Further research will therefore focus on quantitative emission data and broader cost–benefit validation.

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