

Article

Fuel Flow Rate and Rotational Speed Analysis on the Plug-In Hybrid Electric Vehicle Using Hybrid Control System Module Modification Combination Management

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Abstract: This study investigates the fuel flow rate and engine rotational speed characteristics of a plug-in hybrid electric motorcycle using a Hybrid Control System Module Modification Combination Management (HCS-MCM) framework. The proposed system is designed for conversion-based applications at the workshop level, addressing the gap between advanced hybrid control strategies and practical implementation. A parallel hybrid configuration was adopted, integrating an internal combustion engine (ICE) and a 3 kW electric motor with a gear-dependent control strategy. Experimental testing was conducted under first and second gear conditions by analyzing the relationship between vehicle speed, engine speed (RPM), and the time required to consume 5 ml of fuel. The results show that the hybrid system consistently produces longer fuel consumption times compared to the conventional system, indicating improved fuel efficiency. The most significant improvement occurs in first gear, where the electric motor provides dominant torque assistance at low speeds, reducing the load on the ICE. In second gear, the hybrid system still demonstrates better efficiency; however, the performance gap decreases as the ICE becomes more dominant at higher speeds. These findings confirm that the proposed HCS-MCM framework effectively enhances fuel efficiency, acceleration performance, and energy utilization. The study contributes to the development of practical hybrid control systems for motorcycle conversion, particularly for small-scale workshop applications in developing countries.

Keywords: Hybrid Control Module; Plug-in Hybrid; Electric Vehicle

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1. Introduction

The global transition toward sustainable mobility, driven by environmental concerns and fossil fuel depletion, has accelerated the development of electric and hybrid vehicles (EHVs) that combine internal combustion engines (ICEs) and electric propulsion systems to improve energy efficiency and reduce emissions [1-5]. In developing countries, motorcycles remain the dominant mode of transportation; therefore, the development of hybrid motorcycle systems must consider not only performance and efficiency but also cost, simplicity, and adaptability for real-world implementation [6].

However, a critical problem in current hybrid motorcycle systems lies in the lack of practical and modular control frameworks that can be directly implemented in conversion-based applications, particularly at the workshop (small-scale industry) level. Most existing studies focus on advanced control strategies, simulations, or manufacturer-level designs, which are often complex, costly, and difficult to replicate in conventional motorcycle conversion practices [7-14]. As a result, there is a significant gap between theoretical hybrid control strategies and their practical application in small-scale conversion environments.

In addition, conventional motorcycles relying solely on ICEs face increasing challenges related to fuel consumption, emission regulations, and limited torque performance at low speeds. While electric motorcycles provide high efficiency and instant torque, their limitations in range, battery cost, and infrastructure availability hinder widespread adoption. Hybrid systems offer a promising solution by combining the advantages of both technologies; however, their effectiveness strongly depends on the control strategy and system integration approach [15-18].

Another specific limitation identified in existing hybrid motorcycle research is the lack of control strategies that explicitly consider gear-dependent operation in conversion-based platforms. Most hybrid control approaches emphasize power split or energy management at a system level without addressing the practical constraints of mechanical transmission systems commonly found in conventional motorcycles [19-20]. This limitation becomes critical in retrofit applications where maintaining compatibility with existing drivetrain components is essential.

Recent studies also highlight that adaptive and modular hybrid control systems are essential to ensure scalability, flexibility, and cost-effectiveness, particularly for retrofit and small-scale implementations. These studies emphasize that hybrid systems must be designed not only for performance optimization but also for ease of integration and modification in real-world applications.

In Indonesia, regulatory frameworks such as the Minister of Industry Regulation No. 6 of 2022 and the Minister of Transportation Regulation No. 15 of 2022 further reinforce the need for practical, safe, and standardized vehicle conversion systems. These regulations require that hybrid or electric conversion technologies be implementable within certified workshops, highlighting the importance of developing control systems that are compatible with workshop-scale practices.

To address these challenges, this study proposes a Hybrid Control System Module Modification Combination Management (HCS-MCM) framework specifically designed for conversion-based hybrid motorcycles. Unlike existing approaches that focus on high-level control algorithms or manufacturer-oriented systems, the proposed framework emphasizes a modular, practical, and scalable control architecture that can be implemented at the workshop level.

The primary novelty of this research lies in the integration of (1) a structured module modification and combination management framework and (2) a gear-dependent hybrid control strategy tailored for conventional motorcycle transmissions. This approach enables seamless interaction between ICE and electric propulsion systems while maintaining compatibility with existing drivetrain components.

Furthermore, this study explicitly contributes to the development of hybrid control systems for motorcycle conversion from conventional ICE-based vehicles to hybrid electric systems at a small-scale workshop implementation level. The proposed framework bridges the gap between theoretical hybrid control strategies and practical retrofit applications by providing a systematic method for module integration, control synchronization, and performance optimization.

The proposed HCS-MCM framework incorporates real-time monitoring, adaptive calibration, and compatibility assurance, ensuring that the system can be easily modified, upgraded, and maintained within typical workshop environments. This makes the approach highly relevant for developing countries where large-scale manufacturing infrastructure is limited but motorcycle usage is widespread.

The framework is implemented and experimentally validated on a hybrid motorcycle prototype. The results demonstrate improved low-speed torque performance, enhanced acceleration characteristics, and more efficient energy utilization compared to conventional systems. These findings confirm that the proposed approach provides a practical and scalable solution for hybrid motorcycle conversion systems, particularly in workshop-based applications.

2. Materials and Methods

2.1 Hybrid Vehicle Control Systems Subsection

Hybrid vehicles commonly adopt series, parallel, or series–parallel architectures, each with specific advantages and trade-offs depending on packaging, cost, and performance requirements [1], [4]. For motorcycle applications, volume and weight are highly constrained, making the parallel hybrid configuration particularly suitable due to its compactness and torque-sharing capability between the internal combustion engine (ICE) and the electric motor.

In this study, a parallel plug-in hybrid motorcycle layout is adopted (Fig. 1). The electric motor is mechanically coupled to the existing drivetrain so that both the ICE and the electric motor can deliver torque to the rear wheel. This configuration allows:

- Electric propulsion and torque assist during low-speed operation and acceleration, and
- dominant ICE operation at higher speeds or during sustained cruising.

This parallel configuration forms the physical basis for the proposed Hybrid Control System Module Modification Combination Management (HCS-MCM) strategy.

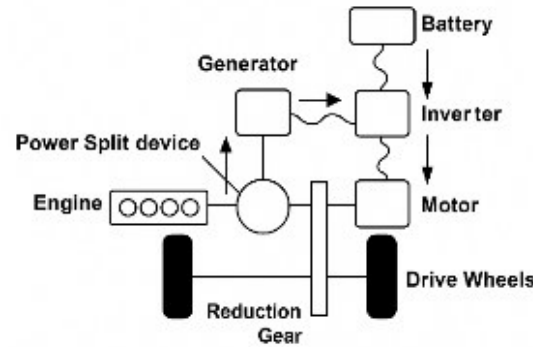


Figure 1. Parallel hybrid control unit configuration.

2.2. Power sizing and parameter assumptions Subsection

The power rating of the electric motor is determined from the required traction power under representative operating conditions. The total mass to be propelled is defined as

$$m_{\text{tot}} = m_{\text{mc}} + m_{\text{conv}} + m_{\text{rider}} \quad (1)$$

where:

m_{mc} = mass of the original motorcycle,

m_{conv} = mass of added conversion components (BLDC motor, controller, battery, battery bracket, brake system),

m_{rider} = rider mass.

For straight-line motion on level road, the required mechanical power at the wheel is approximated as

$$P_{\text{req}} = \frac{\mu m_{\text{tot}} g V}{\eta_{\text{drivetrain}}} \quad (2)$$

where:

P_{req} = required mechanical power (W),

μ = rolling resistance coefficient (–),

g = gravitational acceleration (m/s²),

V = vehicle speed (m/s),

$\eta_{\text{drivetrain}}$ = overall drivetrain efficiency (–).

The parameter values used in this study (rolling resistance, efficiency, and mass breakdown) are defined based on typical motorcycle data and measured prototype values and can be summarized in a design parameter table (e.g., Table 1).

The target top speed for full electric operation of the plug-in hybrid motorcycle is set to 80 km/h, considering safety and typical urban use. The corresponding required motor rotational speed is obtained from the wheel kinematics as

$$N = \frac{60 V}{2\pi r_w i_{\text{gear}}} \quad (3)$$

where:

N = motor speed (rpm),

r_w = effective wheel radius (m),

i_{gear} = overall gear ratio between the motor and the wheel.

Equations (2)–(3) are used to determine the minimum power and speed rating of the electric motor and to verify that the selected motor can meet the performance requirements for electric-only mode and hybrid assist mode.

2.3. Control implementation and simulation tools

The HCS-MCM control logic (gear-dependent operation, torque assist thresholds, and mode transitions) is implemented in the motorcycle's hybrid control unit. The main functions include:

- gear detection and vehicle speed estimation,
- decision-making for mode selection (EV, hybrid, or ICE-only),
- torque request generation for the electric motor,
- protection and limit handling (current, voltage, temperature).

The proposed strategy is first validated in a simulation environment using an equivalent longitudinal vehicle model and drive cycle inputs. A standard simulation tool (e.g., MATLAB/Simulink or an equivalent platform) is used to:

- verify correct mode transitions in response to gear changes and speed,
- evaluate energy consumption and fuel usage over representative driving cycles, and
- perform parameter sensitivity analysis (e.g., effect of mass, rolling resistance, and efficiency).

Simulation results are used to refine control thresholds and to ensure that the HCS-MCM logic operates correctly before implementation on the physical prototype.

2.4. Experimental test setup and validation method

To validate the proposed HCS-MCM framework and gear-dependent strategy under real operating conditions, an experimental prototype hybrid motorcycle is built based on the parallel architecture of Fig. 1. The test setup includes:

- Vehicle: converted hybrid motorcycle with specified ICE, electric motor, and battery system.
- Measurement system: sensors and data acquisition for vehicle speed, motor current and voltage, battery state, and fuel consumption.
- Test environment: repeated tests conducted on a predefined route or chassis dynamometer under controlled conditions.

The validation procedure consists of:

- Baseline tests (ICE-only)
 - The motorcycle is operated with the hybrid system disabled, using only the ICE.
 - Fuel consumption and engine speed profiles are measured for a set of typical driving scenarios (e.g., low-speed urban, stop-and-go, and steady cruising).
- Hybrid mode tests (HCS-MCM enabled)
 - The HCS-MCM strategy, including the gear-dependent logic (concurrent electric + ICE operation in 1st–2nd gears; ICE-dominant operation in higher gears), is activated.
 - The same driving scenarios are repeated, and fuel consumption, electric energy usage, and acceleration performance are recorded.

c. Data analysis and performance metrics

- Fuel consumption expressed as the time required to use up 5 ml of fuel
- Engine speed achieved when using only the internal combustion engine and hybrid mode
- The stability of fuel consumption and the contribution of the electric motor to low-speed torque are quantified.

The results reported in this paper are based primarily on experimental measurements from the prototype hybrid motorcycle, complemented by analytical calculations for component sizing and simulations for preliminary control tuning. This combined approach ensures that the proposed HCS-MCM framework is not only conceptually sound but also practically validated under realistic operating conditions.

3. Results and Discussion

3.1. Result

The analysis canters on 3D plots depicting relationships among Speed (km/h), Engine RPM (Revolutions Per Minute), and Time (s) for both Conventional and Hybrid systems (Fig. 2–3) provide a nuanced understanding of how each system performs under varying operational conditions, facilitating a comparative assessment of their efficiency and responsiveness. The vehicle speed range was set at 13–25 km/h in first gear and 20–35 km/h in second gear. The engine rpm achieved was measured on a dyno, while time was measured based on how long it took the vehicle to consume 5 ml of fuel.

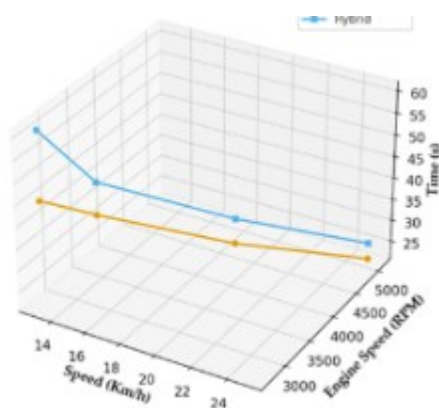


Figure 2. Graphic 1st gear

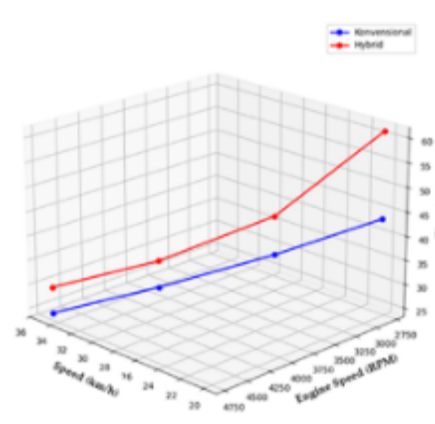


Figure 3. Graphic 2nd gear

3.1.1. Low-Speed Condition

Figure 1. represents the relationship between vehicle speed (13–25 km/h), engine speed (3000–5000 RPM), and fuel consumption time (s) under first gear conditions. The results indicate that the hybrid system consistently produces higher time values compared to the conventional system across all operating points. This implies that the hybrid motorcycle consumes fuel more slowly, reflecting improved fuel efficiency under low-gear conditions.

At lower speeds and RPM, the hybrid system shows a significantly higher time value, indicating that the electric motor contributes substantially to propulsion, thereby reducing the load on the internal combustion engine (ICE). This phenomenon occurs because electric motors are capable of delivering instantaneous torque at low rotational speeds, which improves acceleration while minimizing fuel consumption.

In contrast, the conventional system shows lower time values, indicating faster fuel depletion due to the full reliance on the ICE, especially during initial acceleration where fuel demand is high. This behavior is consistent with the characteristics of electric

propulsion systems, where maximum torque is available at low speeds, enabling efficient acceleration without excessive fuel consumption.

Furthermore, hybrid systems are known to improve efficiency during transient conditions such as start-up and low-speed driving, as the electric motor assists the ICE in reducing fuel load [21]. Therefore, it can be concluded that in first gear conditions, the hybrid system significantly enhances fuel efficiency and low-speed performance due to the dominant role of the electric motor.

3.1.2. High-Speed Condition

Figure 3 illustrates in high-speed conditions. Unlike the first gear condition, both systems exhibit a decreasing trend in time as speed and RPM increase, indicating higher fuel consumption at higher operating conditions. However, the hybrid system still maintains higher time values compared to the conventional system, confirming better fuel efficiency.

The difference between hybrid and conventional systems becomes less pronounced compared to first gear, suggesting that the contribution of the electric motor decreases as the vehicle transitions to higher speeds and gears. This behavior aligns with hybrid system characteristics, where electric motors dominate at low-speed/high-torque regions, while ICE becomes dominant at higher speed/steady-state conditions. At higher RPM, the ICE operates closer to its optimal efficiency range, reducing the relative advantage of the electric motor. Consequently, the hybrid system still performs better, but the margin of improvement decreases. Additionally, the smoother decline in the hybrid curve indicates more stable power distribution between the ICE and electric motor, resulting in improved energy management and reduced fluctuations in fuel consumption. This is supported by recent studies showing that hybrid control strategies optimize torque sharing between power sources, improving overall system efficiency and stability under varying driving conditions.

3.2. Discussions

The experimental results presented in Figures 2 and 3 demonstrate a clear difference in fuel consumption characteristics between the conventional and hybrid motorcycle systems under varying operating conditions. The analysis focuses on the relationship between vehicle speed, engine speed (RPM), and the time required to consume 5 ml of fuel as an indicator of fuel efficiency.

In the first gear condition (Figure 2), the hybrid system consistently shows higher time values compared to the conventional system across all tested speeds and engine RPM ranges. This indicates that the hybrid motorcycle consumes fuel more slowly, reflecting improved fuel efficiency. The significant gap between the two systems at low speeds suggests that the electric motor plays a dominant role in propulsion by providing instantaneous torque, thereby reducing the load on the internal combustion engine (ICE). As a result, the ICE operates under lighter conditions, leading to lower fuel consumption rates. This finding aligns with previous studies reporting that hybrid propulsion systems improve efficiency during low-speed and transient driving conditions through electric motor assistance.

In contrast, the conventional system relies entirely on the ICE, which results in higher fuel consumption, particularly during initial acceleration where torque demand is high. The absence of torque assistance leads to increased fuel injection to maintain performance, thereby reducing overall efficiency. In the second gear condition (Figure 2), both systems exhibit a decreasing trend in time as vehicle speed and engine speed increase. This indicates that fuel consumption increases at higher operating conditions due to greater power demand. However, the hybrid system still maintains higher time values than the conventional system, confirming its superior fuel efficiency.

Nevertheless, the performance gap between the hybrid and conventional systems becomes smaller compared to the first gear condition. This suggests that the contribution of the electric motor decreases as the vehicle operates at higher speeds and gears, where the ICE becomes the primary power source. At this stage, the ICE operates closer to its optimal efficiency range, reducing the relative advantage provided by the electric motor. Furthermore, the smoother trend observed in the hybrid system indicates a more stable power distribution between the ICE and the electric motor. This reflects the effectiveness of the hybrid control strategy in managing torque sharing and reducing energy losses under varying driving conditions. Such behavior is consistent with recent findings that hybrid control systems can optimize energy utilization and improve system stability by coordinating multiple power sources.

Overall, the comparison between the two gear conditions highlights that the hybrid system provides the greatest efficiency improvement at low speeds (first gear), where electric motor assistance is most effective. As the vehicle transitions to higher gears, the hybrid advantage remains but becomes less pronounced due to increased ICE dominance. These results confirm that the implementation of a hybrid system significantly enhances fuel efficiency and performance, particularly in urban driving conditions characterized by frequent acceleration and low-speed operation.

4. Conclusions

This study successfully demonstrates the implementation of a Hybrid Control System Module Modification Combination Management (HCS-MCM) framework in a plug-in hybrid electric motorcycle prototype. The proposed system integrates a parallel hybrid configuration with a gear-dependent control strategy, enabling effective coordination between the internal combustion engine (ICE) and the electric motor. Experimental results indicate that the hybrid system consistently achieves better fuel efficiency compared to the conventional system, as evidenced by longer fuel consumption times under all tested conditions. The most significant improvement is observed in first gear operation, where the electric motor provides dominant torque assistance, reducing the load on the ICE and enhancing low-speed performance. In second gear operation, the hybrid system continues to demonstrate superior efficiency; however, the performance gap decreases due to increased reliance on the ICE at higher speeds. This indicates that the effectiveness of the hybrid system is strongly influenced by operating conditions and gear position.

Overall, the proposed HCS-MCM framework proves to be an effective and practical solution for hybrid motorcycle conversion, particularly for workshop-scale implementation. The system improves fuel efficiency, acceleration characteristics, and energy utilization while maintaining compatibility with existing drivetrain components. Future work should focus on the development of adaptive control strategies based on real-time load conditions, integration of regenerative braking systems, and long-term durability testing to further enhance system performance and reliability.

Supplementary Materials: -

Author Contributions: Conceptualization, 3rd. and 2nd.; methodology, 2nd.; validation, 3rd.; formal analysis, 4th.; investigation, 1st.; resources, 3rd.; data curation, 1st.; writing—original draft preparation, 1st.; writing—review and editing, 1st. and 2nd.; visualization, 1st.; supervision, 4th.; project administration, 2nd.; funding acquisition, 3rd.

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