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Dynamic Modelling and Control an Electric Motorcycle for Energy Recovery via Regenerative Braking

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Abstract. The rapid expansion of the automobile industry, largely driven by population growth and urbanization, has intensified the demand for sustainable transportation solutions. In response, electric vehicles (EVs) have gained significant traction as cities strive to mitigate carbon emissions and improve energy efficiency. This paper presents the development and modelling of an electric motorcycle system incorporating energy recovery mechanism to enhance overall energy efficiency. The system was formulated using longitudinal vehicle dynamics equation and simulated in MATLAB to evaluate its performance. A regenerative braking system (RBS) was integrated into the model to investigate its effectiveness in energy recuperation, laying the groundwork for future advancements in electric motorcycle technology. Unlike conventional motorcycles, electric motorcycles leverage energy recovery to optimize performance and extend operational range. In this study, the World Motorcycle Test Cycle (WMTC) was selected as standardized drive cycles to assess the system's response. The braking control was implemented using a Proportional-Integral controller to regulate braking force distribution effectively. Simulation results demonstrate that the integration of regenerative braking significantly enhances the state of charge (SOC), thereby extending the travel range. These findings highlight the potential further optimization through the implementing of advanced braking control strategies, contributing to the evolution of more efficient and sustainable electric mobility solutions.

1. Introduction

The rapid expansion of the automotive industry is evident in the increasing number of registered vehicles, encompassing not only traditional internal combustion engine (ICE) vehicles but also a growing of electric vehicles (EVs). While this growth underscores technological advancement, it also contributes significantly to air pollution and greenhouse gas emissions. The transition towards electric mobility presents a viable solution to mitigate environmental degradation,



aligning with national ambitions for sustainable urban development and the realization of smart city initiatives. In Malaysia, data from the Road Transport Department indicates that approximately 12.26 million motorcycles have been registered since the year 2000, of which only 7,096 are electric motorcycles [1], highlighting the vast potential for electrification in the two-wheeler segment. Despite the growing interest in electric mobility, the adoption rate of electric motorcycles in Malaysia remains relatively low. One contributing factor is the limited public awareness of the benefits of electric motorcycles, particularly their reduced maintenance requirements compared to conventional internal combustion engine (ICE) motorcycles. Additional barriers include the limited availability of charging infrastructure and the prevalent issue of range anxiety, which undermines rider confidence in the vehicle's ability to support longer travel distances [2].

Electric motorcycles face several technological challenges, particularly in the areas of battery performance and regenerative braking system. Battery degradation not only reduces the performances but also shortens its operational lifespan. To address this issue, current research emphasizes the development of advanced Battery Management Systems (BMS) that enhance the efficiency and reliability of energy storage [3]. Selecting the right battery technology is vital, as it directly affects the motorcycle's energy efficiency and sustainability. Alongside battery advancements, regenerative braking is a technology that allows electric vehicles to recover kinetic energy during deceleration and convert it into electrical energy, which is stored in the battery for later use [4]. This process significantly improves the energy efficiency of electric motorcycles by reducing the net energy consumption from the battery. Recent studies focus on intelligent braking control strategies that optimize the energy recovery process, ensuring more effective use of stored energy. Therefore, improvements in both battery systems and regenerative braking technologies are essential to extend the range travelled, increase performance, and support the long-term environmental sustainability of electric motorcycles [5].

This paper is structured as follows: Section 2 details the development of the electric motorcycle model using MATLAB simulation, with a particular focus on the integration of regenerative braking into the system design. Section 3 presents the simulation results, highlighting how regenerative braking influences the battery's state of charge (SOC), which fluctuates depending on the dynamics of the drive cycle. Finally, Section 4 concludes the paper, summarizing key findings and outlining potential directions for future research.

2. Methodology

In this study, a mathematical model was developed based on the longitudinal dynamics of the electric motorcycle. As illustrated in Figure 1, the block diagram represents the electric motorcycle system, with the input signal generated from a predefined drive cycle. This model facilitates a comprehensive analysis of the vehicle's performance with parameters such as the battery's state of charge (SOC), energy recuperation through the regenerative braking system, and the estimation of maximum travel distance corresponding to a given SOC level. The integration of these dynamics provides a foundational framework for evaluating energy efficiency and optimizing control strategies in electric motorcycle operation.

In this system, the desired speed profile derived from the drive cycle is interpreted by the rider model, which generates the required torque at the rear wheel. During deceleration, the braking control system modulates the braking force to enable regenerative braking, thereby allowing mechanical energy to be converted into electrical energy and recovered. Simultaneously, the battery model simulates the delivery of electrical power to fulfil the torque demand of the

electric motor, ensuring sufficient energy supply for propulsion at the targeted velocity. Once the motor torque is produced, it is transmitted through a simulated single-gear transmission system, where the gear ratio is incorporated to calculate the resulting wheel torque. Furthermore, the longitudinal vehicle dynamics are considered to model the deceleration behaviour of the motorcycle, contributing to an accurate representation of its motion response under various operating conditions. Based on this concept, the electric motor propels the E-motorcycle through a single-gear transmission connected to the rear wheel. During motion, the motorcycle is subjected to several primary resistive forces, including aerodynamic drag, rolling resistance, and gravitational resistance due to road gradients. While braking forces can be distributed between both the front and rear wheels, the regenerative braking system is typically constrained to the rear wheel.

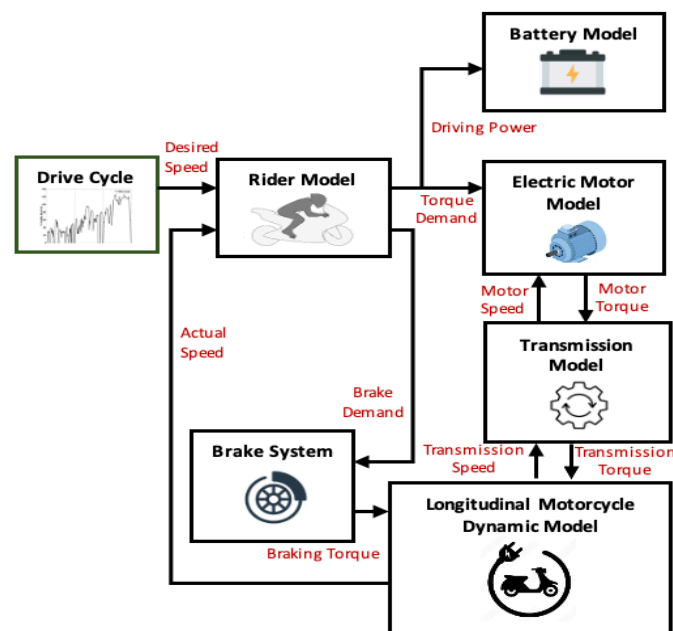


Figure 1. Electric motorcycle system.

2.1 MATLAB Simulink for Regenerative Braking System

The motorcycle dynamic system was developed using MATLAB Simulink (version 2024a) to enable comprehensive performance analysis and evaluation. The primary objective of the simulation is to investigate the dynamic behaviour of the regenerative braking system, particularly its influence on the battery's state of charge. Figure 2 illustrates the integrated configuration comprising the motorcycle, electric motor, driver controller, and battery. The mathematical model governing the longitudinal motorcycle dynamic is systematically implemented within the simulation framework. The DC motor is operated based on mechanical torque input and managed through an H-Bridge motor controller. A voltage is applied across the H-Bridge, with gate pulses controlled by a PWM block referenced to the desired input. The PWM mechanism modulates the H-Bridge switching actions, thereby ensuring precise and responsive motor control essential for accurate system representation. In this simulation, Lithium-based battery is calculated using Equation 1, related to the ratio between the remaining energy in battery at a given time and the maximum possible energy with the same state of health conditions.

$$SOC(t) = \frac{Q_{remaining}(t)}{Q_{max}(t)} \times 100 \% \quad (1)$$

During braking, the speed decreases as the rider applies a braking force. Within the simulation environment, a Proportional-Integral (PI) controller is used to replicate the rider's braking behaviour by regulating the vehicle's speed, which this control algorithm due to its simplicity and effectiveness in eliminating steady-state errors. The PI controller generates a braking current reference based on the error between the actual motor speed and the reference speed, that being sourced from a drive cycle.

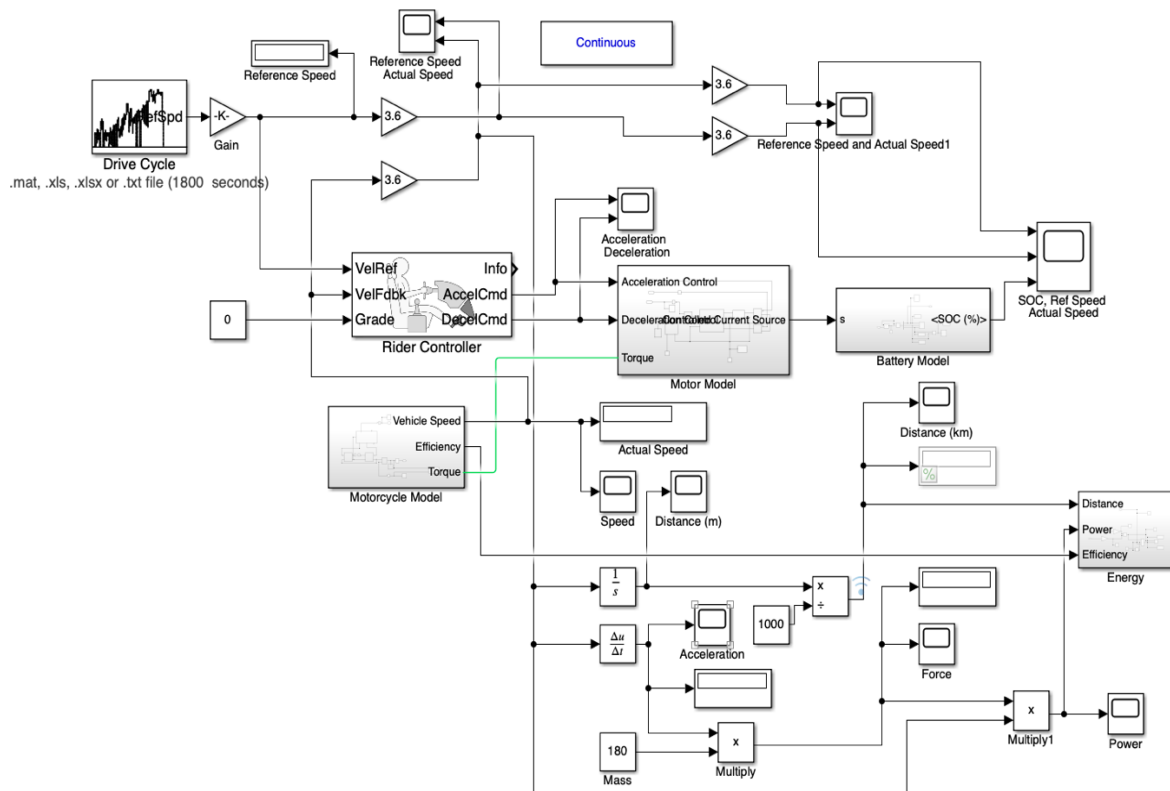


Figure 2. MATLAB simulation for electric motorcycle.

The equation of PI control formula can be defined as Equation 2, combines two components: the proportional term, which responds to proportionally to instantaneous error signal, $e(t)$, and the integral term, accumulates the error over time to correct long-term drift. In this formulation, $y(t)$ represents the system output, K_p is the proportional gain, and T_i is the integral time constant. The error signal $e(t)$ is computed as the difference between the desired input and the actual output.

$$y(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(t) dt \right] \quad (2)$$

In this simulation, the electric motorcycle parameters are derived from a retrofitted Honda CBR250RR model [6], ensuring that the system reflects realistic operational characteristics. The parameters have been listed in Table 1, where their parameters can be adjusted as needed changed and configures to align with those of the motorcycle model. The study adopts the WMTC as the representative drive cycle. The WMTC consists of three phases, which are urban, rural, and motorway segments that provides a comprehensive and accurate approximation of real-world riding conditions, making it suitable for evaluating the motorcycle's dynamic and energy performance under diverse scenarios.

Table 1. The list of parameter for E-motorcycle

Parameter	Symbol	Value	Parameter	Symbol	Value
Motorcycle mass	M	180 kg	Motorcycle frontal area	A_f	0.6 m ²
Acceleration due to gravity	G	9.81 m/s ²	Aerodynamic drag coefficient	C_d	0.7
Rolling resistance coefficient (on road)	f_r	0.013	Gear ratio	GR	1:7.4
Grading angle	θ	0	Battery nominal voltage		48 V
Density of air	ρ	1.202 kg/m ³	Battery rated capacity		60 Ah
Rear wheel radius	r_w	0.3149 m			

3. Results and Discussion

This study mainly focuses on modelling the electric motorcycle and integrating a regenerative braking system within the simulation framework. The regenerative braking mechanism is essential for energy recovery, allowing kinetic energy to be captured, stored in the energy storage system, and reused, thereby enhancing overall energy efficiency. The MATLAB simulation model is developed based on the longitudinal dynamics equations of the motorcycle, with particular emphasis on analyzing the battery's state of charge (SOC) and the maximum achievable travelled distance under specified speeds and SOC levels. Under the WMTC drive cycle, it reaches a peak speed of 130 km/hr. Figure 3 illustrates the simulation results for both the actual and reference speeds, as well as SOC variation under the WMTC drive cycles. The PI controller is set to $K_p = 100$ and $K_i = 15$.

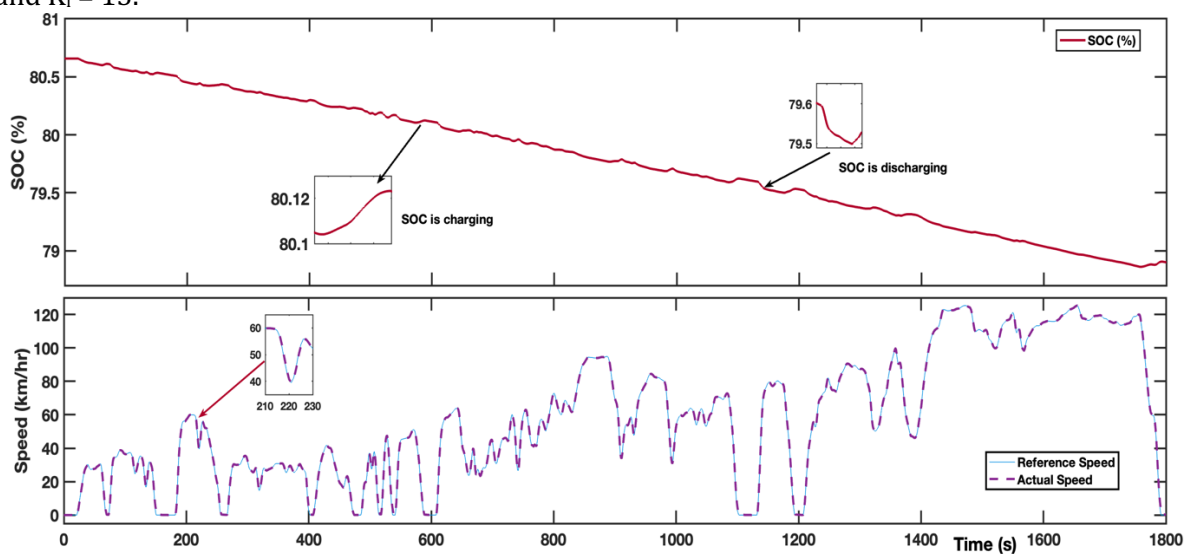


Figure 3. The relationship between SOC and speed under the WMTC drive cycle with $K_p = 100$ and $K_i = 15$.

The actual speed closely follows the reference speed, demonstrating the effectiveness of the PI controller integrated within the system. The rider control system significantly reduces tracking error, ensuring precise speed regulating and improved dynamic response of the electric motorcycle. The results highlight the dynamic interaction between vehicle operating conditions and battery energy status, where SOC varies in response to speed fluctuations throughout different phases of the drive cycle. This configuration of PI gains ensures effective speed regulation while facilitating observable energy recovery during deceleration phases and energy consumption during acceleration.

Additionally, the regenerative braking system demonstrates high energy recovery efficiency throughout the braking phases, enabling rapid and precise control of brake torque, as known the

electric motor operates as a generator. In contrast, during acceleration, the SOC decreases as a result of battery discharge. The degree of SOC fluctuation is influenced by the drive cycle profile. Regenerative braking is most active when the braking torque becomes negative, corresponding to a reduction in vehicle speed. In this state, the system optimizes energy recovery by maximizing the conversion of mechanical energy into electrical energy, thereby minimizing energy losses that would otherwise be dissipated as heat.

Table 2 summarizes the total energy consumed and recovery with different inputs of SOC for the WMTC drive cycles. It was observed that when the integral gain (K_i) was set below 1, the speed control became instability and reduced smoothness. However, the values of the distance travelled remained relatively consistent across different SOC settings, indicating that variations in proportional gain primarily influence speed tracking performance without significantly affecting overall travel range.

Table 2. Total energy consumed versus total energy recovered under the WMTC drive cycle.

	Kp		100			
	Ki	15	20	80	50	0.1
Total distance travelled (km)		28.94			29.12	
SOC (%)	80	50	20	80	50	20
Total energy consumed (Wh/km)	3.375	3.719	3.756	4.082	3.656	3.555
Total energy recovered (Wh/km)	1.446	1.594	1.610	1.750	1.567	1.523
Difference (Wh/km)	1.929	2.125	2.146	2.332	2.089	2.032

4. Conclusion

In summary, this study successfully modelled the E-Motorcycle based on longitudinal dynamics and integrated regenerative braking, demonstrating effective brake control and energy recovery through SOC fluctuations. The system's performance ability to study and analyze the energy recovery. Future work could explore advanced braking control strategies, such as Model Predictive Control (MPC), fuzzy logic control (FLC), or neural networks (NN), to further enhance system stability, efficiency, and adaptability through AI integration.

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