Impact of riding posture and regenerative braking on electric motorcycle energy consumption

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***Abstract*—In this paper, the impact of riding posture and regenerative braking on electric motorcycle energy economy is described. The motorcycle longitudinal dynamic model is first built to describe the motorcycle acceleration, tyre load transfer and energy consumption. Through energy consumption analysis based on the world motorcycle test cycle-class 3-2 (WMTC 3-2), the low riding posture can save up to 22.65% of energy consumption than the high riding posture, and regenerative braking can help to save up to 7.65% of energy consumption, which demonstrates the benefit of riding posture control and regenerative braking on energy saving. It is also demonstrated that riding posture has an impact on the rear tyre load and the available rear tyre longitudinal force. At low tyre road friction conditions, higher riding posture can provide more rear tyre longitudinal force for accelerating and regenerative braking, which improves the motorcycle dynamic performance and energy economy.**

***Index Terms*—Electric motorcycle, riding posture, regenerative braking, vehicle aerodynamics.**

I. Introduction

Transportation electrification is rapidly moving forward to reduce fossil fuel consumption and carbon emissions. For on-road transportation, significant progress has been made in commercial and family vehicles such as buses, vans and passenger cars. At the same time, research and development of electric motorcycles, especially in developing countries [1]–[3], is also attracting more and more attention and showing their positive impacts on energy, environment and climate [4], [5]. Electric driving systems and various energy storage systems such as lithium-ion battery, super-capacitor and fuel cell have been applied to motorcycles.

Since the multi-gear transmission and clutch can be canceled in the electric motorcycle owing to electric motor advantages, motorcycle launching and driving are only controlled by the throttle grip and braking is only controlled by the front brake lever and rear brake pedal. Electric motorcycle provides the option of using the motor for regenerative braking [6], [7] in addition to the front and rear mechanical brake actuators, which helps to recover the kinetic energy and reduce energy consumption. Regenerative braking also reduces the mechanical brake discs wear and heat degradation which bring maintenance requirements and safety problems in engine-driven motorcycles. Due to the rider mass being more comparable to the motorcycle mass than is the case in a car, the riding posture has an obvious impact on the tyre load distribution and air resistance.

At the moment, research on the impact of electric motorcycle riding posture and regenerative braking on the energy economy is scarce. As to regenerative braking, it is available on some production electric motorcycles but is normally designed as a constant portion of the total braking force demand and there is a lack of research on regenerative braking control strategy optimization. The regenerative braking control strategy is required in the electric motorcycle to allocate the demanded braking force to motor and mechanical brake actuators [8].

The regenerative braking efficacy is affected by the maximum rear tyre longitudinal force which is determined by the rear tyre vertical load and tyre road friction coefficient [9]. For a motorcycle, its rear tyre load changes with different acceleration and riding postures. During braking, load transfer happens where the front tyre load is increased and the rear tyre load is decreased [10]. The riding posture can change from leaning forward to more upright. When riding posture is closer to upright, the rear tyre gets more load and can provide more longitudinal force for regenerative braking. However, a higher riding posture increases the frontal area and introduces more air resistance at the same time [11]. This paper investigates the electric motorcycle energy economy considering riding posture and regenerative braking with the aim of finding a more efficient riding strategy to improve the electric motorcycle energy economy.

This work was funded by Innovate UK through the Advanced Propulsion Centre [Grant Number 10020994].

II. Electric motorcycle dynamic modelling

A. Electric motorcycle longitudinal dynamic model

In the electric motorcycle, the electric motor drives the motorcycle through a single gear and the rear wheel. The resistance acting on the motorcycle mainly consists of rolling resistance, air resistance and road slope resistance. The electric motor can also output negative torque to realize regenerative braking which recovers the kinetic energy and charges the battery. Since the motorcycle researched is rear wheel-driven, the driving force can only be provided by the rear wheel and the regenerative braking can only be conducted by the rear wheel [12]. Braking force provided by mechanical brake actuators can be applied to both the front wheel and rear wheel. In the longitudinal direction, the motorcycle dynamics can be described by (1):

$$m\delta a = F_m - F_{bf} - F_{br} - mgsin\phi - 0.5\rho AC_d V^2 - mgcos\phi f \tag{1}$$

where *m* is the total mass of the motorcycle and rider, δ is the equivalent rotational components factor, *a* is the motorcycle acceleration, F_m is the force on rear wheel generated by the motor, F_{bf} is the front wheel mechanical braking force, F_{br} is the rear wheel mechanical braking force, *g* is the gravitational acceleration, ϕ is the road slope, ρ is the air density, *A* is the frontal area of motorcycle and rider, C_d is the air drag coefficient, *V* is the motorcycle speed, *f* is the tyre rolling resistance coefficient.

$$F_m = \begin{cases} T_m i\eta/R, & Driving \\ T_m i/(\eta R), & Braking \end{cases} \tag{2}$$

where T_m is the motor torque, *i* is the powertrain gear ratio between motor and wheel, η is the powertrain efficiency, *R* is the dynamic tyre radius.

During motorcycle acceleration and deceleration, the inertial force causes load transfer between the front and rear tyres, which can be described by (3):

$$\begin{cases} F_{zf} = mg\frac{L_r}{L} - ma\frac{H_c}{L} \\ F_{zr} = mg\frac{L_f}{L} + ma\frac{H_c}{L} \end{cases} \tag{3}$$

where F_{zf} is the front tyre load, F_{zr} is the rear tyre load, L_f is the distance from the front wheel to the centre of gravity (CoG) of combined motorcycle and rider mass, L_r is the distance from the rear wheel to the CoG, *L* is the motorcycle wheelbase and H_c is the height of the CoG. The parameters and their descriptions are listed in Table I. L_f, L_r, H_c and AC_d have different values under different riding postures, which are variables in this research.

B. Electric motor model

The maximum motor torque is modelled as a lookup table determined by motor speed. The real-time motor torque according to the rider's command can be expressed as (4):

$$T_m = \alpha_p T_{mmax}(\omega_m) \tag{4}$$

TABLE I
Motorcycle dynamic model parameters

Symbol	Description	Value	Unit
m	Motorcycle and rider mass	345.7	kg
δ	Equivalent rotational components factor	1.05	/
L	Wheelbase	1.48	m
f	Tyre rolling resistance coefficient	0.013	/
ρ	Air density	1.23	kg/m^3
η	Powertrain efficiency	0.93	/
R	Dynamic tyre radius	0.31	m
i	Powertrain gear ratio	7.4	/

where α_p represents the driver accelerating or braking demand and T_{mmax} is the maximum motor torque at speed ω_m. The motor efficiency is modelled as a 2-D lookup table with motor speed and torque as inputs, as shown in Fig. 1.

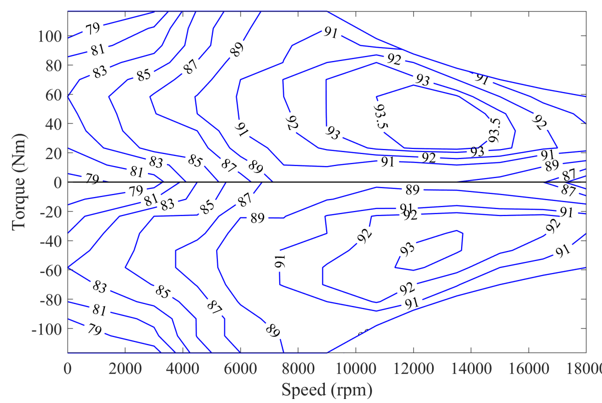


Fig. 1. Electric motor efficiency map (%).

C. Battery model

The equivalent circuit battery model is adopted in this research. In the model, the state of charge (SoC) changing rate is described as (5):

$$S\dot{o}C = \frac{\sqrt{U_{oc}^2 - 4R_bP_b} - U_{oc}}{2Q_{max}R_b} \tag{5}$$

where U_{oc} is the open circuit voltage (OCV), R_b is the battery internal resistance, Q_{max} is the maximum battery capacity and P_b is the battery output power which is calculated by (6):

$$P_b = \begin{cases} T_m\omega_m/\eta_m, & Driving \\ T_m\omega_m\eta_m, & Braking \end{cases} \tag{6}$$

where η_m is the motor efficiency obtained from the efficiency map shown in Fig. 1.

As shown in Fig. 2, the battery has different U_{oc} and R_b characteristics during charging and discharging which are calibrated at the temperature of 25 °C.

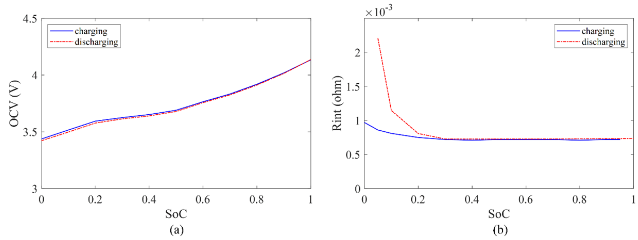


Fig. 2. Battery characteristics. (a) OCV. (b) Internal resistance.

D. Air resistance and CoG position variation with different riding postures

In this study, a wind tunnel test was conducted to evaluate the air resistance with different riding postures, which is described by the factor of AC_d. Three postures were tested namely low riding posture, mid riding posture and high riding posture, as shown in Fig. 3 from the left to the right respectively. The test results are shown in Table II. Due to commercial considerations, the values are normalized in the table where AC_d of low riding posture is treated as 1 and AC_d of mid and high riding postures are presented as ratios to the low riding posture.

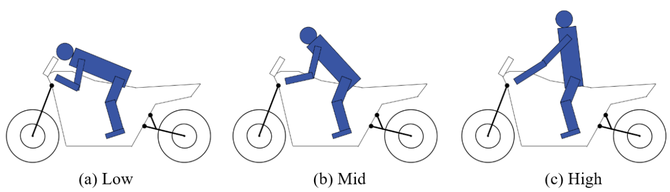


Fig. 3. Test with different riding postures.

TABLE II
NORMALIZED AIR RESISTANCE FACTORS AT DIFFERENT RIDING POSTURES

Riding posture	Low	Mid	High
AC_d	1	1.36	1.44

III. IMPACT OF RIDING POSTURE AND REGENERATIVE BRAKING ON MOTORCYCLE ENERGY ECONOMY

A. Motorcycle energy consumption and motor working condition analysis

To investigate the motorcycle energy economy, a motorcycle model is built in Matlab/Simulink where the world motorcycle test cycle-class 3-2 (WMTC 3-2) is used as the target driving cycle. The motorcycle speed is controlled by a PID controller where the inputs are the error and its integral between the target speed from WMTC 3-2 and the real-time motorcycle speed. The output is the motor torque during driving and the total braking torque during braking. The simulation contains two scenarios: non-regenerative braking and regenerative braking. In the non-regenerative braking scenario, the braking force is provided by the mechanical brake actuators and no kinetic energy is recovered, which is the same as the conventional engine-driven motorcycle. This research focuses on exploring the potential of regenerative braking on electric motorcycle energy economy, therefore it is assumed that in the regenerative braking scenario, all the braking is conducted by the motor through the rear wheel to recover the kinetic energy. The following results demonstrate that the motor is capable of conducting pure regenerative braking when the tyre road friction condition can provide sufficient force. However, it should also be noticed that considering braking stability and steering, combined braking of the front wheel and rear wheel might be preferred in real applications.

Fig. 4 shows the speed control results which demonstrates that the PID controller works effectively to follow the driving cycle under all the riding postures.

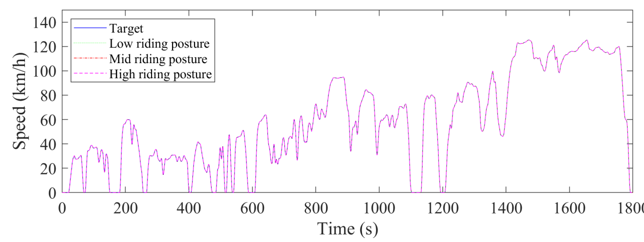


Fig. 4. Motorcycle speed following control for WMTC 3-2.

The motorcycle energy consumption is shown in Fig. 5 and summarized in Table III. Compared to the non-regenerative braking conditions, the energy consumption is reduced by 7.65% for low riding posture, 5.88% for mid riding posture and 5.26% for high riding posture respectively with the help of regenerative braking, which indicates notable energy economy improvement by adopting regenerative braking. Furthermore, it can be found that the riding posture shows a remarkable impact on the motorcycle energy consumption. Without regenerative braking, mid riding posture and low riding posture save 3.64% and 20.65% energy consumption respectively compared to high riding posture. With regenerative braking, mid riding posture and low riding posture save 4.27% and 22.65% energy consumption respectively compared to high riding posture.

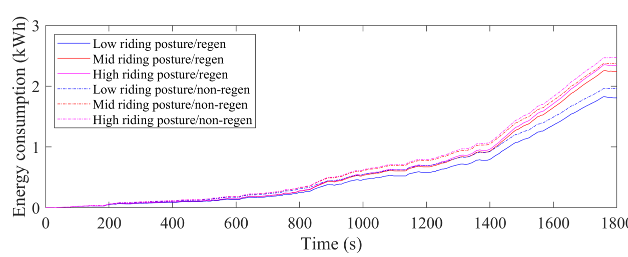


Fig. 5. Effect of riding posture and regenerative braking on motorcycle energy consumption.

The required longitudinal tyre force and motor power in the regenerative braking scenario are shown in Figs. 6 and 7 which indicate that at low motorcycle speed, the main resistance is tyre rolling resistance. The riding posture has less impact on the motorcycle's total resistance in this condition.

TABLE III
EFFECT OF RIDING POSTURE AND REGENERATIVE BRAKING ON MOTORCYCLE ENERGY CONSUMPTION

Riding posture	Energy consumption /non-regen (kWh)	Energy consumption /regen (kWh)	Energy saved by regen
Low	1.96	1.81	7.65%
Mid	2.38	2.24	5.88%
High	2.47	2.34	5.26%

However, with high motorcycle speed, the riding posture shows a significant impact on the motorcycle's total resistance and electric motor power.

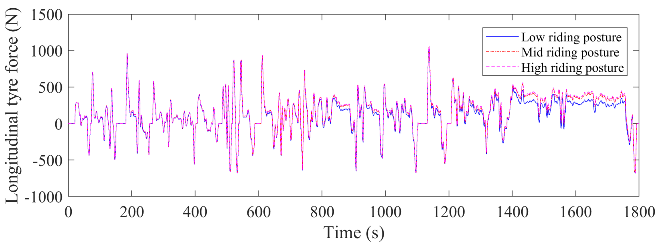


Fig. 6. Required longitudinal tyre force.

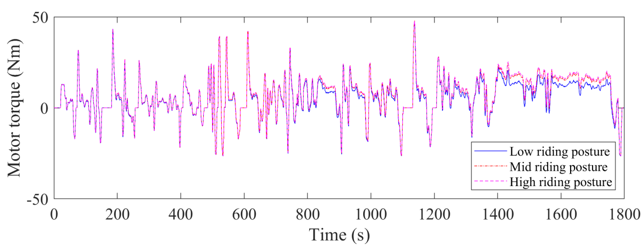
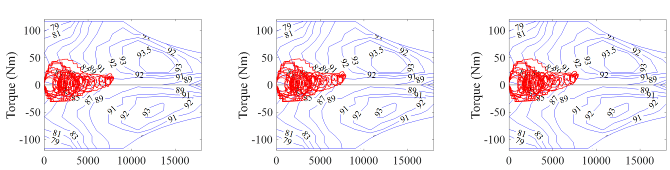


Fig. 7. Motor power in regenerative braking scenario.

The motor working points in the regenerative braking scenario are shown in Fig. 8 which shows that the motor can provide torque for any of the driving and braking if the tyre road friction is satisfied. This indicates that all the rear braking force can be provided by regenerative braking if the rear tyre road friction condition permits.



(a) Low riding posture (b) Mid riding posture (c) High riding posture

Fig. 8. Motor working points in regenerative braking scenario.

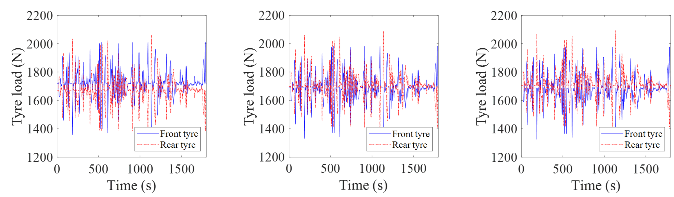
To improve the motorcycle energy efficiency, the preferable driving strategy is to use the lowest riding posture to reduce the air resistance and use rear wheel regenerative braking as much as possible to recover more kinetic energy.

B. Effect of tyre road friction condition on motorcycle acceleration and regenerative braking

While low riding posture is beneficial to motorcycle energy economy, it could reduce the rear tyre load and make the rear tyre incapable of providing sufficient longitudinal force for regenerative braking, especially under low tyre road friction conditions, which inversely degrades the motorcycle energy economy. Based on the normalized CoG position variation with riding posture, as shown in Table IV, the effect of riding posture on tyre load distribution is illustrated in Fig. 9. In standstill conditions, mid riding posture and high riding posture can provide 1.6% and 2% more rear tyre load than low riding posture, which increases the rear tyre force limit and improves the motorcycle accelerating and regenerative braking performance. During accelerating and decelerating, higher riding postures also bring more rear tyre load variations according to Eq.(3).

TABLE IV
NORMALIZED COG VARIATION AT DIFFERENT RIDING POSTURES

Riding posture	Low	Mid	High
Rear tyre load ratio	1	1.016	1.02
CoG height	1	1.004	1.02



(a) Low riding posture (b) Mid riding posture (c) High riding posture

Fig. 9. Tyre load variation under different riding postures.

On different road surfaces, the tyre road friction condition varies significantly, which affects the maximum available rear tyre force for motorcycle accelerating and regenerative braking, as described in (7):

$$F_t = \mu F_z \tag{7}$$

where F_t is the maximum tyre force, μ is the tyre road friction coefficient, F_z is the vertical tyre load.

Assuming the tyre road friction coefficient is 1, the maximum rear tyre force can be obtained from tyre load, as shown in Fig. 10. It is shown that at this tyre road friction condition, the rear tyre is capable of providing the required tyre force for all the driving and braking demands at all the riding postures. The rear tyre force margin shown in Fig. 11 indicates that the rear tyre still have remaining capability to support other manoeuvres such as steering, climbing, accelerating and braking.

When the motorcycle drives on slippery roads such as wet roads or icy roads, the tyre road friction coefficient is reduced and the maximum rear tyre force is also degraded. A tyre road friction coefficient of 0.55 is considered to study the

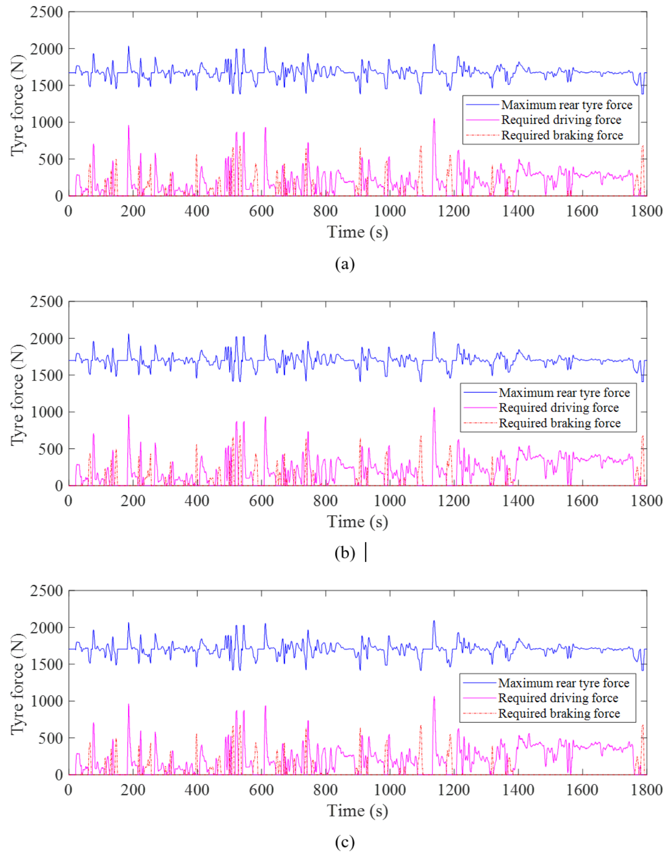


Fig. 10. Maximum rear tyre force and required tyre force (μ=1), (a) Low riding posture, (b) Mid riding posture, (c) High riding posture.

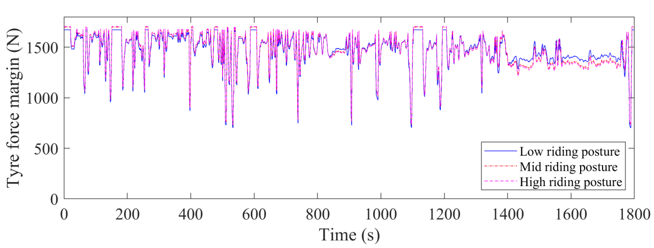


Fig. 11. Rear tyre force margin (μ=1).

rear tyre force capability for driving and braking at lower tyre road friction conditions. As shown in Fig. 12, at low riding posture, there are more occasions when the required driving and braking force is closer to the maximum rear tyre force. In the case of the required driving force is larger than the maximum rear tyre force, the motor torque should be derated to avoid tyre slip. As a result, the motorcycle can't achieve the target acceleration. When the required braking force is larger than the maximum rear tyre force, the braking can't only be conducted by rear wheel regenerative braking to avoid wheel lock up. Front wheel mechanical braking has to be used as compensation. Fig. 13 demonstrates that at low tyre road friction conditions, the rear tyre margin is reduced where adjusting riding posture can slightly help to increase the rear tyre load if required.

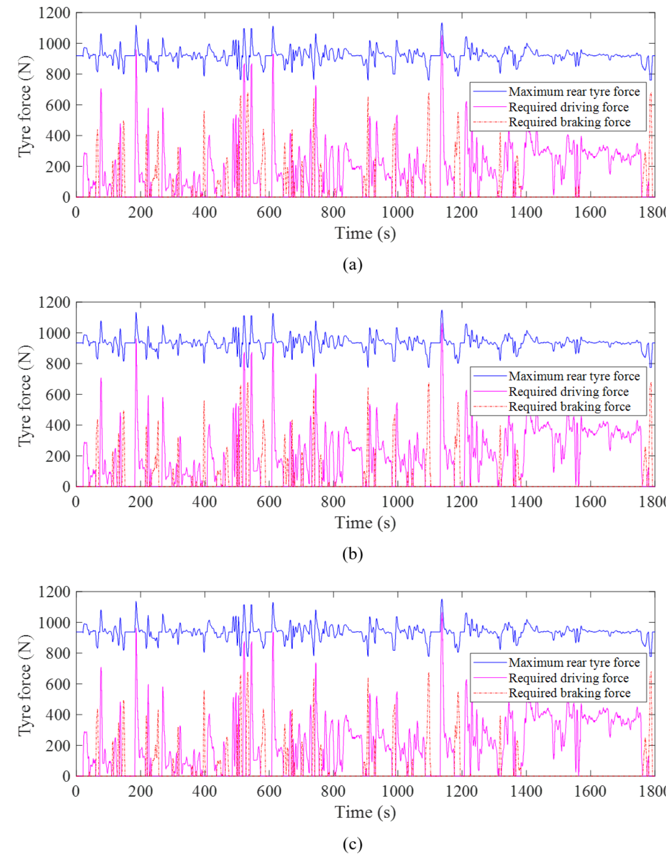


Fig. 12. Maximum rear tyre force and required driving and braking force (μ=0.55), (a) Low riding posture, (b) Mid riding posture, (c) High riding posture.

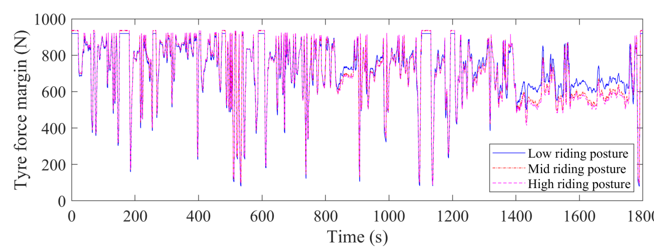


Fig. 13. Rear tyre force margin (μ=0.55).

IV. Conclusions

Based on the widely used WMTC 3-2 driving cycle, the motorcycle energy consumption is investigated for different riding postures considering regenerative braking. It is shown that low riding posture can help to save 20.65% energy consumption compared to high riding posture without regenerative braking and 22.65% with regenerative braking. Taking advantage of regenerative braking, low riding posture, mid riding posture and high riding posture can save 7.65%, 5.88% and 5.26% of energy consumption respectively. The motor can provide all the required braking force on the rear wheel, but regenerative braking can be restricted by the maximum rear tyre force at low tyre road friction coefficient conditions. In the engine-driven motorcycles, the front and rear braking are separately controlled by the rider. If the braking system is also separated in the electric motorcycle, the rider is recommended to use the rear braking as much as possible and the onboard braking control strategy should use the motor for rear wheel braking to recover more energy. In the future, the integrated braking control structure can be designed for the electric motorcycle where only one braking command input is required from the rider and the braking force is allocated to the mechanical brake actuators and electric motor by the advanced braking control strategy.

References

[1] A. D. Murtiningrum, A. Darmawan, and H. Wong, “The adoption of electric motorcycles: A survey of public perception in Indonesia,” J. Clean. Prod., vol. 379, pp. 134737.

[2] L. R. Jones, C. R. Cherry, T. A. Vu, and Q. N. Nguyen, “The effect of incentives and technology on the adoption of electric motorcycles: A stated choice experiment in Vietnam,” Transp. Res. A: Policy Pract., vol. 57, pp. 1–11.

[3] S. Z. Rajper, and J. Albrecht, “Prospects of electric vehicles in the developing countries: a literature review,” Sustainability, vol. 12, pp. 1906.

[4] G. Carranza, M. D. Nascimiento, J. Fanals, J. Febrer, and C. Valderrama, “Life cycle assessment and economic analysis of the electric motorcycle in the city of Barcelona and the impact on air pollution,” Sci. Total Environ., vol. 821, pp. 153419.

[5] B. L. Cox, and C. L. Mutel, “The environmental and cost performance of current and future motorcycles,” Appl. Energy, vol. 212, pp. 1013–1024.

[6] J. P. Fernández, J. M. V. García, M. G. A. Vargas, J. J. C. Aguilar, and J. A. C. Carrillo, ”Influence of system dynamics in brake blending strategies for electric vehicles,” in Advances in Dynamics of Vehicles on Roads and Tracks: Proceedings of the 26th Symposium of the International Association of Vehicle System Dynamics, IAVSD 2019, August 12-16, 2019, Gothenburg, Sweden, 2020: Springer, pp. 1555-1564.

[7] Suyanto, P. A. Darwito, R. A. Wahyuono, M. S. Arifin, and B. Sudarmanta, ”Design of Regenerative Braking System for Electric Motorcycle Based on Supercapacitor with Fuzzy PID,” Int. J. Automot. Technol., vol. 24, pp. 187-194.

[8] N. Rego, and R. Castro, “Regenerative Braking Applied to a Student Team’s Electric Racing Motorcycle Prototype: A Theoretical Study,” Appl. Sci., vol. 13, pp. 3784.

[9] P. Huertas-Leyva, M. Nugent, G. Savino, M. Pierini, N. Baldanzini, and S. Rosalie, “Emergency braking performance of motorcycle riders: skill identification in a real-life perception-action task designed for training purposes,” Transp. Res. F Traffic Psychol. Behav., vol. 63, pp. 93–107.

[10] A. Phalke, and M. R. B. Agrewale, “Optimal brake force distribution in motorcycle for straight-line braking,” Mater. Today: Proc., vol. 72, pp. 1335–1341.

[11] L. T. Hieu, N. X. Khoa, and O. Lim, “An Investigation on the Effects of Input Parameters on the Dynamic and Electric Consumption of Electric Motorcycles,” Sustainability, vol. 13, pp. 7285.

[12] A. Farzaneh, and E. Farjah, “Analysis of Road Curvature’s Effects on Electric Motorcycle Energy Consumption,” Energy, vol. 151, pp. 160–166.