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# Modelling and Brake Blending Control for Multi-Drive Mode Electric Two-wheelers

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**Abstract**—In electric two-wheelers, high riding performance in terms of energy consumption, ride comfort and rapid acceleration is known as a key enable for the sustainable development. The key performance indicators are dependent upon factors like length of the trip, state of charge of the battery, current traffic conditions and rider behaviors. This leads to the need to develop a highly efficient and convenient motorcycle with multiple drive modes, to enhance customer satisfaction. It is therefore critical to design a brake blending control strategy capable of working effectively with different drive modes to maximize the braking energy recoverability without impacting ride comfort. In order to address this challenge, a simple but efficient brake blending strategy based on serial braking concept, has been developed in this paper, for a two-wheeler electric vehicle with multiple drive modes.

**Keywords**—Two-wheeler Dynamics, Multiple Drive Modes, Brake Control, Regenerative Braking, Brake Blending Strategy.

## I. INTRODUCTION

Developing countries promote e-mobility as an alternative means to IC engine powered vehicles for transport in order to boost their rapid economic growth, to suffice the growing travel demand due to increasing urbanisation, and to ensure energy protection. In addition, e-mobility produces zero or ultra-low tailpipe emissions and significantly low noises, hence, reducing local air pollutions.

Though the performance of electric vehicles in terms of acceleration and max speed are on par with the IC engine vehicles of the same market segment, the major challenge is the limited range due to lesser energy density by mass of batteries. Regenerative braking is unique to electric powertrain offering a good potential in reducing the overall energy consumption by recovering the kinetic energy during braking. However, it is highly challenging to design a regenerative braking strategy for two-wheelers to maximize the recuperation energy, without impacting the vehicle performance and stability under various driving conditions.

The user's need on the vehicle performance in terms of acceleration, max speed and energy consumption is dependent on many factors, such as trip length, rider behaviour, battery states and traffic conditions which can contradict each other. Thanks to the development of electrification technologies, effective control of driving torque of an electrical propulsion system, could help to meet the customer requirements. It is therefore necessary to design multi-drive modes in order to offer a good number of degrees of freedom for user interactions. For instance, the rider can choose economical driving mode for the best range, or sporty drive mode for the best power performance. For any mode, braking performance is always of significant importance. So, it is critical to design a front - rear wheel brake proportioning algorithm that allows, multiple regenerative braking and brake blending scenarios to deal with different power and energy requirements and rider expectations for individual drive modes.

The development of regenerative braking and brake blending strategy for electric two-wheelers involves two major steps: 1) proportioning the total brake torque requirement to the front and rear wheel brake torques considering brake safety and, 2) proportioning the rear wheel brake torque into brake torques to be produced by friction braking system and regenerative braking.

The maximum braking force which can be applied to a wheel is dependant mainly on two factors: (i) the normal load on the wheel axle and, (ii) the coefficient of friction between the tire and the road surface. When the applied brake force is greater than the braking force corresponding to the maximum coefficient of friction between the tyre-road surfaces, the wheel locks [1] making the vehicle unstable.

In order to ensure safety and stability during braking of two-wheelers, a brake torque distribution strategy needs to be designed to proportion the net brake torque calculated from the driver's brake input into front and rear wheel brake torques by controlling the front and rear wheel slip in order to avoid wheel lock. In the existing literatures, brake distribution strategies are majorly based on limiting curves of braking [2]. These curves are known as: the i-curve (ideal distribution curve) which proportions the brake torque such that the front and rear wheels lock at the same time; the m-curve (based on Regulation No 13 of the Economic Commission for Europe of the United Nations (UN/ECE) - ECE R13) which ensures minimum rear wheel brake force while the front wheel is locking while braking; and the f-curve which establishes the brake force relationship when front wheel is locking and rear wheel is unlocking. In the existing state of art, major focus has been given for the four wheeler electric vehicles with parallel braking concept for front and rear wheels. Brake torque proportioning strategies based on braking curves, have been proposed for different vehicle configurations such as vehicles with independently driven front and rear wheels [3], [4] and front wheel drive configurations [5].

In a parallel braking strategy, the total brake torque requirement is always distributed to both front and rear brake systems with constant or variable distribution ratio. On the contrary, in a serial braking strategy [6], only one of the brakes is used during low or mild braking requirements. During extreme braking requirements, the primary brake system is used to its maximum limit and the remaining brake torque is distributed to the other brake system. The existing literatures also propose different brake blending strategies for vehicles [6], [7]. In these strategies the amount of regenerative braking torque at an instant motor speed is calculated based the battery states (like the state of Charge (SOC) and max allowable charge current) and powertrain parameters (like max regenerative brake torque) using either a deterministic rule-based controller or a heuristic fuzzy controller.

The strategies for brake force distribution presented in the literatures concentrate on brake proportioning methods for

four-wheelers which work on parallel braking driven by a single brake pedal and, the total brake demand is proportioned to the front and rear brakes. In a typical two-wheeler, there are two independent brake levers through which the rider can control the front and rear brakes independently. Also, the parallel braking concept results in less recuperative braking energy in two-wheelers as the powertrain is usually connected only to the rear wheel and the brake force is distributed to the front wheel even under low/mild braking conditions. Also, the proposed algorithms do not prevent wheel lock while braking but ensure that the front wheels lock first.

In order to achieve the maximum energy recovery by regenerative braking without compromising vehicle stability, the slip rate of the wheels need to be maintained at the optimum slip ratio where the coefficient of friction between the tyre-road surfaces are maximum with a serial braking strategy which maximizes the usage of rear wheel braking. Also, from the above studies on existing literature, the conventional strategies the rider does not have any direct control on the amount of regenerative brake torque.

In this work, to address research gaps found in the existing literatures, a brake blending strategy based on serial braking concept, have been developed for a two-wheeler electric vehicle with multiple drive modes with varying objectives like maximizing EV range, maximizing ride comfort or a balanced drive, taking multiple user inputs to provide methods to provide direct control over regenerative braking.

## II. SYSTEM OVERVIEW

### A. Vehicle and Subsystems

Configuration of the electric two-wheeler studied here is described in Figure 1. The vehicle is powered by a li-ion battery pack managed by a battery management system (BMS). The vehicle control unit (VCU) receives the driver's inputs (such as throttle opening and brake lever travel), generates the motoring or regenerative braking torque request which are sent to the motor control unit (MCU) to drive the motor to follow the request. The electric motor is connected to the rear wheel of the vehicle through a transmission system with a gear box. The front and rear wheel brakes with ABS have been connected to the respective wheels for brake safety.

The vehicle has 3 user selectable drive modes namely Economy, City and Race. The Economy mode has been designed to have the least energy consumption during the ride, the Race mode has been designed to have the maximum acceleration and maximum speed to provide a sporty feel to the ride, while the City mode has been designed to have a balanced performance and drive feel to provide a comfortable ride to the rider while riding in a city. The user can choose the drive mode depending on the expected performance.

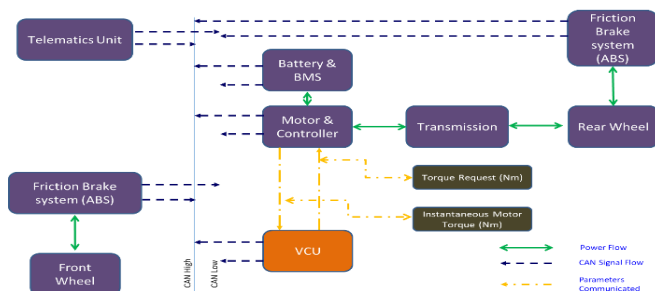


Figure 1: Overview of Vehicle Configuration

### B. Problem Definition

As discussed, the brake blending strategy needs to be developed to deal with multi-drive modes using the serial braking concept for two-folds: (1) ensuring brake safety by preventing front and rear wheel lock and, (2) maximising the amount of regenerative braking.

### III. ELECTRIC VEHICLE MODELLING

To develop the brake blending control for the targeted electric two-wheeler, a representative model is designed using MATLAB/Simulink Environment with the parameters of two-wheeler given in Table 1. The overall layout of the two-wheeler electric vehicle model is shown in *Figure 2* while the detailed model design is presented below.

### A. Drive Cycle Input

The drive cycle input subsystem provides the reference speed vs time as the input to the driver subsystem to drive the vehicle in order to test the performance in the intended drive cycle. In addition to the reference speed, it also provides the current user selected drive mode and the accelerometer measurement data for the brake blending controller to choose the strategy and calculate the Road inclination respectively.

### B. Rider model

The rider model takes the reference speed from the drive cycle input and the current vehicle speed feedback from the longitudinal vehicle dynamics subsystem to generate the acceleration request varying from 0 to 1 / deceleration request varying from -1 to 0. Here, the rider is modelled by a fuzzy inference. The speed tracking error and rate of change of the speed error are selected as the inputs. The output of the fuzzy model varies from -1 to 1 which is later subdivided into acceleration and deceleration requests as seen in Figure 3. Triangular membership functions (MFs) are used for both the inputs and output. For each input, 5 fuzzy sets containing LNE (Large Negative Error), SNE (Small Negative Error), ZE (Zero Error), SPE (Small Positive Error) and LPE (Large Positive Error) are employed (see Figure 4 and Figure 5).

TABLE 1: MODEL PARAMETERS

No	Two-Wheeler - Model Parameters		
	Parameter	Value	Unit
1	Mass of the vehicle and Rider (m)	200	kg
2	Horizontal distance from CG to front axle ( $l_f$ )	0.5	m
3	Horizontal distance from CG to rear axle ( $l_r$ )	0.7	m
4	CG height above ground (h)	0.5	m
5	Frontal Area (A)	2.5	m <sup>2</sup>
6	Drag coefficient ( $C_d$ )	0.15	-
7	Rolling Radius of Tyres ( $R_f$ , $R_r$ )	0.2	m
8	Rolling Resistance Coefficient ( $\mu_{rr}$ , $\mu_{fr}$ )	0.02	-
9	Gear Ratio of the Transmission System ( $G_r$ )	6	-

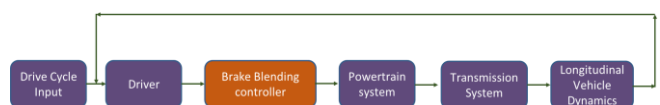
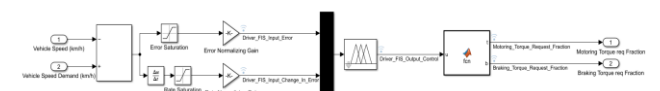


Figure 2: Electric two-wheeler model



*Figure 3: Driver Subsystem*

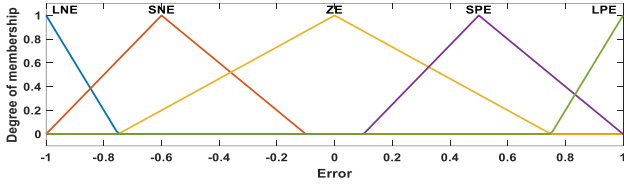


Figure 4: MFs for 1st fuzzy input, Error

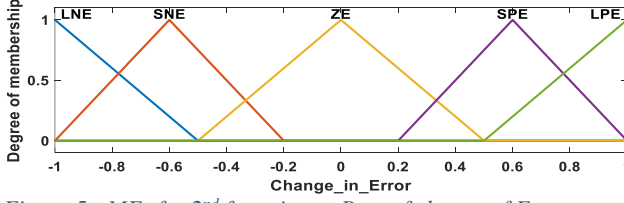


Figure 5: MFs for 2nd fuzzy input, Rate of change of Error

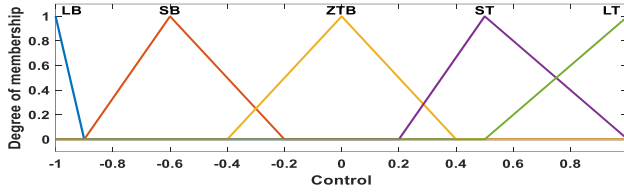


Figure 6: FLC Driver - MFs for Controller's Output

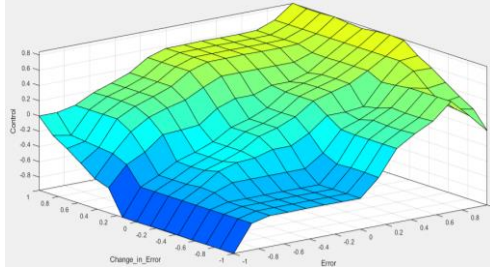


Figure 7: Control Surface - Driver FLC

Table 2: Rule Table - Driver FLC

	Rate of Change of Error				
Error	LNE	SNE	ZE	SPE	LPE
LNE	LB	LB	SB	SB	ZTB
SNE	SB	SB	SB	ZTB	ZTB
ZE	SB	SB	ZTB	ST	ST
SPE	ST	ST	ST	ST	ST
LPE	ZTB	ST	LT	LT	LT

Similarly, 5 MFs labelled as LB (Large Brake), SB (Small Brake), ZTB (Zero Throttle Brake), ST (Small Throttle) and LT (Large Throttle) are used for the output (see Figure 6). The fuzzy rules are then defined as in Table 2 and the fuzzy surface is therefore obtained as shown in Figure 7.

### C. Brake Blending Controller

The brake blending controller has 3 main functions:

- Calculation of road inclination angle from accelerometer (resultant of Gravity of 3 axes (axes ( $G_x$ ,  $G_y$ ,  $G_z$ )).
- Distribution of total brake torque required into front & rear wheel brake torques.
- Distribution of wheel brake torque into regenerative and frictional brake torques.

Road inclination angle ( $\phi$ ) is calculated as per the equation (1) using the outputs of accelerometer from the drive cycle input subsystem.

$$\phi = \frac{180}{\pi} \cdot \tan^{-1} \frac{-G_y}{\sqrt{G_x^2 + G_z^2}} \quad (1)$$

The objective of the FW&RW Brake proportioning algorithm is to provide a serial brake distribution between FW & RW brakes avoiding rear wheel lock. Front & Rear wheel brake torque proportioning algorithm is designed as per the flowchart in Figure 8. It is modelled as a Fuzzy inference with the error (Difference in Optimal slip with RW slip) and the rate change of the error to output the brake torque distribution ratio. Driver's Brake command is converted to the total wheel brake torque. Then, the distribution ratio is used to distribute the total wheel brake torque into FW and RW Brake torques.

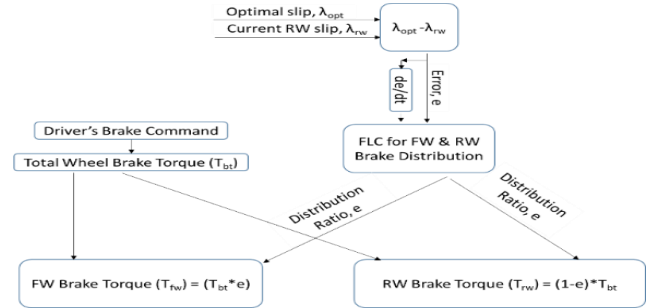


Figure 8: FW&RW Brake Torque Distribution algorithm

In the FLC, Triangular MFs are used for error and rate of change of error, dividing them into 3 fuzzy sets containing LNE (Large Negative Error), SNE (Small Negative Error), ZE (Zero Error) with error varying from -1 to 0 and NEGATIVE, ZERO and POSITIVE with rate of change of error varying from -1 to 1 as seen in Figure 9 and Figure 10.

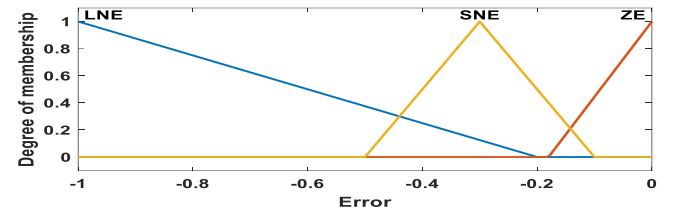


Figure 9: FLC BFD-MFs for Error

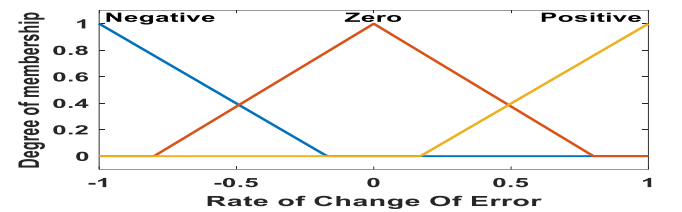


Figure 10: FLC BFD-MFs for Rate of change of Error

Triangular MFs of the output contain containing Only Rear (Only Rear wheel braking), LR\_SF (Large Rear and Small Front wheel braking) and LF\_SR (Large Front and Small Rear wheel braking) as seen in Figure 11.

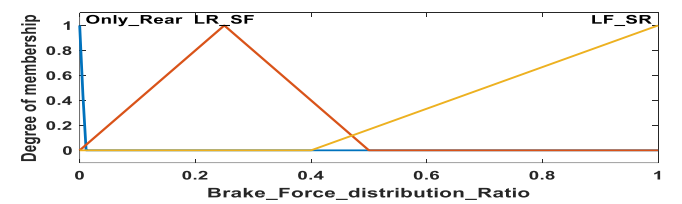


Figure 11: FLC BFD-MFs for Controller's Output

The rules as per Table 3 are defined as to design a control surface as seen in Figure 12.



Table 3 : Rule Table – BFD FLC

	Rate of Change of Error		
Error	NEGATIVE	ZERO	POSITIVE
LNE	LF_SR	LF_SR	LR_SF
SNE	OR	OR	LR_SF
ZE	OR	OR	OR

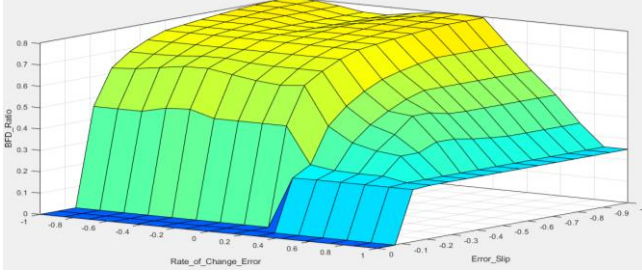


Figure 12: Control Surface - BFD FLC

The rear wheel brake torque is then distributed to the regenerative brake torque and friction brake torque by brake blending controller with the drive mode dependant brake blending strategy as described in Section IV.

#### D. Powertrain and Transmission Models

The powertrain subsystem represents the motor control unit and electric motor which provide motoring and regenerative braking torque to drive the wheels based on the inputs from the brake blending controller. The torque maps in the form of 2-D Matrix, Motor speed, Throttle Opening (%) vs Motor Torque, are used determine the amount of motoring/regenerative braking torque to be delivered at an instant for the current drive mode as represented in Figure 13. Also, a similar efficiency map in the form of 2-D Matrix, Motor speed, Motor Torque vs Efficiency (%), is used to determine the Instantaneous Battery Current for the given Battery Voltage.

During braking, the torque value from the map is added with the additional regen torque calculated by the Brake blending controller subject to constraints of the Powertrain's maximum & minimum Torque for the given motor speed and the battery's acceptable maximum charge current.

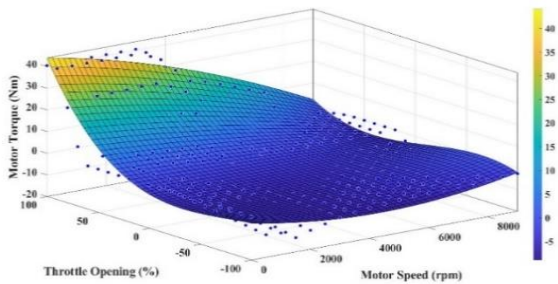


Figure 13: Torque Map for a Drive Mode

The transmission system consists of a gear pair with ratio  $G_r$  ( $G_r=6$ ) between the motor shaft to the rear wheel shaft.

#### E. Longitudinal Vehicle Dynamic Model

Generally, an electric two-wheeler has an electric motor which provides the required tractive power for the ride, a transmission system to multiply the motor torque to the wheel torque, wheel axles and tyres with which, the tractive force is applied on the Road-tyre surfaces. The vehicle also contains

front and rear brake systems connected to the wheels, actuated by left and right brake control levers to decelerate the vehicle by applying brake torque based on driver's requirements. Even though, the vehicle consists of multiple subsystems and parts, all of them move as a single unit. Thus, the two-wheeler can be assumed to be a single lumped mass located at its centre of gravity (CG) with its inertial and mass properties as shown in the Figure 14.

Based on the longitudinal dynamics of the electric two-wheeler vehicle, the acceleration of the vehicle ( $a_x$ ) is determined using Newton's second law with the driving force on the wheels ( $F_w$ ) and the resistive force ( $F_{Rt}$ ) given by the road load equations (2)-(6),

$$a_x = \frac{1}{m} \cdot (F_w - F_{Rt}) \quad (2)$$

$$F_{Rt} = F_r + F_a + F_g \quad (3)$$

$$F_r = (\mu_{rr} \cdot F_{zr} + \mu_{fr} \cdot F_{zf}) \quad (4)$$

$$F_a = \frac{1}{2} \cdot C_d \cdot \rho \cdot A \cdot (V_x + V_w)^2 \quad (5)$$

$$F_g = m \cdot g \cdot \sin \phi \quad (6)$$

$$F_{zr} = \frac{mg}{(l_f + l_r)} \left( l_f + \frac{a_x h}{g} \right) \quad (7)$$

$$F_{zf} = \frac{mg}{(l_f + l_r)} \left( l_r - \frac{a_x h}{g} \right) \quad (8)$$

In the equations (2)-(8), as represented in Figure 14,  $F_r$ ,  $F_a$ ,  $F_g$  represent the rolling resistance, aero-drag and gradient resistance forces acting on the vehicle respectively.  $\mu_{rr}$ ,  $\mu_{fr}$  respectively, represent the coefficient of rolling resistance between the tire-road surfaces of rear and front wheels.  $F_{zr}$ ,  $F_{zf}$  represent the dynamic axle loads on respective wheel axles.  $V_x$ ,  $V_w$  represent the vehicle's longitudinal velocity and wind velocity respectively.  $m$ ,  $g$ ,  $\phi$ ,  $C_d$ ,  $\rho$ ,  $A$ , represent the mass of the vehicle including rider, acceleration due to gravity, the slope angle of the road, drag coefficient, density of air and frontal area of the vehicle, respectively.  $l_r$ ,  $l_f$  represent the distance of CG from rear and front axles.  $h$  represents the height of CG above ground.

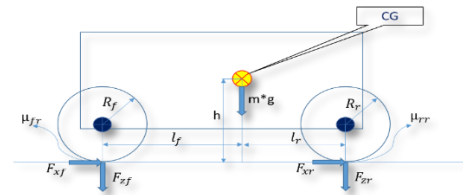


Figure 14 : Free Body Diagram of the Vehicle

The empirical relationship between the wheel slip ( $\lambda$ ) and the coefficient of friction between the tire-road surfaces ( $\mu$ ) is established by the tire magic formula [10] of Pacejka (9),

$$\mu = D \cdot \sin(C \cdot \tan^{-1}\{B\lambda - E[B\lambda - \tan^{-1}(B\lambda)]\}) \quad (9)$$

Where  $\mu$ ,  $\lambda$ ,  $B$ ,  $C$ ,  $D$ ,  $E$  are the coefficient of road friction, slip rate of wheel, magic formula coefficients for stiffness, shape, peak and curvature respectively.

We can infer from the  $\mu$ ,  $\lambda$  relationship (see Figure 15) there is single extremum for the coefficient of friction between the road-tire surfaces over the range of slip rate. In Figure 16,  $\frac{d\mu}{d\lambda}$  and  $\mu$  have been plotted along the slip rate. Also,  $\frac{d\mu}{d\lambda}$  is zero when  $\mu$  reaches extremum value for the given road-tire surface

during acceleration or deceleration. The optimal slip can be calculated analytically by finding the roots of equation (10). Alternatively, it can also be found by zero-crossover detection of  $\frac{d\mu}{d\lambda}$  during braking. (See Figure 16)

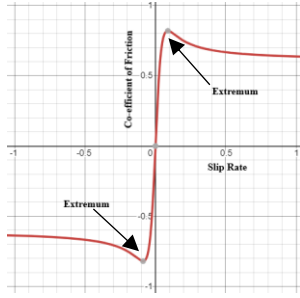


Figure 15: coefficient of friction showing Maximum and Minimum

$$\frac{d\mu}{d\lambda} = \frac{(C \cdot D \cdot \cos(C \cdot \tan^{-1}(B \cdot \lambda + E \cdot (\tan^{-1}(B \cdot \lambda) - B \cdot \lambda))) \cdot (B \cdot E \cdot B - B / (B^2 \cdot \lambda^2 + 1))) / ((B \cdot \lambda + E \cdot (\tan^{-1}(B \cdot \lambda) - B \cdot \lambda))^2 + 1)}{(10)}$$

At  $\lambda = \lambda_{opt}$ ,

$$\left(\frac{d\mu}{d\lambda}\right) = 0 \quad (11)$$

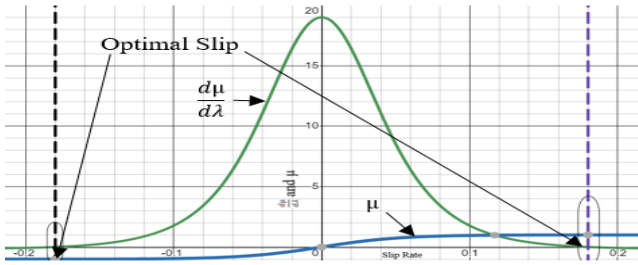


Figure 16: Optimal slip calculation

The calculated optimal slip is the reference input for brake blending controller which implements the serial braking strategy to control the wheel slip during braking.

#### IV. BRAKE BLENDED CONTROL STRATEGY

The algorithm of the drive mode dependant brake blending control strategy is discussed in this section.

##### A. Brake Blending Control Design for Multi-Drive Modes

As discussed in the vehicle configuration section, the vehicle has 3 user selectable drive modes (Economy, City and Race), with each drive mode targeting different user needs on vehicle performance and handling.

To maximize the rider's control over regenerative braking strategy, based on multiple user inputs like throttle closure, front and rear brake lever position and reverse throttling, has been developed.

- Level 0 (L0) and Level 1 (L1) – Minimal (L0) and Optimal (L1) regeneration during throttle closure, to achieve gliding feel and deceleration similar to IC engine powered two-wheelers during vehicle coast down respectively. Torque values corresponding to 0% throttle opening on the torque maps of applicable drive modes are designed for L0, L1 regeneration.
- Level 2 (L2) – Braking regeneration based on brake lever actuation to achieve complete user control over amount of vehicle deceleration with the serial braking strategy for regeneration and friction brake systems. 1D torque map of

motor speed Vs motor torque has been designed for level 2 regeneration to be used in the applicable drive modes.

- Level 3 (L3) – Regenerative braking based on reverse throttle application to provide user's independent control on amount of regenerative braking. Torque values of throttle opening region -100% to -10% on the torque maps of applicable drive modes are designed for L3.

The levels of regenerative braking are mapped to drive modes based on the user's requirements. (See Table 4)

Table 4: Mapping levels of regeneration to drive modes

Drive Mode (Number)	User Requirements	Applicable Levels
Economy (1)	Max Energy Recovery	L 0, L2 & L3
City (2)	Balance on Energy recovery and ride comfort	L1, L2 & L3
Race (3)	Max Ride comfort and Gliding feel	L1 & L2

##### B. Brake Blending Control Algorithm

As discussed in the previous section, L0 and L1 levels are activated in the applicable drive modes on throttle closure.

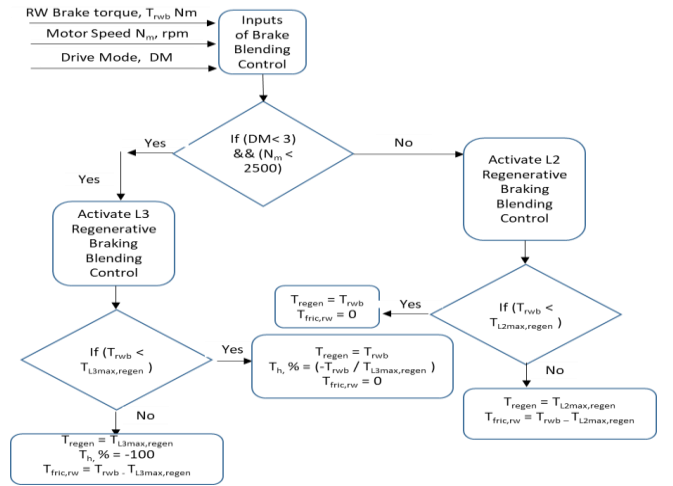


Figure 17: Brake Blending Control Algorithm

As shown in the Figure 17, when the drive mode is 1 or 2, and motor speed is less than 2500 rpm, L3 is activated. For the current motor speed, the Max L3 regenerative braking torque is determined by interpolating the values from the designed 1D lookup-table. Then, the reverse throttle % and the rear wheel frictional brake torque are calculated from total rear wheel brake torque requirement.

When drive mode is 3 or motor speed > 2500rpm, L2 level is activated. For the current motor speed, the Max L2 regenerative braking torque is determined by interpolating the values from the designed 1D lookup-table. Then, the amount of rear wheel frictional brake torque is calculated based on the total rear wheel brake torque requirement.

#### V. SIMULATION RESULTS

In this section, the proposed brake blending control strategy is tested with the simulation model on WMTC Class 2-1. The net energy consumption and the energy recovered by regeneration is compared in different drive modes.

In i-curve based brake force distribution, front brake is used even during low and mild braking on dry tarmac road (see Figure 18) whereas slip control based serial braking strategy uses only rear brakes until the wheel slip reaches optimal slip (-0.18). With slip control, energy consumption per cycle of WMTC reduces by 1.64Wh in race mode.

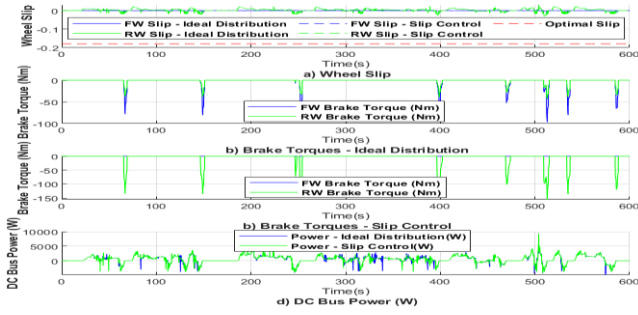


Figure 18 : Performance of Ideal curve vs Slip control

Torque inputs from the powertrain and the rear wheel brake system to the rear wheel against the vehicle speed can be seen in Figure 19. It is evident that, the usage of friction brakes increases from economy mode to race mode. Regenerative braking is utilized to the maximum in eco mode to meet the vehicle's deceleration requirements using L0, L2 & L3 regenerative braking levels.

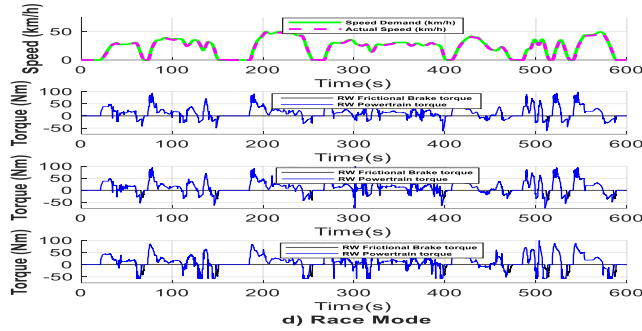


Figure 19: Vehicle Speed (km/h) Vs Rear Wheel Torques (Nm)

Motor Torque against the motor speed can be seen in Figure 20. The peak motoring torque requirement in WMTC is 20Nm for all the drive modes (see Figure 20). Limited acceleration and max speed requirements in economy mode and the designed torque map has enabled the user to effectively control the motoring and regenerative torques of the powertrain to achieve the least net energy consumption.

As seen in Table 5, the energy consumption in economy mode is the lowest with the highest energy recovery by regeneration among the other drive modes. In the Race mode, maximum energy consumption and the least energy recovery can be seen due to the torque map designed for maximum acceleration and vehicle.

Table 5 : WMTC Energy Consumption Test Results

Drive Mode	Energy Consumed (Wh)	Energy Consumption (Wh/km)	Energy Recovered by Regen (Wh)	Energy Recovery (Wh/km)
Economy	88.76	23.7516	38.8808	10.40428
City	90.05	24.0835	30.5828	8.183784
Race	97.69	26.1413	25.3112	6.773134

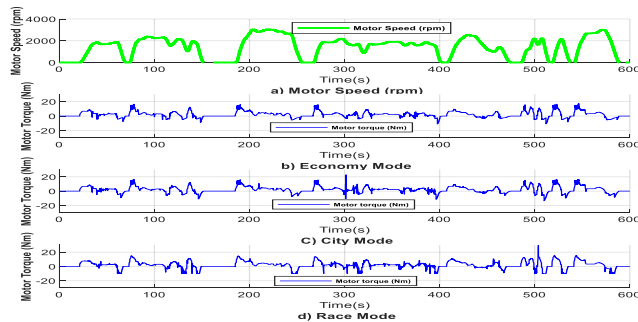


Figure 20: Motor Speed (rpm) Vs Torque (Nm)

## VI. CONCLUSION

For the given electric two-wheeler vehicle, a brake blending control algorithm based on serial braking concept has been developed for multi-drive modes taking different user inputs such as throttle closure, reverse throttling and brake lever position. The proposed algorithm has offered the user flexibility in direct control whilst maximising the amount of regenerative braking during reverse throttle.

As the future work, the rule based brake blending control algorithm will be replaced by an energy management system based on a Model Predictive Controller (MPC) which will optimize the regenerative braking torque to maximize the electric two-wheeler's performance meeting the constraints of the powertrain.

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