

eABS: Regenerative Anti-Lock Braking for Electric Motorcycles

John Robinson and Tarunraj Singh
University at Buffalo

ABSTRACT

Linked front and rear braking systems are difficult to implement properly on motorcycles due to the large changes in wheel loading under braking. At the braking limit, there is little to no load on the rear wheel and any brake torque could lock it, making the vehicle laterally unstable. Therefore, most motorcycles have independent controls for the front and rear brakes, requiring the rider to balance the brake force distribution. Electric motorcycles have the ability to utilize the drive motor to apply braking torque at the rear wheel. In this paper a control technique has been developed to link rear wheel braking torque to the front brake lever without risking rear tire lock. Thereby, it is also possible to recapture the energy from rear wheel braking. The control strategy has been tested on a transient pitch model, with rotating wheels and tire model data. It has been found that the control strategy provides significant reduction of stopping time and distance when compared to only using the front brake, while maintaining lateral stability of the motorcycle and not requiring any additional effort from the rider.

CITATION: Robinson, J. and Singh, T., "eABS: Regenerative Anti-Lock Braking for Electric Motorcycles," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(3):2013, doi:10.4271/2013-01-2064.

INTRODUCTION

A system for electronic motorcycle Anti-Lock Braking (eABS) which uses the traction motor to brake the rear wheel is presented here. The system aims to simplify the motorcycle braking process by providing rear braking torque which is linked to the front brake control. The system does not replace a traditional rear brake, rather it supplements the existing brakes. A possible implementation is shown in [Figure 1](#). The traction motor and final drive system shown in green, and the brake rotors are shown in red. The aim of the braking control system is to provide additional braking support from the rear wheel, allowing the rider to focus on the proper use of the front brake. Since the front tire has the largest braking capacity, riders who focus on proper front braking technique may be able to stop faster than those who split their attention between the two brakes. The eABS control system aims to further assist riders who focus on use of the front brake, by automatically applying the proper rear braking torque for the current operating conditions.

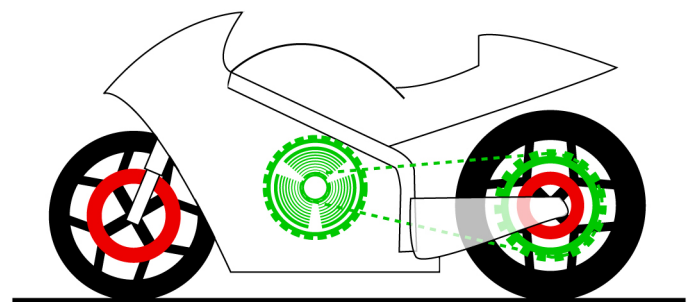


Figure 1. Braking layout with motor, chain and rear drive sprocket in green, front and rear brake rotors in red.

The electric motorcycle industry currently focuses on using regenerative braking to harvest energy and reproduce the engine braking feel of traditional internal combustion motorcycles [1], [2], [3]. The proposed system improves upon currently implemented systems by increasing the amount of braking torque applied and implementing anti-lock braking.

Anti-lock braking has been extensively studied, and has been shown to increase vehicle control in hard braking

situations. Studies have shown that anti-lock braking based on targeting a tire-slip ratio is effective across a wide variety of operating conditions [4], [5], [6], [7].

Optimal motorcycle braking was studied by Corno et. al. in [8]. They concluded that optimal motorcycle braking consists of two phases; tracking the optimal tire slip ratio and preventing the rear tire load from falling too low. Due to the high center of gravity and short wheelbase of motorcycles, under heavy braking the rear wheel load can fall to zero. If the braking force is not immediately reduced the motorcycle will start to pitch forward with the rear wheel leaving the ground, an unstable condition known as a “stoppie”. Therefore Corno et. al. concluded that optimal braking for motorcycles would switch from regulating the maximum braking force to maintaining a minimum rear load for various operating conditions.

Electric motorcycles present an appealing opportunity for implementing rear wheel ABS as the traction motor can be used. Since the motor is already part of the motorcycle's construction the implementation is inexpensive and requires minimal hardware additions. Electric motors are also ideal for implementing ABS as fine velocity control is more easily implemented than pulsing brake calipers used in traditional ABS systems.

The paper is organized into three main sections; the dynamic model of the motorcycle and regenerative braking system is described, the braking control strategy is explained, and results for a braking maneuver are presented.

DYNAMIC MODEL

Braking is a dynamic maneuver, and the transient weight transfer effects can have a significant impact on braking performance. For instance, hard application of the front brake in a very small period of time is likely to cause the front tire to lock, while the same brake application over a longer period of time may cause the motorcycle to do a stoppie. Therefore, a transient model is preferred over a quasi-static one. The model presented here will contain longitudinal, vertical and pitch degrees of freedom for the main body, and rotational degrees of freedom for each of the wheels. Note that the model assumes no lateral, yaw or roll motion. Therefore, the work presented here serves as an initial study into electronic motorcycle regenerative braking, not a complete stability analysis.

The model uses a non-linear tire model from Milliken Research Associates (MRA), which was provided with the Formula SAE Tire Test Consortium (FSAE TTC) data. The FSAE TTC data is for small racing tires, not motorcycle tires. However, it is assumed for straight line braking that the FSAE tires behave in a similar manner to motorcycle tires. It is the authors' view that using real tire data, even if it is not the correct tire, is more representative of the true tire physics than assuming parameters for a motorcycle tire.

Figure 2 illustrates the forces and moments used to derive the motorcycle equations of motion. These equations are

listed in equation (1), derived using the ISO axis system shown in the figure.

$$m\ddot{x} = (F_{x_F} + F_{x_R}) - F_D \quad (1a)$$

$$m\ddot{z} = \Delta F_{z_F} + \Delta F_{z_R} \quad (1b)$$

$$J_\theta \ddot{\theta} = \Delta F_{z_R} b - \Delta F_{z_F} a - F_x(h + z) - F_D(h_{CP} - h) + F_L(a_{CP} - a) \quad (1c)$$

$$J_F \dot{\omega}_F = \tau_F - F_{x_F} R_{L_F} \quad (1d)$$

$$J_R \dot{\omega}_R = \tau_R - F_{x_R} R_{L_R} \quad (1e)$$

Equation (1a) defines the longitudinal degree of freedom. The longitudinal tire forces are given by F_{x_F} and F_{x_R} , and the aerodynamic drag is given by F_D . The drag force is a nonlinear function of velocity, given by equation (2a). In this equation C_d is the drag coefficient, A_F the motorcycle's frontal area, ρ the air density and $\dot{x}$ the motorcycle's velocity.

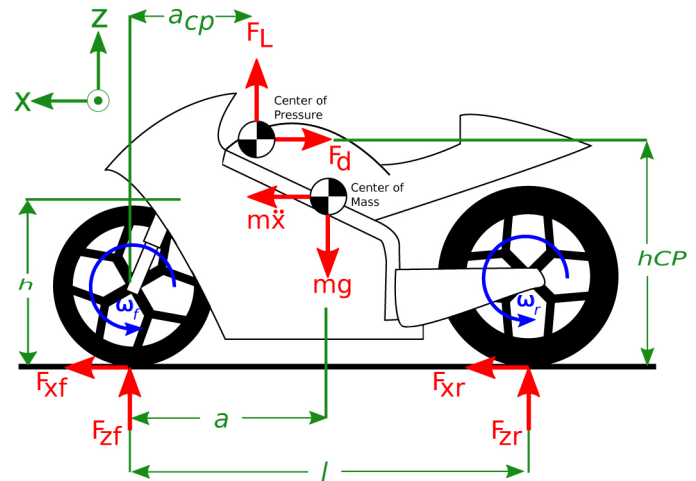


Figure 2. Motorcycle model

$$F_D(\dot{x}) = \frac{1}{2} C_d A_F \rho \dot{x} |\dot{x}| \quad (2a)$$

$$F_L(\dot{x}) = \frac{1}{2} C_l A_P \rho \dot{x} |\dot{x}| \quad (2b)$$

Equation (1b) defines the heave degree of freedom. The ΔF_z terms represent the change in vertical load from the static values. The changes in wheel loading are modeled through suspension deflections, shown in equation (3). The variable b used in these equations is the distance between the rear axle and the motorcycle's center of gravity, given by $b = l - a$. The

coefficients K_F and K_R represent the front and rear spring constants, C_F and C_R the front and rear damping constants. Note that the suspension forces do not account for the angle of installation of the front and rear suspension, it is assumed that the spring and damper constants contain a correction for installation angle.

$$F_{z0_F} = mg \frac{b}{l} \quad (3a)$$

$$F_{z0_R} = mg \frac{a}{l} \quad (3b)$$

$$\begin{aligned} \Delta F_{z_F} &= (F_{K_F} + F_{C_F}) \\ &= (a\theta - z)K_F + (a\dot{\theta} - \dot{z})C_F \end{aligned} \quad (3c)$$

$$\begin{aligned} \Delta F_{z_R} &= (F_{K_R} + F_{C_R}) \\ &= (-b\theta - z)K_R + (-b\dot{\theta} - \dot{z})C_R \end{aligned} \quad (3d)$$

The pitching moments around the center of mass are shown in [equation \(1c\)](#). The aerodynamic moments have a non-negligible impact on the pitch, and are therefore included. F_L is the aerodynamic lift force, given by [equation \(2b\)](#). Note that it is normal to assume that motorcycles make lift, not downforce [8]. The parameters in [equation \(2b\)](#) correspond to those in [equation \(2a\)](#), with C_l the lift coefficient, and A_P the planar area (cross section viewed from above).

Note that the change in vertical loads (ΔF_z) is used to define the vertical forces in the equations for vertical acceleration ($\ddot{z}$), and pitch acceleration ($\ddot{\theta}$). Therefore both vertical translation and the pitch angle are measured relative to their initial positions, not their absolute values relative to the axis system shown.

The rotational acceleration of the front and rear wheels are given by [equations \(1d\)](#) and [\(1e\)](#), respectively. The applied drive/brake torque is given by τ_F and τ_R for the front and rear wheels. The tire forces, F_X are assumed to act through the tires loaded radius R_L . The inertia of the front and rear wheel assemblies are represented by J_F and J_R .

Tire Model

The tire model used here was provided by MRA to the FSAE TTC. Some modification of the input vertical load was required. The motorcycle and rider weigh roughly the same as a FSAE car, which has the load split between two front tires. Therefore, the input normal loads to the model was halved, and the resulting output longitudinal force doubled. The assumption here is that two FSAE tires have roughly equivalent braking to one motorcycle tire.

Using this assumption a friction ellipse is plotted in [Figure 3](#). In this figure, the horizontal lines represent constant

slip ratio, and the vertical lines constant slip angle. Slip ratios of -3%, -6% and -9% are labeled.

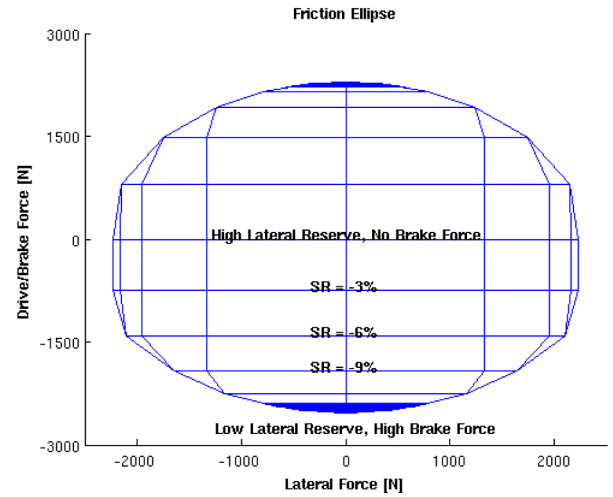


Figure 3. Friction Ellipse. Horizontal lines are of constant slip ratio, and vertical lines are of constant slip angle.

The SAE definition of slip ratio was used to as the input to the tire model, and is shown in [equation \(4\)](#). Here R_e is the tires effective radius, as defined in [9, Chapter 2].

$$SR = \frac{\omega R_e - \dot{x}}{\dot{x}} \quad (4)$$

Since the lateral degree of freedom is not being modeled, another metric must be used to determine lateral stability. In this case, the total amount of lateral force reserve, or the amount of lateral force a tire can make at a given slip ratio, is chosen. The larger the lateral force reserve at the rear tire, the larger the restoring moment will be for disturbances. The interested reader is encouraged to explore the Milliken Moment Method in [9, Chapter 8].

According to the tire model used, at zero slip ratio there is the most lateral force reserve available. At -3% slip, 100% of the lateral force reserve is still available. At -6% and -9% there is 94% and 86% of the maximum lateral force reserve available, respectively. Since the primary goal of this eABS system is to maintain stability while improving stopping performance, -6% slip is chosen as the maximum slip target for the controller. This provides a high percentage of lateral force reserve, while still providing significant braking force.

Regenerative Braking Model

The traction motor is modeled as a simple Direct Current (DC) motor. The motor has a resistance (R_m) and produces a voltage (E_{emf}) proportional to its rotational speed. The motor is attached to a super-capacitor which is used to capture the energy from braking. The circuit diagram for the motor model is shown in [Figure 4](#).