



Modelling and Validation of an Electronic Wedge Brake System with Realistic Quarter Car Model for Anti-Lock Braking System Design

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Abstract: With the advancement in battery and electronics technologies, soon Electric Vehicles (EV) will replace traditional vehicles as they are more efficient and environment friendly. This will require replacement of all mechanical systems in vehicles with their electrical counterparts. This study focuses on electromechanical brakes (EMB) as replacement of hydraulics brakes. Particularly a type of EMB known as Electronic Wedge Brake (EWB) which uses wedges to create self reinforcing braking force and consume less power than other EMBs. Detailed mathematical model of an EWB system is presented which provides braking force and torque to the disk brake. A Quarter Car Model (QCM) with realistic parameter values and aerodynamic deceleration is modelled to validate the EWB system. The system is validated for different road conditions and anti-lock braking system (ABS) is demonstrated for snowy road using a single PID controller. The results validate the brake and car model and a need for cascaded control strategy to implement ABS is established.

Keywords: Anti-lock braking system (ABS); Electric Vehicle (EV); Electronic Wedge Brake (EWB); Quarter Car Model (QCM); slip.

1. Introduction

Automotive vehicles are an integral part of almost every human being in every part of the world. The coming years will see increasing electrification of vehicles. The shift to electric vehicles is driven by the need of energy efficient and eco-friendly vehicles with low CO₂ emission. Efficient use of the available energy requires the following [1]:

- Minimizing power losses in passive mode.
- Maximizing efficiency of components.
- Controlling power consumption via intelligent battery management and consumers.

These factors motivate car companies to move towards drive-by-wire solutions in the future. With the advent of faster and more powerful computers and electronic components, the shift from mechanical systems to mechatronic systems is becoming reality. Mechatronic systems provide smarter, safer and more efficient solutions for vehicles.

Drive-by-wire refers to automotive systems which replace the bulky and prone to failure mechanical systems like steering, braking, throttling, by mechatronic components. In drive-by-wire systems, the command signals to achieve the different tasks are carried by wires in form of electric signals and the command is passed on to mechatronic actuators. One such system is brake-by-wire (BBW), where the bulky brake fluids, pumps and pipes are replaced by electric wires,

mechanical components and sensors. This reduces the weight and space requirements significantly and are easier to modify according to the user's requirements and brake safety features like anti-lock braking system (ABS), traction control system (TCS), Electronic stability control (ESC) and active braking (AB) are easier to implement. Also, these systems are safer and easier to diagnose in case of problem. Another motivation to switch to BBW is the need to reduce power requirement, increase efficiency and be eco-friendly. BBW systems were first developed and implemented in the aerospace industry to decrease weight and increase safety and efficiency [2], and it has slowly found its way in automotive industry as it provides similar advantages. BBW replace heavy hydraulic and mechanical parts and enhance the efficiency and stability of brake control due to fast and accurate generation of brake torques by electric motors and improve diagnostic capability of the braking system. On the other hand, BBW systems come with its own challenges. Design and development of a BBW involves complete change in requirements from existing brake systems. Particularly, due to safety critical nature of brakes, the new technology should be highly reliable and must be tolerant to hardware and software faults.

BBW systems can be classified into two types; wet and dry BBW systems. In wet systems the brake command is transferred through wires via brake controller and the brake actuator is hydraulic. These are called Electro-Hydraulic brakes (EHB). In dry systems, the brake signal is transmitted by wires and brake system is mechanical. These are called Electromechanical brakes (EMB). First research on EMB started in 1990s [3]. Continental company invented an EMB brake in 1995 which was tested in vehicles in 1997 [4]. Companies like Bosch, Siemens, Continental TEVES and other companies also presented their EMB ideas [5]. Continental, Siemens and BREMBO collaborated for development of fourth generation of EMB [6]. Many universities also carried on research on EMB like Tsinghua University, Jilin University [7], Tonogji University and Beijing Institute of Technology [8]. Classical EMB design includes motors to produce torque and gears to amplify and transfer torque to brake pads. The required braking force can be achieved by using higher gear ratio but conflicts with the actuator dynamics required for ABS. Second option is to use larger and more powerful motors (42V), but this increases the power requirements for the brakes which increases the fuel consumption of the vehicle [1].

Researchers have found a unique solution to this problem i.e. the Electronic Wedge Brakes (EWB) which uses the principle of self reinforcement. Self reinforcement mechanism requires very little power to produce large braking force. So, a 12V motor is enough to power actuator in EWB [3, 6, 8, 9]. In fact, power is required to pull back the brake pad when braking force is no longer required. Second issue is that force disappears after vehicles comes to stop. This is critical on slopes, when brakes are applied to a car going uphill, once it halts, it will start rolling downwards. Thus, the force which normally assists the brake, acts against it and tries to open it. Any brake system designed to use self reinforcement implement a strategy to deal with this problem smoothly and safely.

Siemens VDO are pioneers of making a working EWB systems from 2004 to 2007. They developed the 'beta' in 2004 which had dual motor activation for backlash prevention [10]. The brake was designed to be mounted on a brake disk inside a wheel and was tested in test vehicles. The EWB system had extra functionalities like automatic pad wearing adjustment and self release. In 2007, they made new prototype with just one motor. This EWB system was more efficient in terms of cost, weight and control strategy [11]. They also presented state-space model and two control strategies. The working principle of EWB and brake actuator can be seen in fig 1.

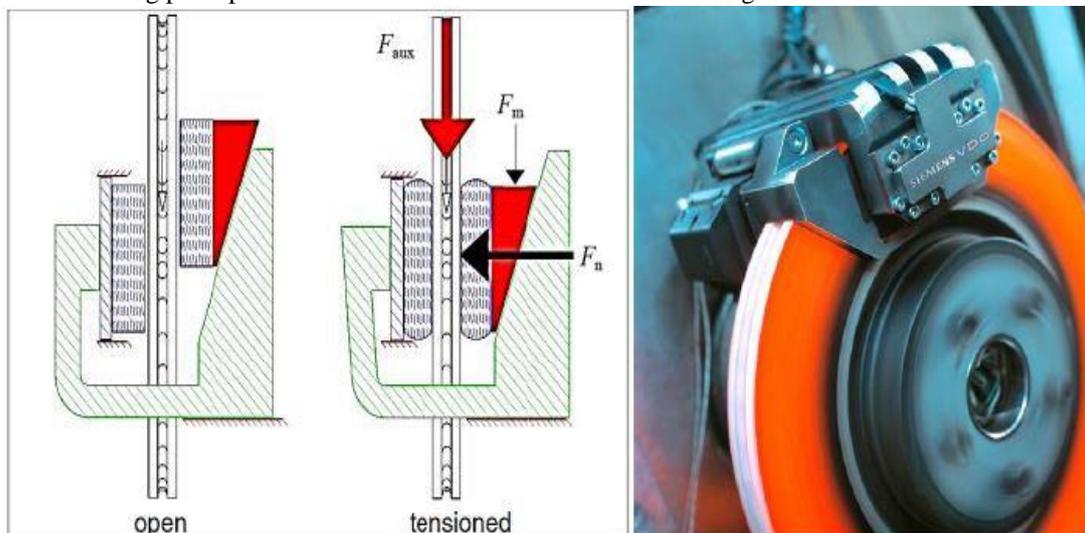


Fig. 1: Siemens wedge structure and brake actuator

Vasily and Beslah in [12] suggest two designs as improvement in EWB specifically for solving the brake jamming problem. First design uses pre-defined wedge shapes in a self adjusting design with one moving wedge. The second uses an externally adjustable wedge and an actively moving wedge with similarly pre-defined wedge shapes. This design helps in reducing energy consumption.

A team at Technical University Malaysia (UTeM) developed a prototype EWB system in 2013 by modification of existing standard brake caliper[13]. A piecewise mathematical model was developed, and the performance of the system was evaluated by the model and experimentally on test rig. Model in loop (MIL) setup is made for the EWB in [14] to control gap and torque. This setup had hardware and software components working together. Diagram of internal components of this design can be seen in fig 2. A new model for the same EWB system is developed in [15] using bell shaped model. The UTeM team then developed a fixed caliper EWB system with two wedges, and each wedge has one part fixed and one moving, drive shaft, slider beam and driven by a single motor [16]. A mathematical model is developed by system identification tool to obtain a model which approximates the behaviour of real system. Fig 3 shows the working of this EWB.

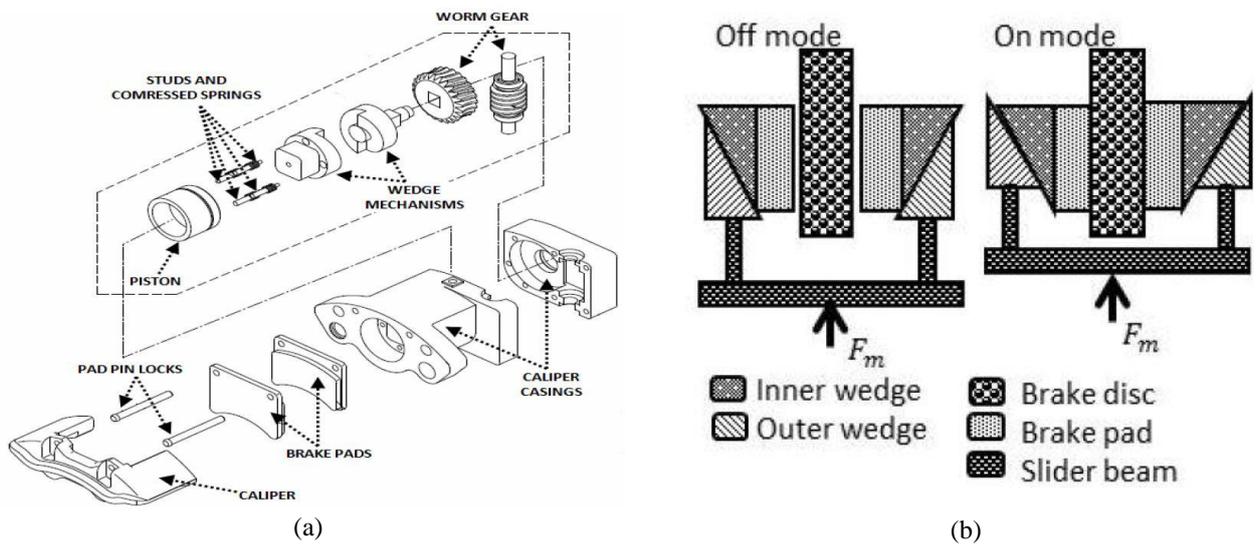


Fig. 2: (a) Internal view of EWB [13] (b) Working of fixed caliper based EWB [16]

In order to test the performance of the EWB developed by UTeM in [13], this paper develops a working model of the entire system consisting of the brake actuator system, the quarter car vehicle model, wheel model and wheel slip ratio. The complete system model is given in Section 2. Simulation results and discussion are given in Section 3 and conclusion in Section 4.

2. Modelling of EWB system

The brake actuator model consists of two parts; a DC motor model and the EWB model. The DC motor takes voltage as input and gives the rotation angle as output. The EWB model takes the rotation input from motor and gives the braking torque to the wheel system. The vehicle is modeled as quarter car model (QCM) because it is adequate for evaluating brake performance under different road conditions and types and for testing ABS system. The vehicle model also includes aerodynamic deceleration which depends on frontal area and shape of vehicle. One fourth aerodynamic deceleration is added as the total deceleration is distributed on four tyres and we are modeling one tyre. The wheel is modelled separately, and vehicle and wheel velocities are measured. The two velocities are used to calculate the slip ratio which helps us in designing the ABS system. To calculate the adhesion coefficient, Burckhardt's formula [17] is used which depends on vehicle velocity, slip ratio and road condition parameters. The complete model is tested by using constant voltage and by a simple PID controller to keep the slip ratio at an optimal value.

In this study the EWB system is represented by combination of two parts. First is the EWB actuator with DC motor. Second is the QCM containing the vehicle speed model, wheel speed model, aerodynamic deceleration, slip ratio calculation and friction coefficient model. The following section presents the EWB and QCM models in detail.

2.1 EWB actuator

The EWB actuator is divided in two parts. The DC motor and the wedge.

2.1.1 DC motor

The DC motor provides rotational input to the wedge mechanism. It is implemented as a state space plant [18]. The motor used here is permanent magnet direct current (PMDC) motor.

$$\begin{aligned} \frac{dx}{dt} &= A \cdot x(t) + B \cdot u(t) \\ \frac{dy}{dt} &= C \cdot x(t) + D \cdot u(t) \end{aligned} \tag{1}$$

where x is state vector, y is output vector, u is input vector and A, B, C, D are state-space matrices. State vector is given by;

$$x(t) = \begin{bmatrix} i_s(t) \\ \theta(t) \\ \omega(t) \end{bmatrix} \tag{2}$$

where $i_s(t)$ is the supply current, $\theta(t)$ is the angular displacement and $\omega(t)$ is the angular velocity. Input vector is given by;

$$u(t) = V_a(t) \tag{3}$$

where $V_a(t)$ is the terminal voltage.
The state space matrices are;

$$\begin{aligned} A &= \begin{bmatrix} -\frac{R}{L} & 0 & -\frac{K_v}{L} \\ 0 & 0 & 1 \\ \frac{K_t}{J} & 0 & \frac{D}{J} \end{bmatrix} ; \quad B = \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} \\ C &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} ; \quad D = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \end{aligned} \tag{4}$$

where J, D, R, L, K_t, K_v are the moment of inertia, friction constant, resistance, inductance, torque constant and electromotive constant.

Table 1 gives the motor parameters.

Table. 1: Motor parameters

Symbol	unit	Value
L	H	0.3
R	ohm	2.5
K_v	Vs/rad	0.0195
K_t	Nm/A	0.0195
J	kgm^2	17.2×10^{-7}
D	N.m.rad/s	1×10^{-6}

2.1.2 Wedge model.

The wedge part of the EWB actuator takes the rotational DC motor input and applies braking force and torque to the disc brake.

The piston displacement is modeled by;

$$x = 3.7 * 10^{-9} \theta^2 + 1.1 * 10^{-6} \theta - 0.00079 \tag{5}$$

Braking friction F is given by piecewise function;

$$F = \begin{cases} 0 & \text{if } d \leq x \leq e \\ \frac{F_{cs}}{ff-e}(x - e) & \text{if } e < x \leq ff \\ F_{cs} & \text{if } ff < x \leq 0 \end{cases} \quad (6)$$

where F_{cs} is the maximum clamping force, d is start of gaping mode, e is start of clamping mode and ff is start of saturation mode.

Braking torque is given by;

$$T_p = 2\mu_f r_{ref} F \quad (7)$$

where μ_f, r_{ref} are pad friction coefficient and effective pad radius. The parameters used in the EWB model are given in Table 2.

Table. 2: Wedge parameters

Symbol	unit	Value
F_{cs}	N	3500
μ_f	unitless	0.65
r_{ref}	m	0.15
d	mm	-0.85
e	mm	-0.6
ff	mm	-0.11

2.2 Quarter car model.

This section describes the Quarter Car Model. A basic QCM is good model for implementing ABS as it holds essential characteristics of the whole car. Several assumptions have been made in the model. First, the path is plane i.e. there are no slopes. Second, the steering angle is zero. The QCM is divided in 4 parts.

2.2.1 Wheel dynamics

The wheel model takes the applied torque and friction coefficient and output the wheel acceleration. Diagram depicting a QCM is shown in figure 3.

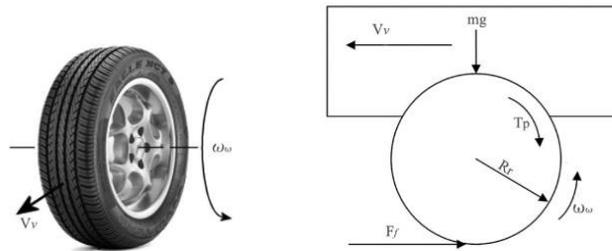


Fig. 3: Wheel model.

Wheel dynamics is given by;

$$\frac{d\omega_\omega}{dt} = \frac{m\mu g R_r - T_p}{I} \quad (8)$$

where ω_ω is the wheel rotational velocity, m is the quarter car mass, μ is the friction coefficient, g is the acceleration due to gravity, T_p is the braking torque from the EWB and I is the moment of inertia of the wheel.

2.2.2 Vehicle dynamics

Vehicle model takes the friction coefficient as input and outputs the vehicle acceleration. One fourth of aerodynamic deceleration is subtracted because this deceleration is acted on all four wheels and we are working on QCM.

$$\frac{dV_v}{dt} = -\mu g - \frac{1}{4} \left(\frac{c_r A_f \delta V_v^2}{2m} \right) \quad (9)$$

where c_r is the aerodynamic friction coefficient; A_f is the car frontal area; δ is the air density; and V_v is the vehicle speed.

The QCM parameters are given in table 3. The values are taken from a commercial EV.

Table. 3: QCM parameters

Symbol	unit	Value
m	kg	400
R_r	m	0.316
I	kgm^2	0.6
c_r	unitless	0.28
A_f	m^2	2.304
δ	kg/m^3	1.1839

2.2.3 Friction coefficient

Burckhardt’s formula [17] gives us the friction coefficient value based on different road types.

$$\mu = [C_{a1}(1 - e^{-C_{a2}\lambda}) - C_{a3}\lambda]e^{-C_{a4}\lambda V_v} \tag{10}$$

where λ is the wheel slip ratio; V_v is the vehicle speed; C_{a1} is the maximum value of friction curve; C_{a2} is the friction curve shape; C_{a3} is the friction curve difference between the maximum value and the value at $\lambda=1$; C_{a4} is wetness characteristic value. Changing the values of these parameters allow us to model different tyre-road friction conditions.

The values of above parameters for different road conditions are given in Table 4.

Table. 4: Tyre-road friction parameters

Road type	C_{a1}	C_{a2}	C_{a3}	C_{a4}
Dry asphalt	1.029	17.16	0.523	0.03
Dry concrete	1.1973	25.168	0.5373	0.03
Snow	0.1946	94.129	0.0646	0.03
Icy	0.05	306.39	0	0.03

2.2.4 Slip ratio

The slip ratio tells weather the wheels are slipping on the road or not. Slip ratio of 0 means no slipping and 1 means complete wheel lock

$$\lambda = \frac{V_v - \omega_\omega}{V_v} \tag{11}$$

where V_v is vehicle speed; and ω_ω is the wheel speed.

The friction coefficient vs slip ratio plot shown in figure 4, helps us in selecting the optimal slip ratio for all road types.

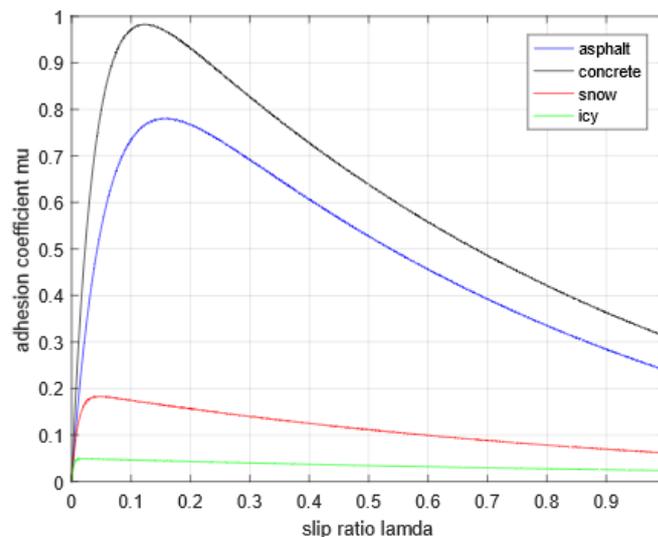


Fig. 4: Friction coefficient for changing slip ratio at 25m/s

As can be seen from fig 4, the ideal slip ratio that we want to maintain is 0.2.

3. Simulation results

The complete EWB system model is simulated in MATLAB Simulink and tests are run. The model can be seen in figure 5. Firstly, only the EWB brake is tested by giving input of 12 V.

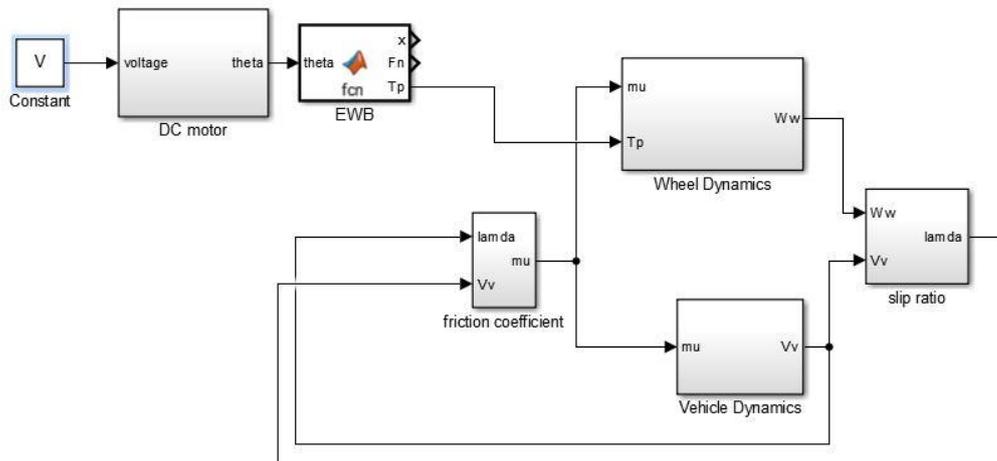


Fig. 5: EWB system model Simulink

The states of EWB system when excited with 12 V input are shown in figure 6.

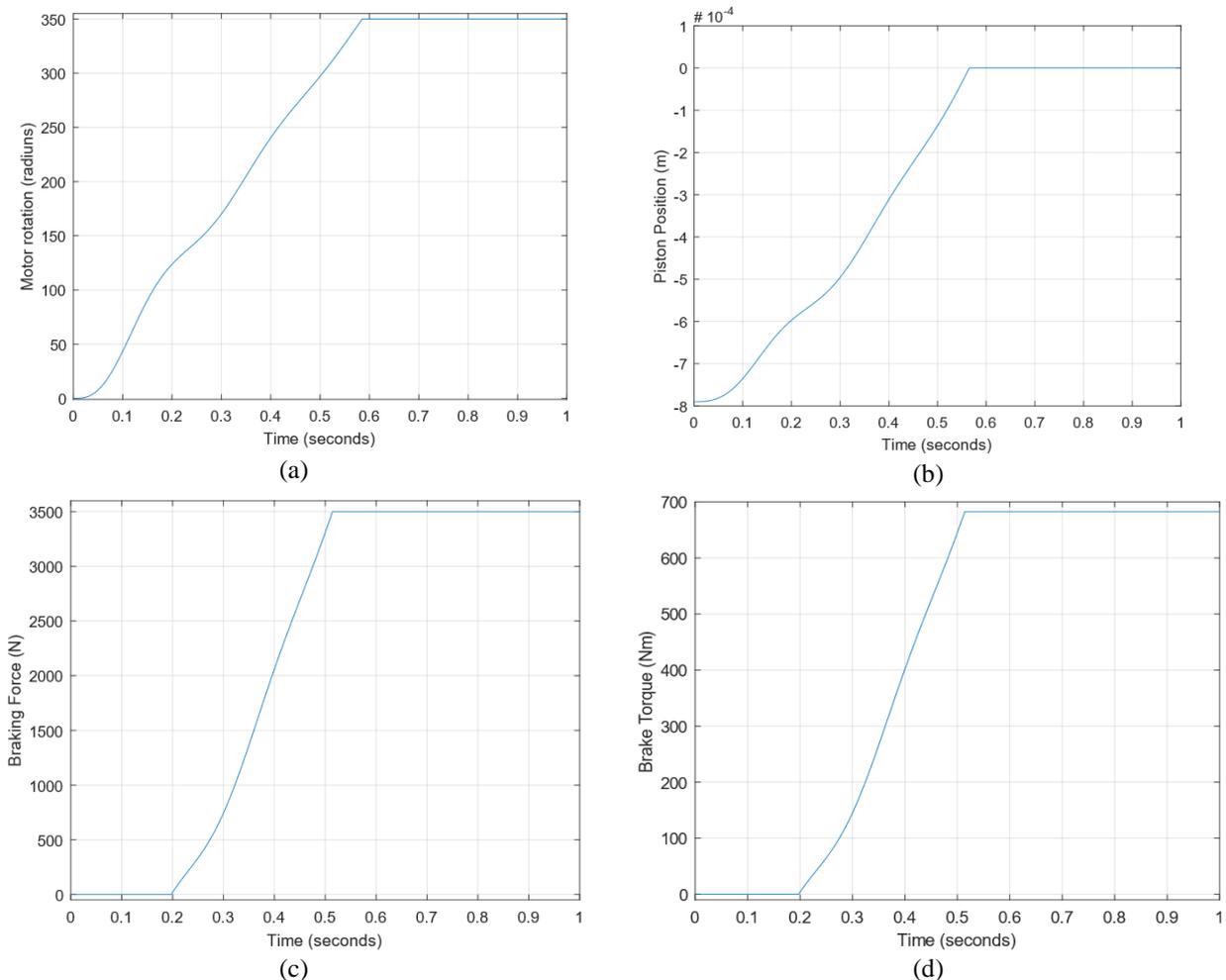


Fig. 6: Motor rotation, piston movement, Force and Torque of EWB

It can be seen from figure 6 (a) that the DC motor produces rotational motion when excited by 12 V input. This rotational motion is translated to linear motion by help of worm/pinion which moves the piston of the EWB which can

be seen in (b). the y values represent piston brake gap. When the piston which is connected to brake pad, comes in contact with the disk, it produces braking force (c) and braking torque (d). The clamping force behavior can be seen in (c) which has three phases. The no contact phase, the clamping phase and the saturation phase.

The system is then tested with the QCM model under different road conditions to see the performance of the complete model. The initial velocity of vehicle and wheel is set to 25 m/s. Figure 7 the vehicle and wheel speed of the QCM under different road types and figure 8 shows the slip ratio.

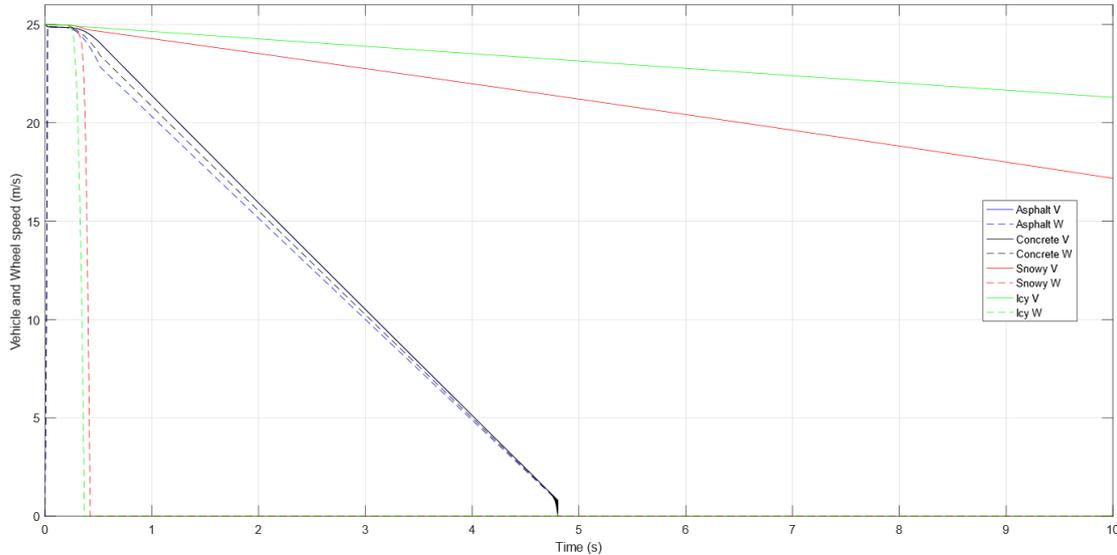


Fig. 7: Vehicle and wheel speed w.r.t time for different road types

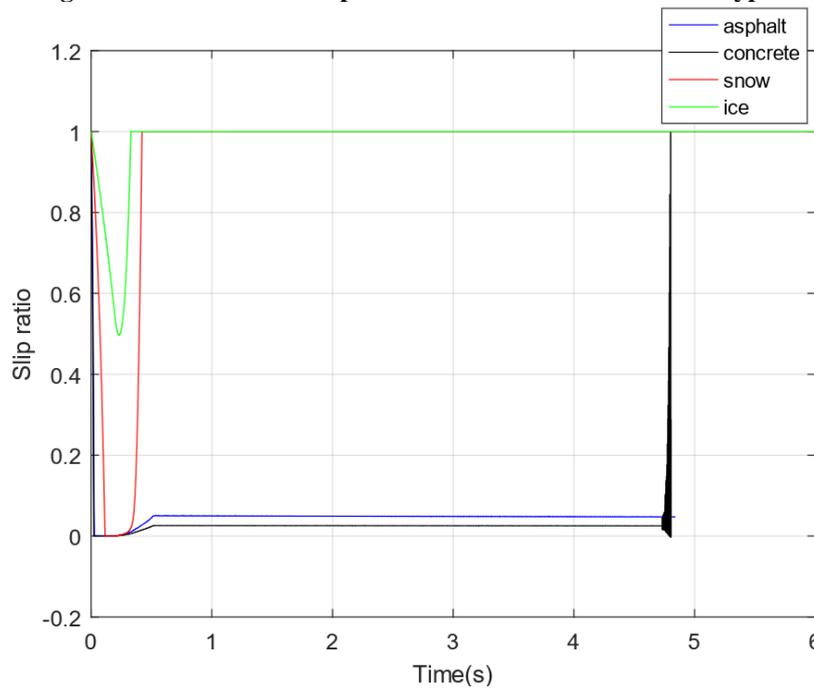


Fig. 8: Slip ratio w.r.t time for different road types

It can be seen in figure 7 that for asphalt and concrete the difference between wheel speed and vehicle speed is nominal and the car comes to stop quickly. Also, the slip ratio seen in figure 8 for the two road types remain close to zero. It shows that friction between tyre and road is good, and the vehicle comes to stop quickly. For snow and icy roads, the wheel speed quickly goes to zero when brake is applied and the car slips. The slip ratio goes to 1 which shows that the wheel is completely locked, and the car is slipping. The braking is worse in case of icy road.

The model is then tested for ABS braking by making a simple feedback system with a PID controller. The purpose of this test is to check the model for ABS functionality. The controller is roughly tuned so good performance is not expected. The controller takes the difference between actual and desired slip ratio as input and gives out voltage as output for the DC motor. The snowy road parameters are selected for this simulation. The system is shown in figure 9.

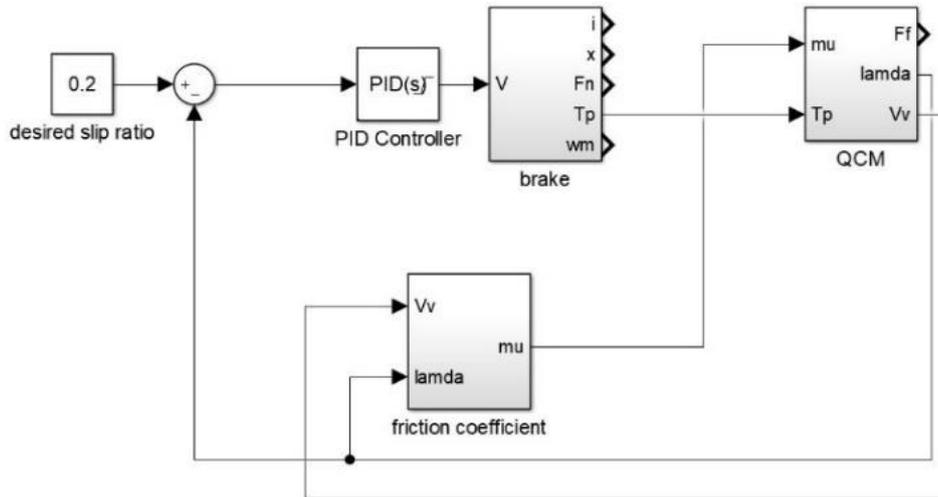


Fig. 9: PID feedback control of EWB system

The vehicle and wheel speeds and slip ratio are shown in figure 10.

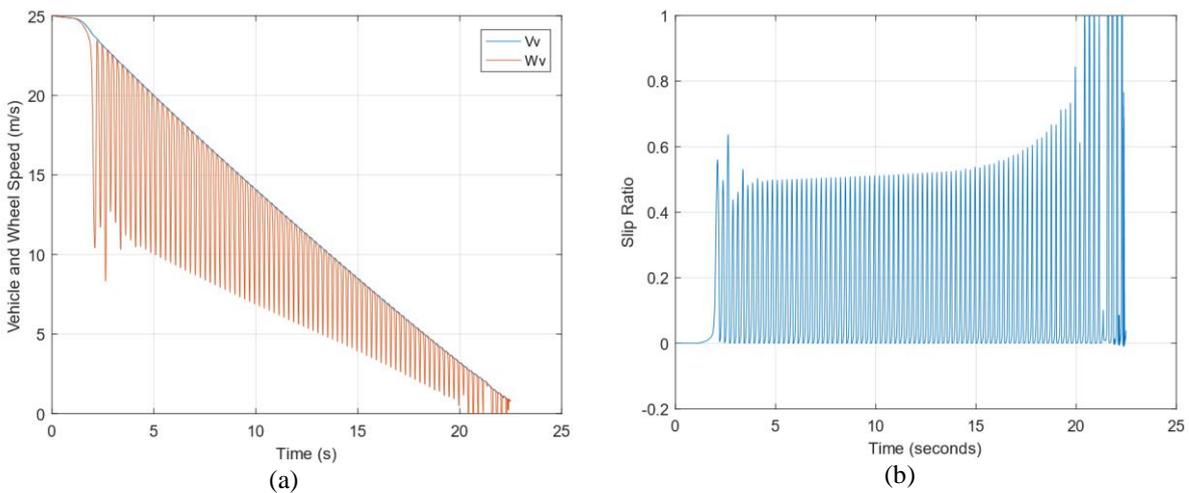


Fig. 10: (a) Vehicle and wheel speed and (b) Slip ratio of EWB system with PID control

The PID controller works to keep the slip ratio on desired value of 0.2 and in order to do that it generates output signal Voltage which changes quickly from +12 to -12V. This makes the brake hold and release in quick intervals. This is the working principle of ABS. The stopping distance under same conditions without ABS is 330.9m and braking time is 26.47s and with ABS is 281.1m and braking time is 22.49s. Not only does ABS reduce stopping distance, it also prevents steering locking so driver can steer while applying brakes.

Using 1 PID control for such a complex system is not robust and neither efficient nor safe. A cascaded control system would be a better choice which can control individual components and cancel out disturbances locally. Different control strategies can be applied and compared for the EWB system. One such proposed control strategy is a Sliding Mode controller (SMC) PID cascaded control shown in figure 11.

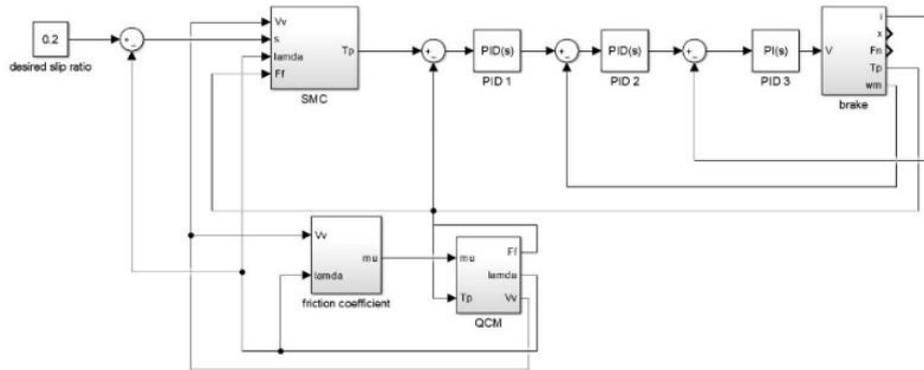


Fig. 11: SMC PID cascaded control for EWB system

4. Conclusion

A new type of EWB system is modelled with real parameter values. The EWB performance is satisfactory and it works on 12 V input. A QCM is modelled to test the EWB system. The QCM is modelled with parameter values from real commercial EV car. The EWB system is simulated and tested for different road conditions and results show that the system works correctly. The tire slippage under snow and icy road types is demonstrated which shows the importance of ABS. ABS is demonstrated using a single PID controller and the results show that brake system with ABS reduces braking distance and prevents wheel locking, allowing driver to steer during braking. Need of better control strategy is established and a SMC PID cascaded control system is proposed.

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