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TOPICAL REVIEW

Electronic Wedge Brakes: A Review of Design, Modeling, Control Strategies, and Testing Methodologies

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ABSTRACT This review examines Electronic Wedge Brake (EWB) technology, a revolutionary vehicle braking system that uses a self-reinforcing wedge mechanism to increase braking force. We demonstrate the transformative potential of this system to improve performance, efficiency, and integration with advanced vehicle safety technologies by charting the transition from hydraulic and electro-mechanical brakes (EMBs) to EWBs. This review analyses state-of-the-art EWB design, modelling, and control contributions from 2002 to 2024. Our research shows that this sector has received little attention despite its importance in vehicular technology. We carefully study EWBs, focussing on the brake factor and how wedge geometry, actuation methods, and material selections affect braking. The examination addresses reverse braking, backlash, wear, Caliper rigidity, and mathematical modelling methods such as state-space representations, system identification, and lead screw, motor, and wedge dynamics. We also examine prototype development and validation methods such real-world vehicle testing, hardware-in-the-loop (HIL) simulations, and dynamometer testing to resolve the experimental-simulation mismatch. EWB control techniques such conventional PID, advanced sliding mode control, ADRC, fuzzy logic, and LQR are prioritised to maintain system stability around the optimal operating point. This evaluation synthesises EWB design, modelling, testing, and control and identifies important problems and future research areas to promote mainstream use, unlike earlier evaluations. The forward-thinking perspective of this study underlines the possibility for hybrid/electric vehicles to seamlessly combine EWB with Anti-lock Braking System (ABS), electronic speed control (ESC), and regenerative braking systems. This integration will enable next-generation intelligent braking solutions. This evaluation emphasises Electronic Wedge Brake technology's contribution to safer, more efficient, and sustainable transportation and UN Sustainable Development Goals including affordable and clean energy for sustainable cities and communities.

INDEX TERMS Brake-by-wire, electromechanical brake, electronic wedge brake, self-reinforcement, control, hardware and testing.

I. INTRODUCTION

Braking systems are vital safety components in automobiles, crucial for deceleration, accident avoidance, and occupant safety. The advancement of braking technology has been propelled by the demand for improved safety, performance, and efficiency, evolving from rudimentary mechanical systems in horse-drawn carriages to contemporary electronically controlled solutions. The initial automobiles utilised lever-operated mechanical brakes, which were subsequently

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supplanted by hydraulic braking systems in the early 20th century [1]. The implementation of drum and disc brakes enhanced braking performance, with disc brakes providing superior fade resistance and efficiency under challenging conditions. Traditional hydraulic systems, comprising mechanical linkages, hydraulic fluids, and main cylinders, exhibit inherent limitations such as delayed braking response, risks of fluid leakage, and difficulties in incorporating contemporary safety features like Antilock Braking Systems (ABS), Electronic Stability Control (ESC), and collision avoidance technologies. A transformative change in braking technology occurred with the advent of Brake-by-Wire (BBW) systems, substituting mechanical and hydraulic elements with electronic sensors, actuators, and control units. In contrast to conventional systems, BBW converts driver input into electronic signals, which are processed by an Electronic Control Unit (ECU) to regulate braking force at each wheel. This method markedly improves response time, accuracy, and safety, facilitating seamless integration with advanced driver-assistance systems (ADAS) including autonomous emergency braking and adaptive cruise control. The elimination of hydraulic components facilitates weight reduction and enhances vehicle economy. BBW systems, also known as electro-mechanical brakes (EMBs), were first created for the aircraft industry to improve safety and operating efficiency before being modified for the automobile sector [2]. This study explicitly examines a distinct subtype of EMB systems, the Electronic Wedge Brake (EWB), in contrast to other review studies [3] that address other EMB systems broadly. This article offers a comprehensive analysis of EWB systems, addressing design variations, modelling methodologies, prototype creation, hardware evaluation, simulation research, and control tactics.

Unlike traditional hydraulic braking systems, electric motor brakes (EMBs) employ electric motors to produce braking force, resulting in quicker response times, superior stability, and advanced diagnostic features. The implementation of EMB systems has distinct problems, especially in maintaining high reliability and fault tolerance due to the safety-critical nature of braking functions. BBW technologies are generally classified into Electro-Hydraulic Brakes (EHBs) and Electro-Mechanical Brakes (EMBs). Electronic hydraulic brakes utilise an electronic controller to convey braking signals, while employing hydraulic actuators to exert the braking power. Conversely, EMBs depend solely on electrical signals and mechanical actuation, hence obviating the necessity for hydraulic components [3], [4], [5]. Investigation into EMBs commenced in the 1990s, with Continental unveiling the inaugural prototype in 1995, subsequently augmented by substantial contributions from Bosch, Siemens, and Continental TEVES [4], [5]. These advancements established the foundation for the fourth-generation EMB, which resulted from a collaborative initiative among Brembo, Siemens, and Continental.

Recent developments in BBW technology have markedly enhanced braking efficacy, safety, and compatibility with autonomous driving systems. A significant advancement is the intelligent booster motor design, which improves the responsiveness and energy efficiency of braking systems in electric and autonomous vehicles (AVs). The integration of high-precision electric actuators and sophisticated control algorithms has enabled BBW systems to attain expedited brake response, fault tolerance, and self-diagnostic functionalities [6]. Moreover, Robust Adaptive Autonomous Braking Control techniques have been developed to guarantee stable braking performance across diverse road circumstances and uncertainties [7]. These controllers employ adaptive learning methodologies, model predictive control (MPC), and deep reinforcement learning (DRL) to enhance braking force allocation and reduce stopping distances in real-time [8], [9]. Researchers have investigated the amalgamation of Vehicle-to-Everything (V2X) communication with AI-driven predictive braking to improve situational awareness in autonomous vehicles, enabling pre-emptive braking based on real-time traffic and environmental data [10]. These developments collectively underscore the essential function of BBW systems in the development of next-generation intelligent transportation systems, significantly narrowing the divide between safety, automation, and energy efficiency.

A primary difficulty in EMB technology is attaining appropriate braking force while minimising power usage. Researchers tackled this issue with Electronic Wedge Brakes (EWB), which employ the idea of self-reinforcement, using the vehicle's kinetic energy and frictional forces to amplify braking force without supplementary input. In 2002, the German Aerospace Centre (DLR) initiated the development of the eBrake®EWB system, enhancing its design via hardware testing, mathematical modelling, and prototype creation [11], [12], [13]. Siemens, Hyundai, and Mando Corporation investigated further developments, such as dual-motor systems and cooperative regenerative braking, enhancing the viability of commercial EMB integration [14], [15], [16], [17], [18], [19], [20]. This review paper offers an exhaustive examination of Electronic Wedge Brakes (EWB) technology, addressing design concepts, mathematical modelling, control strategies, prototype testing, and implementation issues. The document is organised as follows: Section II delineates the principles of EWB systems, whilst Section III explores diverse design options. Section IV examines mathematical modelling, whereas Section V addresses production and testing procedures. Section VI examines control measures for performance improvement, whereas Section VII shares an Incremental Advancements in Electronic Wedge Brake (EWB) Technology followed by challenges and limitations in section VIII. One may find the conclusion along with future recommendations in section IX.

II. WORKING PRINCIPAL AND BASIC DESIGN

To understand self-reinforcement braking, it is essential to first define the **brake factor**. The brake factor, also referred

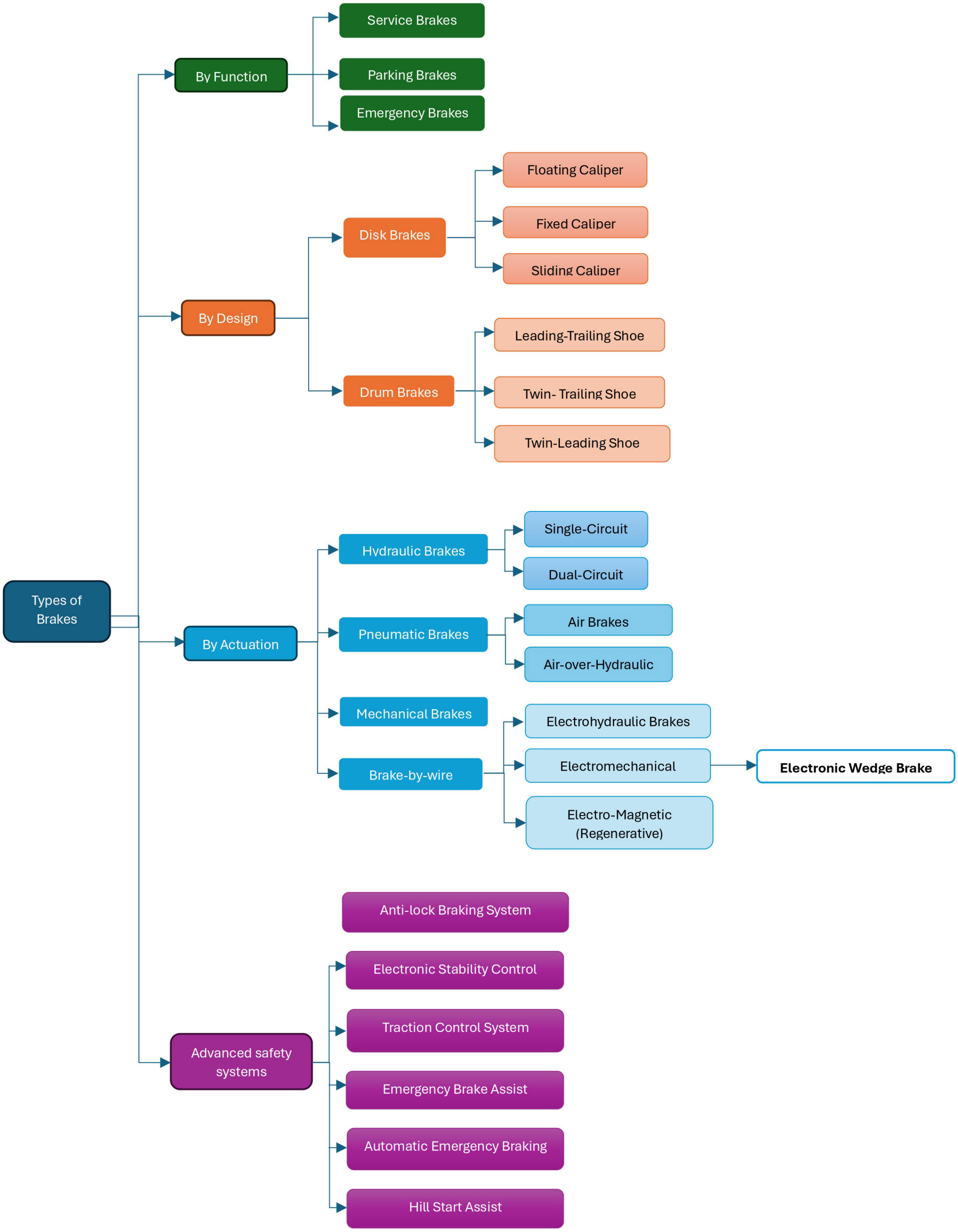

FIGURE 1. Classification of automotive brake systems.

to as the *brake effectiveness* or *shoe factor*, quantifies the mechanical advantage of a braking system by expressing the ratio of the total frictional force generated at the brake interface to the applied actuation force. This parameter is crucial for evaluating a brake system's efficiency and performance.

Mathematically, the brake factor (BF) is defined as:

$$\text{Brake Factor (BF)} = \frac{\text{Total Friction Force}(F_b)}{\text{Total Actuator Force}(F_m)} \quad (1)$$

A higher brake factor indicates greater braking effectiveness, as more braking force is produced per unit of input force. In conventional **Electro-Mechanical Braking** (EMB) systems, the braking force is generated by electric actuators that apply pressure to the brake pads or shoes, pressing them against the rotor or drum. The brake factor in these systems is primarily influenced by the actuator's force output and the friction characteristics of the brake materials. In contrast, Electronic Wedge Brakes (EWB) incorporate a self-reinforcing wedge mechanism that amplifies the braking force by converting a portion of the vehicle's kinetic energy into additional clamping force. This design results in a higher brake factor compared to conventional EMB systems, as the self-reinforcement reduces the required actuation force for a given braking effect. Consequently, EWBs achieve effective braking with lower energy consumption and allow for the use of smaller actuators [12].The visual representation and brake factors of conventional EMB and EWB are illustrated in Figure 2.

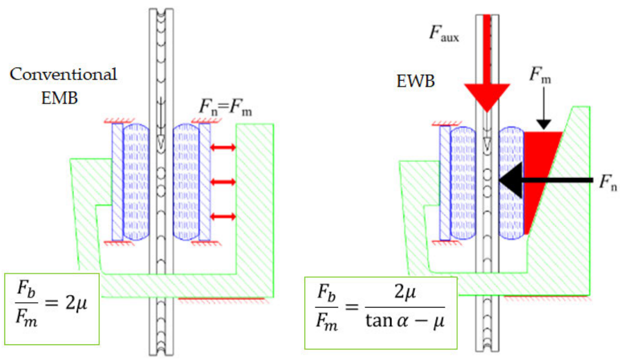

FIGURE 2. Conventional EMB and EWB [7].

The EWB utilizes a wedge mechanism to achieve self-reinforcement, enhancing braking efficiency by amplifying the applied braking force. In this design, an electric actuator drives a wedge-shaped component between the brake pad and the rotor. As the wedge advances, it converts the actuator's linear motion into a clamping force that presses the brake pad against the rotor. The self-reinforcement effect arises from the wedge's geometry. When the brake pad contacts the rotating rotor, friction generates a tangential force. This force, due to the wedge's inclined surface, produces a component that further drives the wedge inward, increasing the clamping force without additional actuator input. This mechanism allows the braking system to achieve higher braking forces with reduced actuator effort, improving energy efficiency.

Brake factor for conventional EMB is 2μ, while that of EWB is $\frac{2\mu}{\tan\alpha - \mu}$, where Î is the frictional coefficient between brake factor and rotor and Î± is the wedge angle. This relationship indicates that the brake factor increases with higher friction coefficients and decreases with larger wedge angles. Optimising these parameters is crucial for achieving maximum braking efficiency while preventing issues such as wedge jamming or excessive sensitivity. For instance, a study found that a wedge angle of approximately 24.5 degrees, combined with a friction coefficient of 0.35, yields an optimal brake factor, balancing self-reinforcement and controllability [23]. For these values, the brake factor of EWB is about 9 times the brake factor of conventional EMB (6.62 compared to 0.7). That means we can get same braking force with 9 times less effort. EWBs, while offering significant advantages in terms of performance and efficiency, face several key challenges that hinder their widespread adoption. One primary concern is achieving robust and reliable performance under diverse operating conditions.

The effectiveness of the wedge mechanism is highly dependent on the coefficient of friction between the wedge and the mating surfaces, which can vary significantly due to temperature changes, wear, and contamination. Ensuring consistent braking performance across these variations requires sophisticated control algorithms and robust material selection. Furthermore, the self-reinforcing nature of EWBs, while beneficial for amplifying braking force, can also lead to instability and potential wheel lockup if not precisely controlled. This necessitates highly accurate sensors, fast actuators, and advanced control strategies to maintain stability and prevent over-braking, especially in emergency situations. A particularly significant design challenge arises from the need for effective braking in reverse. The self-reinforcing mechanism of the wedge is inherently directional, optimized for forward motion. Achieving comparable braking performance when the wheel is rotating in the opposite direction requires careful design considerations, such as symmetrical wedge profiles or additional mechanisms to ensure proper engagement and force amplification regardless of the direction of rotation. Finally, ensuring fail-safe operation in the event of component failure or power loss is a critical challenge. Redundancy in sensors, actuators, and control systems, along with robust fault detection and management strategies, are essential to guarantee safe operation and prevent loss of braking capability.

III. DESIGN VARIATIONS IN EWBs

This section delves into the diverse design variations proposed for Electronic Wedge Brakes (EWBs). While the fundamental principle of utilising a wedge to amplify braking force remains consistent, researchers and engineers have explored numerous configurations to optimise performance, address specific challenges, and tailor EWBs for different applications. These variations encompass differences in wedge geometry, actuation mechanisms, component materials, and overall system architecture. This exploration of alternative designs is crucial for understanding the potential of EWB technology and identifying promising avenues for future development and implementation. The first EWB conceived at DLR $e.V$ named eBrake uses a wedge mechanism between the brake lining and an abutment. The wedge is actuated by a motor force (F_m) to generate braking force (F_b) and achieve self-reinforcement. Various wedge angles were experimented to avoid the supposed jamming that could occur at the critical point $\mu = \tan\alpha$. However, it was discovered that at this critical point, the actuator force becomes zero, and beyond it, the force direction reverses, requiring the actuator to pull the wedge. This critical point is identified as the most effective operating point, offering theoretically infinite self-reinforcement. This understanding suggests optimizing the wedge angle for different friction coefficients, potentially using a declining wedge angle with increasing deflection. The wedge had a V shape and was designed for braking in both forward and reverse directions [12], [13] as illustrated in Figure 3.

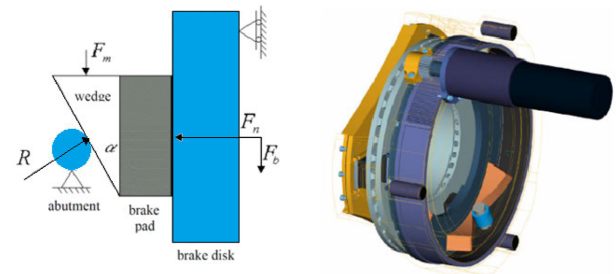

FIGURE 3. Mechanical model and CAD model of first prototype eBrake [7].

The second design by DLR $e.V$ utilises two parallel-mounted Brushless Direct Current (BLDC) motors with roller screws to convert rotational motion to linear motion, driving the "brake heart" containing the wedge mechanism. The design allows for both cooperative motor operation (for suboptimal friction conditions) and preloading (to eliminate free-play near ideal friction) as shown in Figure 4. The wedge consists of two W-shaped surfaces with rollers between them to minimise sliding friction and enable self-reinforcement in both rotation directions. A preloaded spring holds the outer wedge (connected to the brake pad) against the static inner wedge. Motor control is achieved using commercial drives with encoders. Backlash, due to tolerances and wear, is acknowledged as a design challenge [13].

The third prototype by eStop, now acquired by Siemens VDO, was nicknamed the "beta". It improved on design from previous prototype while maintaining the same design principle. This EWB prototype was designed for real-world vehicle testing, featuring a more compact and robust design compared to its predecessor "alpha". It also incorporated additional functionalities, such as automatic pad wear adjustment and a self-release mechanism which stop braking when electric power is lost, crucial for safety [16]. The final prototype from Siemens VDO called Prototype 1 (PT1), a more production-ready design, was developed using a single motor for the wedge mechanism, though the overall brake unit uses two motors: one for service braking via a wedge

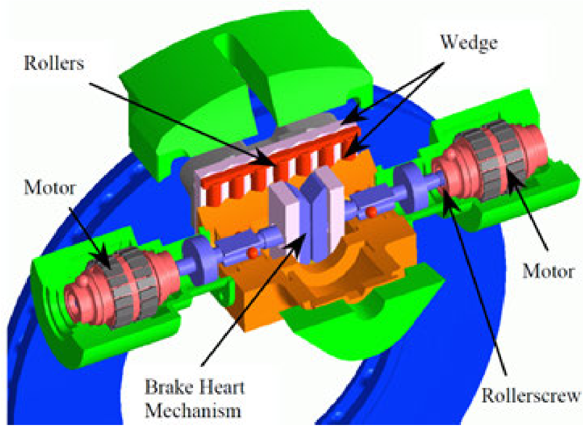

FIGURE 4. Cross Section view of second prototype [8].

brake and floating caliper, and another for parking brake, wear adjustment, and fail-safe functions as illustrated in Figure 5. Enhanced control and self-diagnostics are achieved through position, clamping force, and fail-safe sensors. Key service brake improvements include an angled drive shaft for increased spindle durability in forward braking (though complicating reverse braking), a new low-backlash power screw, and an increased torque capacity of 4500 Nm. PT1 employs an innovative force sensor concept that measures caliper deformation using a linear Hall sensor and a magnet, creating a non-loaded reference arm within the caliper to minimize sensitivity to side forces.

This design achieves a significantly improved signal-to-noise ratio (0.1 percent noise) compared to traditional pressure sensor-based systems (0.4 percent noise) due to the sensor's insensitivity to side forces and the absence of stick-slip effects. A key design change is setting the actuation angle (β) equal to the wedge angle (α) to maximise the brake factor. To enable braking in reverse, a "double-wedge" construction is implemented. This requires a two-jointed rod connecting the spindle and wedge to accommodate the (2α) angle between the spindle axis and wedge velocity vector during reverse braking [17]. Mando Corp.'s (Korea) EWB development progressed through four distinct prototypes. The initial hand-driven prototype validated the self-reinforcement concept. A second prototype employed a commercial off-the-shelf (COTS) DC motor to assess motorised EWB operation. The third prototype incorporated a BLDC motor with integrated Hall sensors, along with key components like pads, housing, and a carrier, and utilised a lead screw and worm gear for force amplification; a dedicated ECU capable of simultaneously controlling two EWB actuators in both position and force (using current and Hall sensors) was also developed. However, this prototype failed to meet braking force requirements, leading to the development of a fourth, more compact prototype designed for vehicle installation. This final iteration featured a custom-designed, high-powered BLDC motor and a "cross wedge" mechanism as shown in Figure 6. This cross wedge, a V-shaped design

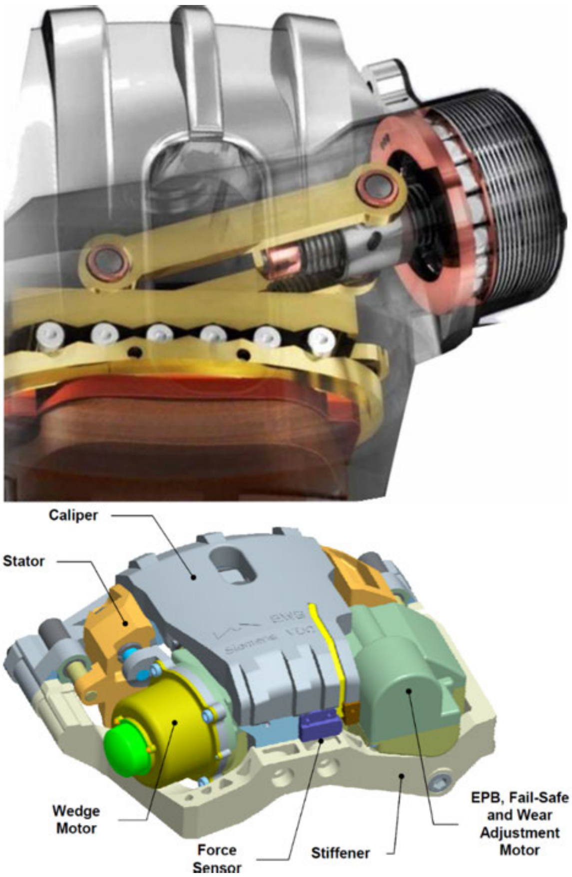

FIGURE 5. Single motor actuation in PT1 [12].

in contrast to Siemens' W-shaped wedge, aimed to improve pad wear uniformity and braking force distribution while eliminating the rollers, which were deemed susceptible to wear and contamination. Notably, this design did not employ an optimised actuation angle [18], [19], [20].

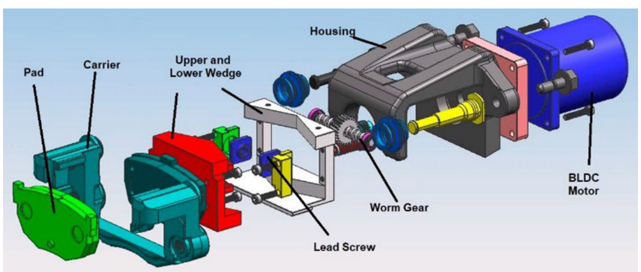

FIGURE 6. Cross-wedge EWB [18].

Caliper stiffness is crucial for a compact design in the braking state, requiring high stiffness with low stress concentration and volume. Structural analysis varying the caliper wing position (L_1/L_2) revealed that a lower (L_1/L_2) value (wing positioned further back) achieves higher stiffness with relatively low stress intensity, making it the preferred design [24]. Ivanov and Ayalew proposed two types of adjustable EWBs: self-adjusting and externally adjustable as shown in Figure 7. The self-adjusting EWB uses a pre-defined wedge shape that changes the effective wedge angle as the wedge moves, initially engaging at a constant angle based on the most probable friction coefficient, then decreasing the angle to reduce actuation force. This design can be further optimised with real-time friction coefficient estimates. The externally adjustable EWB has two independently movable wedges, allowing for adjustment of the effective wedge angle, either actively (by motor) or passively (with a spring), ideally to maintain a relationship where the friction coefficient is approximately equal to the tangent of the wedge angle $\mu \approx \tan\alpha$, minimising actuation force. The basic design and model has been adopted from PT1 of Siemens VDO [17] and simulations are carried out on Simulink to show improvement in energy efficiency and braking performance compared to conventional EWB [25].

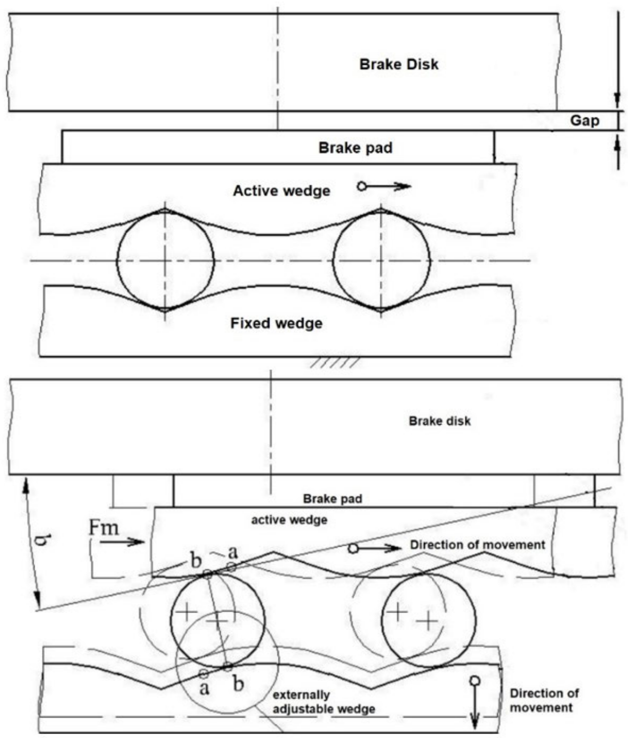

FIGURE 7. Self-adjusting and externally adjustable EWB [25].

Han et al. designed and developed their own EWB employing a Permanent Magnet Synchronous Motor (PMSM) and worm gear/wheel, power screw/nut, instead of BLDC motor and lead screw in previous designs. They also used the less optimal perpendicular motor force angle instead of force angle equal to wedge angle identified in previous studies. No comparative study is done to show superiority of their design compared to others [26].The first prototype EWB by the Vehicle Dynamics control lab, UTeM was developed by modifying an existing automotive brake caliper. A DC motor drives a worm pinion, whose rotation is converted to clamping motion via a worm gear reducer and thrust ball bearing. The worm gear reducer is integrated with a slider-shaped inner cylinder wedge mechanism to maintain alignment with the second wedge. This EWB design lacks the self-energizing feature [27]. One of the Malaysian universities named UTeM developed a second EWB prototype, a dual-sided brake called the Fixed Caliper-based EWB, where the tangential motor force is equally distributed between two sets of wedges. Using brake pads from an existing Malaysian car with a friction coefficient between 0.25 and 0.35, they selected a wedge angle based on achieving optimal braking force at the lower friction coefficient value, using the brake factor formula; $F_c = \frac{F_m}{\tan\alpha - \mu}$ where F_c is the clamping force, and $F_c = \mu F_b$. While the calculated optimal wedge angle was 14.03°, a 15° angle was implemented for ease of control and to prevent wedge jamming. This fixed caliper-based EWB design omits rollers between the wedges, is designed for forward braking only, and does not utilise the optimal motor braking angle [28]. Helwan University in Egypt developed a similar EWB system. The differences lie in the use of a one-sided brake, a brake pad with friction coefficient $\mu = 0.3$, a wedge angle of 12°, and a 24V DC motor [29], [30], [31], [32], [33]. The third prototype, developed by UTeM, employs a new EWB design using a cone wedge (CW) shape, as shown in Figure 8. This design utilises male and female mechanisms to ensure that the wedge displaces tangentially to the brake rotor, effectively preventing slippage during braking. A DC motor, connected via a no-loss planetary reduction gear and a single-start lead screw, actuates the wedge mechanism. The driver screw angle β is set equal to the wedge angle $\alpha = 24.5°$ to enable force amplification at a friction coefficient of 0.35. This prototype is also designed for forward-direction braking only [34].

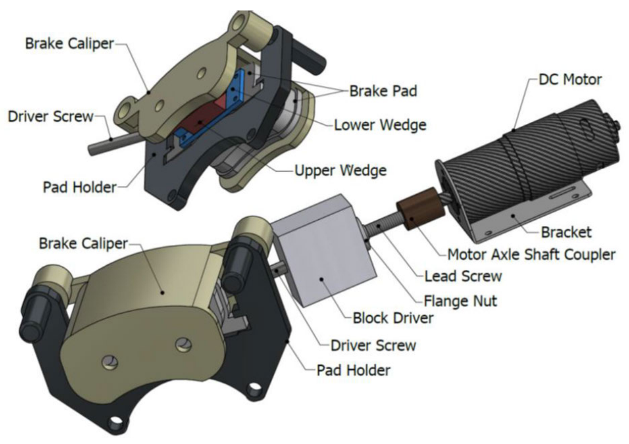

FIGURE 8. Cone Wedge EWB Design [29].

Yu et al. propose an innovative Electronic Wedge Brake (EWB) driven by a Magneto-Rheological (MR) fluid, offering an alternative to traditional motor-driven EWBs shown in figure 9. Magneto-Rheological (MR) fluids are unique materials composed of tiny magnetic particles suspended in a liquid. When a magnetic field is applied, these fluids undergo a rapid and reversible change in their viscosity, transitioning from a free-flowing liquid to a semi-solid state. The strength of this semi-solid state, or yield shear stress, can be precisely controlled by adjusting the magnetic field intensity [30]. In this MR fluid-based EWB design, a gear pair drives a rotor, which in turn rotates the MR brake housing when a magnetic field is applied to the MR fluid. This rotation is then translated into wedge movement via a connecting rod and ball joints, generating the braking force. A return spring provides the necessary counterforce. Notably, the system incorporates a small, coaxially integrated generator that harvests energy, primarily powering the MR brake's Electronic Control Unit (ECU) and coils, or charging a low-voltage battery. This design allows for seamless integration into existing vehicle systems without the substantial powertrain modifications typically required for conventional electric vehicle (EV) regenerative braking. During braking, an electrical current is applied, creating a magnetic field that activates the MR fluid. This causes the housing to rotate, pushing the wedge and applying the desired braking force. Simultaneously, the system facilitates regenerative braking, recovering energy that would otherwise be lost as heat. Simulation results for this MR fluid-based EWB are compared with those of single disc-type MR brakes [31], [32], demonstrating its potential as an efficient and integrated braking solution. Donghwan et al. used analytical methods to determine an optimal wedge angle is 20.55° and actuation angle is between zero and wedge angle for a friction coefficient of 0.375. They then proposed an EWB with an adjustable α to accommodate varying friction coefficients. This design estimates the friction coefficient μ, calculates the corresponding optimal wedge angle α, and adjusts α using a counter wedge connected via a hinge and driven by linear motion components as shown in Figure 10. However, the study remains theoretical and does not offer practical design guidance [33]. Xu and Cho proposed a simplified EWB design for easier chassis adaptation, assembly, and maintenance, with reduced weight and improved environmental impact compared to existing BBW systems that typically use planetary gears or ball screws. Key design considerations included: replacing these complex mechanisms with a powered screw for rotation-to-translation conversion; achieving sufficient braking torque with a single motor by leveraging the wedge's self-energizing capability, selecting a stepper motor for its high torque output; and using a simple limit switch for air gap management instead of complex algorithms. The proposed design only works for braking in forward direction [34].

IV. MATHEMATICAL MODEL OF EWB SYSTEM

Mathematical models play a crucial role in understanding and predicting the complex behavior of Electronic Wedge Brake (EWB) systems. These models, developed by various researchers, aim to capture the essential dynamics of the wedge mechanism, including force amplification, friction characteristics, and system stability. This section will review the different mathematical models proposed in the literature, examining their underlying assumptions, governing equations, and applications in EWB analysis and

TABLE 1. Extended summary of EWB prototypes and their specifications.

S. No	Name	Actuator	Motion Converter	Wedge Shape	Wedge Angle (α)	Actuator Angle (β)	Reference	Other Relevant Details
1	eBrake (1st Prototype)	1 DC motor	Lead screw	V-shape	19.4°, 24.2°	0	[12]	–
2	2nd Prototype	2x BLDC motors	Roller Screws	W-shape with rollers	19.4°	0	[13]	Cooperative motor operation, preloading to eliminate free-play, rollers to minimize friction.
3	"Beta" Prototype	2x BLDC motors	Roller Screws	W-shape with rollers	19.4°	0	[16]	Automatic pad wear adjustment, self-release mechanism (fail-safe).
4	PT1	2x Motors (1 for service, 1 for parking/fail-safe)	Low-backlash power screw	W-shape with rollers	Not specified	α	[17]	Force sensor based on caliper deformation (Hall sensor). Two jointed rods for reverse braking.
5	4th Prototype (Mando)	BLDC Motor	Lead screw	V-shape without rollers	24.2°	0	[18]	Aimed to improve pad wear uniformity.
6	Adjustable EWBs	Not specified (Siemens PT1)	Not specified (Siemens PT1)	W-shape with rollers	Self-adjusting (variable)	α	[25]	Variable wedge shape (self-adjusting); two independently movable wedges (externally adjustable).
7	Han et al.'s EWB	PMSM	Worm gear/wheel, power screw/nut	V-shape without rollers	22°	0	[26]	PMSM motor used.
8	UTeM 1st Prototype	DC Motor	Worm pinion, gear reducer, thrust bearing	Slider-shaped inner cylinder wedge	Not specified	0	[27]	Modified existing caliper; lacks self-energizing feature.
9	UTeM 2nd Prototype (Fixed Caliper)	DC Motor	Drive shaft and slider beam	Wedge (no rollers)	15°	0	[22]	Dual-sided brake; forward braking only; omits rollers.
10	Helwan University EWB	24V DC Motor	Roller screw	Wedge (no rollers)	12°	0	[28]	One-sided brake; forward braking only.
11	UTeM 3rd Prototype (CW-EWB)	DC Motor w/ planetary reduction gear	Single-start lead screw	Cone Wedge (CW), no rollers	24.5°	α	[29]	Male-female mechanism prevents slippage; forward braking only.
12	MR Fluid EWB	MR Fluid	Gear pair, connecting rod, ball joints	Wedge (with rollers)	24.2°	0	[31], [32]	Regenerative braking enabled.
13	Adjustable α EWB	–	–	W-shape with rollers	Adjustable	$0 < \beta < \alpha$	[33]	Theoretical design; adjustable wedge angle based on estimated friction coefficient.
14	Simplified EWB	Stepper Motor	Powered screw	Wedge (no rollers)	22.5°	0	[34]	Limit switch used for air gap management.

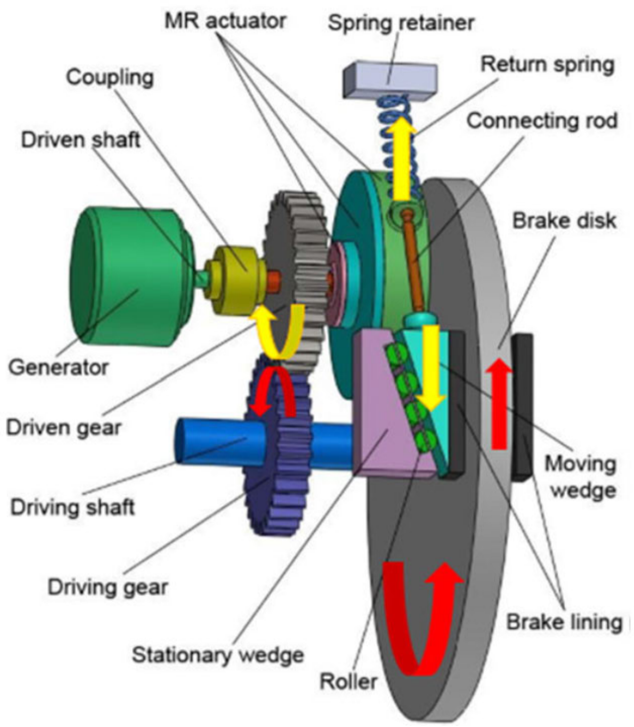

FIGURE 9. MR EWB brake configuration [32].

design. Mathematical modeling of EWB systems typically involves partitioning the system into distinct subsystems: the motor, the lead screw (or alternative transmission mechanism), and the brake heart (comprising the wedge and brake pad). This modular approach facilitates the design of independent controllers for each subsystem. While some researchers combine these subsystem equations into a state-space representation, others maintain them in the form of Ordinary Differential Equations (ODEs). Despite variations in approach, the fundamental principles governing these models exhibit relatively minor differences. Model of first

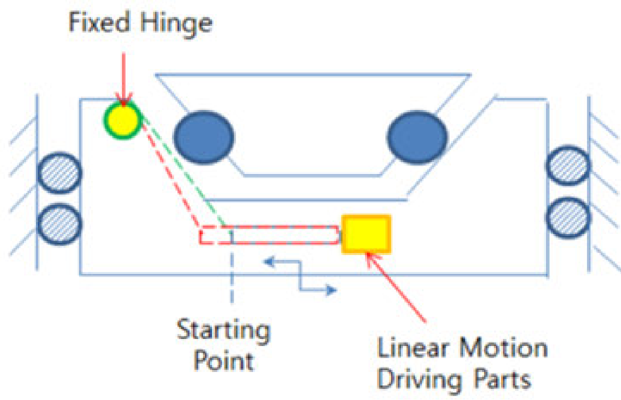

FIGURE 10. Variable wedge structure [33].

prototype by UTeM team [21], [21], [27], [35], [36] is not included in this review because it did not have self-reinforcement. The general model of the complete EWB is given in Figure 11.

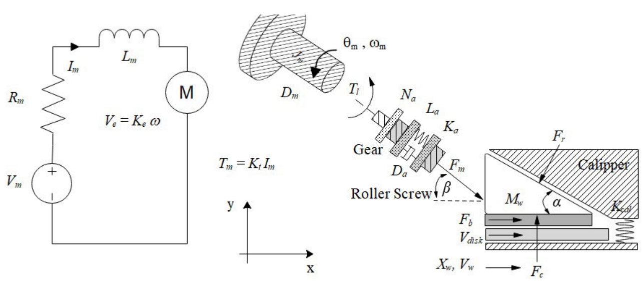

FIGURE 11. Simplified model of the EWB [17].

A. MOTOR

As previously mentioned, various motors can be used, including DC motors [7], [22], Permanent Magnet DC motors [18], [19], BLDC motors [14], [17], [18], [29], PMSMs [26], servo motors, and stepper motors [34]. All of these can be modeled using a general equation with appropriate modifications [37]:

$$\dot{\omega}_m = -\frac{D_m}{J_m}\omega_m + \frac{K_t}{J_m}I_m - \frac{1}{J_m}T_l \tag{2}$$

$$\dot{I}_m = -\frac{K_e}{L_m}\omega_m - \frac{R_m}{L_m}I_m + \frac{1}{L_m}V_m \tag{3}$$

The variables I_m, ω_m, and V_m represent the motor current, angular velocity, and input voltage, respectively. The six key motor parameters involved in modeling are motor resistance (R_m), motor inductance (L_m), electromotive force constant (K_e), motor torque constant (K_t), viscous motor friction (D_m), and motor inertia (J_m). These parameters are sometimes provided by the motor manufacturer; however, in many cases, not all values are specified and must be determined through System Identification (SI) using experimental data [38]. In the case of a two-phase hybrid stepper motor, two separate equations are typically used to describe motor voltage behavior [39]. The variable τ_1 denotes the load torque applied to the motor, which is mechanically coupled to the brake mechanism via a lead screw or an equivalent transmission system.

$$T_l = T_{COG} + T_{SCREW} - T_{FRIC} \tag{4}$$

In most studies, cogging torque is neglected due to its insignificant magnitude. Friction torque is considered only by [8], who found it to be dependent on axial load and shaft speed. Its relatively small value has led to its omission in subsequent studies to simplify the model. Hence all load torque comes from lead screw torque.

B. MECHANICAL LINEAR ACTUATORS (LEAD SCREW)

In EWB systems, the lead screw plays a vital role in converting the rotary motion of the motor into the linear motion required to actuate the wedge. The electric motor provides rotational motion, which is directly coupled to the lead screw. As the screw rotates, the nut, which is connected to the wedge mechanism, moves linearly along the screw's axis. The linear motion of the nut is then transferred to the wedge, causing it to move and apply force to the brake pads. Alternatives to lead screw are ball screw and roller screw. In modelling, the weight of this part is not considered as only the torques and forces are of interest. The screw torque is given by:

$$T_{SCREW} = \frac{F_m L_a N_a}{2\pi\eta} \tag{5}$$

where F_m is the linear force converted from the motors angular motion exerted on the wedge mechanism. According to Siemens team [17], it is given by:

$$F_m = K_a\left(\frac{\theta_m L_a}{2\pi\cos\beta} - X_w\right) + D_a\left(\frac{\omega_m L_a}{2\pi\cos\beta} - V_w\right) \tag{6}$$

whereas according to UTeM team [18] and Ivanov and Ayalew [20], it is given by:

$$F_m = K_a\left(\frac{\theta_m L_a N_a}{2\pi} - \frac{X_w}{\cos\beta}\right) + D_a\left(\frac{\omega_m L_a N_a}{2\pi} - \frac{V_w}{\cos\beta}\right) \tag{7}$$

The parameters K_a and D_a represent the lead screw stiffness and viscous damping, respectively. The lead L_a is a mechanical parameter that converts the motor's angular position θ_m and angular velocity ω_m into the linear displacement X_w and velocity V_w of the wedge. The gear ratio of the lead screw is denoted by N_a, while η represents the lead screw efficiency, typically assumed to be 0.65. The angle β is defined as the angle between the motor-lead screw axis and the wedge direction. As shown in Figure 10, when $\beta = 0$, meaning the motor force is aligned with the wedge's direction of motion, the displacement in the x-direction is directly proportional to the motor force, and $\cos(\beta) = 1$. Notably, only Siemens, UTeM, and Ivanov have explicitly modeled scenarios where the motor force and lead screw are oriented at a non-zero angle β with respect to the wedge. This distinction suggests that further investigation is warranted to analyze the discrepancies between these model formulations. In [26], researchers used a permanent magnet synchronous motor (PMSM) and proposed an alternative model for computing load torque, motor torque, and the lead screw dynamics.

C. WEDGE MODEL

To derive the wedge brake model, all forces acting on the wedge in the x- and y-directions are considered. The wedge, inclined at an angle α, is subjected to four primary forces: the motor force F_m, the normal force F_n between the brake disc and the brake pads attached to the moving wedge, the braking force F_b resulting from the frictional contact between the pads and the disc with a friction coefficient μ, and the reaction force F_R, which is the frictional force perpendicular to the wedge face. The motor force F_m acts at an angle β relative to the wedge. The coordinate X_w is defined as being parallel to the brake disc surface, representing the direction of wedge displacement. The resulting wedge movement equation, as derived and presented in multiple studies [17] and [25] is expressed as:

$$\dot{V}_w = \frac{F_m\left(\cos\beta + \sin\beta\tan\alpha\right)}{M_w\left(1+\tan^2\alpha\right)} + \frac{(\mu - \tan\alpha)K_{cal}\tan\alpha}{M_w\left(1+\tan^2\alpha\right)}X_w \tag{8}$$

where K_{cal} is the brake caliper stiffness and M_w is the mass of the wedge. For the special case of tangential motor force ($\beta = 0$) [28], [40], [41], the equation simplifies to:

$$\dot{V}_w = \frac{F_m}{M_w\left(1+\tan^2\alpha\right)} + \frac{(\mu - \tan\alpha)K_{cal}\tan\alpha}{M_w\left(1+\tan^2\alpha\right)}X_w \tag{9}$$

In the research contributions such as [23] and [42], researchers determined that optimal braking performance is achieved when the motor force angle (β) is equal to the wedge angle (α). As per [42] it can be further simplified as:

$$\dot{V}_w = \frac{F_m}{M_w\left(1+\tan^2\alpha\right)\cos\beta} + \frac{(\mu-\tan\alpha)K_{cal}\tan\alpha}{M_w\left(1+\tan^2\alpha\right)}X_w \tag{10}$$

Considering the geometry illustrated in Figure 11, the **caliper (normal) force** applied by the disk brake can be expressed as:

$$F_c = K_{\text{cal}} \cdot X_w \cdot \tan(\alpha) \tag{11}$$

where K_{cal} is the caliper stiffness, X_w is the displacement of the actuator or piston, and α is the angle of actuation. The resulting **braking force**, due to the frictional interaction between the brake pads and the rotating disc, is given by:

$$F_b = \mu \cdot F_c \tag{12}$$

where μ is the coefficient of friction between the disc and the brake pads. The braking torque generated by pads on both sides of the disc can then be calculated as:

$$T_b = 2 \cdot F_b \cdot r_{\text{ef}} \tag{13}$$

where r_{ef} is the effective radius of the brake pad contact area. In reference paper [40] researchers ignored the movement of the wedge in the y-direction, resulting in a simpler model whereas researchers in [41] developed a mathematical model for the wedge brake mechanism to capture the complex dynamics of a self-energising brake system. This model effectively describes the nonlinear interactions due to friction effects and intermittent pad-disc contact. The model highlights the strong nonlinearity of the system, showing how its qualitative behavior is influenced by the friction coefficient and wedge angle. While the model's predictions align with expected behavior, experimental measurements are necessary to precisely determine model parameters for quantitative accuracy. A local asymptotic stability analysis, performed through linearisation, revealed an instability region. This underscores the importance of a stabilizing feedback controller to ensure stable brake operation and prevent issues like brake lockup.

D. STATE SPACE MODEL

State-space models provide a concise mathematical representation of a system's dynamics using state variables, which describe the system's internal condition, and equations that define how these states evolve over time in response to inputs. This representation is particularly useful for analyzing system behavior, designing controllers, and simulating complex dynamic systems. All sub-models can be combined into a state space model [42], [43], [44]:

$$\dot{x} = Ax + Bu, \quad y = Cx \tag{14}$$

where the state vector is:

$$x = \left[X_w \; V_w \; \theta_m \; \omega_m \; I_m\right]^T \tag{15}$$

an the output is:

$$y = F_c \tag{16}$$

This leads us towards the system matrices as mentioned below:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ \frac{-K_a - a_1 a_4^2}{a_2 a_4^2} & \frac{-D_a}{a_2 a_4^2} & \frac{K_a a_3}{a_2 a_4} & \frac{D_a a_3}{a_2 a_4} & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \frac{K_a a_3}{\eta J_m a_4} & \frac{D_a a_3}{\eta J_m a_4} & \frac{-K_a a_3^2}{\eta J_m} & \frac{-D_m}{J_m} - \frac{D_a a_3^2}{\eta J_m} & \frac{K_t}{J_m} \\ 0 & 0 & 0 & \frac{-K_e}{L_m} & \frac{-R_m}{L_m} \end{bmatrix} \tag{17}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{L_m} \end{bmatrix}, \quad C = \left[K_{cal}\tan(\alpha) \; 0 \; 0 \; 0 \; 0\right] \tag{18}$$

where the variable used in these matrices are mentioned as below:

$$\begin{aligned} a_1 &= K_{cal}\tan\alpha(\tan\alpha - \mu) \\ a_2 &= M_w(\tan^2\alpha + 1) \\ a_3 &= \frac{L_a N_a}{2\pi} \\ a_4 &= \cos\beta, \\ \beta &= \begin{cases} 0, & \text{for Tangential motor force} \\ \alpha, & \text{for optimal motor force} \end{cases} \end{aligned}$$

The state-space model will be different if an alternative lead screw equation from [17] is used. Different assumptions lead to different models. Detailed models are complex but accurate, while simpler models are easier to develop but introduce errors and nonlinearities.

Now moving towards model order reduction. System identification (SI) builds mathematical models from measured input-output data. It is useful for determining unknown parameters within a model when direct measurement is difficult, allowing for accurate system characterisation based on observed responses. Moreover, it utilised SI to obtain the transfer function (TF) of their EWB. The TF is the ratio of the Laplace transform of the clamping force to the drive shaft angle. In [45], a transformed Ordinary Differential Equations (ODEs) into separate TFs for the motor and screw-wedge, later using MATLAB's System Identification Toolbox to fit a TF to experimental data, achieving a 90.6 percent fit. Model Order Reduction (MOR) simplifies complex models by reducing state variables that have minimal influence on system dynamics. This aids controller design by reducing computational complexity. In the research paper [40] ignored M_w, D_a, and L_m, reducing their model from 5th to 2nd order, enabling robust Slide Mode Controller (SMC) design. Whereas in [45], researchers further explored MOR, showing that omitting M_w and D_a resulted in the best reduced-order model (third order), with an RMSE of $1.94e^{-5}\%$, compared to a 2nd order model with 2.08% RMSE. Furthermore, the brake factor measures the efficiency of converting motor force into braking force. Below is a summary of brake factors from different EWB designs:

TABLE 2. Brake factor formulae, max values at $\mu = 0.35, \alpha = \beta = 24.2$.

Source	Brake Type	Brake Factor Formula	Max Value
[4]	EMB	2μ	0.7
[7]	EWB with $\beta = 0$	$\frac{2\mu}{\tan\alpha-\mu}$	7.041
[8]	EWB with $\beta > 0$	$\frac{2\mu}{(\tan\alpha-\mu)(\cos\beta+\sin\beta\tan\alpha)}$	7.7194
[27]	EWB with $\beta > 0$	$\frac{2\mu}{\tan\alpha-\mu} \times \frac{\cos(\alpha-\beta)}{\cos\alpha}$	7.7194
[41]	EWB with $\beta = \alpha$	$\frac{2\mu}{\tan\alpha-\mu} \times \frac{1}{\cos\beta}$	7.7194

Quarter-car models, representing a single wheel and its suspension, allow simplified simulations of EWB performance as illustrated in Figure 12. They help in testing EWB dynamics and ABS control strategies. Researchers in [19], [20], [29], [35], [36], [47], [48] designed vehicle models for ABS implementation using EWB, while [49] developed a 3-DOF model for testing blended regenerative, ABS, and EWB control. A simple QCM from [36] assumes a flat road and zero steering angle, using a wheel model to compute acceleration from applied torque and friction.

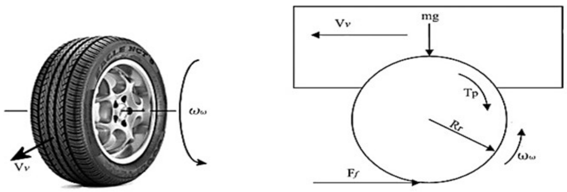

FIGURE 12. Simplified wheel model.

From above Figure 12 one may derive the Wheel dynamics as mentioned below:

$$\frac{d\omega_\omega}{dt} = \frac{m\mu g R_r - T_p}{I} \tag{19}$$

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. The vehicle model uses the friction coefficient to determine vehicle acceleration. Since a quarter-car model (QCM) is used, only one-fourth of the total aerodynamic drag force, which acts on all four wheels of the vehicle, is considered and subtracted from the calculated acceleration:

$$\frac{dV_v}{dt} = -\mu g - \frac{1}{4}\left(\frac{c_r A_f \delta V_v^2}{4(2m)}\right) \tag{20}$$

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 Nissan Leaf.

Whereas Burckhardt's formula as mentioned in [50], gives the friction coefficient value based on different road types:

$$\mu = \left[C_{a1}(1 - e^{-C_{a2}\lambda}) - C_{a3}\lambda\right] e^{-C_{a4}\lambda V_v} \tag{21}$$

TABLE 3. QCM parameters from nissan leaf.

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

where λ is the wheel slip ratio, V_v is the vehicle speed, C_{a1} is the maximum value of the friction curve, C_{a2} is the friction curve shape, C_{a3} is the friction curve difference between the maximum value and the value at $\lambda = 1$, and C_{a4} is the wetness characteristic value. Varying these parameters enables the simulation of diverse tire-road friction conditions. Specific parameter values for different road surfaces are provided 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

The slip ratio indicates the degree of wheel slippage relative to the road surface; a slip ratio of 0 signifies no slip, while a value of 1 represents complete wheel lockup:

$$\lambda = \frac{V_v - \omega_\omega}{V_v} \tag{22}$$

where V_v is vehicle speed and ω_ω is the wheel speed. A slip ratio of 0.2 is typically considered ideal for braking [51], but road conditions can be estimated to determine the optimal slip ratio accordingly [51].

V. PROTOTYPE MANUFACTURING AND TESTING

The development of Electronic Wedge Brakes (EWBs) extends beyond theoretical analysis and simulation; the construction of physical hardware prototypes and their subsequent testing under diverse operating conditions are crucial for validating design concepts, identifying practical challenges, and assessing real-world performance. This section reviews various EWB hardware prototypes documented in the literature, examining their manufacturing processes, experimental setups, and the range of tests conducted to evaluate their efficacy and robustness. Siemens VDO's first two-motor EWB prototype underwent hardware testing on a custom test stand consisting of an AC motor-driven flywheel connected to the brake disc, a floating caliper-based brake, and a moment sensor for torque measurement. Initial tests focused on sensor calibration, validating the motor current loop model, verifying component masses and inertias, and measuring roller-screw efficiency (found to be appximate 65 percent) and drive train stiffness. Frequency response testing of the motor and roller screw revealed the efficiency's impact at higher frequencies. Force fight tests between the two motors, using a force sensor, aided motor model fine-tuning. Moment control tests validated controller stability and brake performance, demonstrating low power consumption (approx 60W) and good agreement between model and hardware, particularly in braking time responses. These results validated the model for control design and paved the way for a second prototype designed for operation in the unstable region to maximize the wedge principle's benefits [13].

Siemens VDO's second two-motor EWB prototype underwent extensive dynamometer testing to evaluate performance under wider variations in friction coefficient and disc temperature, simulating realistic operating conditions. Tests included braking to a standstill, sine wave responses, simulated ABS cycles, and high-temperature tests (reaching over 600°C on the passive pad's backing plate), revealing the brake's performance and limitations, particularly at high temperatures where the lack of wear compensation limited braking torque. These tests demonstrated the brake's functionality under diverse conditions and informed the design of a third prototype [14]. Siemens VDO's third EWB prototype ("beta") utilized an extensive simulation environment and a test trailer with real-world components (tire, suspension, ABS sensor) to facilitate ABS slip controller development. This trailer testing revealed practical challenges like sensor noise, time delays, and wheel load variations, necessitating a more complex ABS controller. A full test vehicle with four EWBs and a central control module running on a dSpace Autobox was also constructed. Using SDK HIL simulation software with advanced 3D graphics, a Pacejka-based tire model extended to zero wheel speed, and a 6-DOF vehicle model, various tests, including -split braking and emergency braking, were simulated and compared with real-world results. These simulations proved valuable for identifying tuning needs and verifying the brake's low-speed behavior, particularly its self-reinforcement at standstill on inclines, consuming less than 50W per actuator on a 2-ton vehicle on a 20 percent slope [15]. Siemens VDO's "beta" EWB prototype underwent further testing using a 160kW dynamometer, a mobile quarter-vehicle test rig (allowing independent control of wheel contact forces and slip angle), and a fully equipped test vehicle with a dSPACE AutoBox for control and EBox platforms for power electronics. Testing methodologies included defining a reference "Golf class" vehicle for load calculations and evaluating various scenarios: high-dynamics braking response (achieving rapid force reduction suitable for ABS), fine controllability for smooth stops, robustness against simulated disk damage (abrasion/thickness change and rust), and wedge-specific functions (handling vehicle standstill on slopes, stopping, and rolling away). ABS performance was validated on varying friction surfaces, including -split conditions, demonstrating effective wheel slip control and coordinated braking. Finally, a soft-stop function was implemented to prevent acceleration overshoot during vehicle halts [16]

FIGURE 13. Siemens' Mobile QC test rig (left) and high temperature testing (right) [16].

Siemens VDO's fourth EWB prototype (PT1), a single-motor design, underwent initial testing on a roller test bench capable of simulating high speeds and torques. Using a cascaded controller embedded on a microcontroller and CAN communication, tests were conducted to evaluate the brake's response to various force demands. Results showed rapid force application with minimal steady-state power consumption (approx. 15W), though some motor current oscillations were observed due to voltage limitations. Tests also revealed a non-linear caliper stiffness. While the presented results reflect an early controller version, they demonstrated the EWB's potential for high-dynamics control, crucial for improved ABS performance and shorter stopping distances [12]. Mando's fourth EWB prototype underwent experimental testing to evaluate its performance. Static clamping force measurements using a load cell established the relationship between motor current and clamping force. Dynamic tests with a rotating rotor demonstrated the wedge mechanism's effectiveness, though limited hydraulic power restricted testing to low speeds (below 200 rpm), resulting in a modest braking torque difference. Dynamometer testing confirmed the prototype's overall performance, achieving a maximum deceleration of approximately 0.8g, indicative of high- road conditions [18].

Mando Corp. investigated a brake-by-wire (BBW) system with front EWBs and rear EMBs, leveraging the EWB's self-energizing mechanism for reduced power consumption on the front axle and the EMB's suitability for parking functionality on the rear. Lab tests on the EWB achieved 2300 Nm torque and a 60ms response time to 1000 kgf clamping force, while the EMB reached 1800 kgf in 150ms and successfully demonstrated parking functionality using a solenoid locking mechanism. Vehicle testing, including brake balance tuning, achieved 1.0g deceleration without wheel lockup. ABS testing demonstrated effective target slip control on the front EWBs and mode control on the rear EMBs [51], [52]. Further testing of a hybrid braking system (HBS), combining front ESC (with a hydraulic actuator) and rear EWBs, was conducted on snowy and icy roads. Conventional braking system (CBS) tests demonstrated the feasibility of EWB control. ABS tests showed promising results, although some refinement was needed to improve the EWB actuator response and reduce post-compensation fluctuations. ESC tests, including lane change and slalom maneuvers, validated the EWB's ability to provide oversteer compensation. Finally, EPB tests confirmed the feasibility of static parking brake functionality (apply, release, drive-away release) with the EWB system [19].

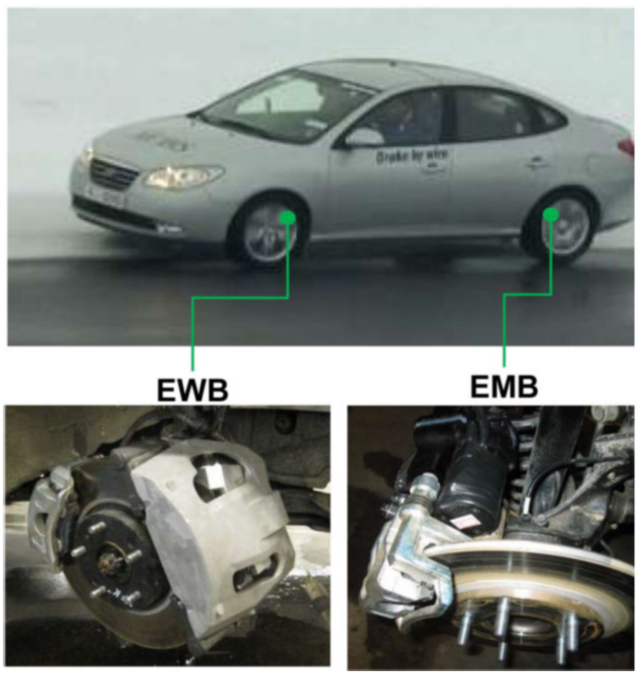

FIGURE 14. BBW test vehicle with mounted EWB and EMB [47].

Researchers at Helwan University developed a simple, forward-acting wedge EWB and conducted experimental tests using a custom rig with a DC motor, roller screw, and data acquisition system as shown in the Figure 15. By varying the e-pedal stroke (and thus the input voltage to the motor), they measured the resulting wedge displacement and response time. Results showed that higher input voltages led to faster motor speeds and quicker wedge displacement, with full stroke (24V) achieving the fastest response time (2.2 seconds to maximum displacement). No further testing was done [27]. Han et al.'s EWB prototype underwent hardware-in-the-loop (HILS) testing on custom made test bench. Contact point detection showed a small error (approx. 0.4mm). Step response tests revealed 0.1s and 0.2s delays in braking and releasing, respectively, attributed to the prototype's structure and load-cell sensor. Clamping force control tests demonstrated the effectiveness and accuracy of their proposed sliding mode controller in following driver-intended force commands based on pedal displacement [28]

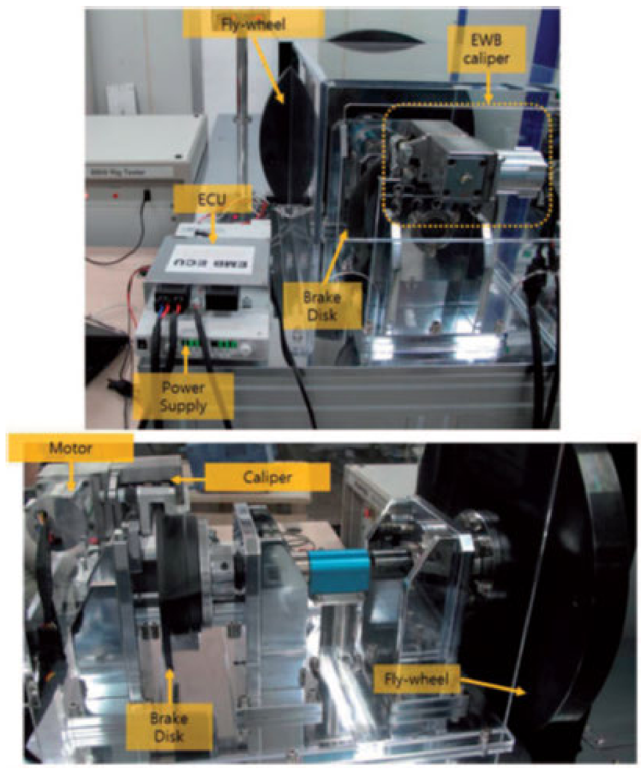

FIGURE 15. Custom Test Bench [21].

A joint study by Hyundai-Kia-Mobid R and D and Sungkyunkwan University proposed a new brake system with front EWBs and rear hydraulic brakes, aiming for improved urgent braking response and simplified design (eliminating the need for a pedal simulator and fail-safe device) as indicated in Figure 16. A regenerative braking cooperative control algorithm was developed and tested on a HEV, with both simulations and vehicle tests conducted at 0.2g deceleration from 100 km/h. Results showed good agreement between simulation and test data, demonstrating effective coordination of regenerative and friction braking to achieve the desired deceleration. Increasing the braking force gradient relative to pedal stroke increased regenerative braking and recovered energy but also increased braking sensitivity, highlighting the need for careful gradient design to balance energy recovery and driving comfort [48], [49].

Although UTeM's first EWB prototype was subjected to various tests [21], [27], [54], the results are not included here because the prototype did not incorporate self-reinforcement. UTeM's second EWB prototype underwent torque tracking controller performance evaluation using step, sine wave, sawtooth, and square input functions. While generally good agreement was observed between simulation and experimental results, some deviations occurred, particularly with the 1200 Nm step input and the sawtooth function, where the experimental response was slower and exhibited jerk phenomena due to motor speed limitations. Overshoots were also present in the square wave tests. These discrepancies were attributed to unmodeled hardware components (e.g., pad and slider beam masses), hardware finishing, and DC motor limitations. Despite these deviations, the proposed transfer function proved adequate for FIXEWB simulation, demonstrating promising torque tracking performance and acceptable stability in both simulation and experimental settings [22]. UTeM's third prototype, a cone-shaped wedge EWB (CW-EWB) powered by a DC motor and single lead screw as shown in Figure 17, was evaluated using hardware-in-the-loop simulation (HILS) as can be visualised in Figure 18. Comparing simulation and experimental data for brake torque, wedge position, voltage, current, and wheel speed, the CW-EWB demonstrated successful braking performance, achieving target torques of 730 Nm and 365 Nm at initial wheel speeds of 250 and 350 rpm, respectively. While transient response delays of up to 1.23 seconds were observed in experiments, the simulation trends closely matched experimental data with deviations generally under 5 percent, validating the proposed mathematical model for future development. These discrepancies were attributed to mechanical factors like internal friction, backlash, and motor inertia [50], [51], [52].

VI. CONTROL STRATEGIES FOR ELECTRONIC WEDGE BRAKES

Effective control strategies are crucial for realizing the full potential of Electromechanical Wedge Brakes (EWBs). This section reviews various control approaches developed for EWBs, encompassing methods for precise force/torque control, robust performance under varying operating conditions, and strategies for integration with higher-level vehicle dynamics control systems like ABS and ESC. A key challenge for EWB control is maintaining stability around the optimal operating point (where the characteristic brake factor is infinite), which represents a point of neutral stability and can lead to instability and wheel jamming with increasing friction coefficients. The discussion will cover both model-based and data-driven techniques, highlighting

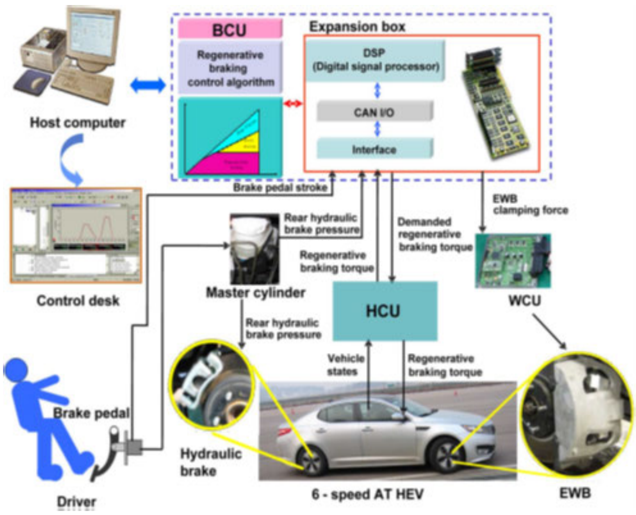

FIGURE 16. Configuration of front EWB + regen, back HB brake test vehicle [53].

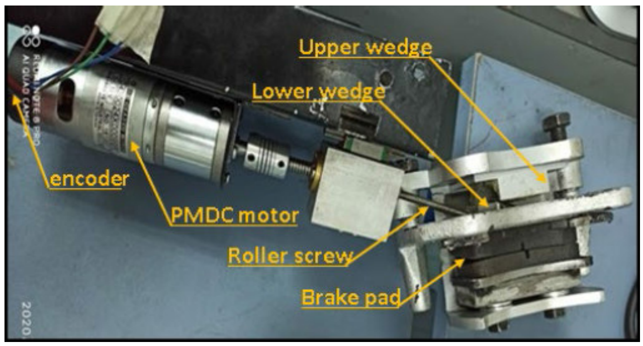

FIGURE 17. CW-EWB prototype [23].

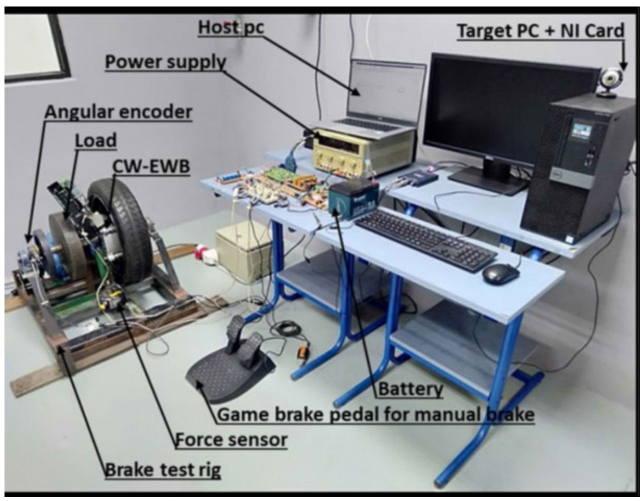

FIGURE 18. CW-EWB Brake test rig setup.

their strengths, limitations, and suitability for different EWB designs and applications. A cascaded controller structure, comprising force, angular velocity, and current control loops, was implemented for the Siemens beta prototype EWB, though specific controller details are not provided [53], [54]. Simulation and test results indicate fast response times and precise control of braking forces, even with small driver inputs. Robust controllability was also demonstrated under conditions of simulated disk damage (abrasion, uneven thickness, and rust). Furthermore, the EWB integrated effectively with ABS, exhibiting good performance on various road surfaces, including μ-split and low-friction conditions [16]. Similarly in [15], authors have developed detailed controllers for EWB, ABS, EPB, ESC but does not give any details of controller design. Authors in [17] presents two control strategies for Siemens PT1, focusing on modeling and control design. A standard cascaded controller, comprising an inner current loop (field-oriented motor torque control), a rate control loop (for stability across friction coefficients), and an outer force loop (for driver demand implementation) using P, I, and D elements with filtering and feed-forward, offers a simpler implementation than the previous dual-motor control by eliminating the need for preload control as shown in Figure 19. In contrast, a new PI state feedback controller utilizes full state feedback designed as a discrete-time output Riccati controller, with an observer (using steady-state Kalman filter gains) estimating unmeasurable states as shown in Figure 20. An outer PI loop minimizes steady-state errors, and a trajectory generator shapes the force demand for physical feasibility and adapts to different braking scenarios.

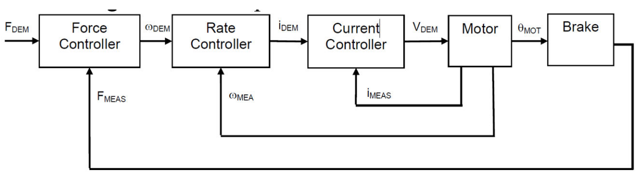

FIGURE 19. Cascaded PID controllers.

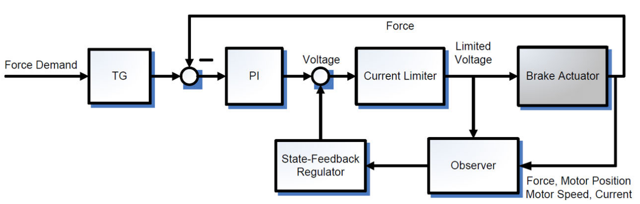

FIGURE 20. PI State feedback controller with observer and trajectory generator.

Experimental roller test bench results for the cascaded controller demonstrate its ability to follow force demands with low steady-state power consumption, although some unevenness in rate demand and oscillations in motor/battery currents were observed, and dynamics were slower than previous dual-motor prototypes. Simulation results for the PI state feedback controller show stable step responses across varying friction coefficients ($\mu = 0$ to $\mu = 1$), achieving a 0.1s rise time at $\mu = 1$, with the outer PI loop effectively minimizing steady-state errors. A similar cascaded PID controller was designed by [20] to compare the performance of their self-adjustable and externally adjustable EWB design with conventional EWB model. All designs achieved the target 12 kN braking force in about 0.1 seconds. The externally adjustable EWB stood out by requiring significantly less actuator force (10 KN vs. 12 KN), motor torque (0.1 Nm vs. 0.3 Nm). Whereas in [17] one may see designed a cascaded PID controller for validation of their FIXEWB. Control uses nested PID torque and position controllers, and a P speed controller. Tuned via Ziegler-Nichols, its torque tracking was evaluated with 400Nm, 800Nm and 1200Nm inputs. Step responses showed good simulation/experiment agreement with minor deviations and approximate 5 percent overshoot. Sine wave tracking was also accurate. Sawtooth inputs had good positive but poor negative torque tracking with some jerk. Square waves showed higher overshoot (12)-23) percent and similar settling times (approx. 4.6 seconds) but slower experimental rise times. Deviations were attributed to unmodeled hardware and motor limitations. The controller was not tested for parametric variation as it was primarily designed for model validation. A simple PID controller was designed and tuned for an EWB system in [42] and [46] with similar results. The controllers were designed, considering actuator saturation of 12V. Testing with step inputs at maximum clamping force (10,217 N) showed good performance with 5.08 percent overshoot, 0.16s rise time, and 0.70s settling time. The controller operated within actuator limits, and the motor operated well below its maximum speed. The simulation did not account for pad-disc contact travel time.

The control structure designed for CW-EWB at UTeM [23] consists of two loops: an outer torque control loop using a PID controller to accurately track the desired braking torque, and an inner position control loop using a PI controller to manage the DC motor actuation and maintain the desired pad-disc spacing. The controller was designed to validate the model and hardware of CW-EWB and results show agreement in simulation and experimental results with 0.5 s time delay. A sliding mode controller (SMC) is designed [26] to regulate the EWB's clamping force by controlling motor current. The control law uses a saturation function instead a signum function to reduce chattering. The control gain is designed for robustness against parametric variation, like. Simulations comparing SMC to a PI controller show superior tracking performance for SMC with both estimated and measured clamping force feedback. Hardware-in-the-loop (HILS) experiments with a prototype EWB further validate the controller, demonstrating accurate contact point detection with a 0.4 mm error. Step response tests reveal minor delays in braking/releasing due to prototype limitations. Dynamic braking tests confirm accurate clamping force tracking using estimated feedback. Another SMC strategy is presented in [40] for EWBs based on a simplified, second-order model using motor angle and rate as states. The SMC aims to precisely control clamping force despite uncertainties in the pad friction coefficient μ. An adaptation law, derived using Lyapunov stability theory, estimates online, compensating for its variations. Simulations demonstrate the adaptive SMC's superior robustness compared to a PI controller under varying friction conditions, screw efficiency changes and during soft braking. The adaptation scheme accurately estimates, with a modified reference input significantly reducing estimation spikes caused by step inputs. Robustness to dynamically varying friction is also shown, with an RMS estimation error of approx. 0.025. This approach enables accurate clamping force control using only motor angle measurements, eliminating the need for a costly and noise-prone clamping force sensor.

An Active Disturbance Rejection Control (ADRC) algorithm is implemented to control the novel EWB stepper motor's rotation angle, directly correlating to the desired clamping force. The ADRC was chosen for its fast response and disturbance rejection capabilities. Simulations compared the ADRC against conventional PID and Sliding Mode Control (SMC). Results showed that ADRC achieved a smoother response with no overshoot, unlike SMC which exhibited significant overshoot (83.68-99.77) percent and chattering, rendering it unsuitable. While PID also had no overshoot, ADRC demonstrated a faster rise time (0.16s vs. 0.24s for PID) and comparable settling time (0.23s vs. 0.33s for PID) while having a slightly larger steady state error (0.35 degrees vs 0.24 degrees for PID). Simulations on a vehicle model (6500kg) with a flywheel simulating wheel inertia (40kg, 0.19m radius) showed a maximum deceleration of 16.4 rad/s^2 and a stopping time of approximately 7 seconds from 25 m/s [29].

In [39], researchers presents a sensorless servo-LQR (SS-LQR) control strategy for an EWB, comparing its performance against a cascaded PI controller. The proposed SS-LQR employs three servo loops (clamp force, motor speed, and current), each with a PI-like LQR controller and a feed-forward integrator. A Kalman Filter (KF) is used for sensorless estimation of motor and wedge states (current, speed, position) using only motor current and voltage measurements. Simulations were conducted under normal and emergency braking conditions, both with the EWB acting alone and integrated with regenerative braking from an in-wheel motor (IWM) in an EV. In normal braking, SS-LQR demonstrated significantly faster response times (0.17s delay vs. >0.9s for PI) and closely matched the performance of a sensor-based S-LQR. In emergency braking, SS-LQR maintained accurate torque tracking even at high brake demands. When integrated with IWM regenerative braking, the EWB effectively supplemented the IWM torque based on a series braking strategy, with the IWM providing the majority of braking force, especially at lower demands. Mohd Hanif Che et al. [42] designed FFPID for ABS control of vehicle using Fixed Caliper EWB as shown in Figure 21. In this controller a fuzzy logic is used to select the fractional order of the P,I and D values based on the actual slip and relative velocity. The EWB is controlled by cascaded PID similar to [17]. This study concludes that the Fuzzy Fractional PID (FFPID) controller significantly improves ABS performance compared to PID and FPID controllers. Simulations showed reduced slip overshoot (1 percent vs. 12 percent and 16.5 percent at 40km/h; 2.5 vs. 10 percent and 25 percent at 60km/h; 4 percent at 150km/h on snow) and shorter stopping distances (2-2.7m shorter than FPID/PID at 40km/h; approximate 1.5-12m shorter at 150km/h). HILS experiments validated these improvements, with minor delays in stopping (approx 0.196s) and rise times (0.31s) and small differences in stopping distance (0.53m) due to hardware/modeling limitations. The FFPID demonstrates strong potential for real-world ABS applications.

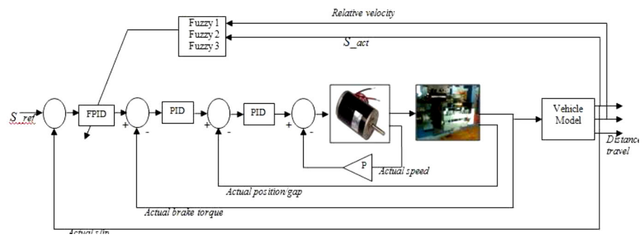

FIGURE 21. FFPID with cascaded PID for ABS control using EWB.

Building upon Ahmed Fauzi's prior research, [43] developed two fuzzy-based PID controllers for ABS control: Fuzzy PID (FPID) and Self-Tuning Fuzzy PID (SFPID). Unlike previous work incorporating fractional order elements, these controllers directly tuned the P, I, and D gains using fuzzy logic. Furthermore, a simplified control structure was implemented, utilizing a single PI torque controller for the Cone Wedge Electronic Wedge Brake (CW-EWB) instead of the cascaded PID approach used previously. Simulations compared these controllers against a conventional PID at 40, 60, and 90 km/h with target slip ratios of 0.2, 0.4, 0.6, and 0.8. SFPID, which used both slip error and relative velocity as fuzzy inputs, generally outperformed FPID and PID, demonstrating faster settling times, reduced jerking, and shorter stopping distances. At 40km/h, SFPID achieved the fastest stopping times across all slips. At 60km/h, SFPID showed slightly longer settling times at 0.4 slip but remained superior at other slips. At 90km/h, SFPID achieved the shortest stopping distances (e.g., at 0.2 slip: 2.560s vs. 2.572s for FPID and 3.014s for PID; at 0.8 slip: 66.72m vs. 67.23m for FPID and 68.32m for PID). Moreover, in [15] and [48] by Hyundai R and D in collaboration with others, proposes a regenerative braking control algorithm for a hybrid electric vehicle (HEV) using front Electronic Wedge Brakes (EWBs) and rear hydraulic brakes, avoiding a pedal simulator. Regenerative braking is prioritized at the front wheels, with rear hydraulic brakes engaging only beyond a certain pedal stroke threshold. Simulations and vehicle tests validated the algorithm's effective distribution of braking forces. Increasing the braking force gradient enhances energy recovery but can reduce driving comfort. Importantly, the paper focuses on the overall braking system and regenerative control strategy, not on the specific EWB control method.

TABLE 5. Summary of control strategies for EWB systems.

S. No	Control Strategy	Authors	Key Features/Details	Limitations
1	Cascaded Controller (Force, Velocity, Current)	Lok Man et al. (2006), Ákos et al. (2006)	Fast response, precise force control, robust to simulated disk damage, integrated with ABS	Good performance on various road surfaces (including μ-split and low-friction)
2	Cascaded Controller (Force, Rate, Current)	Joseph et al. (2007)	Simpler implementation than dual-motor control	Low steady-state power consumption, some current oscillations
3	PI State Feedback Controller (with Observer and Trajectory Generator)	Joseph et al. (2007)	Stable step responses across varying friction ($\mu = 0$ to $\mu = 1$), 0.1s rise time at $\mu = 1$	Outer PI loop minimizes steady-state errors
4	Cascaded PID	Ivanov & Ayalew (2011)	Compared adjustable EWBs with conventional EWB model	12 kN braking force in 0.1 seconds
5	Cascaded PID (Torque, Position, Speed)	Fauzi et al. (2017)	Tuned via Ziegler-Nichols	Good simulation/experiment agreement, 5% overshoot in step response
6	Simple PID	Mohd Hanif Che et al. (2019, 2021)	Designed considering actuator saturation (12V)	5.08% overshoot, 0.16s rise time, 0.70s settling time with step input at max clamping force
7	Outer Torque PID Loop, Inner Position PI Loop	HARIS et al. (2023)	Designed for model and hardware validation	Agreement in simulation and experimental results with 0.5s time delay
8	Sliding Mode Controller (SMC)	Kyutae et al. (2012)	Saturation function used to reduce chattering, robust to parameter variation	Superior tracking than PI, 0.4mm contact point detection error, minor delays in braking/releasing
9	Adaptive SMC	Hwang & Choi (2013)	Online friction coefficient (μ) estimation, robust to varying friction and screw efficiency	Accurate μ estimation (RMS error 0.025), robust to dynamically varying friction
10	ADRC	Feng et al. (2022)	Chosen for fast response and disturbance rejection	Smoother response with no overshoot (unlike SMC), faster rise time than PID
11	SS-LQR	Mahmoud Said et al. (2023)	Kalman Filter for state estimation, three servo loops (clamp force, motor speed, current)	Faster response time than cascaded PI, accurate torque tracking in emergency braking, effective integration with regenerative braking
12	Fuzzy Fractional PID (FFPID) for ABS	Ahmad et al. (2018)	Fuzzy logic selects fractional order of PID gains	Reduced slip overshoot and shorter stopping distances compared to PID and FPID in simulations and HILS experiments
13	Fuzzy PID (FPID) for ABS	Sharil Izwan et al. (2021)	Fuzzy logic tunes P, I, and D gains, single PI torque controller	FPID outperformed PID, faster settling times, reduced jerking, shorter stopping distances
14	Self-Tuning Fuzzy PID (SFPID) for ABS	Sharil Izwan et al. (2021)	Fuzzy logic tunes P, I, and D gains, single PI torque controller	SFPID generally outperformed FPID and PID, faster settling times, reduced jerking, shorter stopping distances

VII. INCREMENTAL ADVANCEMENTS IN ELECTRONIC WEDGE BRAKE (EWB) TECHNOLOGY

The evolution of Electronic Wedge Brake (EWB) systems has seen significant research focus in recent years, with incremental innovations targeting specific limitations of traditional braking systems and early-generation EWBs. This section presents a critical overview of how the proposed contributions in this study diverge from and improve upon prior approaches, particularly in terms of control strategies, mechanical design, and prototyping methodologies.

A. CONTROL STRATEGY IMPROVEMENTS

Previous works have explored various control algorithms for EWB systems, including PID-based tuning, fuzzy logic, and sliding mode control. While these methods have demonstrated viability in specific scenarios, they often suffer from limitations in adaptability, robustness under uncertainty, and responsiveness in dynamic braking conditions. The proposed research introduces a robust control framework leveraging Fractional Order Control and softly switched Model Predictive Control (MPC) with adaptive gain scheduling. This formulation ensures seamless transitions across multiple linear models representing different vehicle states, enhances robustness against disturbances, and mitigates chattering — a persistent issue in switching control schemes. The proposed approach also incorporates Lyapunov-based stability guarantees and model bank reduction using PCA, offering both theoretical soundness and real-time applicability.

B. DESIGN AND MECHANICAL ARCHITECTURE ENHANCEMENTS

Traditional EWB designs have largely focused on either single-wedge or dual-wedge mechanisms, optimized for self-reinforcement through frictional interaction. However, these configurations often face issues such as actuator saturation, slow dynamic response, or mechanical complexity. This study introduces refinements in the geometry of the wedge mechanism to maximize the self-reinforcement effect while reducing actuator load. Moreover, the actuation system has been redesigned to support more compact packaging, lower power requirements (e.g., operation with a 12V motor), and enhanced compatibility with embedded controllers. These mechanical innovations support smoother and more reliable braking performance, especially under varying road surface conditions.

C. PROTOTYPING AND VALIDATION CONTRIBUTIONS

Unlike earlier studies that rely heavily on simulation or lab-scale setups without hardware integration, the present work includes the development of a functional prototype platform. This prototype incorporates real-time feedback from sensors and embedded controllers and is validated under both MATLAB/Simulink simulations and hardware-in-the-loop (HIL) setups. Additionally, extensive validation is performed on a hover testbed platform, demonstrating the system's applicability in replicating real-world braking profiles and validating control accuracy, torque generation, and system response across multiple braking scenarios.

These contributions collectively distinguish the proposed system as a practical, scalable, and intelligent EWB solution, advancing the state of the art in autonomous braking systems.

VIII. CHALLENGES AND FUTURE DIRECTION

A. CHALLENGES AND FUTURE DIRECTION IN EWB DESIGN

This section delineates numerous challenges and future avenues for EWB design. A major challenge is wedge jamming or self-locking, which particularly arises at the critical wedge angle. Although optimising the wedge angle for certain friction coefficients is beneficial, adjusting to fluctuating friction circumstances continues to provide challenges. Another concern is mechanical backlash and wear, especially in screw mechanisms and roller components. Manufacturing tolerances and component degradation adversely affect control accuracy and system durability, particularly in roller-based wedge systems. The intricacy of actuation systems is a further hurdle, as designs that utilise planetary or worm gears, as well as ball or roller screws, typically elevate system complexity, expense, and mass. Streamlining these procedures while preserving performance is a vital area of emphasis. Moreover, the influence of the angle (β) between the motor force and the wedge orientation is inconsistently addressed in research. Certain designs presume $\beta = 0$, whilst others investigate its influence on EWB performance in both forward and reverse orientations. A comprehensive analysis is required to ascertain the value of implementing β variation.

Reverse braking is an additional domain for enhancement, as numerous EWB designs are confined to forward braking. It is imperative to investigate effective and efficient reverse braking systems, including V-shape or W-shape designs and alternate actuation methods. Angled drive shafts enhance forward braking durability but complicate reverse braking design. Sensor integration and sensorless control methodologies present obstacles as well. Conventional sensors for measuring clamping force and wedge displacement are susceptible to noise and necessitate meticulous positioning to mitigate thermal effects, hence elevating system expenses. Conversely, sensorless control systems necessitate strong estimate techniques, such as Kalman Filters, and precise system models to be effective. Attaining elevated Caliper stiffness in a compact configuration presents a significant challenge, since it is essential for effective force transmission and reducing system dimensions. This necessitates structural analysis and material optimisation. Furthermore, thermal and lubrication management must be considered, since elevated friction during braking can result in heat accumulation, thereby impacting component performance and longevity. Efficient heat dissipation and lubrication techniques are essential for ensuring long-term durability.

Several avenues can improve EWB performance in the future. Advanced actuation systems, including magnetorheological (MR) fluids as proposed by Yu et al., present possible benefits in control accuracy, response time, and diminished complexity, necessitating additional investigation. The utilisation of enhanced materials and manufacturing methods could mitigate backlash, decrease wear, and enhance component longevity, particularly in high-stress regions like screw and wedge interfaces. Moreover, improved sensorless control methodologies, perhaps integrating machine learning approaches, may further reduce system expenses while preserving high performance.Incorporating thermal and lubrication management solutions into EWB designs—such as optimised cooling channels or enhanced heat-dissipating materials—can enhance reliability and durability. Moreover, emphasising compact and lightweight designs would enhance vehicle integration while reducing the effects on vehicle weight and fuel economy. Ultimately, the implementation of standardised testing protocols and performance indicators for EWBs will be essential for guaranteeing safety and dependability, while facilitating significant comparisons among various designs in practical implementations.

B. CHALLENGES AND FUTURE DIRECTION IN EWB MODELING

This subsection delineates many obstacles and prospective avenues for EWB modeling. A primary difficulty is reconciling model complexity with accuracy. Comprehensive models that include all physical phenomena, including cogging torque, friction fluctuations, and wedge dynamics in both the x and y axes, are sometimes exceedingly intricate and challenging to manage. Simplified models, although more manageable, result in inaccuracies. Achieving an optimal equilibrium between complexity and precision is essential. A notable problem is parameter identification, as some critical quantities, including motor constants, friction coefficients, and Caliper stiffness, are not readily accessible from manufacturers and necessitate experimental system identification (SI). The precision of SI procedures is contingent upon the quality of the experimental data, and the procedure may be laborious. EWBs demonstrate considerable nonlinearities attributable to friction, fluctuating contact conditions between the pad and disc, Caliper rigidity, and the self-energizing phenomenon. Accurately capturing these nonlinearities in mathematical models is difficult. Moreover, model validation continues to be a significant concern, as experimental validation is frequently constrained. Extensive validation under many operational situations is essential to enhance model reliability. Another problem is the simplification of models by disregarding specific dynamics, like wedge mass, axial damping, and motor inductance. This method aids in control design but may adversely affect model accuracy, particularly under high-dynamic operating circumstances. A meticulous examination is necessary to ascertain which dynamics can be safely disregarded without jeopardising performance.

Subsequent research ought to concentrate on investigating sophisticated modelling methodologies, including finite element analysis (FEA) for comprehensive stress and deformation assessment of the Caliper and wedge, alongside multi-body dynamics for a more precise depiction of mechanical interactions. Furthermore, enhanced system identification techniques, potentially including online adaptation methods, may improve parameter estimation precision and diminish need on substantial experimental validation. Exploring nonlinear model order reduction (MOR) approaches may yield reduced models that preserve the fundamental nonlinear characteristics of the EWB. A possible avenue is the advancement of more intricate friction models that consider fluctuations in temperature, velocity, and contact pressure, thus enhancing model precision and control efficacy, especially under harsh braking scenarios. Extensive experimental validation, encompassing transient braking tests and assessments under many environmental circumstances, is essential for assuring model reliability. Creating a standardised modelling framework for EWBs would enhance the ability to compare various designs and control strategies. Moreover, a comprehensive examination of the variances among the lead screw equations employed by many research organisations is essential to ascertain the most precise model for specific situations.

C. CHALLENGES AND FUTURE DIRECTIONS IN PROTOTYPE MANUFACTURING AND TESTING

This subsection deals in discussing the challenges associated with EWB prototype production and testing, highlighting numerous critical issues and prospective directions. A primary problem is reconciling simulation with reality. Discrepancies between simulation and experimental findings frequently occur and are often ascribed to unmodeled hardware elements, including pad/slider mass, internal friction, backlash, motor constraints, sensor noise, and time delays. Furthermore, defects in hardware finishing and simplifications in mathematical models add to these discrepancies. Precisely replicating real-world phenomena in simulations continues to be a significant difficulty. A notable problem is high-temperature testing. Assessing EWB performance in extreme temperature settings, as illustrated by Siemens VDO, is essential yet technically challenging. Maintaining uniform control and measurement precision at high temperatures poses challenges. Likewise, dynamic testing is frequently restricted by hardware restrictions. Initial testing configurations, exemplified by Mando's and UTeM's prototypes, experienced constrained hydraulic power, hence restricting testing velocities. Realistic dynamic testing circumstances, such as elevated speeds, torques, and authentic ABS/ESC cycles, require sophisticated test rigs and dynamometers. The authenticity of test rigs is a critical element, as correctly simulating real-world vehicle circumstances is necessary for dependable performance assessment. Variables including wheel load fluctuations, suspension dynamics, and tyre performance must be precisely depicted. Moreover, several studies concentrate on particular facets of EWB performance, such as static clamping force or step reaction, instead of doing thorough evaluations across varied operating situations. It is essential to broaden the testing scope to encompass diverse friction surfaces, μ-split braking, emergency braking, and the integration of ABS/ESC to achieve a comprehensive understanding of EWB behaviour. A significant concern is the absence of standardisation in testing protocols and performance measures. The lack of globally recognised benchmarks complicates the comparison of results across various research and the assessment of overall advancements in EWB development. Standardised procedures would enable significant comparisons and promote progress in the field.

Enhancing test rig design will be essential moving forward. Creating advanced test rigs that precisely simulate real-world vehicle dynamics, encompassing wheel load fluctuations, suspension properties, and tyre performance, will improve the authenticity of testing. Utilising mobile test rigs or including full-vehicle testing during the first phases of prototype development may provide enhanced insights. Furthermore, sophisticated measurement techniques, like high-speed cameras, laser vibrometers, and thermal imaging, may yield more comprehensive studies of EWB behaviour under dynamic situations. Implementing extensive testing protocols that cover diverse operating situations, such as severe temperatures, different friction surfaces, and ABS/ESC cycles, is crucial for an exhaustive assessment of EWB performance. Prioritisation of long-term durability and reliability testing, encompassing wear tests, fatigue assessments, and environmental exposure evaluations, is essential to validate the feasibility of EWBs for practical applications. A promising method involves employing Hardware-in-the-Loop (HIL) testing alongside comprehensive and validated vehicle dynamics models to connect simulation with real-world testing. This would facilitate more effective controller development and validation. Standardising testing protocols and performance indicators for EWBs would enhance comparability among various designs and expedite development advancements. Furthermore, specialised thermal management testing, encompassing temperature mapping of vital components and assessment of cooling systems, is crucial for guaranteeing dependable performance under elevated thermal loads. Ultimately, resolving noise, vibration, and harshness (NVH) concerns linked to EWB operation is essential for driver comfort and adoption. Exploring methods to mitigate noise from actuation mechanisms and diminish vibrations communicated to the vehicle chassis will facilitate the wider acceptance of EWB technology.

D. CHALLENGES AND FUTURE DIRECTION IN CONTROL STRATEGIES FOR EWB

The examination of Electronic Wedge Brake (EWB) control systems identifies numerous significant difficulties and potential avenues for progress. A significant challenge exists in preserving system stability approaching the threshold of infinite self-reinforcement, where the braking force theoretically tends towards infinity. This intrinsically unstable zone jeopardises wheel lock-up and presents a considerable control difficulty. Attaining equilibrium between superior performance and durability is a critical consideration, necessitating rapid response times and accurate force regulation while maintaining resilience to variations in system parameters, including friction coefficient, temperature, and mechanical degradation. EWB systems exhibit significant nonlinearities, including friction and hysteresis, as well as uncertainty in system dynamics, which hinder the design of efficient controllers. Seamless integration with existing vehicle dynamics control systems, such as Anti-lock Braking Systems (ABS) and Electronic Stability Control (ESC), necessitates precise coordination across control units. Moreover, although sensorless control methods can diminish system expenses and intricacy, they necessitate sophisticated estimate techniques, such as Kalman filters, in conjunction with resilient algorithms to ensure performance stability. Controller tuning, especially in cascaded PID configurations, is often laborious and intricate, particularly in nonlinear systems characterised by high parameter sensitivity. Moreover, several research concentrate on individual control strategies without comparison assessments, constraining the comprehensive understanding of the advantages of each method.

Future study should investigate sophisticated nonlinear control approaches, such as Model Predictive Control (MPC), adaptive control, and robust control, which may provide enhanced performance and robustness relative to conventional PID or Sliding Mode Control (SMC). Improving friction assessment and compensating methods is crucial for enhancing braking performance across various road conditions, therefore augmenting the reliability of EWBs. Adaptive control systems that may modify parameters in real time, in reaction to variables such as temperature and wear, would enhance system robustness and responsiveness. Integrating electric wheel brakes (EWBs) with advanced driver-assistance systems (ADAS), including Automatic Emergency Braking (AEB) and Adaptive Cruise Control (ACC), might markedly enhance vehicle safety and dynamic responsiveness. Formulating fault-tolerant control schemes is essential to guarantee safe braking in the event of component failures, including sensor or actuator faults. Executing thorough comparisons of various control tactics under uniform testing conditions will yield significant insights and facilitate the identification of the most successful methods. Implementing standardised standards and performance indicators for EWB control systems would enhance consistent evaluation and expedite technical advancement.

Recent breakthroughs in artificial intelligence (AI) and machine learning (ML) offer significant prospects for the optimisation of EWB systems. Reinforcement learning can facilitate adaptive calibration, whilst neural networks may improve friction estimation and predictive braking. The amalgamation of EWB-based friction braking with regenerative braking systems in electric and hybrid vehicles is essential for optimising energy recuperation and enhancing overall braking efficacy. Moreover, formulating control algorithms that stabilise the EWB mechanism at its ideal operational position helps avert wheel jamming and improve braking safety. Ultimately, EWB technology possesses significant potential in sophisticated collision avoidance systems, especially with integrated steering and braking control. By facilitating dynamic regulation of brake force in conjunction with active steering inputs, electronic wheel brakes (EWBs) can enhance vehicle manoeuvrability in emergencies, diminish skidding risks, and lessen collision impact forces. These improvements highlight the necessity of ongoing research and innovation in EWB control algorithms to facilitate their effective implementation in next-generation autonomous and intelligent transportation systems.

IX. CONCLUSION

Electronic Wedge Brakes (EWBs) represent a significant leap forward in automotive braking technology, offering the potential for enhanced performance, improved energy efficiency, and seamless integration with advanced vehicle safety and driver-assistance systems. The inherent self-reinforcing nature of the wedge mechanism allows EWBs to achieve substantial braking force amplification with reduced actuator effort, leading to smaller, lighter, and more efficient designs compared to conventional hydraulic and EMB systems. This comprehensive review has provided a detailed analysis of EWB technology, encompassing its historical context, fundamental principles, diverse design variations, mathematical modeling approaches, prototype development and testing, and a wide range of control strategies. Despite the considerable progress made in EWB research and development, several key challenges remain that must be addressed before widespread adoption can be realized. These challenges include mitigating the risks of wedge jamming and backlash, ensuring effective and efficient braking in reverse, developing robust and cost-effective sensorless control methods, achieving high caliper stiffness within compact designs, and effectively managing thermal effects generated during braking. Furthermore, the seamless integration of EWBs with advanced vehicle dynamics control systems (ABS, ESC) and ADAS features requires sophisticated control algorithms, robust communication protocols, and careful system-level design. Future research efforts should focus on several key areas: exploring advanced actuation mechanisms such as Magneto-Rheological (MR) fluids, investigating improved materials and manufacturing techniques to enhance component durability and reduce wear, developing more sophisticated and accurate friction models and adaptive control strategies to handle varying road conditions, establishing standardized testing procedures and performance metrics to facilitate comparison and evaluation of different EWB designs, and leveraging the power of artificial intelligence (AI) and machine learning (ML) techniques for enhanced control performance and online parameter estimation. Crucially, further research is needed to develop robust control strategies that effectively address the inherent instability around the optimal operating point, preventing wheel lockup and ensuring safe braking performance. By systematically addressing these challenges and pursuing these future research directions, EWBs have the potential to revolutionize automotive braking systems, contributing to safer, more efficient, and higher-performing vehicles of the future.

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REFERENCES

[1] A. Sharma and A. K. Marwah, "Braking systems: Past, present & future," *Indian J. Res.*, vol. 2, no. 3, pp. 29–31, 2013.
[2] C. Bauer, K. Lagadec, C. Bès, and M. Mongeau, "Flight control system architecture optimization for fly-by-wire airliners," *J. Guid., Control, Dyn.*, vol. 30, no. 4, pp. 1023–1029, Jul. 2007.
[3] Z. Yan, H. Peng, X. Chen, and M. Yan, "Design, modeling, and control of electronic mechanical brake system: A review," *SAE Int. J. Vehicle Dyn., Stability, NVH*, vol. 8, no. 4, pp. 467–489, Aug. 2024.
[4] O. C. Emereole and M. C. Good, "Comparison of the braking performance of electromechanical and hydraulic ABS systems," in *Proc. Int. Mech. Eng. Congr. Expo.*, 2005, pp. 319–328.
[5] C. Maron, T. Dieckmann, S. Hauck, and H. Prinzler, "Electromechanical brake system: Actuator control development system," Continental Automot. Group, Germany, Tech. Rep. 970814, 1997.
[6] B. Meng, Z. Zhou, C. Zhang, and F. Yang, "A design method for booster motor of brake-by-wire system based on intelligent electric vehicle," *Green Energy Intell. Transp.*, vol. 2, no. 4, Aug. 2023, Art. no. 100110.
[7] D. Kim, J. Park, S. Kim, and E. Jeong Soo, "Robust adaptive autonomous braking control for intelligent electric vehicles," *IFAC-PapersOnLine*, vol. 56, no. 2, pp. 11821–11826, 2023.
[8] X. Chen, X. Wang, W. Zhao, C. Wang, S. Cheng, and Z. Luan, "Hierarchical deep reinforcement learning based multi-agent game control for energy consumption and traffic efficiency improving of autonomous vehicles," *Energy*, Mar. 2025, Art. no. 135669.
[9] Q. Shi and L. He, "A model predictive control approach for electro-hydraulic braking by wire," *IEEE Trans. Ind. Informat.*, vol. 19, no. 2, pp. 1380–1388, Feb. 2023.
[10] K. Rana and N. Khatri, "Automotive intelligence: Unleashing the potential of AI beyond advance driver assisting system, a comprehensive review," *Comput. Electr. Eng.*, vol. 117, Jul. 2024, Art. no. 109237.
[11] Z. Tan, Z. Chen, X. Pei, J. Zhang, and X. Guo, "Research and simulation of electro-hydraulic braking system based on integrated master cylinder," *SAE Tech. Paper*, Jan. 2015, doi: 10.4271/2015-01-0159.
[12] H. Hartmann, M. Schautt, A. Pascucci, and B. Gombert, "EBrake®—The mechatronic wedge brake," eStop-Innovative brake Technol. GmbH, Germany, Tech. Rep. 2582, 2002.
[13] R. Roberts, M. Schautt, H. Hartmann, and B. Gombert, "Modelling and validation of the mechatronic wedge brake," *SAE Trans.*, vol. 112, pp. 2376–2386, Oct. 2003.
[14] R. Roberts, B. Gombert, H. Hartmann, D. Lange, and M. Schautt, "Testing the mechatronic wedge brake," eStop Eng. GmbH, Co. K.G., Germany Tech. Rep. 2766, 2004.
[15] S. Ákos, R. Roberts, and R. Richard, "Simulation in the development of the electronic wedge brake," Siemens VDO Automot. AG, Germany, Tech. Rep. 0298, 2006.
[16] L. M. Ho, R. Roberts, H. Hartmann, and B. Gomber, "The electronic wedge brake—EWB," Tech. Rep., 2006.
[17] J. Fox, R. Roberts, C. Baier-Welt, L. M. Ho, L. Lacraru, and B. Gombert, "Modeling and control of a single motor electronic wedge brake," Siemens AG Siemens VDO Automot., Germany, Tech. Rep. 0866, 2007.
[18] J. G. Kim, M. J. Kim, J. K. Kim, and K. H. Noh, "Developing of electronic wedge brake with cross wedge," Siemens VDO Automot. AG, Germany, Tech. Rep. 3196, 2009.
[19] J.-G. Kim, M. Kim, J. Chun, and K. Huh, "ABS/ESC/EPB control of electronic wedge brake," Hanyan Univ. China, Tech. Rep., 2010.
[20] J. Ko, G. Lee, S. Ko, S. Ahn, H.-J. Kim, S.-H. Choi, H. Kim, I. Kim, J. Jeong, and D. Hyun, "Co-operative control of regenerative braking using a front electronic wedge brake and a rear electronic mechanical brake considering the road friction characteristic," *SAE Tech. Paper*, vol. 6, pp. 1798–1815, Sep. 2012.
[21] V. R. Aparow, K. Hudha, F. Ahmad, and H. Jamaluddin, "Modeling and validation of electronic wedge brake mechanism for vehicle safety system," *Jurnal Teknologi*, vol. 75, no. 1, pp. 183–191, Jun. 2015.
[22] F. Ahmad, K. Hudha, S. A. Mazlan, H. Jamaluddin, H. Zamzuri, Z. Abd Kadir, and V. R. Aparow, "Modelling and control of a fixed calliper-based electronic wedge brake," *Strojniski Vestnik-J. Mech. Eng.*, vol. 63, no. 3, pp. 181–190, 2017.
[23] S. I. Haris, F. Ahmad, H. Jamaluddin, M. H. C. Hassan, A. K. M. Yamin, and A. S. P. Singh, "Mechanism of cone wedge shape based electronic wedge brake: Model and experimental validation," *Int. J. Automot. Mech. Eng.*, vol. 20, no. 1, pp. 10231–10246, Mar. 2023.
[24] D. H. Shin and J. N. An, "Study of stiffness design of caliper for reducing the weight of an electro wedge brake," *Appl. Mech. Mater.*, vols. 138–139, pp. 159–162, Nov. 2011.
[25] V. A. Ivanov and B. Ayalew, "Adjustable electromechanical wedge brakes with reduced energy consumption," in *Proc. Int. Mech. Eng. Congr. Expo.*, Jan. 2011, pp. 179–186.
[26] K. Han, M. Kim, and K. Huh, "Modeling and control of an electronic wedge brake," *Proc. Inst. Mech. Eng., C, J. Mech. Eng. Sci.*, vol. 226, no. 10, pp. 2440–2455, 2012.
[27] M. L. H. A. Rahman, K. Hudha, F. Ahmad, and H. Jamaluddin, "Design and clamping force modelling of electronic wedge brake system for automotive application," *Int. J. Vehicle Syst. Model. Test.*, vol. 8, no. 2, pp. 145–156, 2013.
[28] M. A. A. Emam, A. S. Emam, S. M. El-Demerdash, S. M. Shaban, and M. A. Mahmoud, "Performance of automotive self-reinforcement brake system," *J. Mech. Eng.*, vol. 1, no. 1, pp. 4–10, 2012.
[29] S. I. Haris, F. Ahmad, M. H. Che Hassan, and A. K. M. Yamin, "The experimental evaluation of cone wedge shape based electronic wedge brake mechanism in vehicle braking system," *Automot. Exper.*, vol. 5, no. 3, pp. 433–451, Sep. 2022.
[30] D. M. Wang, Y. F. Hou, and Z. Z. Tian, "A novel high-torque magnetorheological brake with a water cooling method for heat dissipation," *Smart Mater. Struct.*, vol. 22, no. 2, Feb. 2013, Art. no. 025019.
[31] L. Yu, X. Liu, L. Ma, L. Zuo, and J. Song, "MR based brake-by-wire system with self-energizing and brake energy harvesting capability," in *Proc. Int. Design Eng. Tech. Conf. Comput. Inf. Eng. Conf.*, Aug. 2014, Art. no. V008T11A099.
[32] L. Yu, L. Ma, J. Song, and X. Liu, "Magnetorheological and wedge mechanism-based brake-by-wire system with self-energizing and self-powered capability by brake energy harvesting," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 5, pp. 2568–2580, Oct. 2016.
[33] D.-H. Shin, S. Lee, C.-P. Jeong, O.-S. Kwon, T.-S. Park, S.-H. Jin, D. H. Ban, and S.-H. Yang, "Analytic approaches for keeping high braking efficiency and clamping efficiency of electro wedge brakes," *Int. J. Precis. Eng. Manuf.*, vol. 16, no. 7, pp. 1609–1615, Jun. 2015.
[34] F. Xu and C. Cho, "A novel electronic wedge brake based on active disturbance rejection control," *Energies*, vol. 15, no. 14, p. 5096, Jul. 2022.
[35] V. R. Aparow, K. Hudha, F. Ahmad, and H. Jamaluddin, "Development of antilock braking system using electronic wedge brake model," *J. Mech. Eng. Technol.*, vol. 6, no. 1, pp. 37–63, Jun. 2014.
[36] M. Soomro, M. K. Hassan, and F. Ahmad, "Modelling and validation of an electronic wedge brake system with realistic quarter car model for anti-lock braking system design," *Int. J. Integr. Eng.*, vol. 11, no. 4, pp. 70–80, Sep. 2019.
[37] N. Patrascoiu, "Modeling and simulation of the DC motor using MATLAB and LabVIEW," *Int. J. Electr. Eng.*, vol. 21, no. 1, pp. 49–54, 2005.
[38] M. C. Hasan, M. Hassan, F. Ahmad, M. Marhaban, and S. Haris, "Development and parameter estimation of a compact electronic wedge brake test rig using grey box system identification," *J. Mech. Eng. Technol.*, vol. 15, no. 2, pp. 1–12, 2023.

[39] M. Butcher, A. Masi, R. Picatoste, and A. Giustiniani, "Hybrid stepper motor electrical model extensions for use in intelligent drives," *IEEE Trans. Ind. Electron.*, vol. 61, no. 2, pp. 917–929, Feb. 2014.
[40] Y. Hwang and S. B. Choi, "Robust control of electronic wedge brake with adaptive pad friction estimation," *Int. J. Vehicle Des.*, vol. 62, nos. 2–4, pp. 165–187, 2013.
[41] M. Emam, A. S. Emam, S. M. El-Demerdash, S. M. Shaban, and M. A. Mahmoud, "A theoretical study of the self-reinforcement brake system," *J. Amer. Sci.*, vol. 7, no. 9, p. 7, 2011.
[42] M. H. Che Hasan, M. Khair Hassan, F. Ahmad, and M. H. Marhaban, "Modelling and design of optimized electronic wedge brake," in *Proc. IEEE Int. Conf. Autom. Control Intell. Syst. (ICACIS)*, Jun. 2019, pp. 189–193.
[43] L. Balogh, T. Stréli, H. Németh, and L. Palkovics, "Modelling and simulating of self-energizing brake system," *Vehicle Syst. Dyn.*, vol. 44, pp. 368–377, Jan. 2006.
[44] M. S. Jneid, M. Zöldy, and P. Harth, "Sensorless optimal control of electronic wedge brake based on dynamic model and Kalman filter state multiple-estimation," *Proc. Inst. Mech. Eng., D, J. Automobile Eng.*, vol. 238, no. 9, pp. 2802–2816, Aug. 2024.
[45] M. H. Che Hasan, M. K. Hassan, F. Ahmad, M. H. Marhaban, S. I. Haris, and E. Arasteh, "Simplifying the electronic wedge brake system model through model order reduction techniques," *Bull. Electr. Eng. Informat.*, vol. 13, no. 2, pp. 893–904, Apr. 2024.
[46] M. H. Che Hasan, M. K. Hassan, F. Ahmad, M. H. Marhaban, and S. I. Haris, "A dynamic model of electronic wedge brake: Experimental, control and optimization," *Indonesian J. Electr. Eng. Comput. Sci.*, vol. 23, no. 2, p. 740, Aug. 2021.
[47] F. Ahmad, S. A. Mazlan, K. Hudha, H. Jamaluddin, and H. Zamzuri, "Fuzzy fractional PID gain controller for antilock braking system using an electronic wedge brake mechanism," *Int. J. Vehicle Saf.*, vol. 10, no. 2, pp. 97–121, 2018.
[48] S. I. Haris, F. Ahmad, M. H. Che Hassan, A. K. M. Yamin, and N. R. M. Nuri, "Self tuning PID control of antilock braking system using electronic wedge brake," *Int. J. Automot. Mech. Eng.*, vol. 18, no. 4, pp. 9333–9348, Dec. 2021.
[49] M. S. Jneid and P. Harth, "Blended regenerative anti-lock braking system and electronic wedge brake coordinate control ensuring maximal energy recovery and stability of all-wheel-motor-drive electric vehicles," *J. Transp. Technol.*, vol. 13, no. 3, pp. 465–495, 2023.
[50] J. Guo, X. Jian, and G. Lin, "Performance evaluation of an anti-lock braking system for electric vehicles with a fuzzy sliding mode controller," *Energies*, vol. 7, no. 10, pp. 6459–6476, Oct. 2014.
[51] S. Kang, J. Chen, G. Qiu, and H. Tong, "Slip ratio adaptive control based on wheel angular velocity for distributed drive electric vehicles," *World Electric Vehicle J.*, vol. 14, no. 5, p. 119, May 2023.
[52] C. Jae-Seung, "Brake by wire system configuration and functions using front EWB (electric wedge brake) and rear EMB (electro-mechanical brake) actuators," Hyundai Mobis South Korea, Tech. Rep. 1708, 2010.
[53] J. Ko, S. Ko, H. Son, B. Yoo, J. Cheon, and H. Kim, "Development of brake system and regenerative braking cooperative control algorithm for automatic-transmission-based hybrid electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 64, no. 2, pp. 431–440, Feb. 2015.
[54] V. R. Aparow, K. Hudha, F. Ahmad, and H. Jamaluddin, "Model-in-the-loop simulation of gap and torque tracking control using electronic wedge brake actuator," *Int. J. Vehicle Saf.*, vol. 7, nos. 3–4, pp. 390–408, 2014.

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