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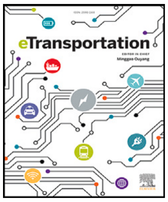

Perspective paper

Brake-by-wire system for passenger cars: A review of structure, control, key technologies, and application in X-by-wire chassis[☆]

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ABSTRACT

Electrification, networking and intelligence are the major development trends of the modern automobile industry for improving efficiency and safety and reducing emissions of the transport system. As an integral component of a wire-controlled chassis in passenger cars, brake-by-wire (BBW) system plays a key role in improving braking energy efficiency, safety, and ride comfort. This paper presents a systematic and complete review on BBW and its related technologies in passenger car applications. First, the architectures and working principles of major BBW systems are covered in details. Then, state-of-art control strategies for BBW systems are expounded. In particular, BBW-involved active safety control are presented. Finally, the remaining challenges and future research directions are discussed. The integrated design of BBW is a major development direction while other BBW systems except the Electro-Hydraulic System still need to solve some key technological challenges. Besides, efficient coordinated control of the X-by-wire chassis remains an open topic. In particular, the application of BBW in the X-by-wire chassis is a research hotspot.

1. Introduction

Electrified, connected and automated vehicles are promising to improve safety, fuel economy and capacity of the ground transport system [1,2]. Brake-by-wire (BBW) system is an indispensable chassis subsystem to enable partially and/or fully autonomous driving. Compared to the traditional hydraulic braking system, it replaces certain mechanical and hydraulic components with electronic sensors and actuators and thus decouples braking actuators with the brake pedal. These render independent, accurate and fast braking execution, which can contribute to improved ride comfort, regenerative braking and dynamics stability of vehicle. To realize these potentials, it is required that a BBW system have resilience and reliability and can efficiently cooperate with the regenerative braking and other chassis subsystems. Besides, the coupling relationship between vehicle dynamics and the BBW system need be well understood.

Substantial efforts have been directed to developing robust system design and enabling control algorithms for BBW systems. Continuous technological advancements have been periodically surveyed in several published review papers. In [3], the system architectures and working principles of the mainstream BBW systems are systematically summarized. Ref. [4] summarized the architecture, control and development trend of BBW system for connected and automated vehicle applications. However, only the electro-hydraulic braking is covered. In [5], the classification, architecture and control methods of the existing BBW systems are introduced in detail. This paper aims to summarize the latest advancements and inform future research directions by conducting a balanced and complete survey on BBW system and related active control technologies in passenger car applications.

The remainder of the paper is organized as shown in Fig. 1. Section 2 introduces the architectures and working principles of the major BBW systems. Section 3 elaborates on common control strategies used in BBW systems. Section 4 points out the remaining challenges and development directions, followed by key conclusions summarized in Section 5.

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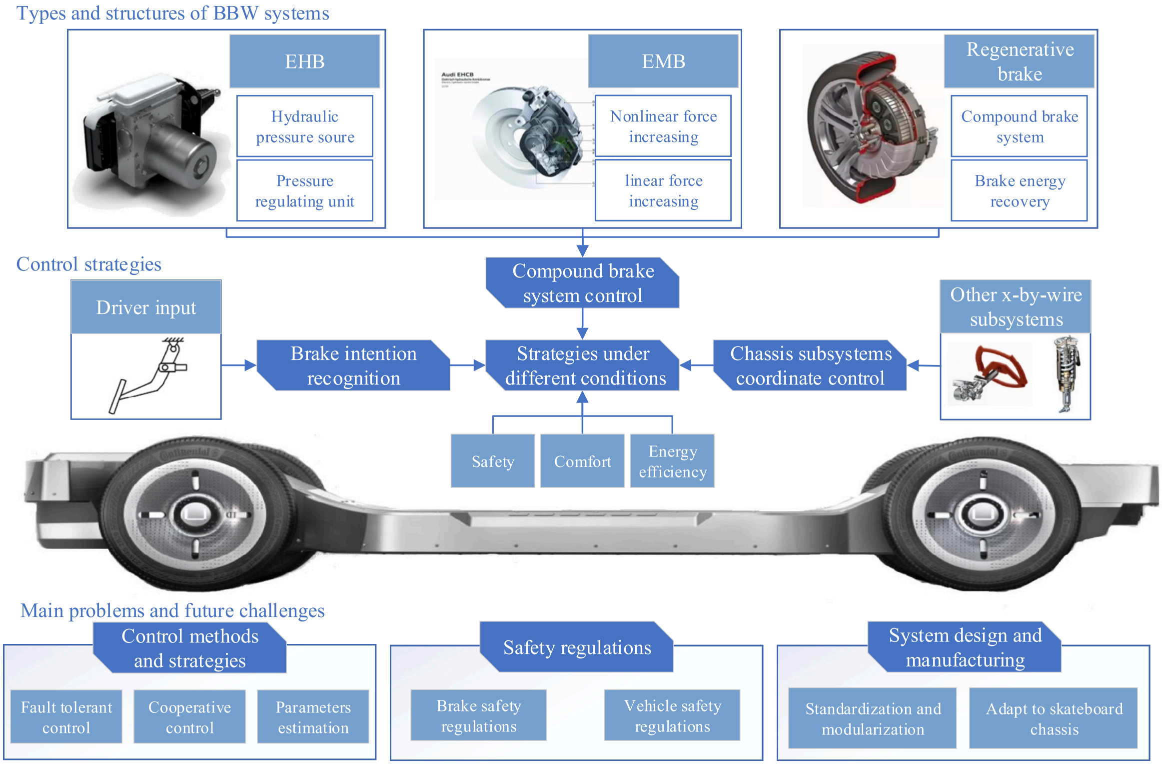
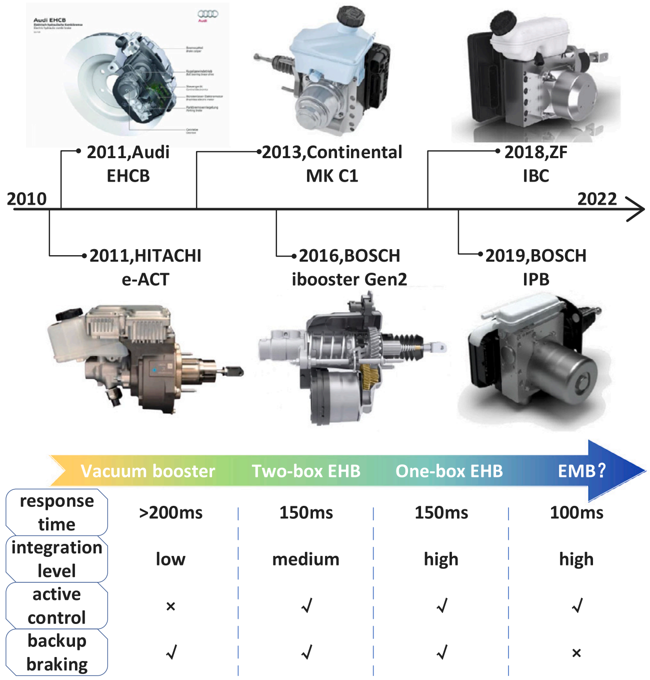


Fig. 1. Frame summary and primary coverage of the perspective.

2. Major types and structures of BBW system

A variety of brake-by-wire systems have been developed by researchers and industrial practitioners. Most of them still rely on either disc or drum brake to slow down wheel movement. The main factor that distinguishes different BBW systems is the device and its underlying mechanism used to generate the required braking pressure. Accordingly, BBW systems can be categorized into the Electro-Hydraulic Brake (EHB), Electro-Mechanical Brake (EMB), Electro-Magnetic Brake and Hybrid Brake. For electric vehicles, the regenerative braking system is also a de facto wire-controlled brake system. Up to now, EHB is the most mature BBW system due to its similarity to the traditional hydraulic braking system. Fig. 2 summarizes the major BBW manufacturers and their products, in which EHB products are in the majority. As for EMB, some companies have launched their prototypes; there are scarcely commercially-available EMB products in the market due to their poor reliability and compliance risk. Only Audi R8 model has been reported to adopt EMB as an redundant brake system at rear wheels. Other types of BBW are still in the initial development phase with no mature products available in the market.

This section mainly introduces the EHB, EMB and regenerative braking systems and explicates their system configurations and key control strategies.



	Vacuum booster	Two-box EHB	One-box EHB	EMB?
response time	>200ms	150ms	150ms	100ms
integration level	low	medium	high	high
active control	×	√	√	√
backup braking	√	√	√	×

Fig. 2. Representative products of BBW systems [6–11].

2.1. Electro-hydraulic brake (EHB)

This subsection provides a detailed review on the hardware configurations and control methods for EHB. Note that we focus on low-level actuator control such as pressure source control and pressure regulating control, while system control for braking execution will be discussed in Section 3.

2.1.1. Types and structures of different EHB systems

As shown in Fig. 3, an EHB is mainly composed of a hydraulic pressure source, a pressure regulating unit, and a pedal input unit. The brake actuator is activated through an electro-hydraulic system for generating braking force. The functionalities of each component are summarized as follows.

- The hydraulic pressure source is used to provide a high-pressure environment to decouple the pedal and the brake actuators.

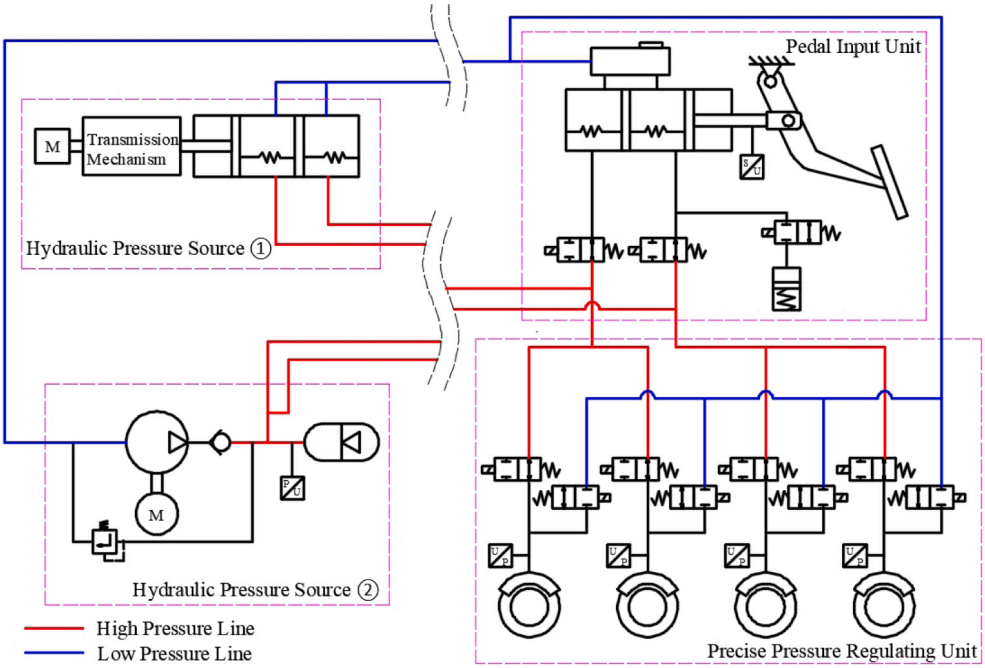


Fig. 3. The main structure of a typical EHB.

- The pedal input unit collects the brake pedal's position and speed signals, and transmits them to the Electronic Control Unit (ECU) to identify the driver's braking intention. It also uses a hydraulic mechanism to generate a simulated pedal force to optimize driving experience. In addition, the mechanical connection between the brake pedal and the brake actuators can be restored for fault-tolerant control in case of emergency braking.
- Aiming at precise braking control, the pressure regulating unit uses a hydraulic control unit to control a group of linear valves to adjust the hydraulic pressure inside each wheel cylinder.

Two types of hydraulic pressure sources are commonly used in EHB, i.e., ① motor + transmission mechanism + brake master cylinder as used in the BOSCH i-booster [6] and ② hydraulic pump + high-pressure accumulator as used in the Toyota Prius model [12]. The principle of the latter is similar to that of the traditional vacuum-assisted braking system, where the hydraulic pump is used to build system pressure with the energy stored in the high-pressure accumulator. During braking execution, the energy stored in the pressure accumulator would be released to wheel cylinders under the regulation of the pressure regulating unit. For the 'motor + transmission mechanism + brake master cylinder' type, there are also several variants. One is the double master cylinder form as shown in Fig. 3. It has two master cylinders that are respectively driven by a motor and the pedel. Under normal conditions, the master cylinder driven by the motor is in function while the master cylinder driven by the pedal intervenes to provide fault-tolerant control when the motor is at fault. This system has been used in a Honda plug-in hybrid electric vehicle model [13]. Another type only employs one master cylinder driven both by a motor and by the pedal. Under normal conditions, the master cylinder is driven by the motor to build the desired hydraulic pressure for braking force generation while the pedal is disengaged. When the motor is dyfunctional, the pedal can be instantly connected to the master cylinder pushrod to realize fault-tolerant control. The Bosch iBooster series products fall into this category [6]. The Hitachi's e-ACT system [10] uses a hollow motor to drive the master cylinder and combines with a ball screw drive to further improve integration.

EHB has several advantages compared with other BBW types. First, it has good compatibility with existing active safety control systems due to its originating from the traditional hydraulic braking system. Second, its system response time is as fast as 150 ms, which is only 30% of that of the traditional hydraulic braking system. Third, it is easy to realize fault-tolerant control that is necessary to meet mandatory automobile regulations. However, there are also explicit limitations. It still necessitates use of the bulky hydraulic system, and this results in low system response time compared to other counterparts. Besides, high-pressure sealing is needed for the accumulator while the motor suffers from the dead zone at low torques.

Despite the aforementioned limitations, the integration and modularization of EHB are constantly pursued. For example, the Integrated Power Brake system (IPB) launched by Bosch [7] and the MK C1 Electronic Hydraulic Control Unit developed by Continental [8] have realized integration of the pedal, pressure building and pressure regulating units, thus enabling the functions of the Electronic Stability Program (ESP) and Anti-lock Brake System (ABS) in a BBW system.

With continuous technological advancements, a large number of mature EHB products have been used in mass production vehicles. Focus has been placed on the hydraulic control that plays a vital role in defining its overall system performance. The state-of-the-art EHB hydraulic control methods will be presented in detail in the following sections.

2.1.2. Control of the hydraulic pressure source for EHB

One research focus of EHB is the hydraulic pressure control of wheel cylinders. For the 'hydraulic pump + accumulator' type, the pressure building unit only needs to provide a stable and reliable pressure source with the solenoid valves used for the pressure control of wheel cylinders; For the 'motor + transmission mechanism + master cylinder' type, the primary task is to accurately control the motor to adjust hydraulic pressure. The major control methods are summarized in Table 1

For the 'motor + transmission mechanism + master cylinder' type, the brake torque control precision hinges on efficient motor control. The hydraulic pressure of the master cylinder is leveraged as a control variable using feedback control [14], Proportional-Integral-Differentialcontrol (PID) [18] or adaptive robust control [21]. This method only needs one hydraulic sensor in the master cylinder, and direct measurement and control can improve the pressure control

Table 1
The major high-pressure source control methods.

Pressure source	Control variable	Control method	Ref.
Motor + transmission mechanism + master cylinder	Master cylinder pressure	Feedback control	[14,15]
		PID control	[16,17]
		Improved PID control	[17–19]
		Feedforward + feedback control	[20]
		Friction compensation + PID control	[17,21]
		Adaptive robust control	[21]
		Friction compensation + sliding mode control	[22]
	Displacement of master cylinder pushrod	PID control	[23,24]
		Sliding mode variable structure control	[23]
		Model predictive control	[24]
	Motor angle	Feedback control	[25]
	Master cylinder pressure + pushrod displacement	Switching control	[26]
		Cascade control	[27,28]
	Master cylinder pressure + motor current	Cascade control	[29]
Hydraulic pump + high-pressure accumulator	Hydraulic pressure	On–off control	[30]
		PWM control	[31]
		PID control	[32,33]
		Sliding mode variable structure control	[34]

Table 2
The commonly-used control methods in the pressure regulating unit.

Control algorithm	Ref.
Logic control	[43]
PID control	[33,41,44–52]
Improved PID control	[40–42,53–55]
Bang-Bang control	[42]
Segmented control	[56,57]
Round-robin scheduling	[58]
Bang-Bang + improved PID control	[42]
Feedforward + feedback control	[59]
H∞ control	[45]
Fuzzy control	[60]
Neural network	[39]
Predictive control	[51,61]
Active disturbance rejection control	[52]

performance. However, it suffers from poor control accuracy in the low braking torque range due to the existence of the dead zone of motor. Additionally, the master cylinder piston may stay in a non-zero pressure position at the end of a braking process, which is also termed as ’residual hydraulic pressure’. To address these issues, the piston push rod displacement of the main cylinder was chosen as the control variable in [23], which effectively enhanced the control performance within the low braking torque range. However, such control configuration poses safety risk as the dramatic drop of the push rod displacement may lead to overshoot and impact within the hydraulic system.

The use of a single control variable often exhibits poor robustness to internal parameter variations and external disturbances as indicated in [26], and thus multi-variant-closed-loop cascade control has gained polarity. In [27], the control system is designed to simultaneously control the hydraulic pressure of the master cylinder and the displacement of the piston push rod. A motor current feedback control is included in [29] to obtain high response speed when the braking demands change frequently. Furthermore, Zhu et al. [35] proposed a dynamic decoupling control method for the permanent magnet synchronous motor (PMSM) in a BBW system to further improve dynamic response performance and reduce braking time. In [36], a fusion predictive control method is proposed, which solves the parameter sensitivity problem in the deadbeat current control of PMSM. The master cylinder pressure control always uses PID controllers that exhibit poor performance under external disturbances. Therefore, chattering compensation and sliding film variable structure control are used to improve control robustness in [22]. In addition, the Integrated Modular Brake system (IBS) from the LSP Innovative Automotive Systems adopts an model predictive controller to regulate the displacement of the master cylinder piston [24], which effectively mitigates the hydraulic fluctuation.

For the EHB with a hydraulic pump and a high-pressure accumulator, there is no need of precise hydraulic pressure control. Instead, only a stable and reliable pressure source is needed. Therefore, common control algorithms such as switch control, PID, and sliding mode control are competent to provide satisfying performance.

2.1.3. Control of the pressure regulating unit

The working principle of the pressure regulating unit is the same as that of the traditional ESP, which controls the hydraulic pressure of each wheel cylinder through solenoid valves. There are two commonly used solenoid valves, i.e., high-speed on–off and linear solenoid valves. The high-speed on–off valve can switch between on- and off-state in a short time. The flow control can be realized by regulating the solenoid valve with different pulse widths, such as pulse width modulation (PWM) and pulse frequency modulation [37]. The influence of the duty cycle and frequency of PWM on wheel cylinder hydraulic pressure control was studied in [38]. It was shown that PWM at low frequencies would lead to low control accuracy and large hydraulic fluctuation. Therefore, the frequency and duty cycle should be considered to maximize the response speed of valves.

The major difference between the on–off and the linear solenoid valve is that the throttle area of the latter is adjustable and its spool can hover at a certain position to obtain desired flow rate. Such feature can effectively solve the shortcomings of the high-speed on–off valve under low-frequency control, and have mitigated noises. However, it is worth noted that ambient temperature has considerable influence on the coil’s resistance in the linear valve, which may compromise its performance. This factor was considered in [39] and a feedback correction module was incorporated into the controller to counteract this adverse effect.

Enormous research efforts have been directed to the hydraulic control of EHB. The major research aim is to simultaneously achieve fast response and high control accuracy. PID is a basic control method for the hydraulic pressure control of wheel cylinders. To deal with the nonlinear characteristics of EHB, improved PID controllers such as piece-wise PID [40] and fuzzy PID [41] were further developed. The Bang-Bang control was also presented to accelerate control speed when the gap between the actual and the expected pressure was large [42]. More advanced control algorithms, such as neural networks, model predictive control and the like have also been presented in the literature, resulting in improved control performance [39]. Adaptive control approaches are pursued to accommodate varying working conditions by incorporating driving intention identification and vehicle state estimation. The commonly-used control methods are summarized in Table 2.

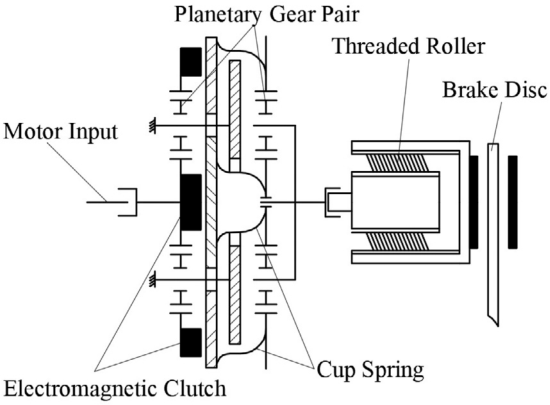


Fig. 4. Diagram of the Bosch EMB [65].

2.2. Electronic-mechanical brake (EMB)

EMB is a distributed braking system that was first used in aircraft and later introduced to automobile applications. An independent braking system is installed at each wheel, and each brake disc is directly driven by a motor and a transmission system to realize desired braking force. The system response is explicitly improved as a result of removing hydraulic pipelines. The advantages of EMB can be summarized as follows.

- Simplified transmission route leads to flexible layout, which is conducive to easy modularization and reduced system weight.
- The response time can reach as high as 100 ms, which is beneficial to improving braking safety.

However, EMB also has some shortcomings including:

- Most motors cannot produce enough torque due to limited installment space at wheels.
- The increased unsprung mass would aggravate vehicle noise, vibration and harshness (NVH).
- System reliability needs improvement as the working conditions for the motors are challenging especially during the pressure maintaining stage.
- The braking control for each wheel is independent and requires additional measurements.
- Realizing backup braking is more difficult due to the cancellation of the hydraulic pipelines. This requires additional backup power supply, redundant communication link, and additional control units.

In a nutshell, the present EMB system cannot meet the safety and regulation requirements. Given its numerous benefits, many manufacturers have prioritized EMB-related research and development. The major developers includes not only auto part giants like Bosch, Continental, and Brembo, but also Original Equipment Manufacturers (OEMs) such as Tesla, Ford, and BMW. In addition, domestic companies such as BYD Auto, Chery Automobile, and Asia-Pacific Mechatronics also acknowledged EMB as a key technology for their next-generation products. Substantial efforts have have been directed to brake force control [62], clamping force estimation [63], and fault-tolerant control [64] for EMB. With continuous technological advancements, the commercialization of EMB is at the horizon and is projected to dominate the market within 5-10 years.

Up to now, EMB systems can be divided into two categories according to different transmission mechanisms. They are the linear and the nonlinear force increasing EMB.

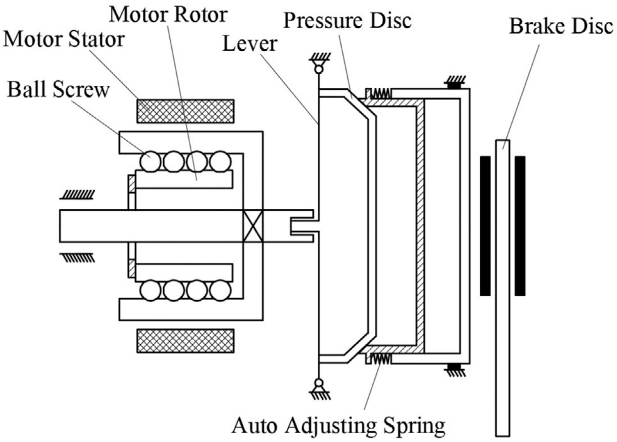


Fig. 5. Diagram of the Siemens lever EMB [66].

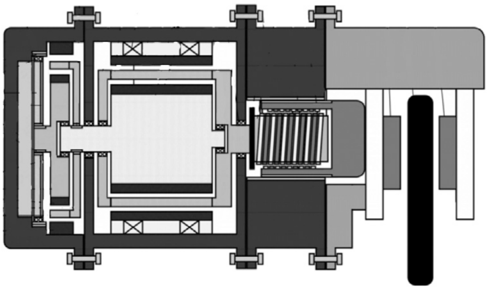


Fig. 6. The EMB prototype developed by Tsinghua University [67].

2.2.1. Linear force increasing EMB

In a linear force increasing EMB, the braking torque is mainly transmitted to the brake disc by the motor, ball screw, and other transmission mechanisms. Consequently, the braking force produced by the brake disc and the torque output from the motor are linearly correlated. Because of its simple and intuitive structure, it has been extensively developed. The classic linear force increasing EMB systems are developed by Bosch, Continental, Siemens, etc. The most widely used transmission form is shown in Fig. 4, which is based on the Bosch's EMB product [65] and adopts a two-stage planetary gear. The gear ring of the second planetary row can be braked or fixedly connected with the gear ring of the first planetary row to realize two transmission ratios, one to quickly eliminate the braking clearance and the other to accurately control the braking force. One of the drawbacks is that there is no mechanical locking mechanism to prevent possible overheating during protracted pressure maintaining braking processes. As shown in Fig. 5, the Siemens EMB system [66] uses a lever mechanism to amplify the braking torque. A displacement sensor is used to measure the displacement of the push-rod for precise brake force control while integrating a brake clearance adjustment structure. However, such design requires large layout space. Ma et al. designed an EMB system [67] as shown in Fig. 6. In the designed EMB system, the ball screw structure is driven by electromagnetic force to realize braking. The magnetic interaction avoids the friction caused by contact and is beneficial to enhancing braking device's reliability. The torque reduction component is set to reduce the required torque, which can contribute to reducing overall energy consumption.

To sum up, the current linear force increasing EMB is mainly based on the 'motor + ball' screw structure, which can provide high torque output and high control accuracy with a relatively small volume. On the other hand, electromagnetic force can effectually solve the problems like friction heat generation. The remaining challenges facing

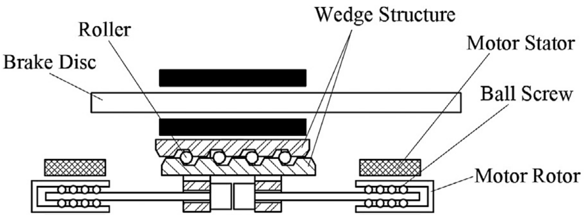


Fig. 7. The diagram of the Siemens EWB [68].

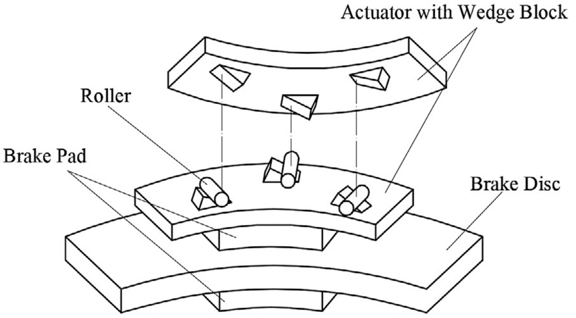


Fig. 8. The self-boosting electromechanical friction brake system developed by Bosch [69].

the linear force increasing EMB mainly include backup braking system development and high-performance motor design. Alternatively, the combination of EHB and EMB provides a feasible option to meet the braking requirements of the skateboard chassis before matured EMB systems reach the market.

2.2.2. Nonlinear force increasing EMB

In the nonlinear force increasing EMB, the motor torque is superposed with a servo brake force to reduce the required torque from motor. Consequently, the braking force and the motor's torque have a nonlinear relationship. One representative is the electronic wedge brake (EWB) [68] developed by Siemens. As shown in Fig. 7, EWB uses two motors as the brake actuation source. When the braking is actuated, the motor pulls the wedge through the ball screw, and the two wedges are combined to generate enough braking force by using the wedges' servo effect. The advantages of this structure lies in that the driving torque does not solely rely on the motor, hence greatly reducing the reliability requirement for motor. However, it is difficult to realize accurate brake torque control, making it challenging to integrate with ESP or other active safety control systems. In addition, the requirements for sensoring and control are more stringent due to the existence of the 'dead point' in wedge friction that is greatly affected by temperature and working environment.

Other forms of wedge-shaped servo braking structure also exist, such as the Bosch's self-boosting electromechanical friction brake [69] as shown in Fig. 8, in which a self-augmenting mechanism at the friction plate is designed to reduce the volume of motor. However, the structure of the friction plate is complex and its reliability may be difficult to obtain.

In general, the nonlinear force increasing EMB can effectively reduce the demand for brake motor torque, thereby reducing cost and improving stability. However, poor braking force control accuracy makes it difficult to meet the requirements of intelligent braking systems. Therefore, the linear force increasing EMB may still be the main development direction in near future, while the nonlinear force increasing EMB needs further development.

2.3. The regenerative braking system

The regenerative braking can transform vehicle's kinematic energy into electricity that can either used immediately or stored for later use while slowing down the vehicle. It can capitalize on the vehicle's momentum for excess kinematic energy recovery that would otherwise be dissipated through heat generation. It can contribute to improving energy efficiency and extending the driving range per charge of an electrified vehicle as well as shortening the brake response time [70]. But there are some limitations on the execution of a regenerative braking system. The maximum braking force is subject to the used electric motor and battery states. For instance, the regenerative braking would be disenabled when battery SOC or temperature surpasses the thresholds to preverve battery life [71]. To solve the issue, a dual-mode regenerative braking control strategy was proposed in [72] by the closed-loop control of both the regenerative current and torque. This can achieve higher energy regeneration efficiency under the dynamic operating conditions and further expand the operating scenarios. Besides, due to the existence of the dead zone of motor, the effect of the regenerative braking would degrade at low speeds and cannot independently bring the vehicle to a standstill. Therefore, the combined utilization of the regenerative and the friction-based braking is necessary.

Permanent magnet synchronous motors have been proverbially used in electric vehicles for propulsion and regenerative braking due to its high power density and reliability [73]. Direct torque control (DTC) and field-oriented control (FOC) are the major motor control methods for PMSMs. FOC has good torque control performance at medium and low speeds, but the transient torque response is relatively slow [74]. Appropriate control parameter selection can to some extent help improve toruqe response speed [75]. In contrast, DTC has simple control logic and excellent dynamic response but with steady-state torque fluctuation especially under high-speed drving conditions. Enormous efforts have been made to optimize the DTC control performance by suppressing torque ripples. For example, Zhang et al. proposed a dual-vector model predictive direct power control method for optimizing DTC control performance [76], and further improved the steady-state performance by incorporating current into the control objectives [77]. Wang et al. presented a predictive torque control strategy using discrete space-vector modulation that achieved calculation time reduction [78]. Analogously, Mora et al. considered the influence of motor structure on torque ripple and accordingly put forward an optimized cost function [79].

In general, the regenerative braking system has the advantages of energy recaperation and response speed. A composite braking system composed of the regenerative braking and other braking systems is still the major choice.

2.4. Other BBW systems

In addition to EHB and EMB, other BBW configurations are also being intensively researched, such as the pneumatic braking, electromagnetic braking and compound braking systems.

The pneumatic BBW system functions similarly to the 'hydraulic pump + accumulator' type of EHB, but it replaces the hydraulic pump and accumulator with a vacuum booster. It leverages the pressure differential between the vacuum produced by the engine intake and the atmospheric pressure for the brake master cylinder to build up pressure. This system is primarily designed for use in internal combustion engine vehicles.

For an electromagnetic braking system, the actuator is driven by electromagnetic force to realize braking operation. Therefore, it has the advantages of simple working principle, high reliability, fast response and small volume. However, current electromagnetic braking systems suffer from low control accuracy, making it incompetent for automobile application.

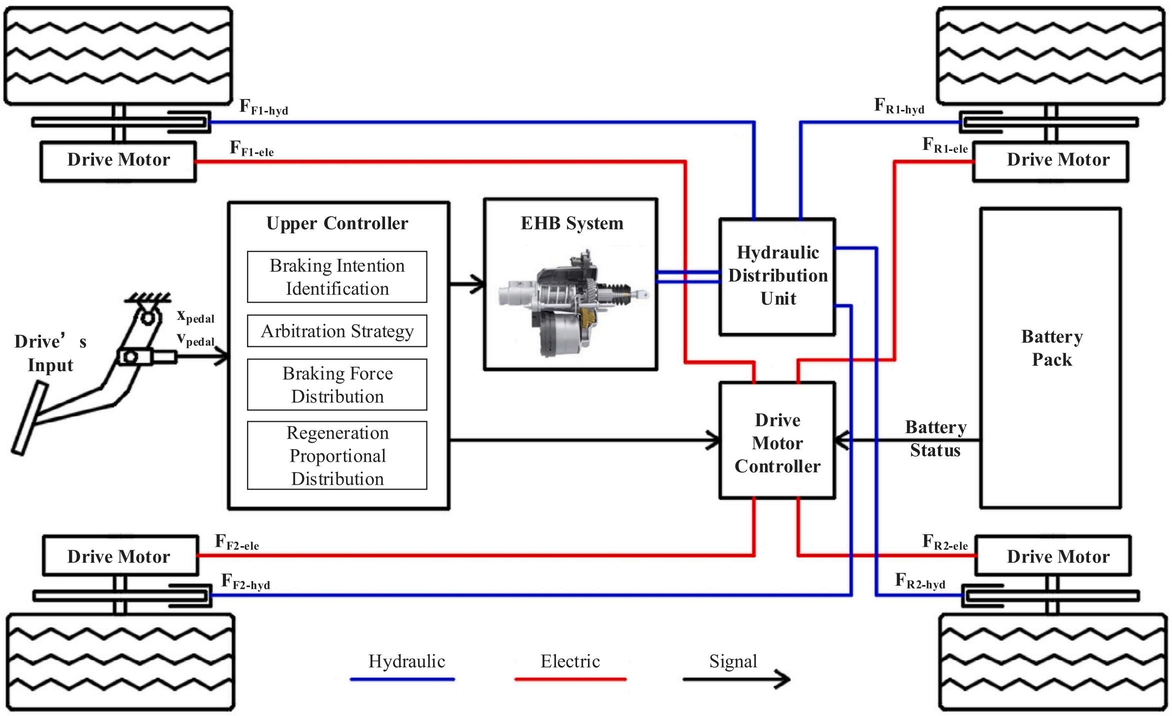


Fig. 9. The classic control structure of a BBW system in a skateboard chassis.

The compound BBW system combines the characteristics of EHB, EMB and other BBW systems. There are various types and implementation modes. One representative is the braking system that integrates a hydraulic system with an EMB system [80]. This configuration can not only increase the output torque from motor, but also allow to detect the hydraulic pressure for braking force adjustment. However, most of compound BBW systems are still in the laboratory prototyping phase.

3. Control strategies

A complete braking execution process with a BBW system is illustrated in Fig. 9. First, the braking intention needs to be identified and deciphered based on the driver's inputs and/or the signals from ADASs. The brake force demand is then passed to the braking force distribution controller, where the braking force demand for each corner is derived considering battery State-of-Charge (SOC), motor states and other vehicle parameters. Finally, the required braking force at each corner is realized by executing respective brake actuators. The complete process involves the coordination of the regenerative and the friction-based braking and the braking forces distribution between the front and rear axles. This part will expound the underlying control strategies under normal and emergency braking conditions.

3.1. Driver intention recognition

Driver intention recognition refers to the ability to predict the next actions or movements of a driver based on their maneuvers behind the wheel. By recognizing driving patterns, a control system can anticipate their future actions and make necessary adjustments to improve safety or other performances. For a BBW system, the braking force at each wheel can be independently adjusted to track the expected deceleration. Thereby, the identification of braking intention can assist the BBW system to achieve better braking performance.

The traditional braking intention recognition is based on the driver's input signals, such as the position, speed, and acceleration of the accelerator pedal and of the brake pedal. By analyzing these signals, the expected vehicle deceleration can be obtained. There are also several studies trying to analyze braking intention by further considering vehicle parameters. For example, Katharina et al. designed a rule-based braking intention recognition method based on the movement and pressing strength of the brake pedal and the measurements of vehicle acceleration and steering wheel angle [81]. In addition to the acceleration and brake pedals, other sensors have also been applied to braking intention recognition. In [82], a braking intention recognition method is proposed based on an eye tracker to track the driver's line of sight for determining the driver's intention. There are also studies trying to determine the braking intention by scanning the driver's brain. For instance, Teng et al. [83] analyzed the electroencephalogram (EEG) characteristics of driver during emergency braking and established a model for emergency braking intention recognition. By detecting the driver's EEG, the braking intention can be recognized even before the driver steps on the brake pedal.

Rule-based braking intention recognition has been well explored. Its efficacy is directly related to rule formulations, which often fail to take the driver's behavioral variation into consideration. Therefore, it can only approximately estimate the braking intention, and more complex rules and extensive debugging are needed to realize more accurate braking intention recognition. Besides, the sensor noises would also compromise recognition accuracy. To overcome these shortcomings, more advanced methods have been developed. For example, Li et al. [84] developed a neural network model for driving style recognition. The model's effectiveness is subject to data quality and quantity for model training. As a nonparametric model identification method, the Gaussian mixture model (GMM) has also been widely used for driving behavior and style recognition. For example, Lv et al. [85] proposed a braking strength recognition method based on a hybrid supervised learning and the GMM algorithm, in which the GMM is employed to automatically aggregate braking events based on braking pressure. Braking behavior and intention can also be embodied by driving operation data and relevant vehicle motion states. In [86], a double-layer hidden Markov models (HMM) is used to identify acceleration and braking actions. However, due to the large number of hidden

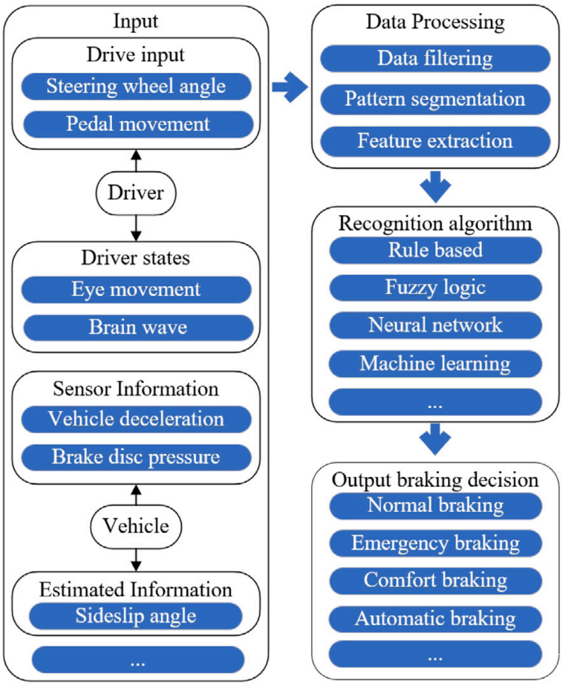


Fig. 10. Schematic of a typical braking intention recognition process.

nodes, the proposed HMM shows high computational complexity especially when using a long window. The Long Short-Term Memory (LSTM) model can fix the problem without bringing in additional computational burden and can make use of driver's operation data to determine the relationship between driving intention and driving operation. On this regard, Jia et al. proposed a LSTM model to detect abnormal emergency braking behaviors [87], where a recognition rate of 95% was achieved. Similarly, Wang et al. conducted a comparative study on HMM and LSTM for braking intention identification [88]. The results show that the LSTM has a recognition accuracy of more than 95% and outperforms the HMM. A typical process of braking intention recognition is shown in Fig. 10.

With the continuous technological development of environmental perception, there remains room for improving braking intention recognition performance. Accurate vehicle state estimation and driving intention identification lay the foundation for developing autonomous driving and active safety control algorithms.

3.2. Control for the compound braking system

A compound braking system comprises of a regenerative and a hydraulic braking system. It can improve energy consumption, safety, and ride comfort of vehicle while realizing driver's braking intentions [89]. Efficient control holds the key to realizing its targets.

According to different intervention mechanisms, the control of the compound braking system can be divided into two categories, i.e., one-pedal drive braking and two-pedal drive braking systems [90]. The one-pedal drive braking system takes the driver's releasing the accelerator pedal as the trigger signal for regenerative braking. When the driver releases the accelerator, the electric machine works in the electric generator mode to provide a regenerative braking force. The original intention of this structure is to maximize energy recovery efficiency and to improve regenerative braking response speed. Although this can simplify driving operations especially in heavy traffic conditions, there are still obstacles to surmount for practical implementation. First, it remarkably changes the driver's behaviors. Besides, the braking characteristics change back to that similar to the traditional braking system when the regenerative braking cannot be activated. This leads to different braking responses under varying working conditions, which could significantly compromise driving safety [91].

In the two-pedal drive braking system, the regenerative braking force is regenerated when the driver steps on the brake pedal. The control system focuses on how to coordinate the regenerative braking and the friction-based braking force. A straightforward way is to superimpose an additional regenerative braking force on the friction-based braking force. But this would inevitably cause a different pedal feeling. A new composite braking system adds a certain idle travel to the traditional braking system, and introduces the regenerative braking force during the idle travel so as to obtain a constant braking feeling. However, the braking energy recovery efficiency is relatively low. In general, the braking performance and energy recovery efficiency of the traditional composite braking system are limited as the friction-based braking force cannot be fully decoupled with the braking pedal. The application of BBW enables the decoupling between the friction-based braking and the regenerative braking. The composite braking system equipped with BBW is referred to as the decoupling composite braking system in the following parts.

In the decoupling compound braking system, the braking force at each wheel can be independently controlled, and the regenerative braking can be maximally used for improved braking energy recovery efficiency. When the regenerative braking is limited, it can be sufficiently compensated for by friction-based braking force to fulfill the required braking force. For safety concerns, various braking regulations have made mandatory requirements for the distribution of the braking forces at the front and rear axles. This should be considered in BBW control synthesis. Moreover, different working conditions need to be considered to improve the comprehensive performance of the braking system. The main objectives are summarized as follows. The first objective is to realize the driver's braking intentions. The second is to maximally capitalize on the regenerative braking to improve energy recovery efficiency. The third is to ensure ride comfort in braking execution while braking safety should be prioritized under emergency braking scenarios.

3.3. Control under normal braking conditions

Under normal braking conditions, there are mainly three objectives that are driver's braking intention realization, braking energy recovery efficiency, and ride comfort. To realize driver's braking intentions, an appropriate braking deceleration is interpreted according to the brake pedal position and the braking force is dispatched to track the desired deceleration based on various control algorithms. As the regenerative and the friction-based braking force are independent, only one braking force is used for feedback control while the other braking force remains constant during the braking process. However, due to their different characteristics in response speed and reliability, the two braking forces need to be efficiently coordinated under different working conditions. Therefore, it is necessary to obtain detailed braking intentions in combination with environmental information and vehicle parameters to fully realize the potentials of BBW.

Regenerative braking can contribute to extending the driving range per charge for electrified vehicles. This makes it desirable to realize high energy recovery rate under normal braking conditions. At a given vehicle state, the maximum regenerative braking torque can be calculated based on the rotational speed and efficiency map of motor, battery SOC, and other vehicle parameters. Generally, the regenerative braking is fully used until the desired total brake force cannot be solely realized by it. Under such circumstances, the deficiency between the desired and the maximum regenerative braking force is supplemented by the friction-based braking force. This principle is straightforward and easy to implement but lacks optimality. Instead, fuzzy control, model predictive control (MPC), and other control algorithms have also been employed. For instance, Wang et al. investigated the influence of

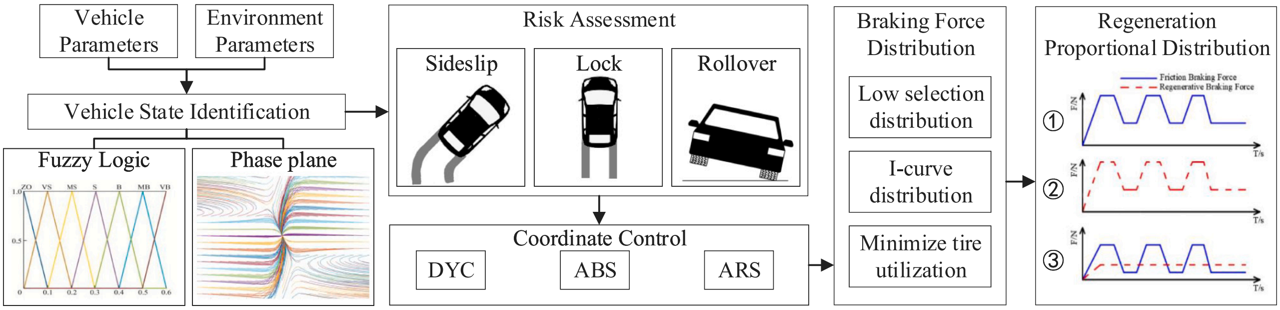


Fig. 11. The control flowchart under emergency conditions.

different braking speed curves on energy recovery efficiency using MPC for a lightweight electric vehicle [92]. Similarly, Nian et al. devised a fuzzy logic-based braking torque distribution controller that prioritizes the use of the regenerative brake [93]. The inputs include the front-axle braking force, battery SOC, and vehicle speed while the output is the proportion of the regenerative braking over the overall braking torque at the front axle. Wu et al. [94] proposed a maximum braking energy control strategy based on nonlinear programming, which optimized the output electric braking force for different braking intensities, and further improved the braking energy recovery efficiency. Similarly, Li et al. [95] designed a series regenerative braking system and proposed a three-layer control architecture for driverless vehicles. With the development of artificial intelligence (A.I.) techniques, A. I.-based control strategies have also been explored. Their efficacy hinges on the quality and quantity of the used training data, which curtails its feasibility in practice. These control strategies increase the braking energy recovery efficiency to different degrees, but lack of consideration of other performance aspects such as braking comfort.

There are two factors to be considered for ride comfort during braking, i.e., the braking force fluctuation and the nodding effect of vehicle body. The braking force fluctuation is common when the friction-based braking comes into function during braking mode switchings. This has been constantly overlooked in existing publications. In order to mitigate this issue, faster friction-based braking response is often pursued through control synthesis [96]. This has an immediate effect on brake force flunctuation but has a limited improvement on response speed. Another idea is to adjust motor's response to make the regenerative braking consistent with the friction-based braking. This proves to be effective in mitigating braking force fluctuation [97]. In addition, predictive control has also been employed to eliminate the brake disc clearance in advance [98]. The above-mentioned methods can only avail under certain scenarios. An enabling method that can deal with comprehensive scenarios is still absent. The nodding effect of vehicle body during braking would give rise to discomfort for occupants. Active suspension control can be implemented under such circumstances by actively adjusting the damping stiffness of suspension. It is pointed out that a proper distribution of the braking force at the front and rear axles can also help regulate the vehicle body pitch motion [99], but the potential safety hazards and braking regulations must be taken into account.

Many studies have been conducted either to maximize regenerative braking or to regulate ride comfort during braking mode switchings for a composite braking system under normal braking conditions. How to coordinate these different priorities in varying driving conditions remains an open topic.

3.4. *Control under emergency braking conditions*

Under emergency braking circumstances, vehicle operates near the boundaries of instability. The anti-lock braking system (ABS) has been widely used to regulate the tire slip ratio to an expected value by actively adjusting wheel cylinder pressure. BBW can also contribute to other safety stability control algorithms under critical driving conditions, such as Direct Yaw-moment Control (DYC) [100] and anti-rollover control [101]. DYC can generate an additional yaw-moment by torque vectoring that can be realized by appropriating different braking torques at different wheels [102]. The involvement of the braking system in anti-rollover control is to increase longitudinal tire force while limiting lateral tire force so as to contain vehicle lateral acceleration. This can benefit reducing the possibility of rollover [103].

The faster response and higher control accuracy of BBW can further improve the performance of these active safety control systems [104]. The remaining challenge lies in the coordination with the regenerative braking. The coordination methods mainly include:

① Control without regenerative braking. When active safety systems are triggered under emergency braking scenarios, the regenerative braking is disenabled and only BBW system is used to generate the braking force [105]. Its functioning is similar to that of the traditional braking system. However, it fails to make full use of the fast response of regenerative braking. Moreover, there may be an obvious lag in the braking force buildup process when the regenerative braking deactivates, which would lead to a sudden decrease in the overall braking force [106]. Due to simplicity and reliability, this strategy is still dominant in most applications.

② Control only with the regenerative braking. Under certain scenarios, the regenerative braking can generate enough braking force as required by active safety systems [107]. It means the braking force is solely provided by the regenerative braking, thus maximizing braking energy recovery while ensuring vehicle dynamics stability [108]. But the applicable scenarios are limited due to the maximum braking force that can be generated by the electric motor.

③ Control with the compound braking. When an active safety system is triggered, the regenerative braking and the friction-based braking can be simultaneously activated, and their respetive braking forces can be actively adjusted in real-time [109]. For example, a sliding mode control algorithm for regenerative braking is proposed in [110] to improve the cooperative control between the regenerative and the friction-based braking during emergency braking scenarios. In [111], a novel allocation method for the renegetive braking and the friction-based braking is developed to improve vehicle stability and braking performance under different emergency driving conditions. It allows to make the most of the advantages of BBW with the expense of increased control complexity [112]. How to efficiently coordinate the regenerative braking and the friction-based braking still poses great challenges.

In summary, the BBW system plays a critically important role in ensuring vehicle dynamics stability under emergency braking conditions as it invovles with the implementation of various active safety control systems. Also, there are potential conflicts when more than one active control systems requiring different braking forces are activated at the same time. Under such circumstance, the larger braking force is always executed. Such a rule-based method is easy to implement in the traditional braking system, but it requires tedius calibration work and only achieves sub-optimal performance. However, the control flexibility

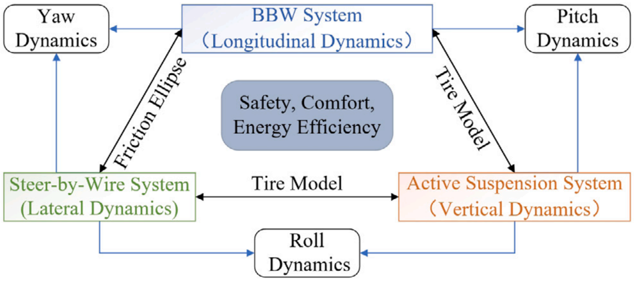


Fig. 12. Relationships between three X-by-wire systems.

of BBW is much greater than that of the traditional braking system to further push the boundaries of vehicle stability. As illustrated in Figs. 11 and 12, a novel control architecture is presented to enable real-time observation and analysis of vehicle states to determine the driving state and perform risk assessment. Based on the probability of side slip, wheel lock-up, and rollover, different wire-controlled actuators and control strategies are selected [113].

Like ABS and DYC, chassis subsystem controllers are often designed for independent control functions and are usually optimized for specific operating regions. However, as shown in Fig. 12, there are high coupling relationships among the longitudinal, lateral, and vertical tire forces and different chassis subsystems. For example, a BBW system can adjust the braking forces on the left and right sides of vehicle to generate an additional yaw moment for yaw dynamics stablization. It can also optimize vehicle's pitch dynamics by adjusting the front and rear brake force distribution. The steer-by-wire system (SBW) can control both yaw and roll dynamics by adjusting the front-wheel steering angle. Furthermore, active suspension systems can change vehicle's pitch and roll dynamics by controlling suspension's stiffness and damping coefficients. Vehicle safety can further enhanced through the coordinated control between the BBW system and other wire-controlled chassis subsystems like SBW and active suspension system (ASS). For example, the combination of ABS and ASS can effectively shorten braking distance and enhance ride comfort during braking [114]. Extensive studies have been conducted on integrated control of braking and steering systems to improve vehicle yaw dynamics. In [115], a coordinated control scheme of SBW and BBW is developed based on two model predictive controllers, which can maintain the stability of vehicle on split-μ roads. The other existing methods can be sorted into sliding model control (SMC)- [116], model predictive control (MPC)- [117], H_∞- [118], and linear quadratic regulator (LQR)-based methods [119].

Coordinated control for X-by-wire chassis has attracted tremendous attention in past years [120]. For instance, Bosch developed the Vehicle Dynamic Management (VDM) system based on active braking, steering and suspension systems. Similarly, Delphi designed the Unified Chassis Control (UCC) system. In research aspect, Zhao et al. [121] devised a three-layer hierarchical control strategy to coordinate the interactions of Active Front Steering (AFS), DYC and ASS. However, these studies only focused on lateral vehicle dynamics while ignoring vehicle roll motion. To address the limitation, Ref. [122] acquired the desired roll moment using the target motion of vehicle and presented a parameter-dependent Linear Parameter Varying (LPV)-based control allocation algorithm to achieve optimal control of lateral and roll vehicle dynamics. Song et al. [123] proposed a novel integrated chassis controller for a full drive-by-wire vehicle to improve vehicle stability and handling performance. Analogously, Lu et al. [124] determined the authority and effective working regions of the steer, brake and suspension systems for rollover prevention based on fuzzy logic.

For X-by-wire vehicles equipped with skateboard chassis, each chassis subsystem such as brake-by-wire, steering-by-wire and suspension-by-wire has its respective active safety control algorithms. There are complex coupling relationships between these different active control agorithms. How to coordinate these subsystems to maximize the overall safety control performance under critical driving conditions remains an open topic.

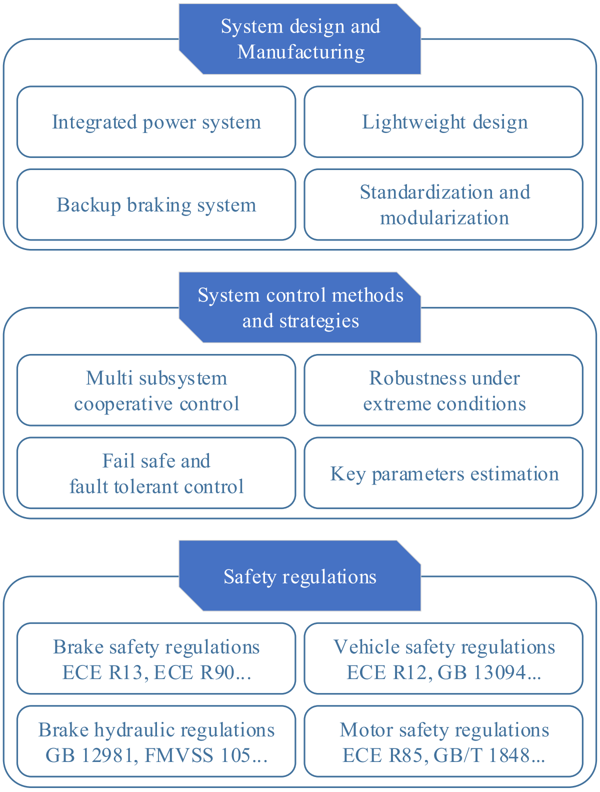


Fig. 13. Key challenges of BBW system development.

4. Remaining problems and future challenges

In past decades, the BBW technology has matured and is in the inception phase of large-scale adoption in passenger car applications. But there are still several obstacles that remain. Fig. 13 shows the key challenges for the BBW system. This section discusses the main problems and challenges from three aspects, i.e., system design, control synthesis and safety regulations.

4.1. System design and manufacturing

The EHB technology is relatively mature, but the existing products are primarily used in traditional chassis. For the skateboard chassis, specialized BBW system design is needed. The original concept of the skateboard chassis was proposed by General Motors in 2002 [125]. In 2012, it was introduced into electric vehicles with Tesla officially launching its Model S equipped with modular chassis systems. In 2018, Rivian staged the concept models of SUV R1S and R1T, whose vehicle body and chassis were separately developed. Overall, the skateboard chassis has the advantages of high integration and rich versatility. It enables the decoupled development of vehicle body and chassis so as to shorten product development time and reduce expenditure while being able to fit with different vehicle models. Besides, its high integration feature can preserve more layout space for vehicle body. Thus, the skateboard chassis technology represents a key research direction for future automobile technologies.

In order to fit with the skateboard chassis, it is necessary to further improve the integration design of BBW, which would favors one-box type. Additionally, there are higher requirements for active comfort control and integration with other subsystems in limited chassis space.

The development of other types of BBW systems is still far behind EHB. The main problems and challenges can be summarized as follows:

- It is required to provide enough braking torque under various driving conditions with the constraints of compact volume and light weight;
- It is desired to have excellent temperature tolerance and high reliability;
- It is needed to have high torque control accuracy and fast response time;
- It should have sufficient hardware redundancy to meet the requirements of braking regulations.

Considerable efforts have been directed to addressing the aforementioned issues with EMB, including actuator and power supply redundancy and thermal safety [126]. There are several design schemes to realize actuator redundancy, i.e., redundant single entity [127], independent pad [128], and additional gear [129]. Power supply redundancy is to provide power to EMB using the backup power source when the primary power source fails [130,131]. Thermal safety measures primarily focus on reducing brake disc temperature by introducing venting holes [132,133], or by mitigating the over-heat failure possibility of one stator assembly with a 2 × 3 phase electric motor [134]. Other BBW systems, such as EMB, can theoretically offer more advantages than EHB systems. However, their commercialization depends on effectually resolving the aforementioned issues.

4.2. System control methods and strategies

The coordination control with other chassis-by-wire subsystems needs further investigations as these subsystems exhibit coupled effects on different vehicle motions [135]. Synthesizing an integrated chassis control scheme to make full use of the characteristics of different chassis-by-wire subsystems for improved safety [136], fuel economy [137] and ride comfort constitutes a major challenge under complex and ever-varying driving conditions [138]. On one hand, it is difficult, if not impossible, to simultaneously achieve optimality on multiple control objectives. On the other hand, different chassis subsystems can impose influence on one vehicle motion at the same time, thus giving rise to conflicts during subsystem implementation.

To achieve better control effects, some key vehicle states need to be accurately and reliably acquired in real-time. Some of them can be directly measured using low-cost on-board sensors, such as vehicle acceleration and hydraulic pressure. But some parameters cannot be directly obtained. Instead, various vehicle state estimation schemes have been developed [139], which have varied estimation performance. Especially, the robust estimations of vehicle sideslip angle β and yaw rate $\dot{\omega}$ that are pivotal for vehicle stability evaluation are still under intensive investigation [140] [141]. In [142], an innovative vehicle kinematic-based sideslip angle estimation method is proposed by making use of Inertial Measurement Unit, Global Navigation Ssatellite System (GNSS), and other onboard sensors. Cheng et al. [143] utilized an adaptive-sliding-mode observer and an adaptive compensation algorithm to respectively estimate the lateral tire force and tire sideslip angle of each wheel. Road adhesion coefficient is an important parameter that determines the limits of braking force [144]. Efficient and robust road friction identification represents a formidable challenge for both academia and industry practitioners [145]. The existing dynamics-based algorithms can achieve satisfying performance when the tires approach their adhesion limits [146]. However, its accuracy is poor under conventional conditions [147], and the road adhesion coefficient ahead of vehicle cannot be accurately predicted. In addition, some scholars employed tire noise [148] or tire deformation detected by wireless piezoelectric sensors [149] or magnetic sensors [150] to estimate road adhesion coefficient; but these incur additional costs by using expensive sensors. A road surface recognition method based on wheel vibration was also proposed in [151], which exhibits good robustness but suffers from poor real-time estimation accuracy. With the development of automated driving vehicles, advanced sensors such as laser scanners [152], acoustic sensors [153], cameras and infrared sensors [154] are increasingly used for road classification and friction estimation by combining with advanced machine learning techniques. These methods are sensitive to environmental influence and are unable to accommodate different road types. Some scholars are trying to combine the dynamics-based method with the image recognition method to obtain better road friction estimation performance.

BBW is naturally a redundant system. For example, the failure of wheel cylinder pressure regulating can be compensated for by actively adjusting the master cylinder pressure. Thus, the actuator fault-tolerant control is to timely and effectually regulate the system based on control algorithms once actuator failure occurs. However, the hardware redundancy also incurs increased cost, energy consumption, and system weight. In contrast, the analytical redundancy method combines the signals of several sensors with a dynamics model to realize redundancy [155]. Fault diagnosis methods based on state and parameter estimation fall into the category of the analytical redundancy-based method. On this regard, Han et al. used an analytical model to perform fault diagnosis for the current sensor in EMB by comparing the residual between the designed state observer and the actual sensor measurement [156]. Wei constructed an unscented Kalman filter-based observer for fault diagnosis through the observed tire force and the friction coefficient between brake caliper and brake disc [157]. The knowledge-based fault diagnosis method aims to quickly infer and diagnose system faults by combining human knowledge into detection algorithms. The commonly used methods include state observers [158], expert system [159], neural network, fuzzy reasoning [160]. With the rapid advancements on chip computing power and A.I. techniques, A.I-based fault diagnosis methods exhibit great potentials especially for complex nonlinear systems.

After a fault is diagnosed, actuator fault-tolerant control without appropriate redundancy design is rather challenging. When the braking force actuator of a wheel fails, the braking force distribution for the other wheels should be immediately adjusted to ensure vehicle dynamics stability. For example, Hayama et al. used the yaw-moment distribution of active braking to achieve vehicle dynamics stability when the SBW fails [161]. However, adjusting braking force distribution only works when the braking intensity is mild. In critical driving conditions, the coordinated control between AFS and BBW has been proposed to improve vehicle stability in case of single wheel failure [162]. It can be predicted that with the further development of X-by-wire vehicles equipped with skateboard chassis, traditional hardware redundant systems would be simplified or even cancelled. Therefore, algorithm redundant systems will play an increasingly important role, and this highlights the coordinated control of the skateboard chassis.

4.3. Safety regulations

A BBW product needs to fully fulfill the requirements of certain technical standards and regulations. The Economic Commission for Europe (ECE) began to implement the ECE regulations on vehicle and component safety in 1958, which have been amended and supplemented time to time until now. ECE R13 [163] and ECE R13H [164] have detailed definitions, technical requirements, and test programs for brake systems in commercial and passenger vehicles. ECE R131 [165] establishes consistent requirements for vehicle emergency braking systems, and ECE R90 [166] specifies the standards for alternate braking system components. In the United States, FMVSS 203 [167] was instituted to establish the requirements for vehicle crash protection. In China, GB 13094-2017 [168] specifies the safety requirements for passenger car structures.

Although each country has developed their own testing regulations, mutual recognition and unification of automobile regulations is a main trend. The applications of BBW systems face substantial barriers from automobile safety regulations due to lack of backup braking system. Therefore, safety regulations are another important factor that affects the development and application of BBW. Reciprocally, the safety regulations would be amended to adapt to the needs of connected and automated vehicles.

5. Conclusion and prospects

Compared with the traditional braking system, BBW has higher control precision and faster response, which can lead to improved braking energy recovery efficiency, ride comfort and safety for passenger cars. With the development of intelligent vehicles and skateboard chassis, BBW system has become a research hotspot and a large number of BBW based active safety control algorithms have been developed. In this paper, the development of BBW systems in passenger car applications is systematically reviewed, covering system structure, working principle and control synthesis. Then, the control framework and major methods are surveyed. Finally, fault tolerant control and other key challenges for BBW systems are analyzed. Conclusions are made as follows: (1) Integrated design is still pursued to better meet the need of flexibility in skateboard chassis; (2) Coordinated control with other X-by-wire chassis subsystems is promising to fulfill the potentials of BBW systems in active safety control and autonomous driving; (3) Fault-tolerant control and driving intention identification should be explored to further improve the overall performance of BBW.

The current challenges facing BBW systems in passenger car application mainly include how to comply with automobile safety regulations and how to improve system reliability. Future research should be carried to solve these challenges.

It is expected that as key technologies continue to advance, BBW technology will be mature and eventually replace the traditional braking system in passenger car applications. In emerging application scenarios, such as automated passenger car fleets, the performance advantages of BBW will be fully realized, making it the predominant braking system.

CRediT authorship contribution statement

Lei Zhang: Conceptualization, Writing – review & editing, Resources. **Qi Wang:** Writing – original draft, Formal analysis. **Jun Chen:** Writing – review & editing. **Zhen-Po Wang:** Supervision, Project administration. **Shao-Hua Li:** Funding acquisition.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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