Review

Advancements in Automotive Braking Technology for Enhanced Safety: A Review

Agus Lutanto[1,*], Aprianur Fajri[1], Kacuk Cikal Nugroho[1,2], Fajrul Falah[1,3]

[1]Department of Manufacturing Engineering Technology, Akademi Inovasi Indonesia, Salatiga, Indonesia
[2]Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta, Indonesia
[3]Department of Research and Development, DTECH Inovasi Indonesia Co. Ltd., Salatiga, Indonesia
* Corresponding: aguslutanto@inovasi.ac.id

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Abstract.
This research explores advancements in braking technology with a focus on enhancing vehicle safety. The topic was chosen due to the critical importance of literature connecting braking technology developments to safety levels. The method employed was a comprehensive review of current literature concerning types and advancements in braking technologies, particularly in automotive vehicles. Analysis indicates that integrating modern braking technologies can significantly enhance driving safety and comfort, although challenges related to costs and maintenance need further attention. Further studies are recommended to optimize the future implementation of these technologies.

Keywords: Braking technology; driving safety; brake-by-wire

INTRODUCTION

The braking system is a vital component in a vehicle, serving to reduce speed or bring the vehicle to a stop. The performance of the braking system significantly impacts driving safety, particularly during emergencies. With the increasing volume of traffic, the performance of braking systems becomes even more crucial. In Indonesia, traffic accident statistics show a rising trend related to the growing number of vehicles, which often stem from brake failures [1]. Failures in the braking system can lead to severe consequences for the driver, passengers, and other road users.

Brake technology has undergone significant advancements to ensure driving safety. Initially, brake systems employed simple mechanisms, such as mechanical brakes with cables, which have evolved into hydraulic and pneumatic brakes [2]–[5]. Furthermore, more advanced braking technologies have developed.

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These include Anti-lock Braking System (ABS) [6], [7], Electronic Brake Distribution (EBD) [8], Emergency Brake Assist (EBA) [9], Regenerative Braking System (RBS) [10], and Magnetorheological Brake (MRB), which is still in the development stages [11], [12]. All these technologies are designed to provide better control and quicker response during braking, especially in emergencies. Such innovations are crucial for reducing the risk of accidents due to brake system failures.

The hydraulic brake system, which uses fluid to transmit pressure from the brake pedal to the brake calliper, offers smoother and more efficient braking performance compared to mechanical systems [13]. ABS is one of the most significant innovations in brake technology, as it prevents wheel lock-up during braking, allowing the driver to maintain control of the vehicle's direction [7]. EBD and EBA further enhance braking performance by optimally distributing braking force between the front and rear wheels and providing additional assistance during emergency braking [8].

Electronic brake systems, often referred to as Brake-by-Wire (BBW), eliminate the mechanical link between the brake pedal and the wheel brakes, using electronic signals to control braking. This technology enhances braking response and precision [14]. BBW has evolved into several types, one of which is the Regenerative Braking System (RBS). RBS is primarily used in electric and hybrid vehicles. It converts kinetic energy into electrical energy during braking, which is then stored in the vehicle's battery [10], [15]. Energy that is usually wasted as heat during braking is converted into electrical energy that can be stored back in the battery.

The reliability and performance of the braking system directly impact vehicle safety. Studies show that efficient brake systems can significantly reduce braking distance, which is a crucial factor in avoiding accidents [1], [16]. For example, ABS can reduce braking distance on slippery roads by preventing wheel lock-up, thereby maintaining traction between the tires and the road surface. EBD ensures the optimal distribution of braking force between the front and rear wheels, which is particularly important when the vehicle is carrying a heavy load or under uneven road conditions. EBA provides additional braking force during emergency braking, which can be critical in preventing collisions. RBS not only improves energy efficiency but also provides additional braking force that can reduce the load on the hydraulic brake system, thereby enhancing safety factors [14], [17].

Existing literature indicates that the integration of various modern braking technologies significantly improves vehicle safety and efficiency. This article serves as a literature review aimed at providing comprehensive insights into the development of brake technology, its impact on vehicle safety, and the latest

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findings from various studies. By understanding the different aspects of braking systems and existing technological innovations, it is hoped that technical and practical knowledge regarding brake system technology will be enhanced. This article can also serve as a reference for further research in the field of automotive and vehicle safety.

CLASSIFICATION OF BRAKING SYSTEMS

Braking technology continues to evolve primarily due to reasons related to enhancing safety, efficiency, and vehicle performance. The increasing number of vehicles and varying road conditions raise the risk of accidents, prompting the design of braking systems to improve vehicle control and reduce braking distances in emergencies. In addition to safety factors, efficiency, performance, and material innovation have become focal points in several brake system studies over the past decade. **Figure 1** shows various classifications of braking systems.

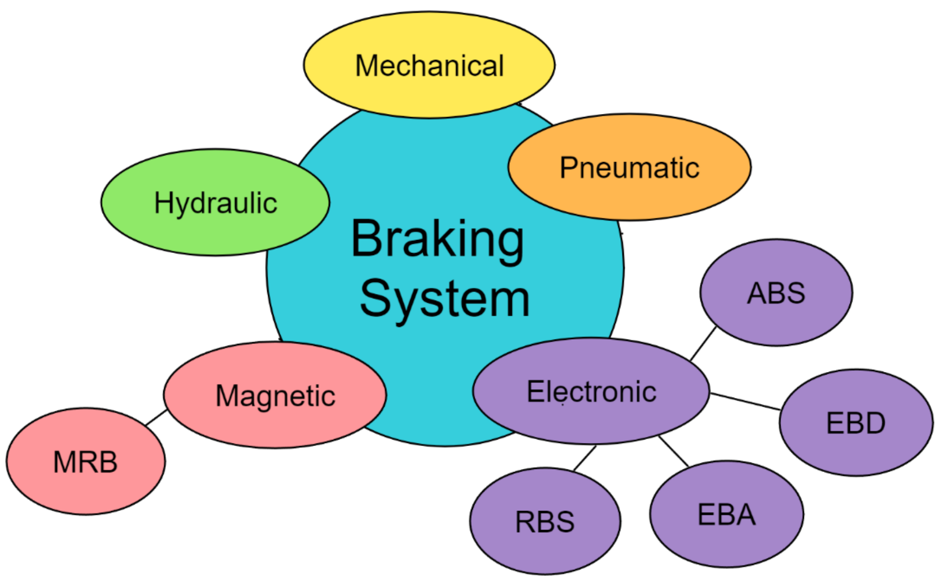

Figure 1. Classification of Braking Systems

Mechanical Braking System

The mechanical braking system, utilizing a linkage rod, is a brake technology commonly used in older vehicles where simplicity and mechanical reliability are paramount. This system consists of components such as the brake pedal, linkage rod, and adjustment mechanism, ensuring consistent and reliable brake operation. The linkage rod is a key component that transmits force from the brake pedal to the braking device on the wheels, typically in the form of drum or disc brakes [18], [19].

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The primary advantages of mechanical braking systems lie in their reliability and simplicity. These systems tend to be more durable and require minimal maintenance. Their simple design facilitates more manageable maintenance and repair, with lower production and repair costs compared to hydraulic or electronic brake systems. However, the mechanical braking system also has certain drawbacks, such as potentially lower efficiency, particularly in brake force distribution, and the need for periodic manual adjustments to ensure optimal performance [13].

In terms of safety, mechanical braking systems can be highly reliable due to the fewer mechanical components that are less likely to experience sudden failure compared to electronic or hydraulic systems. However, the required manual adjustments can pose a risk factor if not performed correctly and regularly. Despite these concerns, mechanical braking systems remain relevant in specific applications due to their simplicity and reliability, and further research may provide deeper insights into their effectiveness and optimal applications [13].

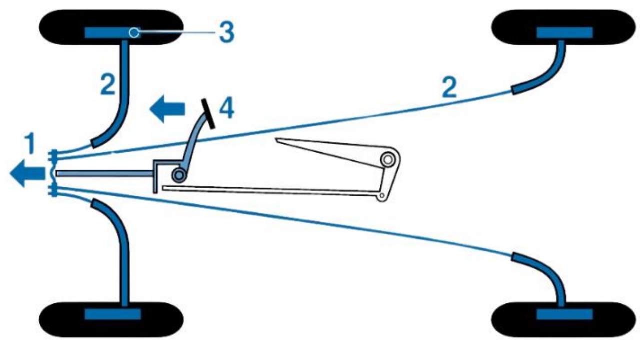


Figure 2. Configuration of Mechanical Braking System [13]

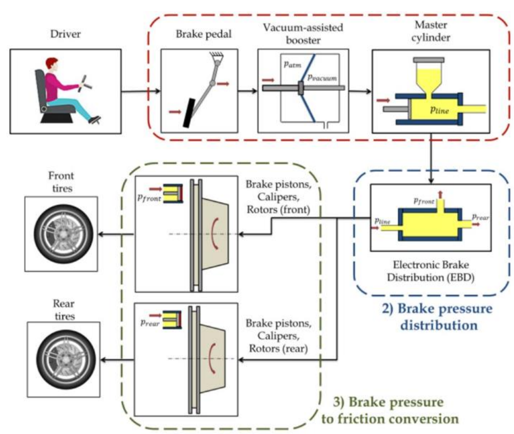
Hydraulic and Pneumatic Braking Systems

Braking systems are vital components in vehicles, ensuring safety by controlling and stopping the vehicle. Two common types of braking systems are hydraulic and pneumatic braking systems, as illustrated in **Figure 3**. Both have distinct mechanisms for transmitting braking force, along with their respective advantages and disadvantages.

Hydraulic braking systems utilize fluid pressure to transmit force from the brake pedal to the braking devices on the wheels. When the brake pedal is depressed, hydraulic fluid in the master cylinder is pressurized and flows through lines to the brake callipers or wheel cylinders. This pressure causes pistons within the callipers or wheel cylinders to push the brake pads against the brake drum or rotor, generating friction to slow or stop the vehicle. The primary advantages of hydraulic braking systems are their precision and consistency, as hydraulic fluid is incompressible, providing accurate and stable braking response [3]. Additionally, the compact design of hydraulic system components facilitates integration within vehicles and requires less routine maintenance compared to pneumatic braking systems. However, these systems are susceptible to fluid leaks, which can reduce braking efficiency, and are affected by extreme temperatures [20].

Pneumatic braking systems, or air brakes, utilize compressed air to transmit braking force. Compressed air is stored in air tanks, and when the brake pedal is depressed, air is released through lines to brake actuators, which apply the braking force. The main advantage of pneumatic braking systems is their power, making them more effective in heavy vehicles like trucks and buses due to their ability to generate substantial braking force [21]. These systems also feature emergency braking mechanisms and are easier to detect and repair air leaks compared to hydraulic fluid leaks. However, pneumatic systems are larger and more complex than hydraulic systems, requiring more frequent maintenance [20], [22].

The choice between hydraulic and pneumatic braking systems depends on the type of vehicle and the specific application requirements. Hydraulic systems are more suitable for light vehicles with high braking precision, while pneumatic systems are ideal for heavy vehicles with strong braking needs and reliable emergency mechanisms [20]. A thorough understanding of each system is crucial for ensuring safety and operational efficiency.



(a)

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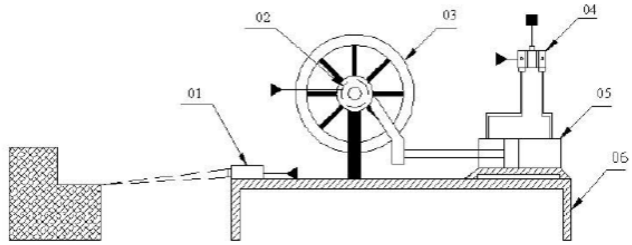

S.NO	PART NAME	S.NO	PART NAME	S.NO	PART NAME
01	ULTRA SONIC SENSOR	04	SOLENOID VALVE	▶—	TO CONTROL UNIT
02	DC/AC MOTOR	05	PNEUMATIC CYLINDER	■—	AIR FROM THE COMPRESSOR
03	WHEEL	06	FRAME		

(b)

Figure 3. (a) Schematic of Hydraulic Brake System Application [3] and **(b)** Schematic of Pneumatic Brake System Application [22]

Electronic Braking System

The electronic braking system (EBS) is one of the most significant innovations in modern automotive technology, designed to enhance driving safety. This system encompasses several types, as illustrated in **Figure 4**, including the Antilock Braking System (ABS), Electronic Brake Distribution (EBD), Emergency Brake Assist (EBA), and Regenerative Braking System (RBS). Each of these technologies has a specific function to ensure optimal braking performance in various driving conditions.

ABS is a technology that prevents vehicle wheels from locking up during sudden braking. With sensors that detect wheel rotation speed and a control module that regulates brake pressure, ABS allows the driver to maintain steering control during hard braking [6], [13], [23]. This is crucial in emergencies as it enables the vehicle to stop faster and avoid obstacles more effectively. When the driver brakes abruptly, ABS automatically modulates brake pressure to prevent wheel lock-up, allowing the driver to steer the vehicle and avoid accidents. According to Huertas-Leyva et al. [23], ABS can reduce the risk of accidents by preventing skidding, which often occurs when wheels lock on slippery road surfaces.

EBD works by distributing braking force optimally to each wheel based on load and road surface conditions. This technology is essential in vehicles carrying uneven loads, such as passenger cars filled with passengers and cargo. EBD operates by detecting the load distribution and adjusting the brake pressure accordingly, ensuring that each wheel receives the appropriate amount of braking force [8], [24], [25]. With EBD, the vehicle can stop more stably and safely, reducing the risk of accidents caused by braking imbalances that can lead to skidding or loss of control [24].

Another technology, EBA, is capable of detecting emergencies when the driver brakes suddenly. This system automatically increases brake pressure to

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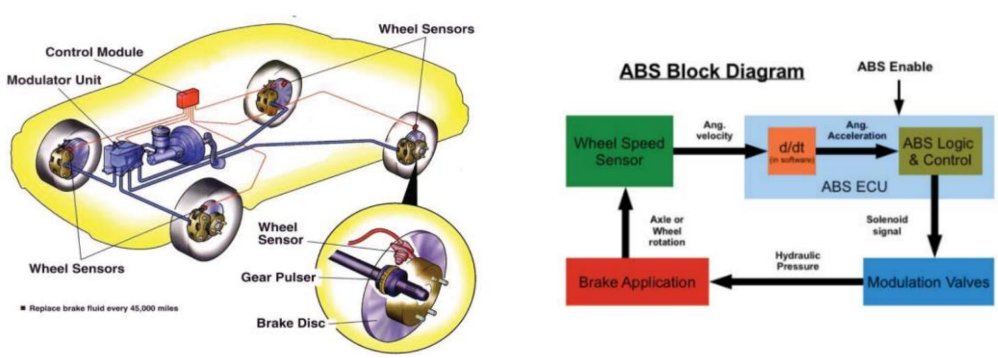
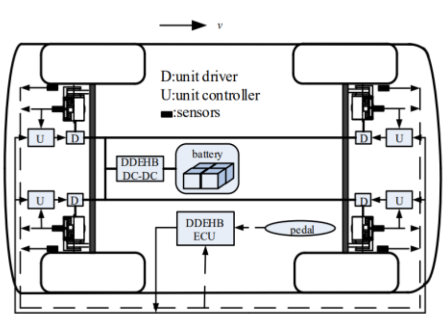
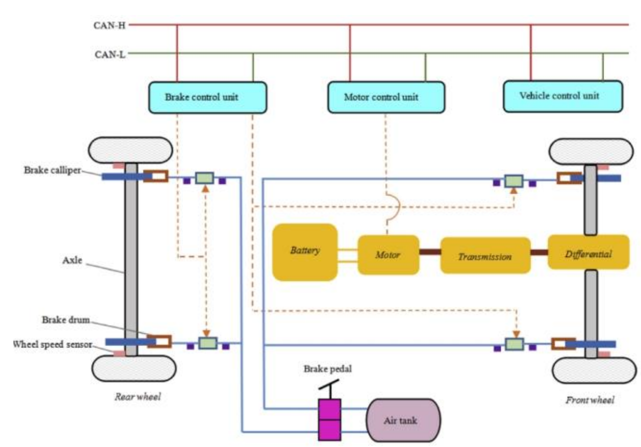
maximize braking power. EBA is highly beneficial in reducing the vehicle's stopping distance and enhancing passenger safety. When EBA detects that the driver is pressing the brake pedal rapidly but not forcefully enough, it automatically boosts the braking force. This can make a significant difference in emergencies where every meter of stopping distance can be critical for driving safety. EBA utilizes sensors that monitor speed and braking force to ensure that emergency braking is applied as quickly as possible, thus reducing the risk of collisions [26], [27].

RBS, on the other hand, is a technology that converts the vehicle's kinetic energy into electrical energy during braking, which is then stored in the battery for reuse. According to Qiu et al. [28], RBS not only aids in energy conservation but also reduces wear on brake components. In the context of electric and hybrid vehicles, RBS plays a crucial role in improving fuel efficiency and reducing exhaust emissions. By converting a significant portion of the energy typically lost as heat during braking into usable energy, RBS supports environmental sustainability and the vehicle's operational efficiency. This technology enables vehicles to recapture energy generated during braking, thereby reducing energy consumption and enhancing overall vehicle performance [15], [28], [29].



(a)





(b) **(c)**

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Figure 4. (a) Component Layout and Working Diagram of ABS Brakes [30], **(b)** EBD System Schematic [24], and **(c)** RBS Configuration in Electric Vehicles [28]

Magnetorheological Brake (MRB)

MRB is an innovative braking system that utilizes magnetorheological fluid to control braking force with precision. This fluid consists of tiny magnetic particles suspended in a carrier liquid, which form chains when a magnetic field is applied, increasing viscosity and altering braking characteristics [31]–[33].

MRB, as shown in **Figure 5a**, is under development for application in motorcycles and cars. The MRB braking system has several advantages over conventional brake systems. MRB offers smoother and more responsive braking control. The magnetic field allows for instant adjustment of the braking level, providing more measured braking according to road conditions or driving needs [34].

In motorcycles, MRB is applied to disc brakes, where MR fluid is placed in a reservoir around the brake disc. When the brake is activated, a magnetic field generated through an electromagnetic process increases the viscosity of the MR fluid, producing the desired braking force. This system enables smoother braking control, especially at low speeds or on slippery road conditions [35].

In cars, MRB can be applied to both disc and drum brakes [36]–[39]. The magnetic field alters the viscosity of the MR fluid, resulting in an appropriate braking force. MRB in cars can also be integrated with electronic control systems such as ABS and EBD, enhancing coordination between the braking system and other safety technologies and providing a safer and more comfortable driving experience [14], [40].

The main advantage of MRB is its adaptability to various road conditions and driving styles. This system can automatically adjust braking force based on input from vehicle sensors such as speed, acceleration, and road conditions, reducing the risk of skidding or loss of control, especially in emergencies [40], [41]. The braking process flow is illustrated in **Figure 5b**.

However, there are challenges in implementing MRB. Production and maintenance costs are higher compared to conventional systems. The integration of MRB technology with existing vehicle systems requires careful design and extensive testing to ensure reliable and consistent performance [31].

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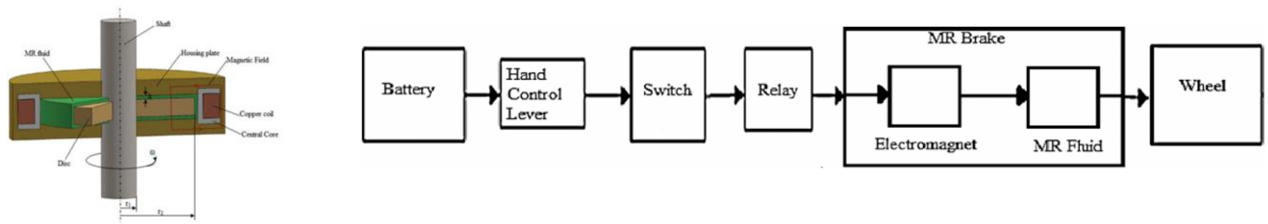

(a) **(b)**

Figure 5. (a) Three-dimensional schematic of a Magnetorheological Brake (MRB) [39] and **(b)** Flowchart illustrating the braking process of an MRB [11]

SAFETY LEVEL ANALYSIS

Braking systems have undergone significant transformations from simple mechanisms to advanced technologies, significantly impacting driving safety levels. Mechanical brakes, which use cables or levers to transmit braking forces, are superficial but often unreliable in providing consistent braking power, especially in emergencies. Hydraulic brakes address some of these shortcomings by using fluid to transfer pressure from the brake pedal to the brake pads, allowing more even and responsive pressure distribution. This enhances safety by offering better control over braking, particularly in larger vehicles. Pneumatic brakes, often used in trucks and buses, provide very strong and consistent braking power but require complex maintenance systems to ensure their reliability.

Advanced braking technologies such as Anti-lock Braking System (ABS), Electronic Brake Distribution (EBD), Emergency Brake Assist (EBA), Regenerative Braking System (RBS), and Magnetorheological Brake (MRB) offer significant improvements in safety. ABS prevents wheel lock-up during sudden braking, allowing drivers to maintain control of the vehicle, which is highly effective on slippery road surfaces. EBD works in conjunction with ABS to optimally distribute braking force, ensuring vehicle stability even when carrying uneven loads. EBA detects sudden braking and increases brake pressure to maximize braking force, reducing stopping distance and the risk of collision. RBS converts kinetic energy into electrical energy, reducing wear on brake components and ensuring optimal performance. MRB, still in the development stage, offers smoother and more adaptive braking control by using magnetorheological fluid whose viscosity can be changed in real time, promising significant improvements in braking responsiveness and safety. The combination and integration of these technologies create a safer and more reliable braking system under various driving conditions.

To enhance the efficiency and safety levels of braking systems, several researchers have conducted in-depth studies to ensure the safety levels of braking systems, as shown in **Table 1**.

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Table 1. Some Research on Braking Technology in 2019-2024

Author	Publication Year	Brake Type	Impact on Safety Level
Aher et al. [42]	2019	Smart Braking System	Smart braking system with ultrasonic sensors and double cylinders to reduce the risk of accidents
Anselma et al. [3]	2019	Hydraulic Brake	Importance of regular maintenance for optimal performance
Gong et al. [24]	2020	Electronic Brake Distribution (EBD)	Optimizes braking force distribution between front and rear wheels and can be combined with ABS
Hamada and Orhan [29]	2022	Regenerative Braking System (RBS)	Improves energy efficiency and reduces the load on the hydraulic braking system
Bhardwaj [27]	2022	Emergency Brake Assist (EBA)	Reduces braking distance in emergencies
Zhang et al. [14]	2023	Brake-by-Wire (BBW)	Faster braking response and higher precision
Singh and Sarkar [12]	2024	Magnetorheological Brake (MRB)	Responsive braking and can adjust the braking level according to needs

DISCUSSION

This discussion integrates the findings of the various studies outlined in this article to provide a comprehensive overview of the development of braking system technology and its impact on driving safety from various perspectives.

Advantages and Limitations of Braking Systems

Each type of braking system has advantages and limitations that need to be considered in the context of its specific application. For example, mechanical braking systems have a simple construction with low production and maintenance costs, but they lack responsiveness. Hydraulic and pneumatic brakes, while capable of delivering large braking power, are still prone to leaks that can reduce braking capability.

ABS has been proven to significantly enhance vehicle safety by preventing wheel lock-up during sudden braking, allowing the driver to maintain control of the vehicle's direction. This is crucial in slippery road conditions, where the risk of skidding is higher. However, ABS requires proper maintenance and calibration to ensure optimal performance.

EBD and EBA are essential innovations that work in conjunction with ABS to improve braking performance. EBD ensures that braking force is optimally distributed between the front and rear wheels, while EBA provides additional braking force in emergencies. The combination of these technologies ensures that the vehicle can stop quickly and safely in various conditions.

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RBS offers dual benefits by improving energy efficiency and reducing wear on mechanical brake components. This is particularly important for electric and hybrid vehicles, where energy efficiency is a top priority. However, RBS also has limitations in terms of energy regeneration capacity, which depends on vehicle speed and battery storage capacity.

Brake-by-wire (BBW), like ABS, EBD, EBA, RBS, and MRB, is a technological breakthrough that eliminates the mechanical link between the brake pedal and the wheel brakes, using electronic signals to control braking. This improves braking response and precision, allowing for better integration with other vehicle control systems. However, BBW also requires a reliable backup system to address electronic system failures.

Impact on Safety and Comfort

Safety is a significant factor influenced by the performance of braking systems. Studies show that advanced braking technologies such as ABS, EBD, and EBA significantly reduce the risk of accidents by ensuring that braking force is applied optimally and the vehicle remains stable during emergency braking. This is crucial in situations where the driver has to make evasive maneuvers or sudden stops.

EBA, for example, provides additional braking force when the driver performs emergency braking, which can reduce braking distance and increase the chances of avoiding a collision. Similarly, EBD ensures that braking force is properly distributed between the front and rear wheels, which is especially important when the vehicle is carrying a heavy load or when road conditions are uneven.

The impact of braking systems on comfort cannot be overlooked. MRB, with its faster braking response and higher precision, offers a smoother and more comfortable driving experience. This system also allows for integration with other control technologies, such as electronic stability control, to enhance safety and driving comfort.

RBS, in addition to improving energy efficiency, also contributes to comfort by reducing the load on the hydraulic braking system, which can reduce vibration and noise during braking. This makes the driving experience more comfortable, especially in heavy traffic conditions.

Implications for the Future

Advancements in braking system technology show great potential for improving driving safety and comfort in the future. Further development of

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predictive braking systems, which use risk-based algorithms to prevent accidents, shows significant potential to enhance safety at intersections without traffic signals and other complex traffic situations.

The integration of braking systems with autonomous vehicle technology also presents exciting prospects. Advanced braking systems can work in conjunction with sensors and control algorithms to ensure that autonomous vehicles can stop safely in various situations. This will be a crucial step towards the safe and reliable implementation of autonomous vehicles.

However, challenges remain in terms of cost, complexity, and maintenance of these advanced braking systems. The implementation of MRB and RBS technology requires significant investment in hardware and software. Additionally, the successful implementation of these technologies depends on adequate infrastructure support and extensive technical training for vehicle maintenance technicians.

Nevertheless, the potential benefits of these advanced braking technologies are immense. With continued research and development, it is expected that significant improvements in driving safety and comfort can be achieved, reducing the number of traffic accidents and supporting the transition to more efficient and environmentally friendly vehicles.

CONCLUSION

Advancements in braking system technology have contributed significantly to improving driving safety and comfort. From simple mechanical braking systems to advanced systems like ABS, EBD, EBA, RBS, and MRB, each innovation brings improvements in braking performance and vehicle stability.

Advanced braking systems such as ABS and EBD have been proven to significantly reduce the risk of accidents by ensuring optimal braking force and maintaining vehicle stability. Technologies like RBS not only improve braking efficiency but also contribute to energy efficiency and driving comfort.

However, the implementation of these advanced braking technologies also faces challenges in terms of cost, complexity, and the need for adequate supporting infrastructure. With continued research and development, it is expected that further improvements in driving safety and comfort can be achieved. Advanced braking system technology will not only reduce the number of traffic accidents but also support the transition to more efficient and environmentally friendly vehicles.

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