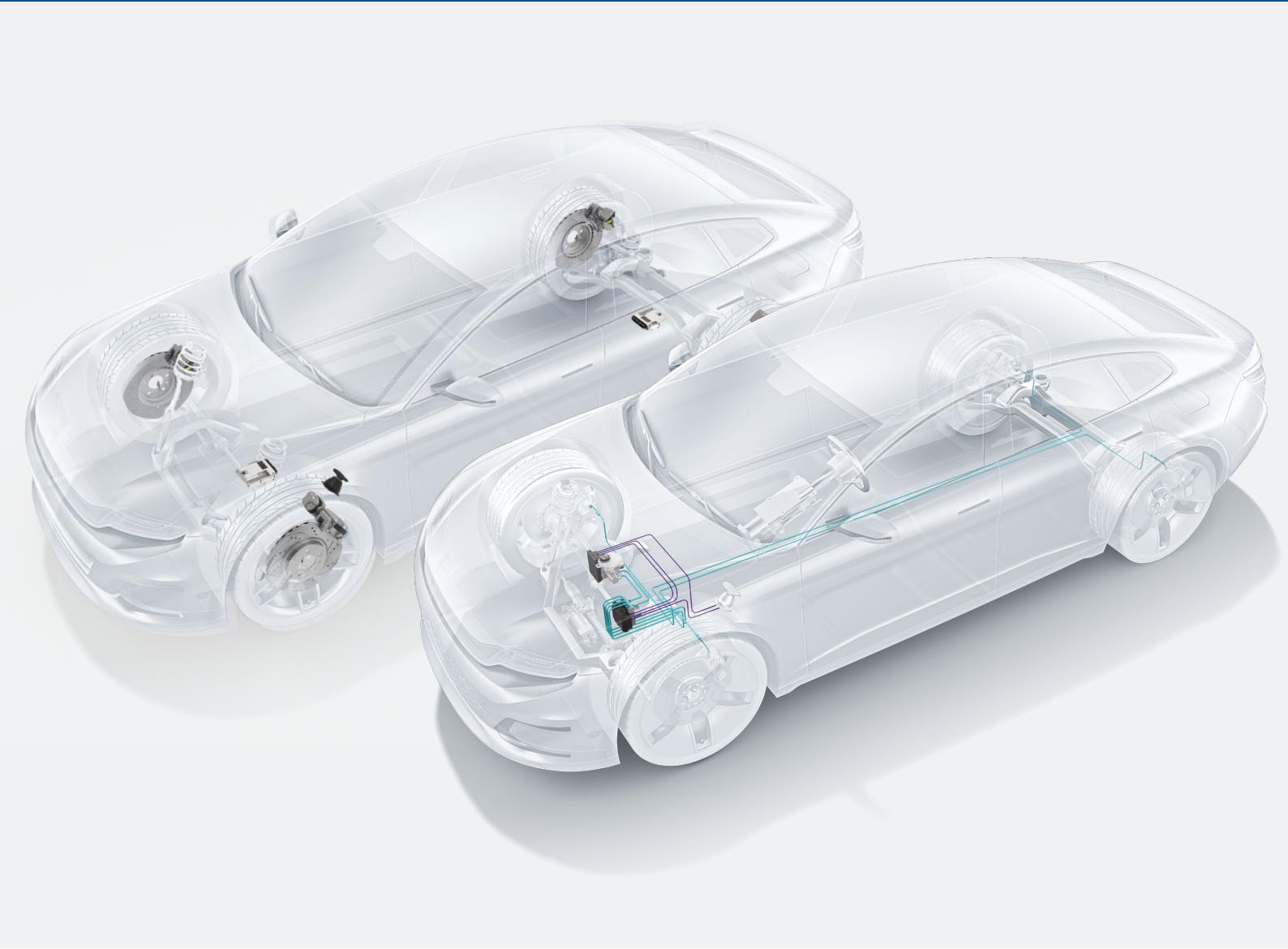


Whitepaper

A dual-path approach for brake-by-wire

For brake-by-wire, Bosch follows a dual-path approach by offering wet and dry solutions. This whitepaper offers an objective evaluation and comparison of both technological paths supporting regulatory compliance at vehicle level, with a focus on relevant aspects of UNECE R13-H.

Invented for life

BOSCH

Table of contents

01
Abstract 03

02
Brake-by-wire architectures 04

03
System comparison 07

04
Regulatory framework 11

05
Summary 12

06
Why Bosch 13

Imprint 14

01
Abstract

The global automotive industry is undergoing a transition towards highly automated driving (HAD) and software-defined vehicles (SDV). Within this context, brake-by-wire technology serves as a key enabler for modern and smart chassis designs. By eliminating the mechanical connection between the brake pedal and the brake system, brake-by-wire provides new freedom in interior design as well as improved packaging and crash safety.

This whitepaper provides an objective comparative analysis of the two technological paths to brake-by-wire: the hydraulic ("wet") system – at Bosch composed of a by-wire brake actuator (BWA) and an electronic stability program (ESP®) – and the electromechanical "dry" system (electromechanical brake; EMB) featuring wheel-individual brake actuators at each caliper which are controlled by redundant central or zonal ECUs.

The core conclusion of this analysis is that both wet and dry brake-by-wire solutions are equivalent in their functional performance. There is no universal technological winner; instead, the selection depends on individual vehicle manufacturers' packaging constraints, E/E platform integration strategies, and factory assembly line capabilities. Furthermore, this paper outlines the regulatory landscape, focusing on the latest updates to the UNECE R13-H standard, which establishes the compliance framework for brake systems operating without a mechanical fallback.

01 Brake-by-wire is a key enabler for modern and smart chassis designs.

02 Brake-by-wire provides new freedom in interior design as well as improved crash safety and vehicle dynamics control.

03 Bosch follows a dual-path strategy for brake-by-wire with wet and dry solutions. Technical evaluations show that both are equivalent in their functional performance.

UNECE R13-H
is an international legislation established by the United Nations Economic Commission for Europe (UNECE) that defines uniform provisions for the type approval of passenger cars and light commercial vehicles with regards to braking.

02
Brake-by-wire architectures

Traditional braking systems rely on a mechanical connection between the brake pedal and the brake system to translate the driver's pedal pressure into hydraulic brake pressure at the wheels. Brake-by-wire systems completely decouple this mechanical interface between the brake pedal and the brake system and replace it with redundant electrical signal lines, also in the backup mode. The main technological paths for brake-by-wire are as follows:

1. **Hydraulic ("wet") brake-by-wire system**
   This system retains a hydraulic fluid medium to transmit pressure to the wheels but completely removes the mechanical connection between the brake pedal and the brake system. A centralized by-wire brake actuator (BWA) works in conjunction with a state-of-the-art electronic stability program (ESP®) to generate, coordinate, and distribute hydraulic brake pressure across two split brake circuits.

2. **Electromechanical ("dry") brake-by-wire system**
   This system represents a completely fluid-free (dry) architecture. Hydraulic lines, brake fluid, master cylinders, and central brake actuators are eliminated entirely. Instead, clamping force is generated directly at each wheel by electromechanical actuators mounted on each caliper. Hydraulic lines are eliminated and replaced by electrical signal lines towards each wheel brake. Actuators are controlled by individual ECUs which are integrated into a centralized or zonal E/E architecture.

For the driver input, both technological paths enable the use of a **by-wire brake pedal with reduced pedal travel:** The driver's intent is captured purely as an electrical signal via redundant pedal sensors (using independent, highly reliable measurement principles) and transmitted via secure, redundant signal lines to the brake system.

Brake-by-wire systems depend on a **redundant E/E architecture,** which was historically uncommon in vehicle design. Today, this barrier is diminishing as modern functions like automated driving (according to SAE level 3) already require and utilize these redundant architectures. Consequently, the technical and economic hurdles for introducing brake-by-wire systems have significantly decreased.

Bosch definition of brake-by-wire

Bosch defines a brake-by-wire system as a brake system that completely replaces the mechanical connection between the brake pedal and the brake system with redundant signal lines, without any mechanical backup modes. Both wet and dry solutions described above are brake-by-wire systems according to this definition.

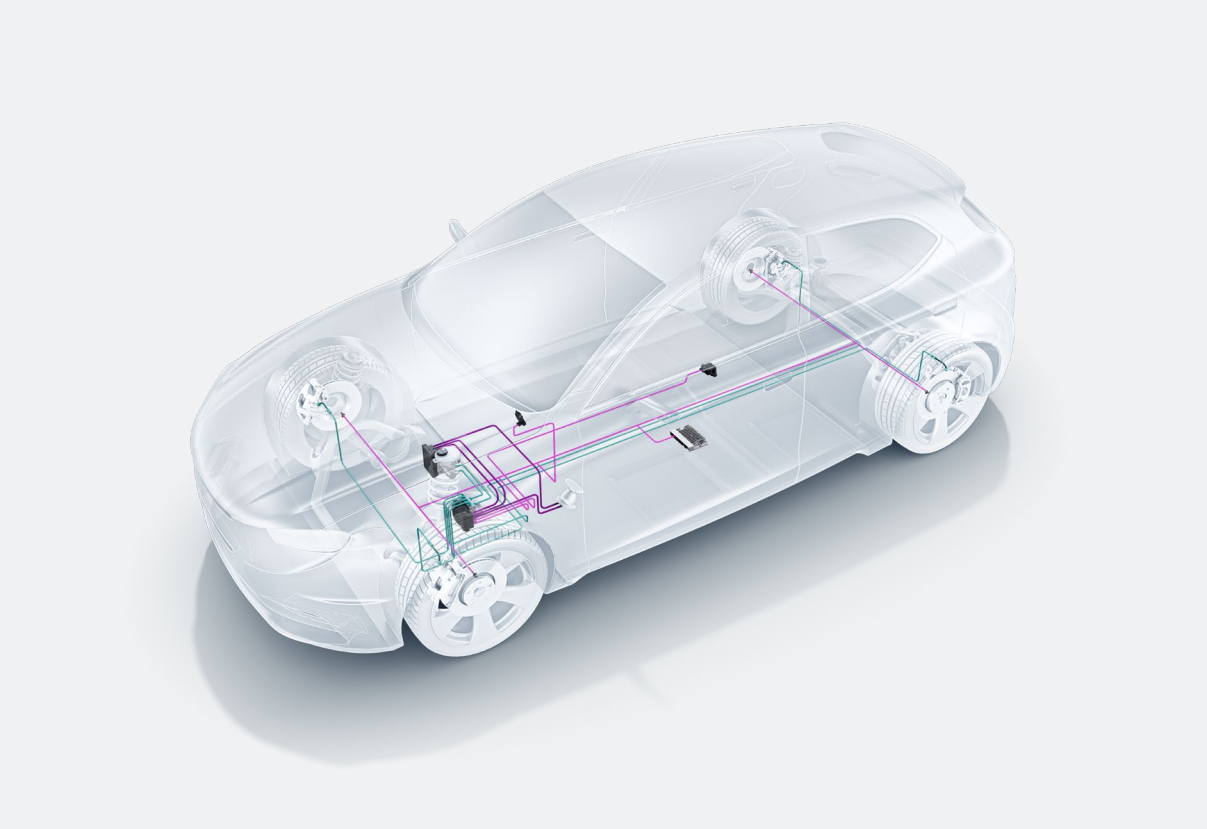


Figure 1: Exemplary and simplified illustration of a wet brake-by-wire architecture in the vehicle (hydraulic lines are shown in turquoise, signal lines in magenta, power supply not included in this illustration)

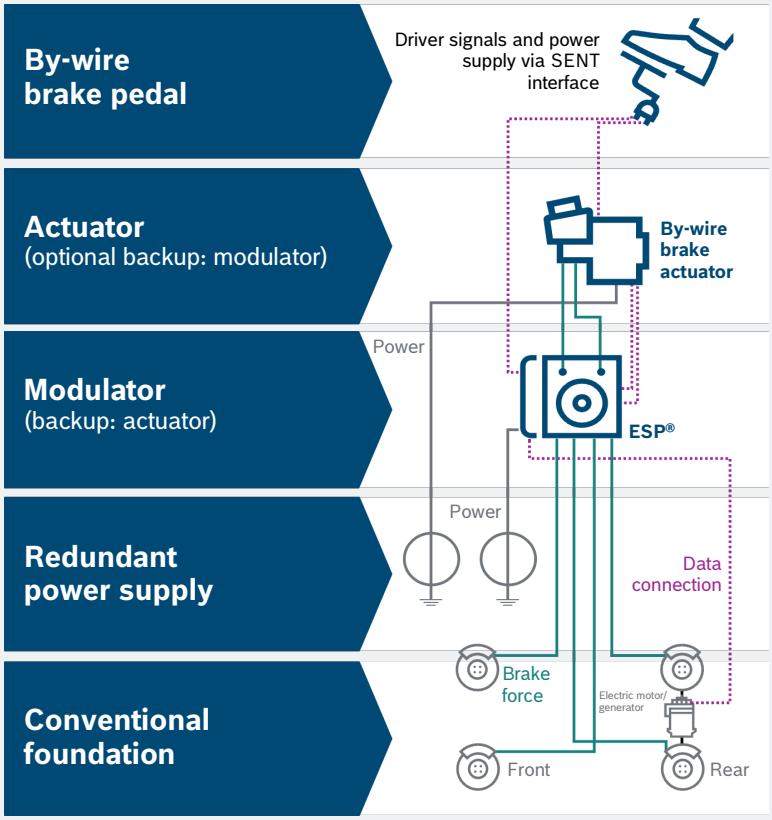


Figure 2: Exemplary schematic diagram of a wet brake-by-wire architecture

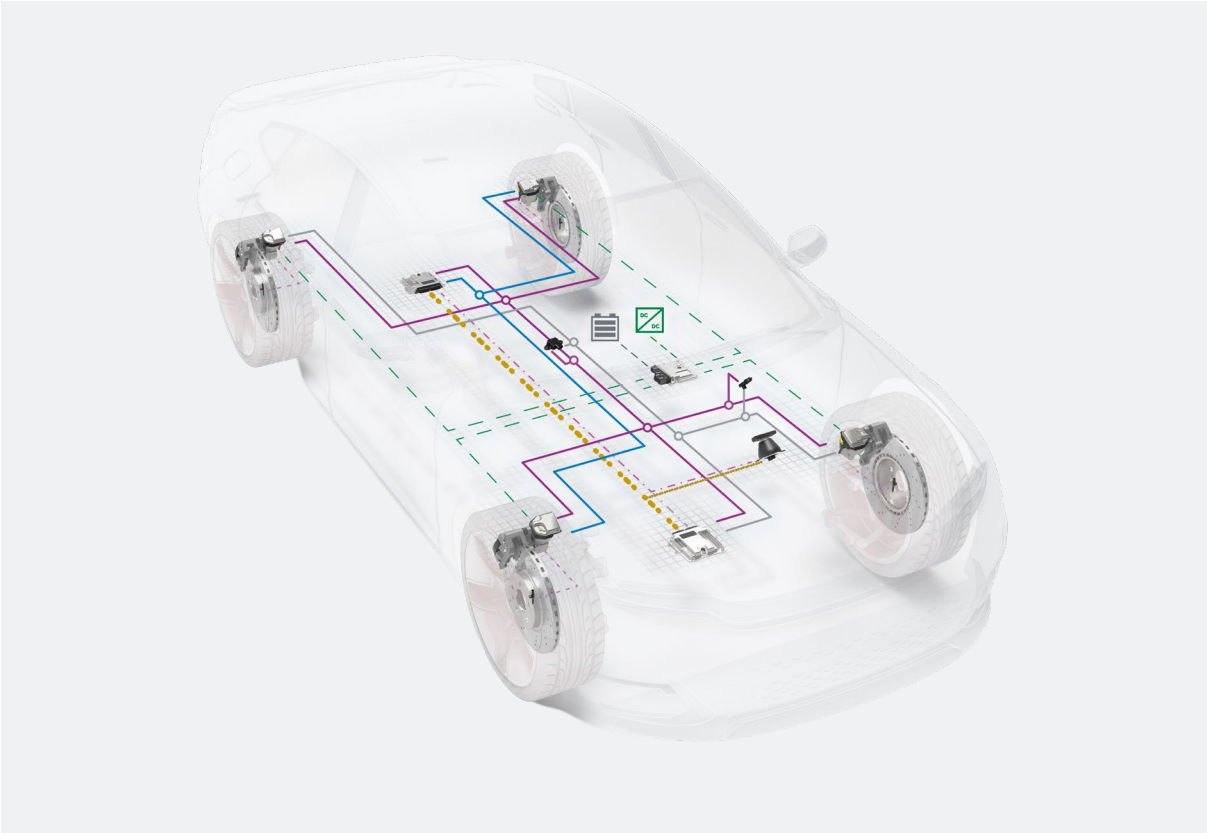


Figure 3: Exemplary and simplified illustration of a dry brake-by-wire architecture in the vehicle (colored solid and dotted lines represent signal and power supply lines)

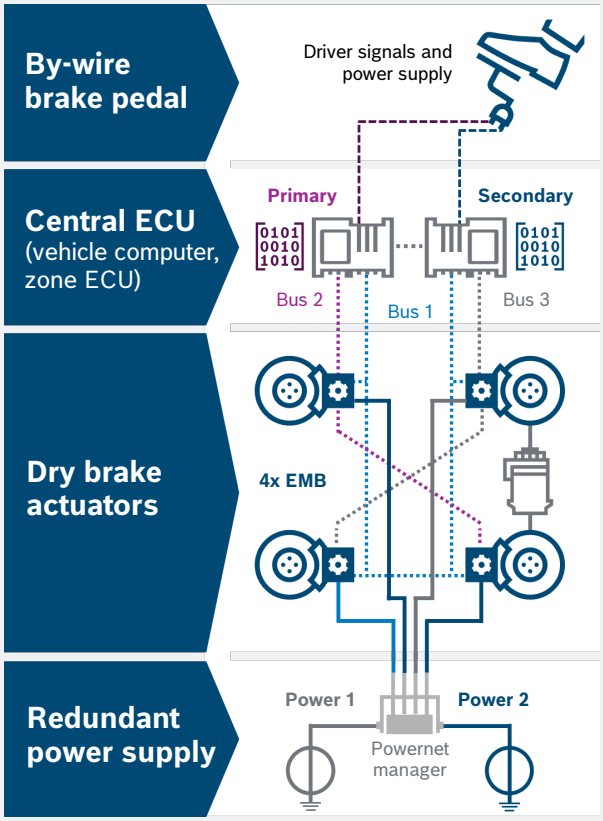


Figure 4: Exemplary schematic diagram of a dry brake-by-wire architecture

03 System comparison

Bosch follows a dual-path approach for brake-by-wire, since both technologies described above – wet and dry – have their own specific advantages depending on the use case and the strategy of each vehicle manufacturer. We advise our customers individually on which brake-by-wire solution is best suited for their needs and their vehicle platform, and which advantages can be achieved in each case.

Based on validated track tests, road assessments, and rigorous mechatronic analysis, wet and dry brake-by-wire systems show comparable performance across all core metrics when integrated into equivalent vehicle platforms.

The hydraulic ("wet") path: By-wire brake actuator + ESP®
The hydraulic 2-box design consists of a by-wire brake actuator and an ESP®.

→ **Industrial maturity:** By-wire brake actuator + ESP® is the primary path to industrialize brake-by-wire at scale. It leverages established, field-proven hydraulic brake technology, existing global manufacturing facilities, and localized supplier networks. The design of the foundation brake and the wheel arch can remain unchanged. For vehicle manufacturers, all this enables an easy transition from traditional brake technology to brake-by-wire and decreases capital expenditure (CapEx) and launch risks.

→ **Packaging:** Because the by-wire brake actuator has no physical connection to the brake pedal, it can be mounted flexibly within the engine compartment, away from the firewall. This optimizes vehicle packaging, improves crash safety, and eliminates the need for separate left-hand and right-hand drive production variants.

→ **Dynamics and weight:** The by-wire brake actuator is a compact and lightweight unit (~2.5 kg; the full system including ESP® totals only ~4.5 kg) capable of building up brake pressure up to 250 bar with high dynamics, which is vital for automatic emergency braking (AEB) systems.



By-wire brake actuator + ESP®
Lightweight hydraulic brake-by-wire system based on field-proven brake technology

~4.5 kg	system weight
up to 250 bar	brake pressure
up to 1g	4-wheel backup

The electromechanical ("dry") path: Electromechanical brake
The electromechanical brake (EMB) comprises four wheel-individual electromechanical actuators directly mounted on the calipers which are integrated into a centralized or zonal E/E architecture.

→ **Assembly and maintenance efficiency:** EMB enables "dry" vehicle assembly by removing the need for brake fluid filling and evacuation processes on the vehicle manufacturer's assembly line. It also eliminates periodic brake fluid service intervals over the vehicle lifetime. However, mechanical friction components like brake discs and pads still require regular inspection, and system diagnosis has to be performed regularly.

→ **Scalability and parking brake integration:** The EMB caliper is highly scalable, offering clamping force variants from 35 to 65 kN. An integrated electric parking brake function can be implemented at the front and the rear axle. The parking brake function enables the removal of the parking pawl and provides parking brake redundancy without extra mechatronic components.

→ **Packaging and weight:** Removing the central mechatronic units and physical hydraulic lines frees up significant volume in the engine bay and underbody. However, EMB might need more adaptations to the packaging of the foundation brake into the wheel arch. The weight increase for caliper + electromechanical brake leads to a higher unsprung mass directly at the wheel.

Detailed technical assessment and comparison of both technologies
Bosch has performed validated track tests, road assessments, and rigorous mechatronic analysis for both brake-by-wire technologies under controlled conditions. The evaluations included the assessment of parameters such as vehicle integration, stopping distance, residual drag torque, NVH performance as well as automation and backup performances.

Please see the table on the following page for the detailed outcomes of these assessments including a further analysis about future-readiness and market requirements.



Electromechanical brake
Hydraulic-free brake-by-wire system comprising four wheel-individual actuators

35 – 65 kN	adjustable clamping force
Park lock feature	on front and rear axle
up to 0.64g	3-wheel backup

Parameter	Hydraulic (“wet”) brake-by-wire system	Electromechanical (“dry”) brake-by-wire system
Vehicle integration	Suitable for centralized and decentralized vehicle architectures. No fundamental change in vehicle design compared to traditional brake systems necessary.	Suitable for centralized and decentralized vehicle architectures.
Stopping distance	Wet and dry brake-by-wire systems can deliver equivalent stopping distances. This is proven by Bosch comparisons under controlled conditions with equivalent tires, sensing, control, vehicle setup and application.	
Residual drag torque	Both systems can be engineered for very low residual drag. The performance depends on the caliper, the air gap, the vehicle and the operating conditions.	
NVH performance	The decoupling of the brake pedal from the brake system and the decoupling of brake actuators from the firewall create strong NVH advantages for both brake-by-wire architectures.	
Automation and backup	Supports automated driving when integrated into a suitable redundant safety concept on vehicle level. Due to the redundant 2-box design, the wet brake-by-wire system allows for full service-brake performance in the backup mode (4-wheel backup up to 1g).	Supports automated driving when integrated into a suitable redundant safety concept on vehicle level. The system allows for degraded service-brake performance in the backup mode which significantly exceeds legal requirements.
Software-defined vehicle and HMI	Both architectures support smart actuators, standardized interfaces and flexible electronic brake pedal concepts.	
Voltage	For both systems, 12V and 48V variants are available.	
Market readiness	Bosch has prepared both architectures for safe market introduction, and has validated concepts by means of extensive road testing and external assessments.	

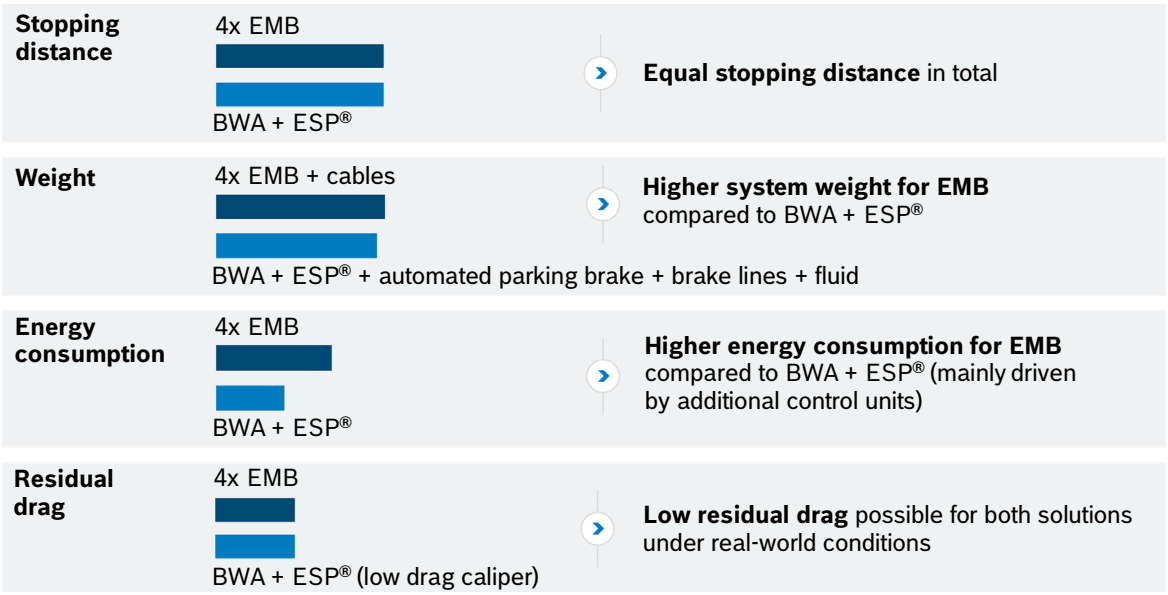


Figure 5: Bosch analysis and comparison of selected technical parameters of wet and dry brake-by-wire systems

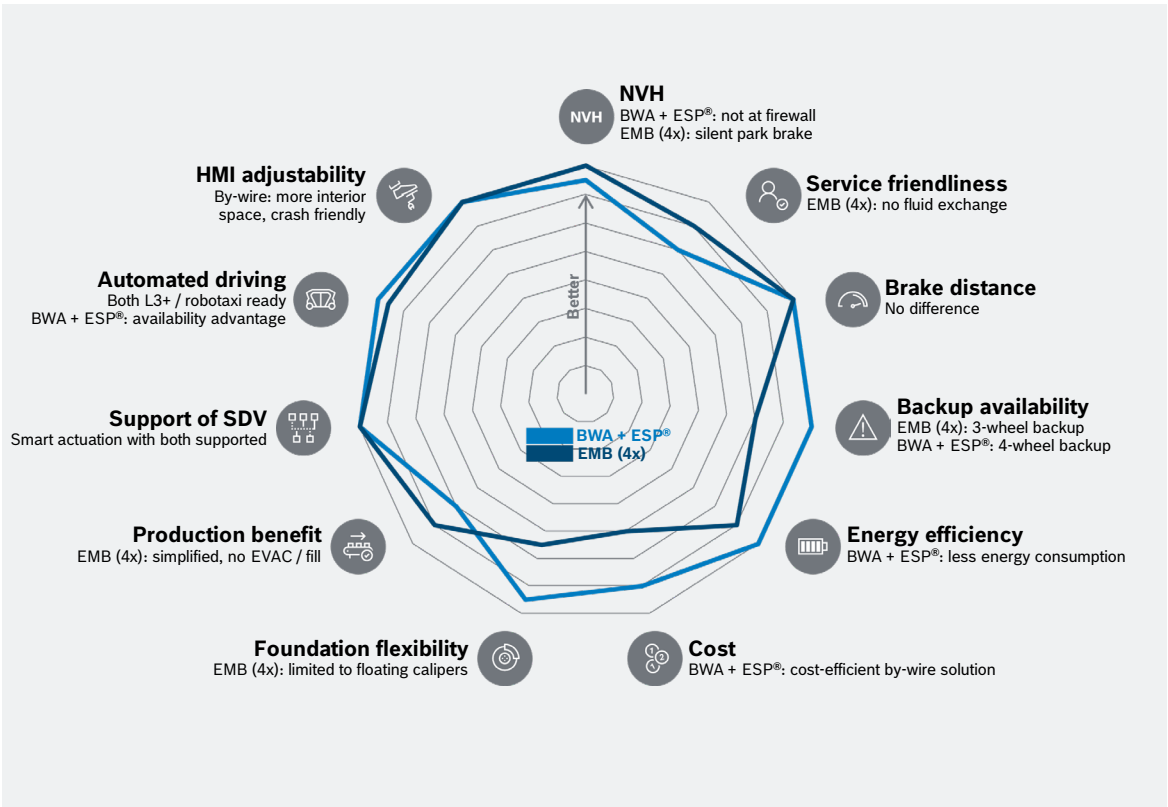


Figure 6: Relative Bosch analysis and comparison of different technical and economic parameters of wet and dry brake-by-wire systems

04 Regulatory framework

Key revisions of the legal standard UNECE R13-H

The legal standard UNECE R13-H (“Uniform provisions concerning the approval of passenger cars with regards to braking”) was revised with key modifications officially entering into force on June 12, 2025. This revision provides the legal basis for homologating full brake-by-wire systems in regions and countries including Europe, Japan and South Korea.

- **Energetic redundancy and energy management systems:** The revised regulation specifically permits mechatronic braking systems without mechanical backup, provided they are supported by an integrated, highly reliable energy management system (EMS). The EMS must continuously monitor the state of health (SoH) and state of charge (SOC) of the redundant electrical power network to ensure that sufficient energy is always available to execute a complete, safe stop.

- **Global harmonization:** Regulatory authorities in other major automotive markets – such as USA (FMVSS 105/135) and China (GB 21670-2025) – have implemented similar legislations which allow to implement brake-by-wire systems.

- **Homologation:** Homologation with regards to the overall brake system has to be performed on vehicle level by the vehicle manufacturer. Where necessary, Bosch can support vehicle manufacturers in this process.

Redundancy and safety concepts under single-failure conditions

Based on extensive system expertise, all Bosch brake-by-wire architectures feature robust safety and redundancy concepts which strictly adhere to all applicable legal requirements and industry standards.

- **Wet brake-by-wire redundancy:** The system utilizes a 2-box design where the by-wire brake actuator and the ESP® act as two independent hydraulic actuators. Under a single-point electrical or mechatronic failure of one of the two actuators, the second actuator takes over. Both acutators can independently build up brake pressure across all four wheels, achieving full service-brake performance (~1.0g deceleration at ~160 N driver pedal force) without altering the driver’s pedal feel.

- **Dry brake-by-wire redundancy:** The EMB system relies on a decentralized topology. Each caliper is powered by independent electrical channels managed by centralized or zonal ECUs. In the event of a single-point actuator failure (e. g., loss of one actuator, caliper or power channel), the system enters a degraded state. The remaining three active wheel-end calipers execute an advanced 3-wheel backup strategy. This ensures a stable, controlled deceleration of ~0.64g, significantly exceeding the minimum residual braking performance of 0.25g at 500 N pedal force required by UNECE R13-H.

05
Summary

Brake-by-wire technology is one of the key enablers for modern and smart chassis designs. This whitepaper analyzes two technological paths: a hydraulic “wet” system (by-wire brake actuator + ESP®) and an electromechanical “dry” system (electromechanical brake; EMB). Our analysis and vehicle tests conclude that both architectures deliver equivalent functional performance, including stopping distance, residual drag torque, NVH and readiness for highly automated driving. The choice of system is strategic, depending on vehicle manufacturers’ priorities on chassis and E/E architecture, packaging, and assembly processes. Both systems are fully compliant with the latest UNECE R13-H regulations, ensuring robust safety and market readiness.

06
Why Bosch

- **System competence:** Wide-ranging experience in hydraulic 2-box and 1-box as well as dry brake systems; vast system competence in state-of-the-art E/E architectures.
- **Variety of brake-by-wire technologies:** Bosch offers both wet and dry brake-by-wire solutions, and we advise vehicle manufacturers indivudually on which brake-by-wire solution is best suited for their needs and their vehicle platform.
- **Industrialization and localization:** Bosch's validated test portfolios, field data availability, global manufacturing footprint and localized supply chain ensure mature systems that meet the highest standards of safety, quality, and commercial viability.
- **Software excellence:** All motion actuators can be controlled by Vehicle Motion Management, Bosch's hardware-agnostic software system solution.

Contact us now

Do you have any questions, comments or business inquiries?

Please do not hesitate to get in touch.

Tamas Csoti

Vehicle Motion
Product Manager Brake-by-Wire

tamas.csoti@bosch.com

Learn more on our website
www.bosch-mobility.com

Bosch Mobility on LinkedIn
www.linkedin.com/showcase/bosch-mobility/

Imprint

References:

UNECE R13-H

https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:42023X0401

Publisher:

Robert Bosch GmbH
Vehicle Motion

Robert-Bosch-Allee 1
74232 Abstatt
Germany