EMBEDDED INTELLIGENCE

BENCHMARKING EMBEDDED INTELLIGENCE

AI Domain Integration Across Legacy and Software-Defined Architectures on the European Market

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Table of contents

1. Abstract

Artificial intelligence (AI), particularly Large Language Models (LLMs) and "vision" models, is rapidly moving from web-based applications to integrated consumer electronics, profoundly changing daily interactions. While the automotive industry is shifting from rule-based or low-level machine learning to integrated LLMs, this adoption is slower due to stringent safety criticality, data protection concerns, and complex integration efforts.

This white paper comprehensively examines the evolving role and current maturity of AI in modern vehicle architectures. Beyond autonomous driving, it investigates AI's pervasive influence on user interaction, electric powertrain optimization, and vehicle dynamics. Combining extensive technological research with a real-world benchmark of production electric vehicles using P3's structured evaluation framework, the analysis assesses AI implementation across critical domains like Human-Machine Interface (HMI), Advanced Driver-Assistance Systems (ADAS) and Electric Powertrain.

Key findings reveal AI's deep integration across nearly all vehicle layers, from in-cabin personalization and predictive energy management to adaptive chassis behavior, delivering tangible customer experiences. The benchmark highlights significant regional disparities: German OEMs excel in ADAS and backend intelligence within modular safety architectures, while Chinese brands face localization hurdles. OEMs without legacy constrains lead in embedded personalization but show weaknesses in structured navigation. Notably, customer-facing AI often leverages Big Tech ecosystems, whereas safety-critical intelligence remains proprietary.

The paper concludes with strategic recommendations for all stakeholders, advocating for the development of certifiable, resilient "systems of systems" and modular AI components. It also emphasizes the need for deeper localization and adaptive governance. Coordinated innovation across hardware, software, and regulatory frameworks is crucial to ensure the safe and scalable deployment of AI-driven mobility as automotive intelligence matures.

2. Introduction

In recent years, artificial intelligence (AI) has evolved from a visionary concept into a foundational component of modern vehicle architectures. While initial applications were limited to rule-based systems and basic automation, today's AI technologies enable data-driven, adaptive functionalities that fundamentally enhance safety, efficiency, and user experience.

AI in the automotive sector spans far beyond the vehicle itself. It plays a growing role across the entire value chain – from internal processes and organizational decision-making to intelligent functions embedded in the vehicle. Accordingly, the term "automotive AI" does not exclusively refer to large-scale language models (LLMs), but also includes compact, domain-specific models and edge AI modules (edge in this context onboard deployed AI modules) – for example, machine learning or deep learning-based optimization of comfort features such as heating or seating systems.

Within the vehicle, AI is found in both visible domains – such as human-machine interaction (HMI) and advanced driver assistance systems (ADAS) – and invisible layers that work in the background: processing sensor data, enabling predictive maintenance, or generating real-time insights for OEMs and platform providers. A further distinction must be made between AI systems operating directly on the edge (within the vehicle), and those supported or orchestrated by backend infrastructures.

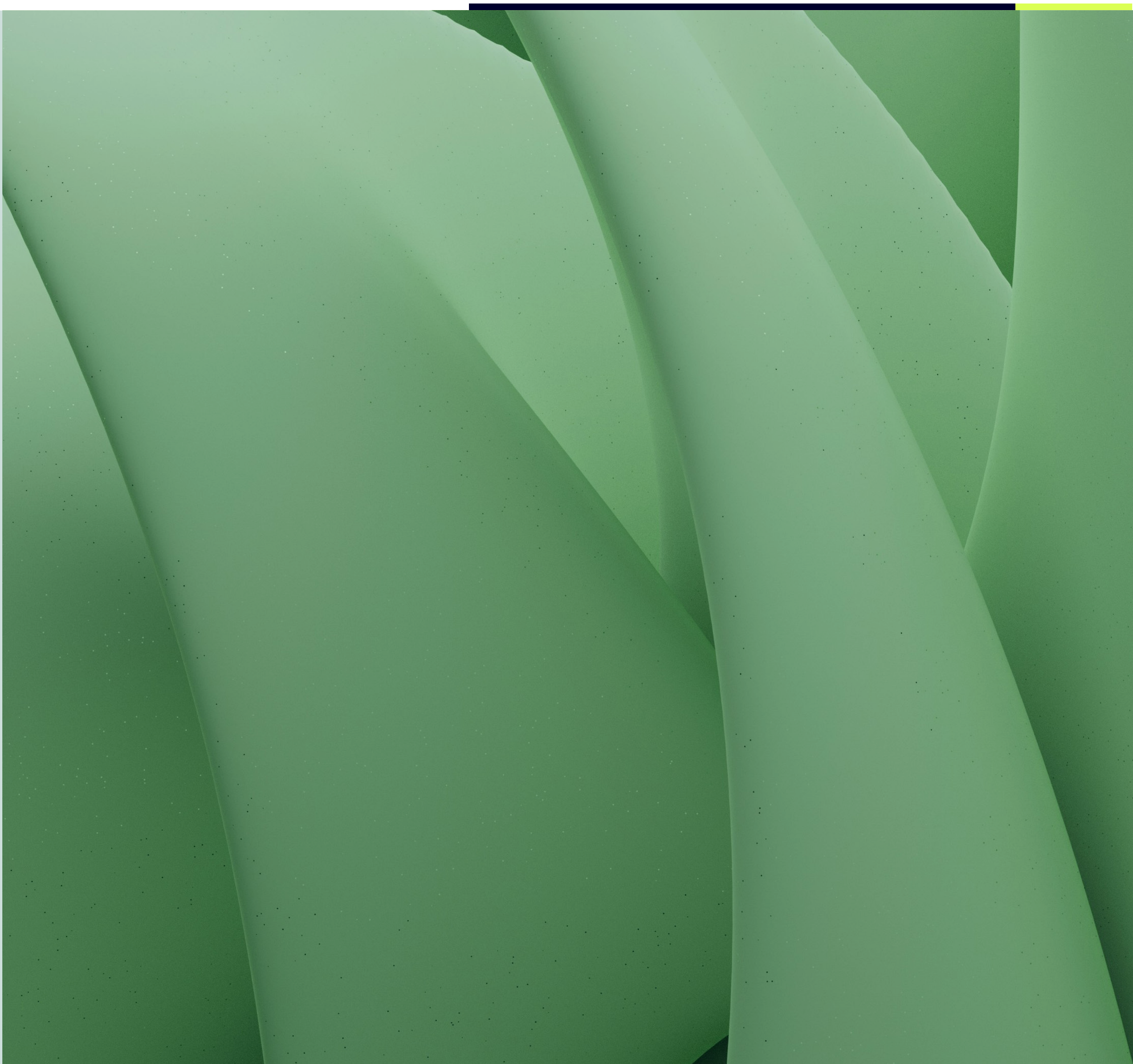
This white paper examines the current maturity of AI in production vehicles, combining market research, technical analysis, and real-world benchmarking. Representative models from leading OEMs were analyzed to assess AI integration across domains such as in-cabin interaction, system responsiveness, and feature usability.

The paper aims to:

1. Provide a structured overview of key automotive AI use cases.
2. Benchmark the real-world deployment and maturity of these features.

Beyond autonomous driving, the focus lies on AI's broader impact on user experience, performance optimization, and intelligent vehicle behavior.

Beyond autonomous driving, the focus lies on AI's broader impact on user experience, performance optimization, and intelligent vehicle behavior. The AI assessment was conducted during the P3 Experience Drive in March 2025. All vehicles had European market specifications. In addition to the AI benchmark, the ADAS functions of each vehicle were thoroughly evaluated and are documented in the separate P3 ADAS Benchmark Report.



3. SW Defined Vehicles as foundation for AI in the onboard

The 2010s witnessed a significant paradigm shift in automotive architectures, spearheaded by new market entrants like Tesla and Nio. This transition moved away from fragmented, decentralized, and ECU-heavy designs toward highly centralized, hardware-agnostic software architectures. This fundamental change facilitated a seamless integration between on-board vehicle systems and off-board backend infrastructure, enabling robust data exchange.

A critical dimension of this transition lies in how OEMs collaborate across the product stack – from hardware and operating systems to cloud and AI-enabled services. The collaboration model an OEM chooses heavily influences the degree of software ownership, AI scalability, and architectural agility.

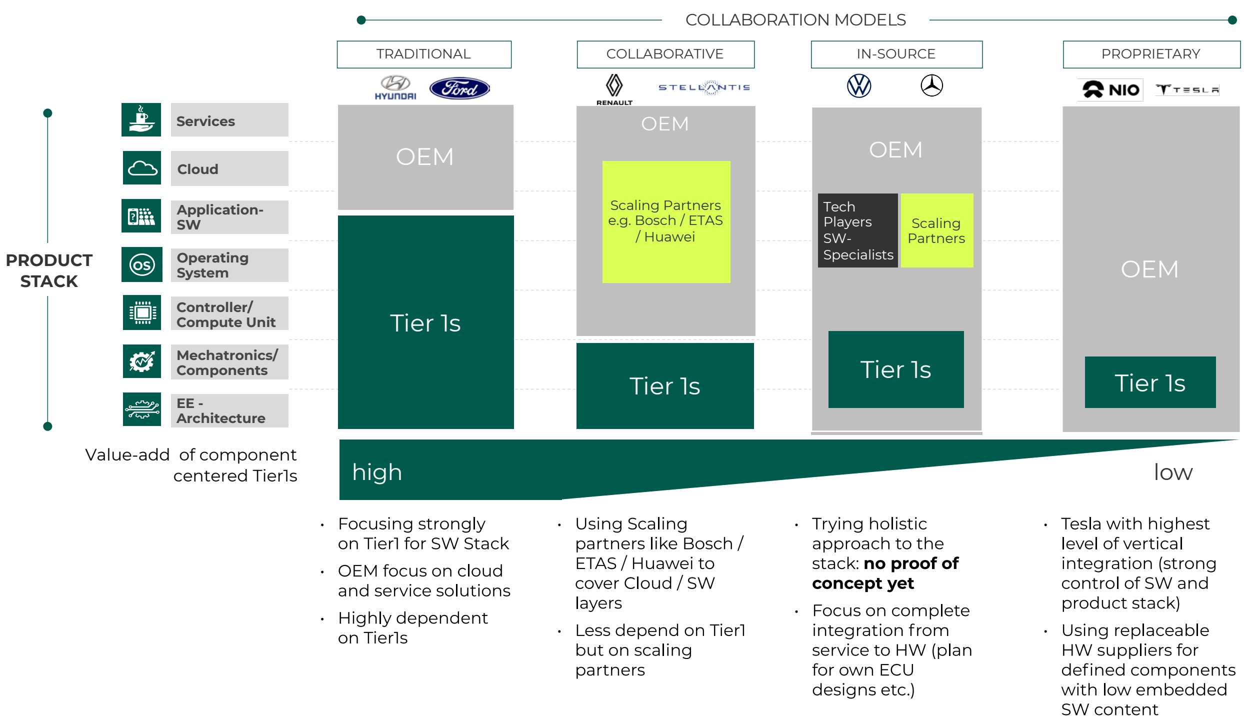


Figure 1: OEM Collaboration Models and Value Distribution Across the Stack

Traditional OEMs like Hyundai and Ford continue to rely heavily on component-centric Tier 1s, with limited in-house software development. In contrast, Tesla and Nio follow proprietary models, internalizing most of the software stack and AI-enabling functions. Between these extremes lie collaborative (e.g. Renault, Stellantis) and in-sourcing (e.g. VW, Mercedes-Benz) approaches, where OEMs selectively partner with scaling providers or tech players to accelerate software-defined vehicle (SDV) deployment.

Access to swarm or fleet data has been pivotal, significantly accelerating the development of novel customer applications and serving as a cornerstone for building end-to-end (E2E) software solutions in autonomous vehicles. The SDV architecture is thus fundamental to enabling continuous data collection and over-the-air (OTA) software updates. It provides clear, standardized middleware and interfaces, crucial for integrating third-party applications and achieving a seamless user experience across on-board and off-board domains.

Consequently, SDV represents a major prerequisite for the effective deployment of AI applications within the vehicle. Furthermore, this architecture supports the deployment of AI functions not only in controlled development environments but also allows for their validation in productive environments through shadowing or controlled beta-user programs. This capability is vital for the iterative refinement and safe introduction of advanced AI features in automotive systems. By the transition of legacy architectures into SW defined vehicle architectures, OEMs can integrate AI in different functions.

3.1. AI in Human-Machine Interface (HMI)

AI plays an increasingly visible role in how drivers and passengers interact with the vehicle. From natural language understanding and predictive infotainment to adaptive interface personalization, intelligent HMI systems are redefining the in-cabin experience. Recent developments include the integration of LLMs such as ChatGPT-like assistants, enabling multimodal, context-aware dialogue systems that go far beyond conventional voice commands. OEMs and Tier-1 suppliers are now experimenting with generative AI for in-vehicle customer support, voice-guided setup processes, and dynamic UX personalization. These developments reflect a broader trend: AI has evolved from an isolated feature to a foundational layer embedded throughout the vehicle, visible especially in how customers interact with voice systems, personalization engines, and adaptive UX flows [1][2].

3.2. AI in Advanced Driver Assistance Systems (ADAS)

AI forms the cognitive backbone of modern driver assistance, enabling real-time perception, predictive modeling, and situational decision-making. These systems are on a trajectory from static rule sets toward self-adaptive learning components that can operate safely in dynamic environments. There is an ongoing debate in the industry regarding the architecture of these systems: Modular vs. E2E. While modular pipelines offer traceability and safety certification advantages, E2E models – especially those based on transformer architectures – promise better generalization and performance in complex environments. Several leading OEMs are now piloting hybrid solutions that combine the strengths of both paradigms. Customers can now perceive the impact of AI not only through typical ADAS interventions but also in subtle behavioral optimizations – such as anticipatory braking, steering adjustments, or adaptive lane changes – reflecting AI's influence in both visible and embedded safety mechanisms. [3][4][5].

3.3. AI in Electric Powertrains

In electric vehicles (EVs), AI supports intelligent energy management through predictive range estimation, driving style analysis, and route-adaptive power distribution. Machine learning models are increasingly used to optimize efficiency, battery longevity, and thermal management. Current advancements focus on data-driven efficiency models, where historical driving behavior, topography, weather data, and live traffic are fused to improve real-time energy optimization. Additionally, AI-based anomaly detection for predictive maintenance of batteries and power electronics is gaining traction as vehicles age and fleets scale [6][7][8].

3.4. AI in Vehicle Dynamics

AI-enhanced chassis control systems can adapt suspension, steering, and braking behavior based on road conditions, driving style, and real-time feedback. These factors enable a more responsive and personalized driving experience while also contributing to safety and performance stability. Emerging trends include reinforcement learning-based controllers, adaptive damping algorithms using vehicle telemetry, and AI-powered virtual sensors that estimate physical quantities like friction or load transfer without additional hardware. These techniques are increasingly used in high-performance and electric vehicles to close the loop between driver intent and dynamic response in real time.

By synthesizing findings from field research and analyzing current trends in AI implementation, this paper aims to provide a holistic view of how AI is transforming the automotive landscape – well beyond autonomy alone. It also outlines key development challenges and opportunities that OEMs, suppliers, and tech providers must navigate to ensure future readiness in the age of intelligent mobility. The boundaries between traditional control algorithms and learning systems are blurring, as AI is increasingly used to modulate battery longevity and chassis response in real time. These systems provide customers with tangible feedback—such as extended range or improved ride comfort—while operating invisibly in the background [9][10][11].

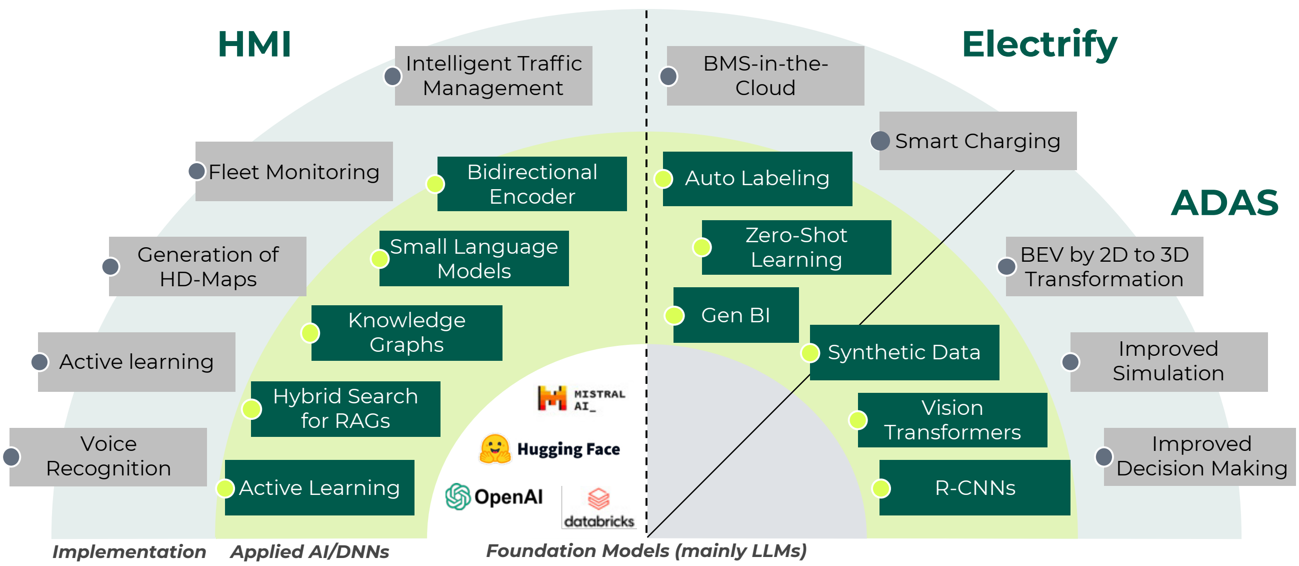


Figure 2: Implementation of AI Models in the Automotive Industry

4. Benchmark

Artificial Intelligence (AI) is rapidly transforming the automotive industry, becoming an integral component of contemporary electric vehicle designs. To effectively evaluate the real-world maturity and capability of current automotive AI systems, this benchmarking study analyzes and compares AI integration in three critical areas: E-Mobility, ADAS, and User Experience & Personalization. The objective is to provide automotive decision-makers with precise insights into which manufacturers lead the market, identify the strengths and weaknesses across competitors, and clarify how AI is enhancing or limiting current vehicle performance.

4.1. Methodology

This benchmarking analysis followed a two-step methodology, combining structured market intelligence gathering with practical on-road testing. The first phase involved collecting and analyzing relevant industry knowledge, including OEM system descriptions, public vehicle documentation, and assessments from independent automotive experts. This provided a solid understanding of each vehicle's AI capabilities and system architecture.

In the second phase, selected AI functionalities were validated through controlled real-world driving scenarios, each limited to a maximum duration of 30 minutes. All vehicles were evaluated across three core AI domains – E-Mobility, ADAS, and User Experience & Personalization – using a consistent scoring framework. Each category allowed for up to 30 points, resulting in a maximum total score of 90 points. This combined approach ensured practical relevance, comparability across manufacturers, and a realistic view of AI maturity in current production vehicles.

4.2. Results: The Current Landscape of AI Integration in Production Vehicles

The benchmark analysis of current-generation AI-equipped vehicles reveals significant disparities in the implementation depth and quality of AI features across OEMs and regions. Premium European manufacturers such as Mercedes-Benz-Benz and BMW lead in overall AI integration, particularly in driving assistance, safety, and route planning. Their strong performance is driven by robust modular AI architectures and integration with backend data ecosystems, enabling personalized in-vehicle experiences and context-aware navigation.

Vehicle		E-Mobility Score	ADAS Score	UX & Personalization Score	Overall Score
Mercedes-Benz EQS		10	22	28	60
BMW 5 Series (i5)		8	19	23	50
BMW iX		8	17	23	48
Polestar 4		8	18	18	44
Nio EL6		8	18	17	43
VW ID.7		7	18	14	39
Xpeng P7		7	14	11	32
Tesla Model Y		8	14	10	32
BYD Seal		5	8	3	16

Table 1: P3 AI Benchmarking Results

Chinese brands like BYD and Xpeng, while innovative in their domestic markets, face challenges in Europe due to limited localization, especially in navigation and smart features. For example, BYD Seal scored extremely low in AI route planning and smart parking functionalities, likely due to software environments not yet adapted to European infrastructures and user expectations. Tesla, known for its end-to-end learning approach, demonstrates strong scores in safety and personalization, but still lags in structured route planning and map-based guidance – areas where Tesla's mapless strategy may impact performance under European test protocols. Emerging EV players like Polestar show a balanced AI feature set with strong safety and personalization capabilities but room for improvement in backend-supported routing and localization.

The conducted benchmark, based on a comparative analysis of selected production vehicles across multiple manufacturers and markets, reveals clear trends in the deployment and depth of artificial intelligence integration in modern automotive systems.

4.3. Clear Leaders in E-Mobility Integration

The benchmark clearly identifies Mercedes-Benz EQS as the leading vehicle in E-Mobility, excelling due to advanced AI-powered battery management systems, highly accurate dynamic range predictions, and effective charging optimization, providing outstanding real-world reliability and efficiency. BMW's offerings, specifically the BMW 5 Series (i5) and BMW iX, closely follow with robust AI integration, offering reliable battery performance and intuitive smart-charging capabilities. Conversely, the BYD Seal is significantly behind, hindered by basic AI integration, limited predictive capabilities, and less efficient battery management, which highlights substantial room for technological advancement.

4.4. Dominance of European Manufacturers in ADAS

In the category of Advanced Driver-Assistance Systems (ADAS), European manufacturers once again take the lead. As part of a dedicated ADAS benchmarking test conducted during the P3 Experience Drive, all vehicles were evaluated based on real-world performance, functional depth, and system responsiveness. The Mercedes-Benz EQS sets a clear industry benchmark through advanced proactive safety features, superior hazard detection capabilities, and highly reliable adaptive driving assistance. The BMW 5 Series (i5) also demonstrates exceptional performance, characterized by intuitive, dependable ADAS features and effective predictive safety interventions. In contrast, the BYD Seal noticeably lags behind, marked by minimal ADAS functionalities, basic hazard predictions, and limited driver support systems.

4.5. Excellence in User Experience & Personalization by Premium Brands

For User Experience & Personalization, Mercedes-Benz EQS emerges as the undisputed leader, distinguished by highly personalized and context-aware interactions powered by sophisticated AI systems. Both BMW models, the BMW iX and BMW 5 Series (i5), also achieve excellent results, delivering adaptive comfort, intuitive interfaces, and strong personalization features. At the lower end, the BYD Seal significantly trails behind, with rudimentary AI integration, minimal personalization capabilities, and basic user interactions, underscoring the potential and necessity for further development.

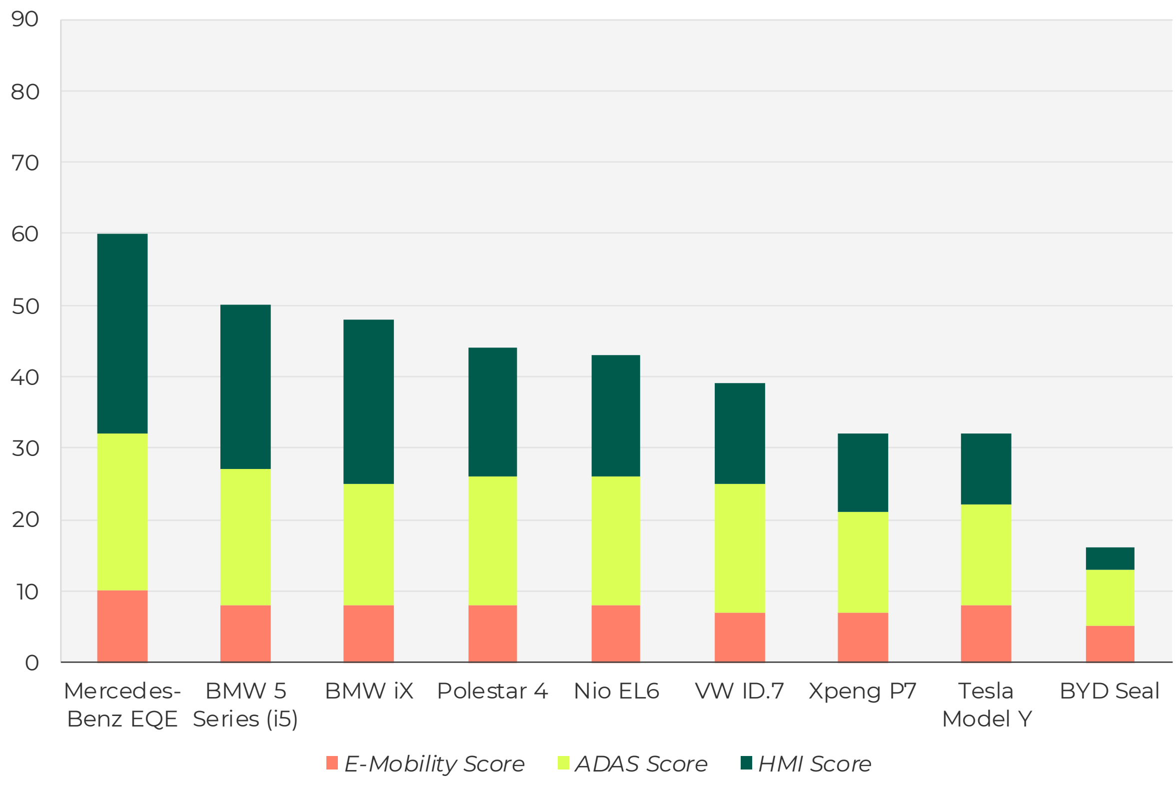


Figure 3: Visual Representation of the Benchmarking Results

5. Key Findings

1. Limited Localization of Chinese OEMs on the European Market

Chinese automotive brands, while technologically advanced in their domestic markets, show noticeable limitations in the European context. A key finding is the insufficient localization of AI-driven functionalities – particularly in HMI systems and speech interfaces. Language processing, regional traffic rule adaptation, and map data integration often lack the refinement expected by European consumers. As a result, the user experience and functionality of AI features such as voice assistants, predictive navigation, and system personalization fall behind those offered by established Western OEMs.

2. German OEMs Lead Through Deep ADAS Integration and Backend Intelligence

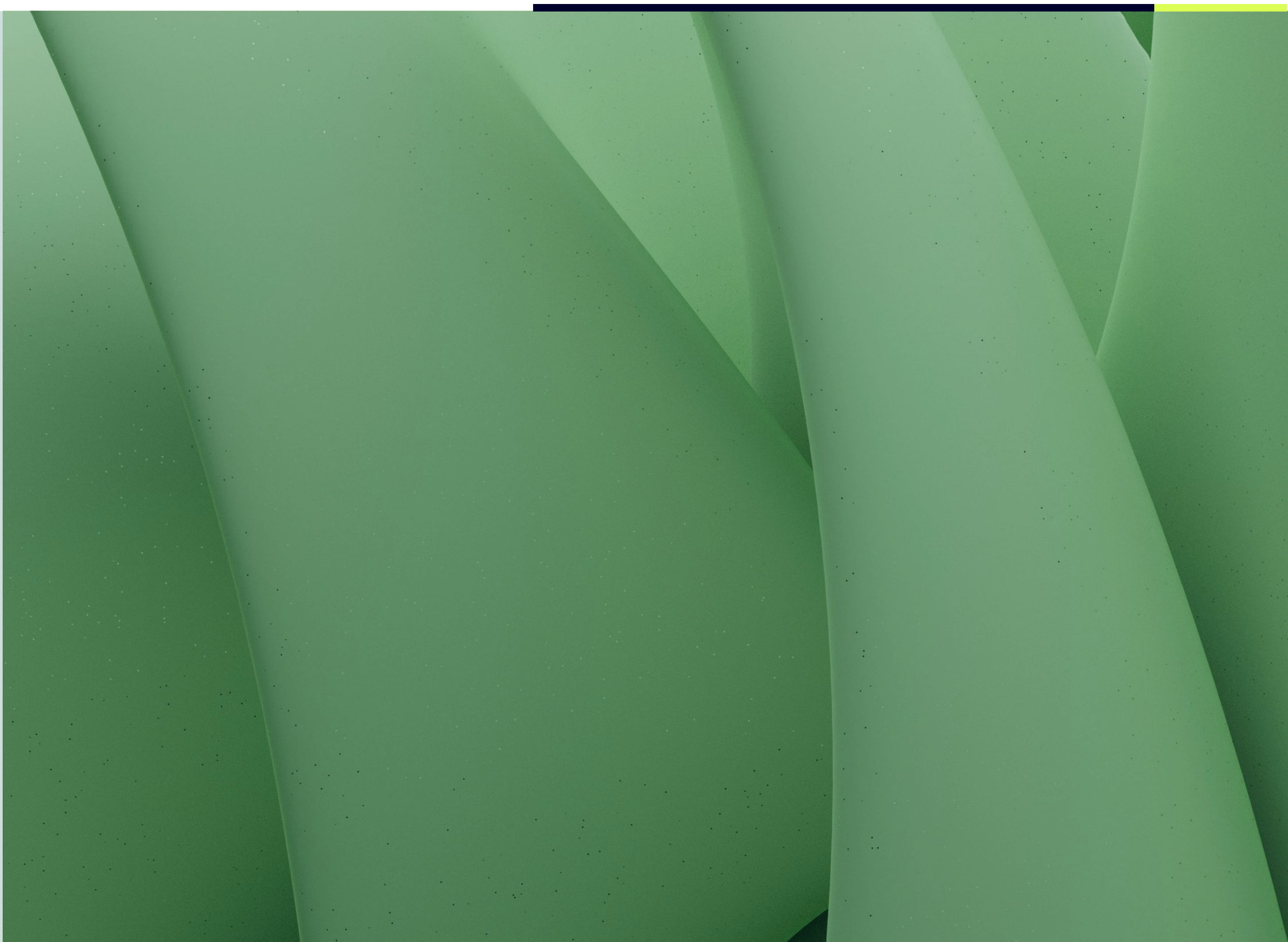
German automotive manufacturers, particularly premium brands, currently exhibit a strong leadership position in the integration of AI across both visible and non-visible vehicle domains. Their advantage lies in robust Advanced Driver Assistance Systems (ADAS), sophisticated route optimization features, and the seamless integration of large language models (LLMs) into backend infrastructures. These backend systems enable more personalized, predictive, and context-aware in-car experiences – supporting driver intent recognition, intelligent suggestions, and advanced customer support services.

3. Depth of AI Determines Control: Proprietary vs. Open Technologies

Another significant trend uncovered is the relationship between the technical depth of AI functionality and the degree of proprietary system use. The deeper the AI is embedded into the core vehicle functions – such as powertrain management, energy optimization, or longitudinal/lateral control – the more likely it is to be based on proprietary in-house developments. Their deep integration with core vehicle systems makes these vehicle functions rarely compatible with third-party reuse.

4. Customer-Facing Functions Often Driven by Big Tech Ecosystems

Conversely, the closer AI systems are to the user interface – particularly in infotainment, voice interaction, and cloud-connected services – the more prevalent Big Tech ecosystems become. Companies like Google, Amazon, and Baidu provide off-the-shelf speech recognition, navigation, and personalization modules, which are often embedded into HMI stacks. This underscores a division in the automotive AI landscape: OEMs tend to retain control over vehicle-critical intelligence, while outsourcing or integrating external platforms for customer-facing digital services.



6. Recommendations and Strategic Implications

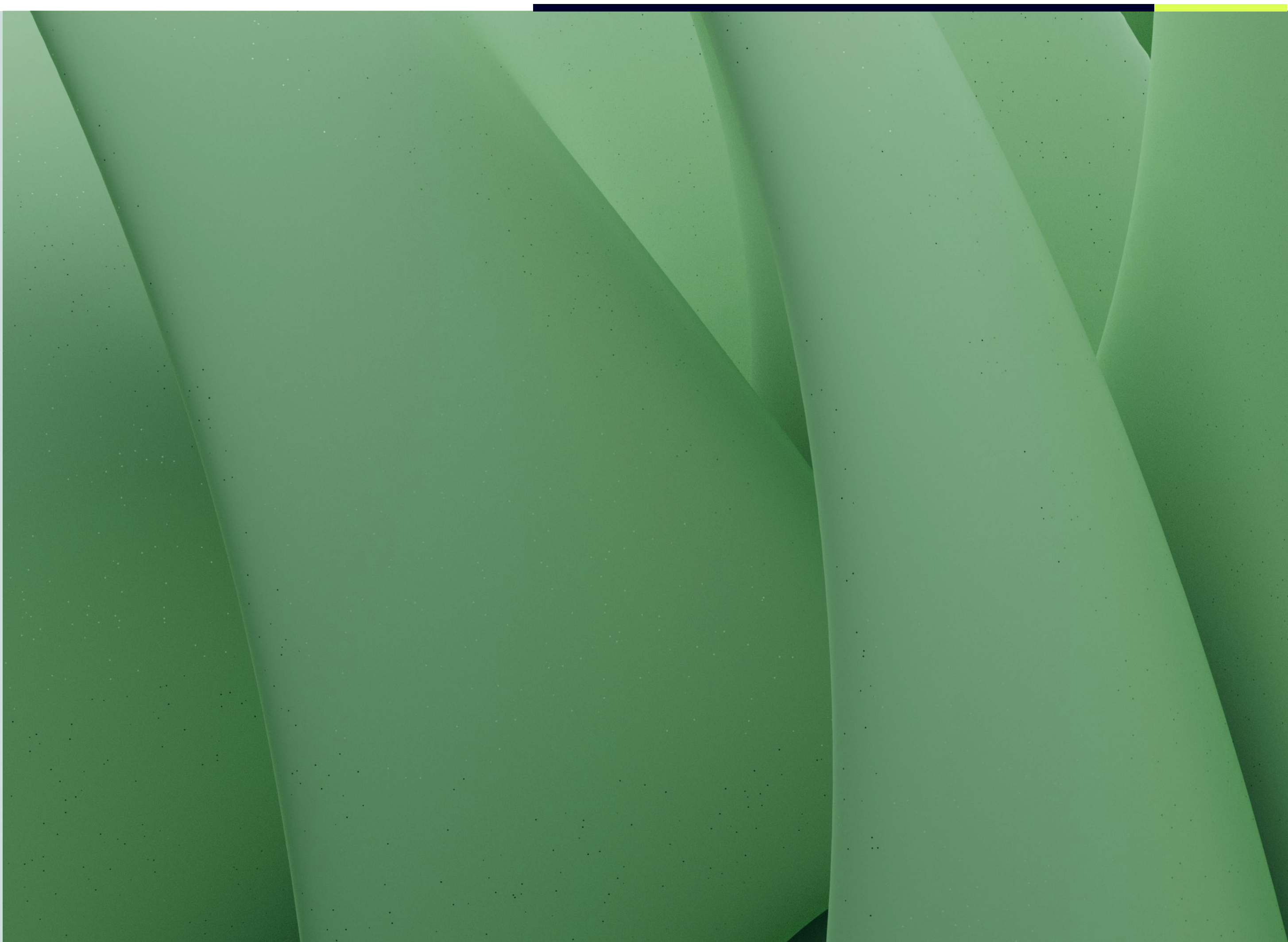
As artificial intelligence (AI) becomes central to modern vehicle systems, strategic imperatives vary across stakeholders. For automotive manufacturers, the challenge lies in balancing innovation with deep system integration. European OEMs like Mercedes-Benz and BMW show strength in AI-driven safety, personalization, and navigation. To stay ahead, however, they must move beyond isolated features and establish interoperable, resilient "systems of systems", enabling seamless domain interaction and lifecycle support for AI-powered functionalities. Chinese OEMs, while technologically advanced, face challenges in localization, often falling short in delivering region-specific voice, navigation, and interface experiences. Addressing this gap requires stronger in-house capabilities and backend adaptations for non-domestic markets.

For Tier 1 suppliers, increasing AI complexity creates both risk and opportunity. Their role as system integrators will be crucial. To succeed, they must offer modular, safety-certified AI components – spanning perception, planning, and interaction – in compliance with ISO 26262, SOTIF, and UNECE standards. In parallel, they should develop middleware and abstraction layers to enable scalable deployment across different OEM environments, reducing time-to-market while maintaining functional safety.

Technology companies and AI startups are uniquely positioned to enhance in-vehicle intelligence through context-aware user interaction and dynamic personalization. The rise of large LLMs and real-time inference is unlocking new potential for smart assistants, behavioral modeling, and adaptive interfaces. Equally important is their role in backend innovation – contributing training infrastructure, synthetic data pipelines, and localization toolkits essential for robust AI deployment.

From a regulatory perspective, current standards must evolve to reflect the adaptive and behavior-driven nature of AI. Component-level validation is no longer sufficient. Authorities must define system-level performance metrics, support scenario-based validation, and create frameworks for transparency, accountability, and explainability. These measures will help ensure both the safety and societal acceptance of AI in critical functions like emergency braking or predictive navigation.

Finally, cross-industry collaboration will be essential. The future of automotive AI depends on coordinated efforts between OEMs, suppliers, tech firms, and regulators. Joint initiatives in simulation environments, federated learning, and continuous system-level testing will be critical to achieving trustworthy, certifiable, and scalable intelligent mobility systems.



7. References

1. Kim, J., & Chen, A. (2024). *Embedded Large Language Models for Enhanced Human-Machine Interface in Autonomous Vehicles. Journal of Automotive AI Research*.

2. Zhou, M., & Wang, L. (2024). *ConnectGPT: Connect Large Language Models with Connected Automated Vehicles*.

3. Müller, T., et al. (2023). *End-to-End Autonomous Driving: Challenges and Frontiers. arXiv preprint arXiv:2306.16927*.

4. Lin, Y., & Lee, S. (2022). *Bridging the Gap Between Modular and End-to-end Autonomous Driving*. UC Berkeley Technical Report.

5. Singh, A., et al. (2021). *Explainable Artificial Intelligence for Autonomous Driving. arXiv*.

6. Nair, P., & Kumar, D. (2023). *Artificial Intelligence Algorithms for Hybrid Electric Powertrain Systems: A Review. Energies*.

7. Silva, R., et al. (2024). *Integration of AI into Energy Management Systems for Electric Vehicles: A Systematic Review. Journal of Electrical Systems and Information Technology*.

8. Zhang, L., et al. (2023). *AI Technique-Based EV Powertrain Condition Monitoring and Fault Diagnosis: A Review. Vehicle Systems and Diagnostics*.

9. Rossi, F., et al. (2024). *Harnessing Artificial Intelligence for Enhanced Vehicle Control and Diagnostics. IEEE Transactions on Intelligent Transportation Systems*.

10. Yu, H., & Tan, K. (2025). *AI2-Active Safety: AI-enabled Interaction-aware Active Safety Analysis with Vehicle Dynamics*.

11. Garcia, M., & Becker, T. (2024). *Vehicle Control Systems: Integrating Edge AI and ML for Enhanced Safety and Performance. Vehicle Technology Journal*.

12. Bathla, Gourav; Bhadane, Kishor; Singh, Rahul Kumar; Kumar, Rajneesh; Aluvalu, Rajanikanth; Krishnamurthi, Rajalakshmi et al. (2022): Autonomous Vehicles and Intelligent Automation: Applications, Challenges, and Opportunities. In: *Mobile Information Systems* 2022, S. 1–36. DOI: 10.1155/2022/7632892.

13. In: *Sensors (Basel, Switzerland)* 24 (18). DOI: 10.3390/s24186139.

14. Tanaji, Bhosale Akshay; Roychowdhury, Sayak (2024): A Survey of Cybersecurity Challenges and Mitigation Techniques for Connected and Autonomous Vehicles. In: *IEEE Trans. Intell. Veh.*, S. 1–18. DOI: 10.1109/TIV.2024.3493938.

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