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Challenges and Solutions in Power-Train System Integration: The Critical Role of Power Electronics and Model-Based Systems Engineering

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Abstract

This review paper examines the challenges and solutions in electric power-train multi-domain system integration, focusing on the critical role of power electronics and systems integration in modern automotive complex systems. The transition from internal combustion engines to electric propulsion has introduced multi-domain complexities, necessitating advanced methodologies like Model-Based Systems Engineering (MBSE) to manage complex systems interdependence. Electric power train has three most important components: high voltage battery, electric motor and power electronics. The paper highlights key challenges of systems integration, reliability gaps in cyber-physical integration, and the lack of standardization in power electronics integration as an example basis for understanding system integration challenges. Emerging solutions, including advanced thermal management techniques and digital twin technologies, are discussed as promising directions for future research. The review underscores the need for standardized approaches and AI-driven co-design platforms to address the growing complexity of automotive power-trains while ensuring safety and efficiency.

Keywords: System Integration; Electric Power Train; Power Electronics; Model Based Systems Engineering; Cyber-Physical Systems.

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1. Introduction

With the invention of the engine, human civilization has seen a rapid transition in industrialization. Engine led humans to develop transportation systems which brought remarkable acceleration in human daily life from an economic perspective. From the beginning of human civilization, transportation has been playing a major role. In today's world it is not imaginable without a transportation system. The first vehicle was simple if we analyze from today's automotive engineering stage. Early days automotive systems were much more simple, thus the production and manufacturing process were simpler. Old vehicles had fewer failure modes in their life-cycle process due to simplicity of their system construction.

Figure 1: Modell 3 Benz by Karl Benz 1888

Karl Benz of Mannheim, Germany is the inventor of the motor car. In the autumn of 1885, his three-wheeled vehicle became the first successful petrol-engined car. He was awarded a patent for it on 29 January 1886, and became the first motor manufacturer in 1888 with his Modell 3 Benz [1]. In the preliminary stage of automotive system development, the requirements were not defined due to constraints and limitations of technological capability. The Modell 3 could maximum reach up to 20 Km/h of speed. From the technical details of Modell 3 Reference [2], it can be assumed that the different types of requirements were stated with a bottom-up approach rather than by the top-down method of design.

Table 1: Technical Details of Modell 3 Mercedes Benz [2]

Feature	Specification
Engine Type	Single-cylinder, four-stroke
Total Displacement	1990 cc
Rated Output	3 hp at 500 rpm
Maximum Speed	Approximately 20 km/h
Wheelbase	1575 mm

The limitation of technical abilities did not allow the vehicle to be designed as per arbitrary requirements from various perspectives such as: performance, efficiency, comfort, and safety.

As for the evolution of automotive development, requirements from multi-domain aspects were also increasing with the help of technological capabilities. The high-level requirements from stakeholders were pushing forward the developers to develop low-level requirements as well. That is why we are witnessing a transition of automotive technology from ICE vehicles to electric propulsion today. As systems are getting more and more complex, it is hard to develop automotive systems with the help of legacy design methodologies. Early days automotive systems were purely mechanical. Nowadays a vehicle is a complex system of different system domains such as: mechanical, electrical, electronics, software, etc. The more multi-domain systems co-exist in vehicles, the more it becomes a challenge for automotive engineers to develop systems because of multi-domain system inter-operation within a vehicle system. For example, if there is a software glitch in an autonomous vehicle, it could lead to potential lethal risk for the passengers [5]. With the gradual application of intelligent network technology in automobiles, the ever-increasing electrical function configuration requirements make the automotive electronic and electrical architecture more complex [3]. Advances in development, most vigorously driven by the progress of electronics, have led to increasingly complex systems, which in turn often involve multi-disciplinary systems engineering with complex elements, e.g., control device hardware and software [4].

Figure 2: Multi-disciplinary in systems engineering [3]

Another emerging concern for automotive system development is the cyber-physical system development. As more and more software and electronics systems are being embedded, there is a need for developing this cross-domain engineering challenge [5]. Modern vehicles are no longer mechanical dominated systems; their physical and functional behavior are mostly influenced by electronic control units and network system cyber components Reference [6].

Automotive systems engineering is a new branch that manages the complexity of multi-domain integration of systems. It is simply the application of systems engineering for developing complex automotive multi-domain systems. Automotive systems engineering is a methodology for developing systems for a vehicle, or vehicle as a system [7]. Systems engineering has been implemented by major automotive players. A model-based system engineering effort was initiated to reduce testing effort and cost in documentation [8]. For the development of BMW's next generation electrified drive-train, efficiency and quality objectives can be achieved through MBSE. The Tesla Roadster has been entirely developed applying model-based system engineering with the help of MATLAB (Mathworks) [9]. Tesla clearly mentioned that with the help of MATLAB model-based design they have enhanced the power train efficiency that could have taken years of development process. Dongfeng, a pioneer Chinese automotive manufacturer, has developed a battery management control system for the Dongfeng hybrid EQ6110 applying model-based design using Mathworks tools [10]. Through the research and application of the top-down V-shaped design method of electronic and electrical architecture, it can not only help enterprises form an electronic and electrical architecture development team and accumulate development experience, but also shorten the project by improving the development efficiency of electronic and electrical architecture [11].

It is now obvious that traditional document-based engineering approaches are not adequate to cope with the fast transition of multi-domain system development in automotive engineering. Engineers are now searching for more robust tools for reducing complexity and unintended functional behaviour of any part or subsystem of a vehicle. Automotive systems engineering is surely playing a major role in eradicating complexities of system design for multi-domain systems. However, model-based system engineering is still evolving to tackle system integration challenges as there is a major shift in automotive power train system development.

2. Evolution of Automotive Power-Trains

2.1 Early Systems

Karl Benz of Mannheim, Germany is the inventor of the motor car. In the autumn of 1885, his three-wheeled vehicle became the first successful petrol-engined car. He was awarded a patent for it on 29 January 1886, and became the first motor manufacturer in 1888 with his Modell 3 Benz [1]. The Modell 3 could maximum reach up to 20 Km/h of speed. From the technical details of Modell 3 [2], it can be assumed that the different types of requirements were stated with a bottom-up approach rather than by the top-down method of design. The limitation of technical abilities did not allow the vehicle to be designed as per arbitrary requirements from various perspectives such as: performance, efficiency, comfort, and safety.

2.2 Transition to Multi-Domain Systems

As for the evolution of automotive development, requirements from multi-domain aspects were also increasing with the help of technological capabilities. The high-level requirements from stakeholders were pushing forward the developers to develop low-level requirements as well. That is why we are witnessing a transition of automotive technology from ICE vehicles to electric propulsion today.

Nowadays a vehicle is a complex system of different system domains such as: mechanical, electrical, electronics, software, etc. The more multi-domain systems co-exist in vehicles, the more it becomes a challenge for automotive engineers to develop systems because of multi-domain system inter-operation within a vehicle system.

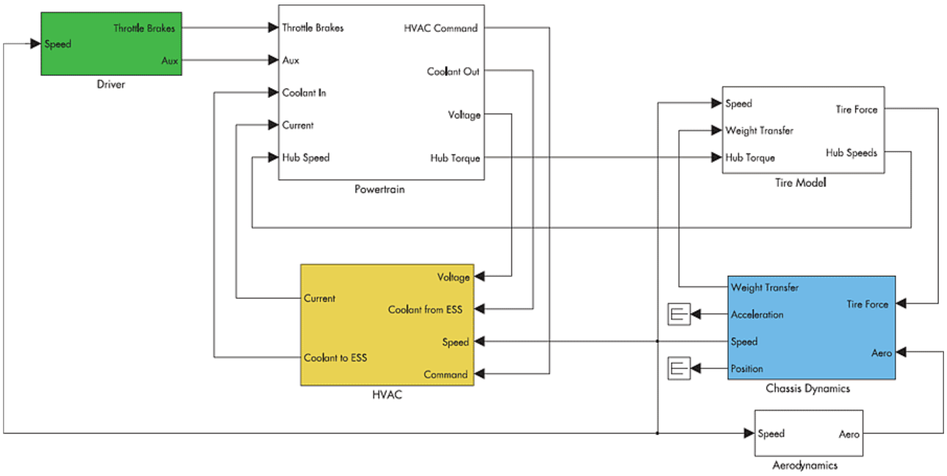


Figure 3: Top-level vehicle performance Simulink model [8]

Model-based system engineering effort was initiated to reduce testing effort and cost reduction in documentation [8]. The Tesla Roadster has been entirely developed applying model-based system engineering with the help of MATLAB (Mathworks) [9]. Dongfeng, a pioneer Chinese automotive manufacturer, has developed a battery management control system for the Dongfeng hybrid EQ6110 applying model-based design using Mathworks tools [10].

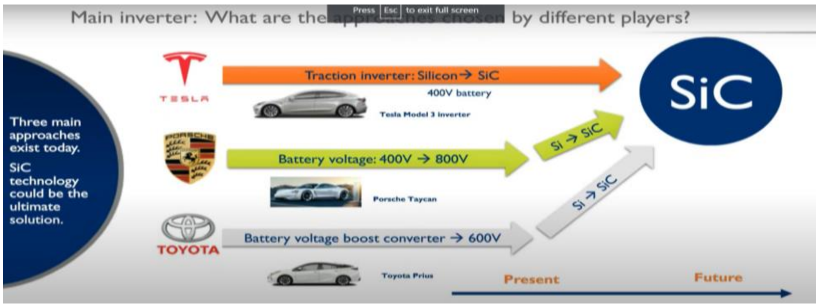
Figure 4: Dongfeng EQ6110 Hybrid Electric Bus [9]

With the gradual application of intelligent network technology in automobiles, the ever-increasing electrical function configuration requirements make the automotive electronic and electrical architecture more complex Reference [5]. AUTOSAR (Automotive Open System Architecture) [6] provides standardized approaches for software integration in modern vehicles.

3. Challenges in Integration

3.1 Functional Complexity

The rapid electrification of automotive power-trains poses significant challenges in managing multi-domain interactions. Power electronics integration exemplifies this complexity, where electrical, thermal and spatial dependencies create design constraints. The electrical-thermal-spatial (size, space, weight) interdependencies of power electronics introduce multiple design constraints that affect overall system performance [12].



Main inverter: What are the approaches chosen by different players?

Three main approaches exist today.

SiC technology could be the ultimate solution.

Traction inverter: Silicon → SiC

400V battery

Tesla Model 3 inverter

Battery voltage: 400V → 800V

Porsche Taycan

Battery voltage boost converter → 600V

Toyota Prius

Figure 5: High voltage shifting trends among major automotive players [14]

Thermal management has become particularly critical with the adoption of wide bandgap semiconductors like Silicon Carbide (SiC). While these materials enable higher efficiency, they also introduce new thermal challenges. The increase of speed causes higher copper and iron losses in the electric motor which increases traction motor heat and hinders operational limits [13]. This thermal coupling between inverter and motor creates a complex optimization problem where improving one parameter often compromises another.The industry's shift to 800V systems illustrates these trade-offs. High-voltage systems (800V) reduce current but increase switching losses [14]. This transition requires careful balancing of semiconductor selection, cooling system design, and packaging constraints to maintain reliability while achieving performance targets.

3.2 Reliability Gaps

The integration of cyber-physical systems introduces new failure modes that are fundamentally different from traditional mechanical systems. Modern vehicles' physical and functional behavior are mostly influenced by electronic control units and network system cyber components [6]. This shift creates vulnerabilities where a software glitch in an autonomous vehicle could lead to potential lethal risk for the passengers [5].The economic impact of integration challenges is substantial. Industry experience shows that no matter how thoroughly the individual components have been tested, there almost always remain unforeseen incompatibilities [15]. This reality makes system integration the most expensive activity in system development [16], with costs stemming from both technical complexity and the iterative nature of resolving integration issues.

4.Methodologies

4.1 MBSE (Model-Based Systems Engineering)

For the development of BMW's next generation electrified drive-train, efficiency and quality objectives can be achieved through MBSE [8]. The model-based system engineering effort was initiated to reduce testing effort and cost reduction in documentation [8]. Through the research and application of the top-down V-shaped design method of electronic and electrical architecture, it can not only help enterprises form an electronic and electrical architecture development team and accumulate development experience, but also shorten the project by improving the development efficiency of electronic and electrical architecture [11].

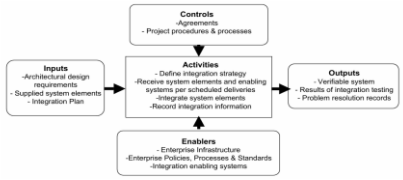


Figure 6: Context diagram for the system integration process [29]

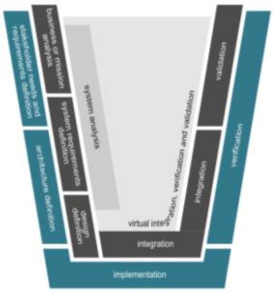


Figure 7: Integration in V model of MBSE [24]

The Tesla Roadster has been entirely developed applying model-based system engineering with the help of MATLAB (Mathworks) [9]. Tesla clearly mentioned that with the help of MATLAB model-based design they have enhanced the power train efficiency that could have taken years of development process [9].

4.2 MBSI (Model-Based System Integration)

The methodology known as "Model-Based System Integration" (MBSI) has emerged as an extension of MBSE. The backbone of this methodology is system interface analysis and functional flow of system [17]. Function is one of the core aspects of system operation. That is why the functional behaviour of a system is the basic baseline for system architecture design. This demonstrates the intrinsic importance of functional modeling in MBSE [18].

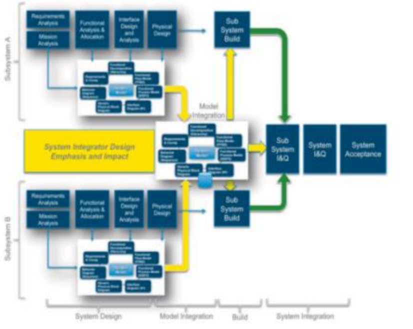


Figure 8: Model-based system integration [17]

System integration is considered one of the most challenging tasks involved in modern system development Reference [16]. It is also considered the most expensive activity in system development. MBSI provides a structured approach to address these challenges by focusing on interface management and functional flow analysis early in the design process [17].

4.3 SSFD (System State-Flow Diagram)

SSFD has been proven a robust tool of functional analysis and decomposition of multi-disciplinary systems at Ford Motor Company [19]. This tool is a robust methodology to analyze functional behaviour in a more detailed manner, which is one of the most important aspects of architecture development [20]. Also for integration strategy development, this tool can assist in the early design phase by analyzing system interfaces [20].

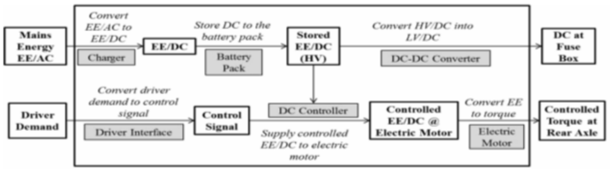


Figure 9: SSFD for Electric Vehicle Power-train [21]

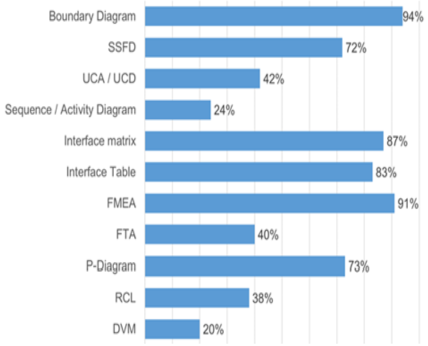


Figure 10: Overall analysis of methods (SSFD) usage in projects [22]

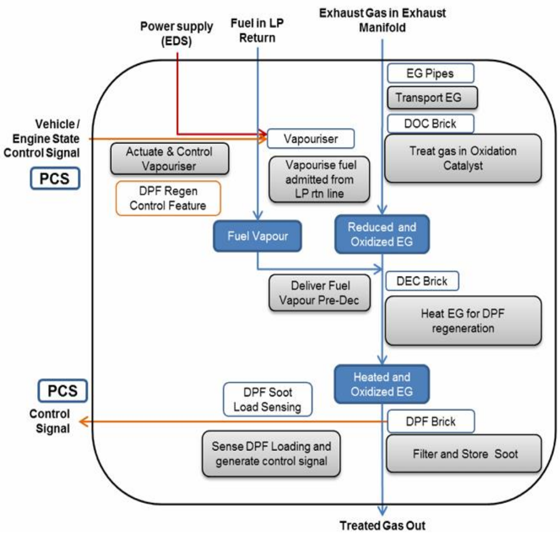


Figure 11: Exhaust after treatment system state-flow diagram [22]

Generic functional analysis early in the product creation process develops the model basis for requirements analysis, architecture design, and integration [21]. 24% of projects have identified at least one quantifiable benefit such as cost avoided/saved, quality improvement, time saved, or customer experience enhancement [22]. A practical example is Ford's exhaust after treatment system state-flow diagram which demonstrates the application of SSFD in complex systems [19].

6. Emerging Solutions

6.1 Thermal Management

Efficient thermal management can significantly improve power density, performance and reliability as well as reducing power electronics cost [23]. Two types of power module cooling have been adopted in many electric vehicles: 1) Single side cool, and 2) Double side cool. For double side cooled modules, a cold plate is cooled on both sides of the modules (2008 Lexus LS HEV, 2014 Camry HEV, 2016 Volt HEV, 2017 Cadillac CT6 HEV) Reference [24].

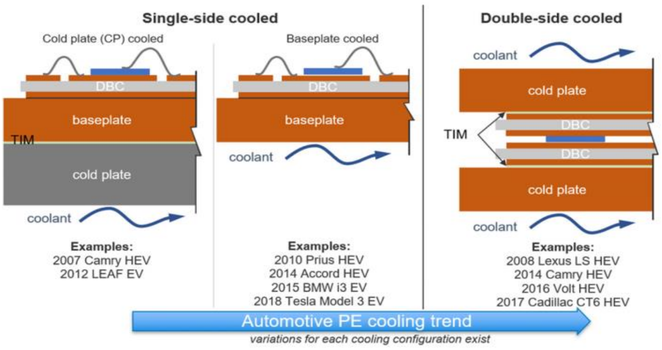


Figure 12: Schematics of typical power module configuration [24]

Tesla Model 3 EV utilizes base-plate cooled power modules which do not require an additional cold plate and TIM (Thermal Interface Material), which reduces weight and size and also simplifies the system [24]. This approach demonstrates how advanced thermal management solutions can address the increasing thermal loads in modern EV power-trains.

6.2 Retrofitting

Electric conversion of ICE vehicles is mostly done for low-powered and short-ranged vehicles. The conversion of Opel Kadett C 1978 by University of Zagreb demonstrates typical challenges in retrofitting, where the battery pack is not integrated as a module with the BIW (Body In White) like pure EVs such as Tesla and BYD etc. Reference [25]. This creates space and insulation constraints inside the power train and vehicle body [26].

Figure 13: EV Conversion of Opel Kadett C 1978, University of Zagreb, Dubrovnik, Croatia - 2014 [25]

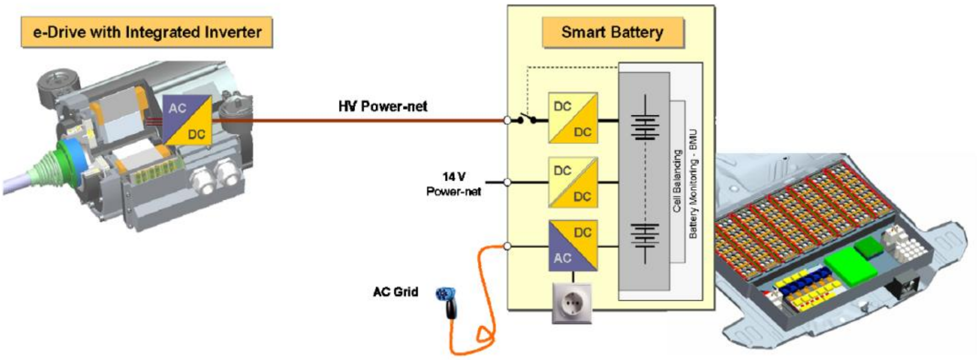


Figure 14: Site of Action Integration of Power Electronics in EV power train [27]

Research shows that site-of-action integration reduces harness weight by 15% but increases thermal stress [27]. This approach integrates power inverters with traction motors and converters with batteries, thus reducing the amount of harness, weight, cost, and installation space requirements [27]. However, site of action integration has major challenges often regarding less installation space for power modules, complex structure, and thermal/mechanical stress [27].

7. Gaps and Future Directions

7.1 Standardization Challenges

There is a significant gap in standardization of power electronics packaging. Most power modules are designed and customized by their chosen suppliers. Currently suppliers such as Infineon, Bosch, and Hitachi etc. are designing power modules for designated OEMs [28]. This lack of standardization in power modules increases the cost of power inverters due to lower production volumes, and OEMs have fewer options for power module design [28].

7.2 Advanced Tool Development

Traditional document-based engineering approaches are not adequate to cope with the fast transition of multi-domain system development in automotive engineering [29]. Engineers are now searching for more robust tools for reducing complexity and unintended functional behaviour of any part or subsystem of a vehicle [29].

Virtual FMEA (Failure Mode and Effects Analysis) approaches are emerging as critical tools, as demonstrated by Ford's implementation where SSFD has been proven a robust tool for functional analysis and decomposition of multi-disciplinary systems [19]. This methodology helps in early fault detection during the design phase.

7.3 Emerging Technological Trends

Digital twin technology is gaining traction in automotive applications. Dongfeng, a pioneer Chinese automotive manufacturer, has developed a battery management control system applying model-based design using Mathworks tools [10]. Recent research suggests that the integration of digital twins has become an important topic of study in advanced manufacturing [30].

The use of MBSE in advanced manufacturing is examined in new bibliometric analysis, which identifies significant trends and important articles. The study divides research into many areas, with particular emphasis on intelligent manufacturing and the integration of digital twins [30].

Table 2: Current Challenges and Future Directions

Category	Current Challenges	Future Directions / Trends	Refs
Standardization Challenges	- Lack of standardization in power module packaging - Customized modules from suppliers like Infineon, Bosch, Hitachi - Higher costs due to low production volumes and limited design flexibility for OEMs	- Develop industry-wide standards for power electronics packaging - Promote modular, interoperable designs	[28]
Advanced Tool Development	- Document-based engineering approaches are inadequate for modern multi-domain systems - Increased complexity and unintended behavior in systems	- Adoption of robust tools like Virtual FMEA - Use of SSFD for functional analysis and fault detection early in design	[19], [29]
Emerging Technological Trends	- Need for better integration of smart technologies in automotive engineering - Fragmented research in digital twin and MBSE	- Increased adoption of Digital Twins in BMS and manufacturing - Bibliometric analysis highlights trend toward intelligent manufacturing and digital twin integration	[10], [30]

8. Conclusion

This review has systematically examined the evolution of electric vehicle power-train integration, from the mechanical simplicity of early systems like Karl Benz's Model 3 [1,2] to today's complex multi-domain architectures. The analysis demonstrates that Model-Based Systems Engineering (MBSE) and System State-Flow Diagrams (SSFD) have become pivotal methodologies, as evidenced by their successful implementation at BMW [8], Tesla [9], and Ford [19].However, significant challenges remain in addressing cross-domain integration issues. The research underscores the persistent need for tools that can simultaneously manage: thermal constraints in high-voltage systems [27,31]; spatial limitations in retrofitting applications [36,37]; and software-hardware interdependencies [4,5].

Future work must prioritize the following critical areas:

1. Standardization of power electronics packaging to reduce costs and improve compatibility [28].

2. Development of AI-driven co-design platforms that can optimize multiple domain requirements concurrently, building on existing model-based approaches [8,9,10].

3. The transition to electric mobility demands fundamentally new integration paradigms that can keep pace with increasing system complexity while maintaining reliability and safety standards [5,16]. This review suggests that combining MBSE methodologies with emerging technologies like digital twins [10,30] and advanced thermal management solutions [24] offers the most promising path forward.

9. Declaration

9.1 Conflict of Interest Statement

The authors declare no known conflicts of interest that could influence the content or conclusions presented in this review paper. This work was conducted independently, and no funding or financial support was received from any organization that may have a direct or indirect interest in the subject matter discussed. All cited references and case studies (including those involving commercial entities such as Tesla, BMW, Ford, and Dongfeng) were selected based on their technical relevance to electric vehicle power-train integration, without preference or bias toward specific manufacturers or methodologies.

To ensure objectivity: Funding — No industry grants or sponsorships were involved. Affiliations — The authors have no financial or advisory ties to automotive companies mentioned. Data Selection — All referenced studies were chosen based on peer-reviewed academic merit or publicly available technical documentation. This statement aligns with ethical guidelines for review articles and aims to maintain transparency in reporting scientific findings.

9.2 Informed Consent Declaration

This review article is based exclusively on analysis of previously published studies and publicly available technical documentation. No original human or animal subject research was conducted, thus requiring no informed consent process. All referenced works are properly cited in accordance with academic integrity standards. All technical data were drawn from peer-reviewed publications or open-access corporate reports; no proprietary or confidential information was used.

9.3 Statement on AI-Assisted Composition

The authors acknowledge the use of AI-assisted tools (specifically ChatGPT-4) exclusively for: Language refinement — improving readability of original author-written content while preserving technical accuracy; and Structural organization — assisting in logical sequencing of existing material from source documents. Human oversight was maintained throughout: (1) All technical content, analysis, and conclusions originate from the authors' direct interpretation of cited sources. (2) AI-generated text was rigorously cross-checked against source materials to prevent hallucination or distortion. (3) Final editorial control remained entirely with the authors. AI was not used for generating original technical concepts or data, conducting literature searches, or writing core academic content. This transparent disclosure aligns with emerging best practices for AI use in academic writing (Nature, 2023; Elsevier, 2024).

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