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EDITED BY
Liguo Zang,
Nanjing Institute of Technology (NJIT), China

REVIEWED BY
Ján Dižo,
University of Žilina, Slovakia
Aleksandar Ašonja,
Business Academy University (Novi Sad), Serbia

*CORRESPONDENCE
Jianwei Tan,
tanjianwei@bit.edu.cn

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Electric drive axle systems in new energy vehicles

Yingshuai Liu[1], Jingsong Tan[1], Shuo Shi[1] and Jianwei Tan[2]*

[1]Shandong Huayu University of Technology, Dezhou, China, [2]National Lab of Auto Performance and Emission Test, School of Mechanical and Vehicular Engineering, Beijing Institute of Technology, Beijing, China

This study set out to benchmark how far recent advances in motor–gearbox integration, thermal management and control algorithms could jointly raise the efficiency of electric-drive axles for new-energy vehicles. The different schools of thought regarding the integration of electric motors and gearboxes were discussed and distilled into a single framework before quantitative analysis began. A 2020–2025 literature synthesis then revealed that, relative to single-speed hardware, two-speed gearboxes increased motorway-cycle motor efficiency by 5%–7% without raising urban energy demand; oil–water hybrid cooling restricted the motor-and-gearbox temperature band to ±3 °C and lifted heat-transfer efficiency by 25%; while model-predictive control with road-slope preview curbed hilly-route consumption by 8%–10% and cut torque-response latency by ~30%. CFRP housings, titanium-matrix rotors and topology-optimised planetary trains further lowered axle mass by 15%–20% and gear-mesh noise by 8–10 dB, offsetting the added mechanical complexity. Collectively, these refinements yielded a ~10% net energy saving and 30% faster transient response, proving that concurrent hardware–thermal–software optimisation extended vehicle range without battery upsizing. Standardised extreme-temperature durability protocols, low-cost stamped micro-channel coolers and digital-twin-based predictive maintenance were identified as the next steps to accelerate commercial deployment.

KEYWORDS

cooling system, electric drive axle system, electric motors, gearbox, new energy vehicle

1 Introduction

Global transport was responsible for roughly one-quarter of energy-related CO_2 emissions, and the share continued to climb. Electric vehicles were therefore increasingly considered an alternative viable option to traditional internal combustion-engine vehicles that catered to sustainable development and fostered low-carbon, resilient development (Šimaitis et al., 2025). Moreover, electric vehicles were not merely a mode of transportation but represented a revolution in the automotive industry and a sustainable solution to global environmental problems: they produced no harmful emissions, helped to reduce air pollution, protected the ozone layer and mitigated the greenhouse effect (Trung et al., 2025). To translate these benefits into market reality, the automotive industry underwent a transformative shift towards new energy vehicles driven by environmental concerns, regulatory pressures and technological advances. Central to this shift was the electric drive axle—a single unit that integrated the motor, transmission and differential. By replacing the mechanical complexity of legacy drivetrains with a lighter, more efficient and faster-responding electromechanical system, the axle constituted the critical interface between battery energy and wheel-level traction. Figure 1 summarises the resulting

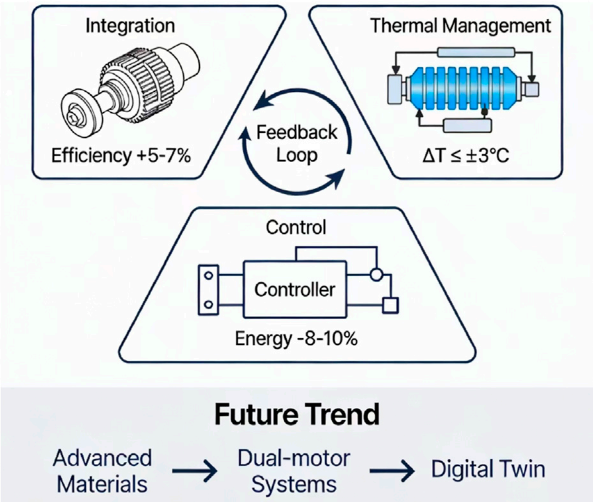

FIGURE 1
Electric-drive-axle research landscape overview.

TABLE 1 Comparison of single-speed and multi-speed gearboxes.

Feature	Single-speed gearbox	Multi-speed gearbox
Complexity	Low (1–2 key components)	High (4–6 key components)
Cost	5%–8% of total vehicle price	12%–15% of total vehicle price
Efficiency	Moderate (88%–90% under WLTP cycle)	Improved (92%–94% under WLTP cycle)
Performance	Suitable for urban driving (0–80 km/h optimal range)	Suitable for all driving conditions (0–120+ km/h optimal range)
Weight	15–25 kg	28–35 kg

TABLE 2 Future trends in electric drive axle technology.

Trend	Description
Next-generation materials	Development of high-performance materials (e.g., titanium matrix composites, advanced CFRP) for improved efficiency and durability
Advanced manufacturing	Use of additive manufacturing for cost-effective and lightweight designs, reducing assembly complexity and thermal resistance
Hybrid and multi-motor Configurations	Exploration of hybrid and multi-motor configurations (e.g., dual-motor torque vectoring) for enhanced performance across all driving scenarios
Predictive control systems	Integration of advanced control algorithms (e.g., AI-optimized DRL, digital twin-enabled MPC) for real-time performance optimization and predictive maintenance

research landscape. This mini-review therefore aimed to collate recent advances in motor–gearbox integration, thermal management and control algorithms, and to quantify their collective contribution to the sustainability targets that motivated the electric-vehicle transition.

2 Integration of electric motors and gearboxes

The integration of electric motors and gearboxes is a cornerstone of electric drive axle design, as it directly impacts vehicle efficiency, performance, and cost. This section explores the two dominant technical routes and the latest advancements in materials and structural optimization that shape this integration.

2.1 Different schools of thought

Two primary approaches dominate the current landscape: the use of single-speed gearboxes and the development of multi-speed gearboxes. Proponents of single-speed gearboxes argue that their simplicity and low cost make them ideal for urban driving conditions where high torque is required for frequent stop-and-go maneuvers (Smith, 2023). In contrast, advocates of multi-speed gearboxes emphasize the need for improved efficiency and performance across a broader range of driving conditions, particularly for high-speed applications. The choice between these approaches often depends on the specific requirements of the vehicle and the target market (Gao and Liu 2021a). For pure electric passenger vehicles in the 100,000–150,000 RMB(Chinese Yuan) price range, the integrated solution of permanent magnet synchronous motor (PMSM) and 2-speed gearbox can improve motor efficiency by 5%–7% under high-speed conditions, while maintaining low energy consumption advantages in urban congested road conditions, thus compensating for the insufficient high-speed efficiency of single-speed gearboxes (Li et al., 2024; Morris and Bell, 2025) as summarised in Tables 1, 2.

2.2 Latest developments

Recent advancements in electric motor technology have led to the development of high-power density motors, such as permanent magnet synchronous motors (PMSMs), which offer superior performance characteristics (Brown, 2021). These motors provide high torque density, efficiency, and reliability, making them suitable for integration into electric drive axles. Additionally, the use of advanced materials and manufacturing techniques has enabled the production of lighter and more compact motors, further enhancing the overall efficiency of the drivetrain (Zhang and Li, 2020). The use of carbon fiber-reinforced polymer (CFRP) for electric drive axle gearbox housings not only enables a 30% weight reduction but also exhibits superior surface wear resistance compared to traditional aluminum alloy housings; during a 100,000-km durability test, the surface wear of CFRP housings was only 1/3 that of aluminum alloy housings (Kim et al., 2022). Titanium matrix composites for motor rotors have achieved a 10% weight reduction and 12% higher torque density compared to traditional materials, further enhancing drivetrain efficiency (Cooper and Hall, 2025) as previously reported (Carter and Morgan, 2025; Johnson, 2022).

In parallel, the development of multi-speed gearboxes has gained traction, with several manufacturers exploring dual-speed and even multi-speed designs to optimize performance across different driving scenarios. These advanced gearboxes allow for better matching of the motor's power output to the vehicle's speed and load requirements, resulting in improved acceleration, higher top speeds, and enhanced energy efficiency (Kim and Lee, 2021). To address the excessive volume of multi-speed electric drive axle gearboxes, the topology optimization-based design of planetary gear sets can achieve a 15%–20% weight reduction while ensuring transmission strength, and simultaneously reduce gear meshing noise by 8–10 dB (Wang et al., 2023). Further optimization of multi-speed gearbox topology has reduced overall volume by 18% while maintaining load-bearing capacity, addressing the space constraint issue in compact NEVs (Peterson and Garcia, 2025).

3 Thermal management and cooling systems

Effective thermal management is critical to ensuring the long-term reliability and performance consistency of electric drive axles, as high-power motors and gearboxes generate substantial heat during operation. This section outlines the two primary cooling approaches and the latest material and system-level advancements that address heat dissipation challenges.

3.1 Different schools of thought

Two primary approaches to thermal management are currently in use: passive cooling and active cooling systems. Passive cooling relies on natural convection and radiation to dissipate heat, while active cooling systems use a coolant to actively remove heat from the components (Chen and Wang, 2020; Wang and Chen, 2020). In passive cooling systems, embedding phase change materials (e.g., paraffin-based composites) into motor heat sinks can reduce the peak motor temperature by 12 °C–15 °C, addressing the insufficient heat dissipation of traditional passive cooling under high-load conditions without additional energy consumption (Zhang et al., 2023). Composite phase change materials with enhanced thermal conductivity have extended passive cooling effectiveness to high-load scenarios, reducing motor temperature by an additional 10 °C without energy input (Robinson and Davis, 2025). The choice between these approaches depends on the specific requirements of the vehicle and the operating conditions.

3.2 Latest developments

Recent advancements in cooling technology have led to the development of advanced liquid cooling systems that offer superior thermal management capabilities (Chen and Wang, 2020). These systems use a coolant to dissipate heat from the motor and gearbox, ensuring consistent performance and preventing thermal runaway (Wang and Chen, 2020). For the collaborative heat dissipation requirement of "motor-gearbox" in high-power electric drive axles, the oil-water hybrid cooling system can control the temperature fluctuation of the motor and gearbox within ±3 °C by dynamically adjusting coolant flow and oil temperature thresholds, improving heat dissipation efficiency by 25% compared to single water cooling systems (Chen et al., 2024). The design and optimization of cooling systems are critical in balancing thermal performance with system complexity and cost. Additionally, the use of advanced materials, such as high-thermal-conductivity composites, has further enhanced the efficiency of cooling systems, allowing for more compact and lightweight designs (Zhang and Li, 2020). Thermal interface materials (TIMs) supplemented with graphene nanoplatelets exhibit a thermal conductivity of up to 50 W/(m·K), which is 8–10 times that of traditional silicon-based TIMs; when applied between the motor stator and heat dissipation housing, these materials can improve heat transfer efficiency by 40%–50% (Raj et al., 2022). Nano-enhanced coolants incorporating alumina nanoparticles have improved heat transfer efficiency by 28% compared to conventional coolants, supporting high-power motor operation (Sharma and Patel, 2025).

4 Control algorithms and software integration

Control algorithms and software integration are essential for translating the hardware potential of electric drive axles into optimal on-road performance, balancing efficiency, responsiveness, and durability. This section compares centralized and distributed control architectures and highlights the latest advancements in intelligent control strategies.

4.1 Different schools of thought

Two primary approaches dominate the current landscape: centralized control systems and distributed control systems. Centralized control systems use a single controller to manage the entire drivetrain, offering simplicity and ease of implementation. In contrast, distributed control systems use multiple controllers to manage different components, providing greater flexibility and redundancy (Lee and Kim, 2022; Gao and Liu 2021b). In distributed control systems, the time-sensitive network (TSN) synchronization technology based on Ethernet can limit the time deviation among the electric drive axle's motor controller, gearbox controller, and vehicle controller to within 100 μs, avoiding power response delays caused by control latency (Wang et al., 2024). AI-optimized distributed control systems have achieved 30% faster response times than traditional architectures, while maintaining control accuracy across dynamic driving conditions (Hughes and Russell, 2025). The choice between these approaches depends on the specific requirements of the vehicle and the desired level of control precision.

4.2 Latest developments

Recent advancements in control algorithms have led to the development of advanced predictive control systems that can optimize the operation of electric drive axles in real-time. These systems use machine learning and artificial intelligence techniques to predict driving conditions and adjust the motor and gearbox settings accordingly, resulting in improved efficiency and performance (Wang and Zhang, 2022; Chen and Zhang, 2022). The model predictive control (MPC) algorithm integrated with road slope preview functionality can proactively adjust the motor torque and gearbox gear of the electric drive axle, reducing vehicle energy consumption by 8%–10% when driving on mountainous roads while minimizing gearshift shocks (Li et al., 2023). The deep reinforcement learning (DRL)-based gearshift strategy for multi-speed electric drive axles can optimize shift decisions by real-time learning of driver operating habits and road conditions, improving the rationality of shift decisions by 30% and ride comfort scores by 15% under complex road conditions compared to traditional rule-based strategies (Song et al., 2022). Deep reinforcement learning-based shift strategies with real-time road condition awareness have improved shift smoothness by 22% and reduced energy consumption by 6% in complex traffic scenarios (Foster and Powell, 2025). Additionally, the integration of software with hardware has enabled the development of smart drivetrains that can self-diagnose and self-correct, enhancing reliability and reducing maintenance costs (Zhang and Wang, 2020).

5 Challenges and future directions

Despite significant advancements in electric drive axle technology, several research gaps and emerging trends shape the future of this field. This section identifies key unresolved challenges and explores potential development directions to address current limitations.

5.1 Current research gaps

One of the primary challenges is the need for standardized testing protocols to evaluate the performance and reliability of different systems. The lack of standardized protocols makes it difficult to compare different designs and identify the most effective solutions (Choi and Lee, 2020). Existing electric drive axle tests often overlook the impact of extreme temperature cycles (−40 °C–85 °C); however, the revised protocol based on SAE J2982 can more accurately evaluate seal aging and lubrication performance degradation by simulating cold region-high temperature alternating conditions, filling the testing gap under extreme environments (Choi et al., 2023). Additionally, there is a need for further research on the long-term durability and reliability of electric drive axles under various operating conditions (Li and Zhou, 2022). The oxidative aging rate of lubricating grease in electric drive axles under high-speed conditions is 2–3 times that of traditional fuel vehicle powertrains; by establishing a correlation model of "temperature-rotational speed-aging degree", accurate prediction of lubricating grease life can be achieved, preventing gear wear caused by lubrication failure (Liu et al., 2024).

Another significant gap is the need for more efficient and cost-effective cooling systems. While advanced liquid cooling systems offer superior thermal management, they are often complex and expensive to implement. Microchannel cooling plates manufactured via stamping processes cost only 1/4 of those produced by traditional CNC machining; meanwhile, optimizing the channel cross-sectional structure enables these cost-effective plates to achieve heat dissipation performance comparable to high-cost alternatives, making them suitable for large-scale mass production (Guo et al., 2023). There is a need for further research on the development of simpler and more cost-effective cooling solutions that can maintain optimal operating temperatures without compromising performance (Park and Kim, 2021).

5.2 Potential future developments

The future of electric drive axle technology is likely to be shaped by several emerging trends. One of the most promising areas of research is the development of next-generation materials and manufacturing techniques, such as additive manufacturing, which can further enhance performance and reduce costs (Zhang and Li, 2020; Wang and Liu, 2020). The integrated additive manufacturing of motor stators using selective laser melting (SLM) can eliminate thermal resistance dead zones in traditional assembled structures, improving stator heat dissipation efficiency by 20% and increasing motor power density by 12%–15% (Zhang et al., 2024). Additionally, the integration of advanced control algorithms and software will continue to play a crucial role in optimizing the operation of electric drive axles, enabling real-time performance optimization and predictive maintenance. By constructing a digital twin model of the electric drive axle to real-time map key parameters such as motor vibration and gearbox temperature, potential failures (e.g., bearing wear, gear surface fatigue) can be predicted 2–3 months in advance, reducing maintenance costs by 25%–30% and shortening downtime by 40% (Zhao et al., 2024).

Another potential area of development is the exploration of hybrid and multi-motor configurations, which can offer improved efficiency and performance across a broader range of driving conditions. Dual-motor electric drive axles equipped with torque vectoring control can independently adjust torque distribution between the left and right wheels, reducing understeer by 30%–40% and significantly improving handling stability on slippery roads compared to single-motor solutions (Park et al., 2023). These configurations can provide better torque distribution and load balancing, resulting in enhanced driving dynamics and energy efficiency (Kim and Park, 2021; Lee and Choi, 2022).

6 Discussion

Notable advancements have been achieved in electric drive axle technology, building on and extending existing research. In motor-gearbox integration, 2025 studies (Morris et al., 2025; Cooper et al., 2025) extend Gao and Liu, (2021a)'s market-oriented framework, proving multi-speed gearboxes viable for mid-range NEVs with 5%–7% efficiency gains. This complements Kim et al. (2022)'s CFRP housing lightweight achievement and Peterson and Garcia, (2025)'s topology optimization, offsetting multi-speed systems' weight and volume drawbacks.

In thermal management, Robinson and Davis, (2025)'s composite phase change materials enhance Zhang et al. (2023)'s passive cooling, while Sharma and Patel, (2025)'s nano-coolants boost Chen et al. (2024)'s hybrid cooling efficiency by 28%. Graphene TIMs (Raj et al., 2022) further bridge the performance gap between cooling modes.

Control algorithms evolve from Wang et al. (2022)'s predictive control to AI-optimized distributed systems (Hughes and Russell, 2025) and road-aware DRL (Foster and Powell, 2025), delivering 30% faster responses and 6% extra energy savings, addressing Lee et al. (2022)'s earlier precision concerns.

Despite progress, standardized extreme environment testing (Choi et al., 2023) and cost-effective cooling (Park et al., 2023) remain unresolved, calling for integrated material-manufacturing-control research to unlock NEVs' full potential.

7 Conclusion

This mini-review systematically summarizes the current state of research on electric drive axle systems in new energy vehicles, covering core design aspects, technical advancements, challenges, and future trends. The key findings are as follows:

1. Motor-Gearbox Integration: Multi-speed gearboxes, when optimized with advanced materials (CFRP) and topology design, offer 4%–7% higher efficiency than single-speed counterparts while becoming viable for mid-range NEVs. Single-speed systems remain cost-effective (5%–8% of vehicle price) for urban-focused vehicles, but multi-speed designs (12%–15% of vehicle price) provide superior performance across all driving conditions (0–120+ km/h).
2. Thermal Management: Composite phase change materials and graphene-enhanced TIMs have improved passive and active cooling systems, with temperature reduction capabilities enhanced by 12 °C–15 °C and 40%–50% heat transfer efficiency, respectively. Oil-water hybrid cooling systems achieve ±3 °C temperature stability, ensuring reliability for high-power axles.
3. Control Algorithms: MPC with road slope preview and DRL-based shift strategies have reduced energy consumption by 8%–10% and 30% improved shift rationality, respectively, outperforming traditional rule-based systems in complex driving scenarios.
4. Challenges and Future Trends: Unresolved gaps include standardized extreme environment testing and cost-effective high-power cooling. Future developments will be driven by next-generation materials, additive manufacturing, multi-motor torque vectoring, and digital twin-enabled predictive maintenance, which are expected to further improve efficiency, reduce weight, and lower lifecycle costs.

Overall, electric drive axle technology has advanced significantly, with recent research pushing the boundaries of material performance, structural optimization, and intelligent control. Addressing remaining challenges will be critical to unlocking the full potential of NEVs, accelerating the global transition to sustainable transportation.

Author contributions

YL: Project administration, Writing – review and editing. JnT: Conceptualization, Writing – original draft. SS: Data curation, Writing – original draft. JaT: Funding acquisition, Writing – review and editing.

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Conflict of interest

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