

# Transforming Wheels: AI Revolution across the Automotive Value Chain

Mayank Rai

General Motors LLC, USA



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## ABSTRACT

This article examines the transformative impact of artificial intelligence across the entire automotive value chain, from vehicle conceptualization and design through manufacturing, user experience, and business operations. The article analyzes how AI technologies revolutionize traditional automotive engineering paradigms through generative design algorithms, digital twins, and materials science applications. The article explores autonomous vehicle systems, detailing advances in perception, decision-making frameworks, validation methodologies, and computing architectures that enable increasingly sophisticated autonomous capabilities. Additionally, it investigates how AI enhances the in-vehicle experience through natural language processing, driver monitoring, predictive maintenance, and emotion recognition systems. The business operations section examines AI applications in customer segmentation, virtual showrooms, inventory management, mobility services, and usage-based insurance models. Finally, the article addresses critical challenges, including data privacy, safety

certification, ethical considerations, cybersecurity risks, and workforce development needs. The article reveals how AI is not merely augmenting existing automotive systems but fundamentally redefining the industry's technological foundations, business models, and consumer relationships.

**Keywords:** Automotive Artificial Intelligence, Autonomous Vehicles, Digital Twins, Intelligent User Experience, Vehicle Design Optimization

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## Introduction

The automotive industry is experiencing a revolutionary transformation powered by artificial intelligence (AI) technologies. Initially implemented for basic driver assistance functions, AI now permeates virtually every aspect of the automotive value chain [1]. This evolution represents a fundamental shift from conventional mechanical engineering to software-centric innovation, where vehicles increasingly function as complex computational platforms.

Modern automotive AI applications span multiple domains, including advanced driver-assistance systems (ADAS), autonomous driving, manufacturing optimization, and enhanced user experiences. The integration of computer vision, deep learning, and sensor fusion technologies has enabled unprecedented capabilities in environmental perception and decision-making [2]. These systems process and analyze massive data volumes collected through cameras, LiDAR, radar, and ultrasonic sensors to construct comprehensive environmental models and execute appropriate vehicle responses.

The global automotive AI market is projected to grow at a CAGR of 39.8% through 2030, with autonomous driving technologies representing the largest investment segment [1]. This growth is driven by increasing consumer demand for safety features, regulatory pressures, and competitive differentiation strategies. The stakeholder landscape has diversified beyond traditional OEMs, including technology companies, semiconductor manufacturers, specialized

AI startups, and mobility service providers, creating complex collaborative ecosystems.

Regulatory frameworks continue to evolve alongside technological advancements, with significant regional variations in approach. Safety standards development presents unique challenges due to the probabilistic nature of AI systems, which contrasts with traditional deterministic certification paradigms. Key regulations include UNECE's Working Party on Automated/Autonomous and Connected Vehicles (GRVA) frameworks and ISO/PAS 21448 for Safety of the Intended Functionality [2].

The technical foundation of automotive AI systems typically implements multi-layered architectures that balance performance requirements with power constraints and reliability standards. Deep learning frameworks—particularly convolutional neural networks for perception and transformer architectures for temporal processing—form the computational core of these systems [1]. Increasingly, these are deployed on specialized hardware accelerators optimized for automotive environments, with redundancy-oriented designs ensuring robust performance under variable conditions.

## AI in Vehicle Design and Development

Artificial intelligence has fundamentally transformed vehicle design and development processes, enabling unprecedented efficiency, innovation, and optimization across the automotive value chain. Integrating AI-powered tools has revolutionized traditional approaches to vehicle engineering,

creating opportunities for enhanced performance, reduced development cycles, and improved sustainability [3].

Generative design algorithms represent a paradigm shift in automotive design methodology. They employ machine learning techniques to automatically explore thousands of design possibilities while optimizing for multiple objectives simultaneously. These systems generate innovative concepts that human designers might never consider while ensuring compliance with engineering constraints and manufacturing requirements. Computer vision algorithms further enhance this process by analyzing existing designs to identify patterns and optimization opportunities [4].

Digital twins and simulation environments have become central to modern vehicle development, creating virtual replicas that accurately mirror physical vehicle characteristics. These AI-enhanced environments enable comprehensive testing across thousands of scenarios without physical prototypes, significantly reducing development time and costs. Machine learning models continuously improve simulation accuracy by correlating virtual predictions with physical test results, creating increasingly reliable digital validation platforms [3].

Materials science applications leverage AI to discover and optimize novel materials with tailored properties. Algorithms analyze vast materials databases to predict performance characteristics without extensive physical testing, accelerating the development of lightweight, high-strength components. This capability has proven particularly valuable for

identifying non-intuitive material combinations that traditional experimentation might overlook [4].

Machine learning integration with CAD systems has streamlined engineering workflows through intelligent automation of repetitive tasks and design optimization. Feature recognition algorithms identify patterns across component libraries to suggest standardization opportunities, while natural language processing techniques can translate design requirements directly into preliminary models. These capabilities reduce design heterogeneity while ensuring the systematic application of best practices [3].

AI has become instrumental in optimizing battery systems and powertrain components for electric vehicles. Machine learning algorithms analyze battery performance data to identify optimal cell chemistry compositions, thermal management strategies, and pack configurations. Similar approaches optimize motor design, power electronics, and control strategies, yielding significant efficiency improvements directly translating to extended range or reduced battery requirements [4].

Manufacturing processes benefit from AI through adaptive control systems that continuously monitor and adjust production parameters to maintain optimal quality and efficiency. Computer vision systems perform automated quality inspections with greater accuracy than human inspectors, while reinforcement learning algorithms discover optimal scheduling and resource allocation strategies that maximize throughput while minimizing waste [3].

Application Area	AI Technologies Used	Key Benefits
Generative Design	Machine learning, Computer vision	Automatic exploration of thousands of design possibilities, Innovative concepts beyond human consideration, Compliance with engineering constraints
Digital Twins & Simulation	AI-enhanced virtual environments, Machine learning models	Comprehensive testing without physical prototypes; Reduced development time and costs; Continuously improving simulation accuracy
Materials Science	Predictive algorithms, Database analysis	Discovery of novel materials with tailored properties; Reduced physical testing; Identification of non-intuitive

Application Area	AI Technologies Used	Key Benefits
		material combinations
CAD Systems Integration	Feature recognition algorithms, Natural language processing	Streamlined engineering workflows; Automated repetitive tasks; Design standardization; Translation of requirements to models
EV Battery & Powertrain	Machine learning algorithms	Optimal cell chemistry compositions; Enhanced thermal management; Improved power electronics; Extended vehicle range
Manufacturing Processes	Adaptive control systems, Computer vision, Reinforcement learning	Continuous production parameter adjustment; Automated quality inspection; Optimal scheduling; Waste reduction

**Table 1:** AI Applications in Vehicle Design and Development [3, 4]

### Autonomous and Intelligent Vehicle Systems

Autonomous and intelligent vehicle systems represent a transformative technology integrating advanced perception, decision-making algorithms, and communication infrastructure. These systems use multi-modal sensing approaches to construct comprehensive environmental models under diverse operational conditions [5]. The perception stack typically combines cameras, LiDAR, and radar sensors through sophisticated fusion algorithms that leverage the complementary strengths of each modality while mitigating individual weaknesses. Recent advances in deep learning have substantially improved object detection, classification, and tracking capabilities, enabling robust operation across varying environmental conditions.

Decision-making frameworks for autonomous vehicles have evolved from rule-based systems to sophisticated neural network architectures that can handle complex driving scenarios. These architectures implement hierarchical approaches with distinct modules for perception, prediction, planning, and control [5]. The development of end-to-end models that learn driving policies directly from data has been particularly significant, reducing the need for explicit programming of driving rules. Integrating attention mechanisms has further enhanced these systems'

ability to focus on relevant environmental features while filtering irrelevant information.

Validation methodologies for autonomous systems have progressed beyond traditional testing approaches to incorporate simulation-based verification, formal methods, and scenario-based testing [6]. These methodologies systematically evaluate system performance across operational design domains, identifying potential failure modes before deployment. Safety certification frameworks increasingly focus on continuous monitoring and verification rather than one-time qualification, reflecting the dynamic nature of learning-based systems.

Edge computing has become essential for autonomous vehicles, enabling real-time sensor data processing with minimal latency. This approach is complemented by cloud infrastructure that supports computationally intensive tasks, including high-definition mapping and fleet learning [5]. The optimal processing distribution between edge and cloud represents an ongoing research challenge, balancing performance requirements with connectivity limitations and security considerations.

Advanced Driver Assistance Systems (ADAS) represent commercially deployed applications of vehicle intelligence, implementing functions ranging from adaptive cruise control to automated parking. These systems are both practical enhancements to

current vehicles and developmental platforms for future autonomous capabilities [6]. Human-machine interface design remains critical for these systems, ensuring appropriate driver engagement and preventing mode confusion.

Vehicle-to-everything (V2X) communication extends autonomous capability through information exchange with other vehicles, infrastructure, and networks. Infrastructure-Enabled Autonomy (IEA) represents a

promising paradigm that distributes intelligence between vehicles and roadside infrastructure, reducing onboard sensing and processing requirements [6]. This approach enables faster deployment of autonomous functions while leveraging existing infrastructure investments, though it requires significant coordination across stakeholders and standardization of communication protocols.

System Component	Key Technologies	Functionality
Perception Systems	Cameras, LiDAR, Radar, Sensor fusion algorithms, Deep learning	Environmental modeling: Object detection, classification, and tracking across diverse conditions
Decision-Making Frameworks	Neural networks, Hierarchical architectures, End-to-end models, Attention mechanisms	Complex scenario handling; Driving policy learning; Focus on relevant environmental features
Validation Methods	Simulation-based verification, Formal methods, Scenario-based testing	Systematic performance evaluation; Failure mode identification; Continuous monitoring
Computing Infrastructure	Edge computing, Cloud processing, Distributed architectures	Real-time sensor processing; High-definition mapping; Fleet learning; Balancing performance and connectivity
Advanced Driver Assistance	Adaptive cruise control, Automated parking, Human-machine interfaces	Current commercial applications; Building blocks for future autonomy; Driver engagement maintenance
V2X Communication	Vehicle-to-Vehicle, Vehicle-to-Infrastructure, Infrastructure-Enabled Autonomy (IEA)	Extended capabilities through information exchange and distributed intelligence; Reduced onboard requirements

**Table 2:** Components and Technologies of Autonomous Vehicle Systems [5, 6]

**AI-Enhanced User Experience and Vehicle Features**

Artificial intelligence has transformed the in-vehicle experience, creating more intuitive, personalized, and responsive interfaces that enhance safety and user satisfaction. These AI-powered systems span multiple domains, from natural language processing to predictive maintenance, collectively redefining how users interact with modern vehicles [7].

Natural language processing has enabled sophisticated in-vehicle assistants that understand complex, contextual commands without requiring users to learn specific phrases or command structures. These

systems can simultaneously process requests across multiple domains, controlling navigation, climate, and entertainment functions through conversational interfaces that minimize driver distraction. Understanding natural speech patterns, including various accents and dialects, represents a significant advancement over previous generation systems that relied on rigid command structures [8].

Driver monitoring systems employ computer vision and machine learning to assess attention levels, fatigue, and emotional states in real time. These systems analyze facial expressions, eye movements,

and other physiological indicators to detect potential safety issues before they become critical. The data collected also enables unprecedented personalization capabilities, with vehicles automatically adjusting settings based on identified driver preferences and current state. Research shows these adaptive interfaces can significantly reduce cognitive load during driving tasks [8].

Predictive maintenance represents another significant AI application, with algorithms analyzing sensor data to detect anomalies and forecast potential component failures before they affect vehicle operation. Unlike traditional schedule-based maintenance, these systems enable condition-based servicing that optimizes component lifetime while reducing unexpected failures. The economic benefits include direct maintenance cost reduction and decreased vehicle downtime [7].

Over-the-air update capabilities have evolved from basic infotainment updates to comprehensive platforms that modify core vehicle systems. These updates enable continuous feature enhancements and performance improvements throughout the vehicle

lifecycle, allowing vehicles to improve with age rather than becoming technologically obsolete. These systems' security and validation requirements are exceptionally stringent, with multiple safeguards to ensure update integrity [7].

Emotion recognition systems assess occupant emotional states through facial expression analysis and voice tonality, enabling vehicles to respond appropriately to user needs. These insights power adaptive interfaces that dynamically modify information presentation based on driving conditions, emotional state, and user preferences. Studies indicate that emotionally responsive interfaces can reduce driver stress and improve overall satisfaction [8].

Entertainment and productivity features have similarly evolved, with AI-powered systems delivering personalized content recommendations based on user preferences and driving context. These systems increasingly integrate with external ecosystems, creating seamless transitions between home, mobile, and vehicle environments. Context-aware scheduling ensures these features enhance rather than distract from the driving experience [7].

Experience Domain	Traditional Approach	AI-Enhanced Approach	User Impact
Vehicle Control	Command memorization and structured inputs	Natural language processing with contextual understanding	Simplified interaction; Reduced learning curve; Lowered distraction
Driver Safety	Reactive warning systems	Proactive monitoring of attention, fatigue, and emotional states	Early intervention, Personalized settings, Improved safety outcomes
Vehicle Maintenance	Schedule-based service intervals	Predictive algorithms detecting potential failures before occurrence	Optimized component lifetime; Reduced unexpected failures; Lower costs
Feature Evolution	Static functionality after purchase	Over-the-air update platforms for continuous improvement	Extended vehicle relevance; Ongoing enhancements; Improved satisfaction
Occupant Comfort	Manual adjustment of settings	Emotion-responsive systems adapting to user states	Reduced stress; Improved satisfaction; Personalized environment

Experience Domain	Traditional Approach	AI-Enhanced Approach	User Impact
Media & Information	Basic content selection	Personalized recommendations based on preferences and context	Relevant content delivery; Seamless ecosystem integration; Enhanced journey

Table 3: Evolution of In-Vehicle Experience Through AI [7, 8]

**AI in Automotive Business Operations**

Artificial intelligence has fundamentally transformed automotive business operations, creating new opportunities for enhanced customer experiences, operational efficiencies, and innovative business models. These applications extend far beyond the vehicle, reshaping the entire automotive value chain from marketing to after-sales services [9].

Customer segmentation has evolved dramatically with AI algorithms analyzing vast datasets to identify micro-segments with unprecedented precision. These systems enable hyper-personalized marketing strategies that target consumers based on specific preferences, behaviors, and purchase indicators. According to recent industry reports, dealerships implementing AI-powered customer targeting have seen conversion rate increases of up to 30% and significant improvements in customer satisfaction metrics [9]. This targeted approach allows automotive retailers to optimize marketing spend while delivering more relevant communications to potential customers. Virtual showrooms and AR/VR experiences represent another significant application area, transforming how consumers interact with vehicles before purchase. These technologies create immersive digital experiences that enable comprehensive product exploration without physical presence, addressing pandemic-related restrictions while expanding market reach beyond traditional geographic limitations. Implementing these digital tools has reduced the average vehicle purchase journey from 5-6 dealership visits to just 1-2 physical interactions, with consumers conducting most research and configuration activities online [10].

Predictive analytics has revolutionized inventory and supply chain management through demand forecasting algorithms that optimize stock levels across dealer networks. These systems analyze historical sales data alongside market indicators to predict demand patterns more accurately than traditional methods. Automotive manufacturers implementing these technologies have reported inventory-carrying cost reductions of 15-20% while improving product availability [10].

Mobility-as-a-Service (MaaS) platforms represent an emerging business model enabled by AI algorithms that optimize multimodal transportation networks. These platforms integrate various mobility options to provide flexible transportation solutions that may eventually reduce private vehicle ownership in urban areas. The algorithmic intelligence behind these systems continuously optimizes resource allocation based on current demand patterns and user preferences [9].

Fleet management systems leverage AI to maximize operational efficiency through route optimization, predictive maintenance, and driver behavior analysis. These technologies enable commercial fleet operators to reduce fuel consumption by 8-12% while extending vehicle lifespans through proactive maintenance scheduling [10].

Usage-based insurance models employ telematics data and AI analysis to create personalized risk profiles based on driving behaviors. This approach enables premium structures that reflect individual risk levels more accurately while encouraging safer driving practices. The data from connected vehicles also creates additional monetization opportunities across

urban planning, retail analytics, and location-based services [9].

Business Application	AI Technologies Used	Measurable Benefits
Customer Segmentation	Data analytics algorithms, Behavior analysis	30% increase in conversion rates; Improved customer satisfaction; Optimized marketing spend
Virtual Showrooms & AR/VR	Immersive 3D rendering, Digital experience platforms	Reduction from 5-6 dealership visits to 1-2 physical interactions; Expanded market reach; Pandemic-resilient sales process
Inventory & Supply Chain	Demand forecasting algorithms, Predictive analytics	15-20% reduction in inventory carrying costs; Improved product availability; More accurate demand prediction
Mobility-as-a-Service	Multimodal optimization algorithms, Resource allocation systems	Flexible transportation solutions; Optimized resource usage; Potential reduction in private vehicle ownership
Fleet Management	Route optimization, Predictive maintenance, Behavior analysis	8-12% reduction in fuel consumption; Extended vehicle lifespans; Operational efficiency improvements
Usage-Based Insurance	Telematics data analysis, Risk profiling algorithms	Personalized premium structures; Safer driving incentives; Additional data monetization opportunities

**Table 4:** AI Applications in Automotive Business Operations [9, 10]

### Challenges and Future Directions

As artificial intelligence transforms the automotive industry, several critical challenges must be addressed to realize its full potential. These challenges span technical, ethical, and organizational domains and require coordinated efforts across industry, academia, and regulatory bodies [11].

Data management presents significant challenges as modern connected vehicles generate massive volumes of heterogeneous data. This data requires sophisticated processing pipelines to ensure quality and reliability, particularly for safety-critical applications. Privacy concerns are equally significant, as vehicle data can reveal sensitive personal information, including location patterns, driving behaviors, and lifestyle choices. Regulatory frameworks, including GDPR impose strict requirements on data handling, necessitating privacy-

by-design approaches that balance analytical capabilities with user protection [12].

Safety certification for AI-powered automotive systems requires new methodologies that address the probabilistic nature of machine learning models. Traditional automotive validation approaches based on deterministic testing are insufficient for neural networks that may exhibit unexpected behaviors in edge cases. The development of specialized frameworks, including SOTIF (Safety Of The Intended Functionality) represents progress, though significant gaps remain, particularly for systems employing continuous learning capabilities [11].

Ethical considerations extend beyond technical safety to fundamental questions about algorithmic decision-making. Autonomous vehicles must navigate complex scenarios where harm may be unavoidable, raising questions about how these systems should prioritize different stakeholders' interests. A cyclic framework



for ethical AI integration suggests iterative assessment throughout the development lifecycle, continuously evaluating alignment with human values and societal expectations [12].

Cybersecurity risks have intensified as vehicles become more connected and software-dependent. Modern vehicles contain numerous electronic control units and communication interfaces, creating multiple potential attack vectors. Defense-in-depth approaches implementing multiple security layers throughout the vehicle architecture have emerged as best practices, including secure boot processes, intrusion detection systems, and hardware security modules to protect critical components [11].

The automotive industry faces a substantial technical skills gap as vehicle development increasingly requires artificial intelligence, software engineering, and data science expertise. This challenge necessitates transformed educational programs, reskilled workforces, and organizational structures that support interdisciplinary collaboration across traditionally separate domains [12].

Emerging technologies, including quantum computing and neuromorphic systems, present promising capabilities for automotive applications, potentially enabling breakthrough performance in optimization problems and perceptual tasks. Integrating smart city infrastructure represents another frontier, with cooperative perception systems and traffic management algorithms optimizing mobility beyond individual vehicle capabilities [11].

Sustainable mobility remains a critical goal, with AI increasingly optimizing transportation networks for environmental performance alongside traditional metrics like travel time and cost. These systems enable more efficient resource utilization across multiple transportation modes, potentially redefining the automotive industry's boundaries toward comprehensive mobility service provision [12].

## Conclusion

Integrating artificial intelligence across the automotive value chain represents a paradigm shift beyond incremental technological improvement. This transformation redefines vehicles from mechanical transportation devices to intelligent, connected platforms that continuously evolve throughout their lifecycle. As demonstrated throughout this research, AI applications in vehicle design have compressed development cycles while expanding the exploration of innovative solutions through generative algorithms and digital twins. The progression from rule-based approaches to sophisticated neural networks has enabled unprecedented environmental perception and decision-making capabilities in autonomous systems. The in-vehicle experience has similarly evolved through intelligent interfaces that adapt to user states and preferences, creating personalized environments that enhance both safety and satisfaction. Business operations have been revolutionized through AI-powered customer targeting, virtual experiences, and predictive analytics that optimize resources while creating new business models. Despite significant progress, substantial challenges remain in data privacy, safety certification, ethical frameworks, cybersecurity, and workforce development that must be addressed through collaborative efforts across industry, academia, and regulatory bodies. The future trajectory suggests continued convergence between automotive and computing technologies, with emerging paradigms like quantum computing and integration with smart city infrastructure potentially enabling new mobility concepts that prioritize sustainability alongside traditional performance metrics.

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