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Electrical and Communication Architectures for Safe Integration of Autonomous and Electric Vehicles: A Review of Emerging Technologies

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Abstract

The transition toward autonomous and electric mobility is reshaping transportation into an integrated cyber-physical ecosystem in which vehicle electrical systems, communication networks, charging infrastructure, and intelligent control platforms must operate with high reliability and safety. This review examines the architectural requirements supporting this transformation, with emphasis on high-voltage power distribution, zonal electronic control, functional safety, fault tolerance, vehicle connectivity, charging systems, grid interaction, and emerging digital technologies. A structured narrative review approach was adopted to synthesise relevant engineering, transportation, communication, and power-system literature published up to 2024.

The findings indicate that safe autonomous-electric mobility depends on the convergence of efficient power-electronic architectures, centralised and zonal computing, deterministic in-vehicle communication, resilient V2X connectivity, and coordinated charging infrastructure. High-voltage systems require robust isolation, protection, thermal management, and bidirectional energy control, while electronic architectures increasingly favour software-defined platforms capable of supporting complex sensing and decision functions. Functional safety further requires redundancy, fault containment, graceful degradation, and validated fallback strategies. At infrastructure level, smart charging, vehicle-to-grid coordination, mobile-network coverage, grid capacity, and environmental resilience materially influence deployment performance. Digital twins, artificial

intelligence, edge computing, and advanced cybersecurity are emerging as key enablers of predictive operation and system-wide optimisation.

The review concludes that technological progress alone is insufficient without interoperability, infrastructure readiness, governance, and workforce capability. It recommends stronger cross-domain standards, field validation under diverse operating conditions, secure V2X architectures, resilient charging networks, explainable artificial intelligence, and coordinated investment in communication and electrical infrastructure. These priorities are essential for achieving mobility systems that are not only technologically advanced, but also safe, resilient, scalable, and operationally sustainable.

Keywords: autonomous vehicles; electric vehicles; zonal architecture; V2X communication; functional safety; smart charging

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1. Introduction

1.1 Electrification and Autonomous Mobility Transformation

Electrification and autonomous mobility are reshaping road transport from a mechanically dominated system into a digitally coordinated energy-and-information ecosystem. Battery-electric propulsion, advanced driver-assistance systems, automated driving functions, high-performance computing and ubiquitous connectivity increasingly coexist within the same vehicle platform. This transformation is driven by decarbonisation objectives, energy-security concerns and the pursuit of safer, more efficient mobility. Nigerian research on renewable-energy integration illustrates the broader technical shift toward electricity-dependent systems, where distributed generation and power-electronic interfaces become central to reliable energy use (Sunday & Omoegun, 2018).

At the transport-system level, electrification changes the relationship between vehicles and electricity networks. Electric vehicles are no longer only transportation assets; through charging infrastructure, smart charging and bidirectional power exchange, they become controllable electrical loads and potentially distributed storage resources. Reviews of international EV standards show that large-scale adoption therefore requires coordinated development of charging interfaces, grid interconnection rules, communication protocols and energy-management strategies capable of maintaining interoperability across manufacturers and infrastructure providers (Das et

al., 2020). This connection becomes more significant as alternative energy carriers are incorporated into national grids, expanding the technological pathways through which low-carbon transport may interact with electricity generation and distribution systems (Adeniji et al., 2019).

Automation introduces a parallel transformation. Autonomous vehicles depend on dense networks of cameras, radar, lidar, positioning systems, electronic control units and computational platforms that must exchange large volumes of data within strict timing constraints. Contemporary electrical/electronic architectures are consequently moving away from numerous isolated control units toward domain-based and zonal architectures that consolidate computation, simplify wiring and provide higher-bandwidth networking for automated-driving workloads (Wang et al., 2024). Electrification and automation are therefore converging architecturally: traction batteries provide energy for increasingly sophisticated electronic systems, while communication networks coordinate sensing, propulsion, braking, steering and external connectivity.

The mobility implications extend beyond individual vehicles. Nigerian evidence on essential travel and mode substitution demonstrates that transport demand can change rapidly in response to external conditions, emphasizing the importance of flexible mobility systems capable of adapting service provision and infrastructure use to changing patterns of movement (Ajayi, Alaka & Tiamiyu, 2020). Across Johannesburg, Kigali, Lagos and Nairobi, electrified, automated and shared mobility has similarly been identified as a potentially important pathway for lower-carbon urban transport, although infrastructure limitations, affordability, governance and uneven technological capacity influence the pace and form of transition (Sovacool, Daniels & AbdulRafiu, 2022).

Electrification also strengthens the interdependence between transportation and smart grids. Systematic evidence indicates that unmanaged charging can create transformer loading, voltage and peak-demand challenges, whereas coordinated charging and vehicle-to-grid operation can provide flexibility, storage and ancillary services when appropriately controlled (Sultan et al., 2022). The transformation is therefore not adequately understood as a simple replacement of internal-combustion vehicles with battery-powered alternatives.

1.2 Safety Requirements for Connected Vehicle Systems

Safety in connected and increasingly autonomous vehicles must be engineered across electrical, electronic, communication, and control domains because unsafe behaviour can emerge from component failure, corrupted information, inadequate perception, or interactions among otherwise functional subsystems. Conventional functional-safety principles address hardware and software faults, but autonomous operation introduces additional hazards when sensors or decision algorithms perform inadequately under complex environmental conditions. Safety of the Intended

Functionality therefore requires systematic identification of perception limitations, triggering scenarios, operational boundaries and foreseeable misuse alongside conventional fault-oriented assurance (Wang et al., 2024).

Electrical integrity remains fundamental, particularly where electric vehicles combine high-voltage traction systems with sensitive low-voltage electronics. Effective grounding and fault-current management provide essential protection against abnormal electrical conditions and demonstrate the wider engineering importance of controlled fault paths, voltage limitation and dependable protective operation (Shittu et al., 2020). These principles become increasingly significant at vehicle–charger and vehicle–grid interfaces, where electrical failures may affect both onboard systems and external infrastructure.

Connected vehicles also require continuous health awareness. Sensor-based fault detection demonstrates how measured operating parameters can expose deviations before they develop into significant system malfunction, supporting automated alerts and timely intervention (Sunday & Omoegun, 2022). Similarly, vibration monitoring of rotating machinery illustrates the value of continuous diagnostic surveillance for identifying mechanical deterioration in components whose failure could impair propulsion or auxiliary functions (Omoegun et al., 2023).

Safety requirements must additionally account for road users beyond the vehicle itself. Evidence from Ghana demonstrates persistent pedestrian vulnerability where driver compliance and road infrastructure are inadequate, reinforcing the need for automated vehicles to recognise vulnerable road users reliably and respond conservatively in complex traffic environments (Agyemang et al., 2021).

1.3 Convergence of Electrical and Communication Networks

The transition toward autonomous and electric mobility is increasingly characterised by convergence between electrical power networks and digital communication systems. Electric vehicles no longer operate as isolated electrical loads; their batteries, power converters, charging interfaces, electronic controllers and sensing systems exchange information continuously with charging stations, grid operators, roadside infrastructure, other vehicles and cloud-based services. This convergence creates a cyber-physical environment in which reliable movement of electrical energy increasingly depends upon equally reliable movement of operational data.

At the infrastructure level, supervisory architectures illustrate how electrical equipment can be monitored and controlled through integrated communications, sensing and automation. SCADA-based systems demonstrate the value of combining field measurements, communication channels and supervisory control within a common architecture capable of providing real-time operational awareness (Omoegun et al., 2024). Comparable principles underpin connected charging

infrastructure, where vehicle and network controllers must coordinate power demand, charging state and operational constraints.

Secure information exchange becomes critical because compromised data may influence physical energy flows or vehicle behaviour. Blockchain-supported architectures can enhance integrity and traceability across distributed power-system communications, providing a potential foundation for trusted interactions among vehicles, charging systems and electricity networks (Opara et al., 2022). Access-control mechanisms add another layer by restricting data and system functions according to authenticated privileges, an important requirement where multiple infrastructure operators, vehicles and service providers exchange sensitive operational information (Shittu & Nabil, 2023).

Vehicular connectivity introduces additional requirements for continuity and latency. South African research on vehicular ad hoc networks demonstrates that reliable handover between communication links is necessary to maintain information exchange as vehicles move rapidly through changing network environments (Oladosu et al., 2023). Such continuity becomes safety-critical when connectivity supports cooperative perception, traffic warnings or infrastructure-assisted automated driving.

The convergence also enlarges the cybersecurity boundary. V2X ecosystems connect vehicles with vehicles, infrastructure, pedestrians and external networks, creating vulnerabilities involving authentication, privacy, message integrity and malicious manipulation (Yoshizawa et al., 2023). Electrical and communication architectures must therefore be co-designed around interoperability, deterministic information exchange, cybersecurity and graceful degradation. For autonomous-electric vehicles, dependable energy transfer and trustworthy communications are becoming inseparable engineering requirements, making their architectural convergence fundamental to safe and scalable mobility.

1.4 Review Aim, Scope, and Approach

This review aims to critically examine the electrical and communication architectures that enable the safe, reliable, and scalable deployment of autonomous and electric vehicles within increasingly interconnected transportation and energy systems. Its principal objective is to evaluate how onboard electrical systems, electronic control platforms, communication networks, charging infrastructure, and cyber-physical interfaces interact to support dependable mobility while managing emerging technical and safety risks.

The scope encompasses high-voltage and low-voltage vehicle architectures, traction batteries, power-electronic converters, electronic control units, zonal and domain-based computing structures, in-vehicle communication networks, vehicle-to-everything connectivity, smart charging, vehicle-to-grid interaction, and supporting roadside and grid infrastructure. Particular

attention is directed toward functional safety, fault tolerance, communication reliability, cybersecurity, interoperability, energy coordination, and the growing convergence of electrical and digital subsystems within software-defined vehicles.

A structured narrative review approach is adopted to synthesise relevant engineering, transportation, power-system, and communication literature. The analysis compares established and emerging technologies, identifies architectural dependencies, evaluates implementation constraints, and examines how safety requirements influence system design. It also considers technological maturity, infrastructure readiness, regulatory compatibility, and future research priorities. Through this approach, the review provides an integrated perspective on the technical foundations required to support secure, resilient, energy-efficient, and interoperable autonomous-electric mobility across diverse operating environments.

2. Integrated Vehicle Electrical Architectures

2.1 High-Voltage Power Distribution Systems

High-voltage power distribution constitutes the electrical backbone of contemporary battery-electric and increasingly autonomous vehicle platforms. Unlike conventional vehicles, where a comparatively low-voltage network primarily supports auxiliaries, electric vehicles require coordinated distribution of substantial electrical power among the traction battery, inverter, propulsion motor, onboard charger, DC–DC converter, thermal-management system and auxiliary loads. The architecture must therefore achieve high efficiency while maintaining electrical isolation, controllability and protection under rapidly changing propulsion and charging conditions. Optimisation of electrical load distribution in hybrid energy systems demonstrates the wider importance of allocating power intelligently among interconnected loads so that excessive current, imbalance and avoidable conversion losses are limited (Sunday & Omoegun, 2019).

The traction battery typically establishes the principal high-voltage DC bus, from which power-electronic converters regulate energy flow according to component requirements. Inverters transform battery DC into controlled AC for propulsion motors, while DC–DC converters interface voltage domains and support bidirectional energy transfer during regenerative braking or vehicle-to-grid operation. Contemporary converter research demonstrates that topology selection directly affects efficiency, power density, thermal performance, voltage gain and reliability, making power electronics a defining element of EV electrical architecture rather than a peripheral subsystem (Islam, Rafin & Mohammed, 2023).

High-voltage distribution also creates significant protection requirements. Short circuits, insulation degradation, ground faults, overcurrents and switching disturbances must be detected

and isolated rapidly before they propagate across interconnected vehicle components. Cyber-physical protection approaches developed for distributed electrical systems demonstrate how adaptive sensing and intelligent protection can improve resilience as power networks become increasingly digital and bidirectional (Shittu et al., 2024). In vehicles, analogous principles require coordinated battery-management systems, contactors, fuses, isolation monitoring and electronic protection logic capable of transitioning the powertrain into a safe state when abnormal conditions arise.

Thermal behaviour is equally important because high current densities in batteries, converters, motors and cabling generate heat that affects efficiency, insulation life and component durability. Effective control of thermally intensive electrical systems demonstrates the relationship between temperature regulation and energy performance, reinforcing the requirement for coordinated cooling strategies within compact high-voltage vehicle platforms (Sunday et al., 2019).

High-voltage architecture increasingly extends beyond the vehicle boundary. Bidirectional charging enables traction batteries to exchange electrical energy with homes, buildings and distribution networks, transforming vehicles into mobile energy resources. Reviews of vehicle-to-grid architectures show that converter configuration, grid-connection standards and coordinated control determine whether such exchanges support grid flexibility without introducing voltage, protection or power-quality problems (Shuai, Maillé & Pelov, 2022). South African network analysis similarly demonstrates that increasing EV charging penetration can challenge residential feeder hosting capacity, making coordinated charging and network planning important where existing infrastructure has limited electrical headroom (Umoh, Adebiyi & Moloi, 2023).

Infrastructure-level efficiency further requires electrical design to be considered alongside transportation demand and charging location. Integrating energy efficiency with transportation-system planning can improve the alignment between mobility demand and available electrical infrastructure, particularly where charging loads become geographically concentrated (Opara et al., 2024). High-voltage distribution architecture must therefore be designed as part of a broader energy ecosystem rather than solely as an onboard powertrain problem.

Digitalisation is strengthening this system-level perspective. AI-enabled digital twins can maintain virtual representations of electrical assets and use operational data to assess performance, identify emerging degradation and optimise maintenance interventions (Shittu & Shittu, 2024). Applied to autonomous-electric vehicles, such techniques could support continuous evaluation of batteries, converters, cables and charging interfaces. High-voltage architectures must consequently combine efficient power conversion, selective protection, thermal control, bidirectional energy management and intelligent diagnostics so that growing electrical capability does not compromise safety, reliability or interoperability.

2.2 Electronic Control and Zonal Architectures

Electronic control architectures provide the computational framework through which sensors, actuators, powertrain components and safety functions interact within autonomous-electric vehicles. Traditional vehicles distribute functionality among numerous electronic control units, often interconnected through separate communication buses. Increasing sensor density, automated-driving workloads and software complexity, however, are accelerating migration toward domain-centralised and zonal designs. Programmable automation demonstrates the underlying engineering value of integrating measurement, logical processing and actuator control within coordinated digital environments capable of deterministic system supervision (Sunday & Omoegun, 2022).

Zonal architectures reorganise electronic resources according to their physical location within the vehicle. Local sensors and actuators connect to nearby zonal controllers, while computationally intensive functions migrate toward central high-performance computers. This arrangement can reduce wiring complexity, simplify hardware distribution and facilitate software-defined functionality. Contemporary E/E architecture development consequently places central computation, high-performance processing, standardised software platforms and over-the-air updating among the principal technologies enabling software-defined vehicles (Jiang, 2024).

Communication performance becomes decisive as control functions are consolidated. Service-oriented in-vehicle Ethernet provides the bandwidth required for high-volume exchanges among cameras, radar, controllers, and vehicle computers; however, data consistency and deterministic delivery must be preserved when several subscribers depend on the same safety-critical information (Li et al., 2024). Advanced gateway processors can consequently provide hardware-assisted traffic handling between heterogeneous networks while maintaining low latency and predictable quality of service across zonal interfaces (Gonzalez Mariño et al., 2024).

Control architecture must also support autonomous decision-making. Path-planning research in autonomous mobile systems demonstrates how computational platforms can integrate environmental information with optimisation algorithms to determine feasible movement trajectories, a principle applicable to vehicle-level planning and coordinated actuator commands (Akanbi & Sunday, 2024). Digital identification technologies likewise illustrate how electronically tagged information can be automatically acquired, interpreted and communicated across connected systems, reinforcing the broader importance of dependable machine-readable data exchange (Yusuf et al., 2023).

Architectural evolution must nevertheless reflect deployment context. Ghanaian evidence indicates that autonomous-vehicle adoption in African environments is influenced by infrastructure readiness, perceived safety, technological familiarity and institutional conditions,

meaning advanced electronic architectures cannot be considered independently of their operating ecosystem (Ackaah, Van Laar & Osei, 2022). Zonal design therefore requires balanced integration of centralised computing, local control, deterministic networking, cybersecurity and redundancy so that architectural simplification simultaneously enhances scalability, maintainability and safe autonomous operation.

2.3 Functional Safety and Fault-Tolerant Design

Functional safety is a fundamental design requirement for autonomous-electric vehicles because propulsion, steering, braking, perception and communication increasingly depend on interconnected electronic and software-controlled systems. A malfunction in one component may propagate across architectural boundaries and compromise vehicle controllability. Safety engineering must therefore identify hazardous failure modes, determine their severity and ensure that faults are detected, isolated and managed before they produce unacceptable consequences. Predictive maintenance principles complement this requirement by shifting technical intervention from post-failure response toward anticipatory detection of degradation (Sunday, Omoegun, Essien & Oluokun, 2020).

Fault-tolerant architecture consequently relies on redundancy, diagnostic coverage and controlled degradation. Autonomous steering provides a representative safety-critical application: combining intelligent fault estimation with sequential detection can identify abnormal actuator behaviour and activate compensating control before steering performance becomes unsafe (He et al., 2023). Such mechanisms are especially important in highly automated vehicles where human intervention may be unavailable or too slow to prevent escalation.

Safety assurance must additionally extend beyond component faults to uncertainties arising from complex operating environments. Scenario-based assessment can systematically explore combinations of environmental, traffic, and system parameters to expose hazardous regions that conventional test cases may overlook, strengthening validation of automated-driving functions before deployment (Coppola et al., 2023). Naturalistic trajectory data can further support quantitative safety evaluation across multiple logical scenarios, allowing designers to assess how automated vehicles respond to realistic interactions rather than idealised operating conditions (Zhang et al., 2023).

Root-cause analysis provides another essential layer of fault prevention. Systematic investigation of equipment failures can distinguish immediate symptoms from underlying design, process or operational mechanisms, enabling corrective action to remove recurring failure pathways rather than repeatedly treating their consequences (Akanbi, Ganiu & Sunday, 2023a). Continuous process-improvement methods similarly support defect reduction by identifying variation,

monitoring performance and institutionalising corrective controls across complex technical systems (Akanbi, Ganiu & Sunday, 2023b).

Connected vehicles also introduce communication-related safety dependencies. Moroccan research on 5G-enabled Internet-of-Vehicles environments highlights confidentiality, integrity and availability threats capable of affecting connected autonomous functions, demonstrating that cybersecurity failures may ultimately become functional-safety hazards (Saber & Mazri, 2022).

3. Vehicle Communication and Connectivity Architectures

Vehicle communication architecture provides the information backbone through which autonomous-electric vehicles coordinate onboard control, environmental perception, neighbouring traffic, charging infrastructure and external digital services. Modern platforms therefore combine intra-vehicle networks with vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-network and vehicle-to-grid communications. Autonomous-driving surveys demonstrate that reliable connectivity is required not only for infotainment but also for cooperative perception, navigation, traffic awareness and safety-critical information exchange (Ahangar et al., 2021).

Within the vehicle, communication historically relies on protocols such as Controller Area Network, LIN and FlexRay, while Automotive Ethernet is increasingly adopted where cameras, radar, lidar and centralised computing create substantially higher bandwidth requirements. These heterogeneous networks must coexist without allowing latency, congestion or message corruption to affect safety-critical functions. Security analysis of in-vehicle protocols shows that legacy buses can be vulnerable to spoofing, injection and denial-of-service attacks because security properties such as authentication were not always incorporated into their original designs (Anwar et al., 2023).

External connectivity expands this architecture into V2X. Dedicated short-range communication and cellular V2X provide mechanisms for exchanging information concerning hazards, manoeuvres, road conditions and traffic states. Evolution toward the Internet of Vehicles increasingly integrates V2X with cloud and edge computing, enabling vehicles to function as mobile nodes within a continuously connected digital transportation environment (Zhou et al., 2020). Cellular sidelink communication is particularly important because it enables direct vehicle interaction without requiring every safety message to traverse a distant core network; LTE-V2X and 5G NR-V2X developments consequently emphasise reliability and low latency for cooperative driving applications (Bazzi et al., 2021).

Network performance is nevertheless constrained by spectrum availability, mobility, interference and rapidly changing topology. Resource-allocation research shows that vehicular communication must dynamically distribute radio, computing and networking resources while preserving quality-

of-service requirements across competing applications (Noor-A-Rahim et al., 2020). Vehicular edge computing addresses part of this challenge by moving processing closer to vehicles, reducing backhaul dependence and enabling latency-sensitive applications to analyse locally generated information more rapidly (Meneguette et al., 2021).

African deployment conditions introduce additional architectural considerations. Nigerian evidence demonstrates that mobile-network coverage can constrain digitally mediated transport outside major urban centres, implying that connected autonomous services cannot assume continuous high-quality cellular access across all operating environments (Alaka, Ajayi & Bolaji, 2022). Broader research across African intelligent transportation systems similarly identifies disparities in communications infrastructure, digital readiness and technology deployment between countries and cities, reinforcing the need for connectivity architectures capable of degraded or intermittent operation (Ajayi et al., 2021). Geospatial and field-survey integration can further improve infrastructure decision support where conventional transport and communications datasets remain incomplete (Tiamiyu et al., 2023).

Connectivity also intersects increasingly with energy infrastructure. Peer-to-peer blockchain energy models demonstrate how distributed electrical participants can exchange energy-related information and transactions securely, principles relevant to future vehicle-to-grid and vehicle-to-vehicle energy ecosystems (Shittu et al., 2021). Such environments require trusted identity, transaction integrity and communication interoperability between vehicles, chargers, aggregators and electricity networks.

Governance becomes equally important as connected vehicles generate large quantities of operational, location and user data. Established IT-governance frameworks illustrate the importance of clear controls for information ownership, access management, compliance and service accountability within complex digital environments (Fadero et al., 2018).

Accordingly, vehicle communication architecture must combine heterogeneous in-vehicle networking, resilient V2X connectivity, edge intelligence, cybersecurity and infrastructure-aware service design. It should maintain essential control even during communication degradation while prioritising safety-critical traffic, authenticating messages and isolating compromised interfaces. For autonomous-electric mobility, connectivity is therefore not an auxiliary service but a core architectural function that links vehicle intelligence with surrounding transport and energy systems.

Table 1. Communication architecture for connected autonomous-electric vehicles

Communication Layer	Typical Technologies	Primary Function	Critical Requirement

In-vehicle network	CAN, LIN, FlexRay, Ethernet	ECU and sensor communication	Determinism and integrity
Vehicle-to-vehicle	DSRC, C-V2X, NR-V2X	Cooperative manoeuvres and warnings	Low latency
Vehicle-to-infrastructure	V2I, roadside units	Traffic and infrastructure exchange	Coverage and reliability
Vehicle-to-network	4G/5G, cloud services	Remote services and updates	Availability and security
Edge-computing layer	MEC, vehicular edge nodes	Local computation and analytics	Minimal processing delay
Vehicle-to-grid	V2G communications	Charging and energy coordination	Authentication and interoperability
Security layer	Encryption, IDS, access control	Protect communications	Confidentiality, integrity, availability

Table 1: Author's synthesis of the principal communication layers required for safe and interoperable connectivity of autonomous electric vehicles.

4. Charging, Grid, and Infrastructure Integration

Large-scale autonomous-electric mobility requires charging infrastructure to function simultaneously as transportation infrastructure, an electrical load, and an intelligent interface with the power system. Charging architecture must therefore coordinate charger capacity, location, grid connection, user demand, communication, energy management and physical accessibility. International evidence shows that charging-station development must integrate technical standards, distributed energy resources and interoperability requirements to ensure safe and dependable interaction between vehicles and utility networks (Sachan et al., 2022).

Charging technologies range from residential AC charging to high-power DC fast charging, with substantial differences in power demand, conversion architecture, charging duration and network impact. Rapid-charging deployment can improve vehicle availability but may produce concentrated peaks capable of stressing transformers, feeders and local voltage profiles. Comprehensive charging-infrastructure analysis therefore emphasises coordinated planning, renewable-energy integration and standardisation as essential components of scalable deployment (Mastoi et al., 2022). Smart charging can mitigate these impacts by shifting flexible demand according to grid conditions, electricity prices, renewable generation and vehicle departure requirements.

Control architecture is consequently central to grid integration. Hierarchical charging-station operation can coordinate device-level converter control, station-level energy management and grid-level objectives, allowing charging loads to respond dynamically to network constraints while preserving user requirements (Wu et al., 2022). Within South Africa, smart electromobility research similarly highlights renewable-supported charging, energy-storage integration and intelligent control as important pathways for strengthening charging resilience in electricity systems facing capacity and sustainability pressures (Ayoade & Longe, 2024).

Infrastructure location must also reconcile transportation demand with electrical feasibility. Charging stations placed solely according to traffic volume may overload weak network nodes, whereas grid-optimal sites may provide inadequate accessibility for drivers. Multi-objective placement approaches therefore consider power losses, voltage stability, installation cost, traffic flow and charging demand simultaneously when identifying suitable locations (Ahmad et al., 2022). In high-density urban environments, contextualised location-allocation modelling further demonstrates that charger deployment should account for spatial constraints, projected demand and travel time, rather than merely expanding infrastructure wherever physical space is available (He, Kuo & Sun, 2022).

The Nigerian transport environment illustrates why spatial planning must extend beyond conventional charging metrics. Clustering of crash locations along intercity corridors can identify transport-risk concentrations that should inform infrastructure design, emergency planning and placement of roadside facilities serving increasingly automated mobility systems (Alaka, Tiamiyu & Bolaji, 2021). Emergency-response coverage gaps likewise reveal that infrastructure availability is uneven across highway networks, making resilience planning particularly important where charging failures, collisions or electrical emergencies occur far from support services (Tiamiyu, Alaka & Ajayi, 2021).

Climate exposure adds another dimension. Flood mapping of Nigerian road segments demonstrates that transport infrastructure can experience significant seasonal disruption, indicating that charging equipment, substations, communication cabinets and feeder connections should be sited with environmental exposure and access continuity in mind (Alaka, Bolaji & Tiamiyu, 2022). Infrastructure prioritisation can therefore benefit from multi-criteria methods that combine physical condition, population, accessibility and service importance when investment resources are constrained (Alaka et al., 2023).

User economics must also be incorporated into infrastructure planning. Evidence concerning willingness to pay for digitally mediated transport after fuel-price increases illustrates how affordability and perceived service value influence mobility choices, factors equally relevant to pricing models for public EV charging (Ajayi, Alaka & Tiamiyu, 2023).

The resulting infrastructure must connect vehicle, charger, grid and transport-network intelligence within a coordinated architecture. Smart charging, renewable generation, stationary storage and eventually vehicle-to-grid operation can transform EV fleets from unmanaged electrical demand into flexible grid resources. Safe integration therefore requires not merely more chargers, but appropriately located, electrically resilient, digitally connected and interoperable charging infrastructure capable of supporting both mobility requirements and power-system stability.

Table 2. Integrated charging and infrastructure architecture

Integration Domain	**Principal Elements**	**Primary Requirement**	**Expected Benefit**
Vehicle interface	Battery, onboard charger, connector	Compatibility and safety	Reliable energy transfer
Charging station	AC/DC chargers, converters	Capacity and availability	Reduced charging delay
Grid connection	Feeders, transformers, protection	Voltage and thermal stability	Secure network operation
Smart control	EMS, scheduling, communications	Coordinated charging	Peak-load reduction
Renewable integration	Solar PV, storage	Energy balancing	Lower grid dependence
Spatial planning	Traffic, demand, grid capacity	Optimal location	Improved accessibility
Resilience planning	Flood, crash, emergency data	Infrastructure robustness	Service continuity
V2G interface	Bidirectional converter, aggregator	Interoperability and control	Grid flexibility

Table 2: Author's synthesis of the principal electrical, spatial, operational, and resilience dimensions required for integrated autonomous electric vehicle charging infrastructure.

5. Emerging Technologies and Research Priorities

The next generation of autonomous-electric mobility will depend increasingly on technologies capable of connecting physical vehicles, energy infrastructure, communication networks and virtual intelligence within adaptive cyber-physical ecosystems. Digital twins are among the most consequential developments because continuously updated virtual representations can integrate

sensor data, operational models and predictive analytics to support monitoring, simulation and fault recognition. Experience with smart-substation digital twins demonstrates how real-time information can be combined with virtual models to identify deviations and emerging faults, offering transferable principles for vehicle batteries, power electronics, charging systems and roadside electrical infrastructure (Shittu et al., 2023).

For autonomous-electric vehicles, digital twins can extend beyond component monitoring to represent propulsion, battery condition, charging behaviour, vehicle dynamics and connectivity within a unified virtual environment. Current research identifies promising applications in battery management, tracking, predictive maintenance, cybersecurity and autonomous-system validation, although model fidelity, synchronisation, computational demand and trustworthy data exchange remain unresolved challenges (Ali et al., 2023). At transportation-system scale, digital-twin intelligent transportation systems could integrate vehicles, traffic infrastructure and network conditions dynamically, but future research must establish interoperable models and credible methods for synchronising large heterogeneous systems in real time (Ge & Qin, 2024).

Artificial intelligence will further shape both vehicle perception and infrastructure intelligence. The combination of advanced sensing with AI demonstrates how complex sensor outputs can be transformed into rapid classifications and decision-support information, illustrating the wider potential of intelligent sensing architectures where conventional threshold-based analysis is insufficient (Olorunkosebi, Ayinde & Kofi, 2023). Future autonomous vehicles will require comparable advances in multisensor fusion, uncertainty estimation, edge intelligence and explainable models so that safety-critical decisions are not only accurate but interpretable and auditable.

Technological progress must nevertheless be accompanied by organisational readiness. Adoption frameworks indicate that employee preparedness, acceptance and capability influence whether advanced technologies progress successfully from demonstration to routine operational use (Akhigbe et al., 2024). This is especially important as mobility systems increasingly require expertise spanning high-voltage engineering, software, communications, artificial intelligence, cybersecurity and transportation operations. Capability-building frameworks therefore underscore the need for deliberate workforce development across distributed technical environments rather than assuming that infrastructure investment alone will generate operational competence (Falemi, Akhigbe & Akin-Oluyomi, 2020).

Risk governance must evolve simultaneously. Autonomous-electric ecosystems create interconnected risks involving battery safety, software failure, communication disruption, cyberattack, grid instability and algorithmic error. Integrating operational analytics with enterprise risk structures can help translate rapidly changing technical indicators into prioritised organisational responses and investment decisions (Falemi, Akhigbe & Akin-Oluyomi, 2024).

Within African settings, technological transformation is additionally influenced by institutional capability, policy implementation and leadership, indicating that emerging mobility technologies must be adapted to heterogeneous regulatory, infrastructure and socioeconomic conditions rather than transferred without contextualisation (Enaifoghe et al., 2020).

Conclusion

This review has demonstrated that the safe and scalable deployment of autonomous and electric vehicles depends on the coordinated evolution of electrical, electronic, communication, charging, and digital control architectures. The study met its objectives by examining the transformation of vehicle electrification and automation, evaluating high-voltage power-distribution and zonal electronic architectures, assessing functional-safety and fault-tolerance requirements, analysing connected-vehicle communication systems, and reviewing charging, grid, and infrastructure integration together with emerging technological priorities.

The findings show that autonomous-electric mobility cannot be treated as a collection of isolated subsystems. High-voltage traction networks, power-electronic converters, electronic control units, zonal controllers, in-vehicle Ethernet, V2X communications, smart charging, and grid interfaces increasingly operate as an integrated cyber-physical environment. Their effectiveness depends on interoperability, deterministic communication, secure data exchange, resilient power delivery, and the ability to maintain essential functions during electrical, software, communication, or sensor failures. Digital twins, artificial intelligence, edge computing, predictive diagnostics, and software-defined architectures further strengthen monitoring, optimisation, and adaptive control, but they also introduce new requirements for validation, cybersecurity, explainability, and governance.

The review further establishes that infrastructure readiness remains as important as vehicle-level innovation. Charging availability, distribution-grid capacity, mobile-network coverage, environmental exposure, emergency-response accessibility, and institutional capability can determine whether emerging mobility technologies perform reliably outside controlled environments.

Accordingly, future development should prioritise interoperable electrical and communication standards, fail-operational architectures, secure V2X platforms, resilient charging networks, bidirectional grid integration, and transparent AI-based decision systems. Researchers should expand multi-country and real-world validation under weak-grid, mixed-traffic, intermittent-connectivity, and extreme-environment conditions. Regulators and industry should also promote common testing frameworks, cybersecurity requirements, workforce development, and infrastructure investment. These measures are essential for ensuring that autonomous-electric

mobility advances not only in technological sophistication, but also in safety, resilience, accessibility, and long-term operational sustainability.

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