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REVIEW

Eco-Innovation in Transportation: Linking Smart Vehicle Technologies with Environmental Sustainability

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ABSTRACT

The decarbonization of transportation and environmental quality enhancement have become more and more reliant on eco-innovation, which incorporates both technological change and systemic coordination and governance. The review is a summary of the evidence that can be translated into environmental sustainability outcomes on how smart vehicle technologies, including electrified powertrains and vehicle-grid interfaces, connected and cooperative systems (Vehicle-to-Everything, V2X), automation and advanced automation, and Artificial Intelligence (AI)-enabled optimization can be transformed. Using a structured analytical framework linking technology capability to eco-innovation mechanisms and sustainability impacts, we reconcile findings across operational, well-to-wheel, and life-cycle boundaries. The literature indicates that electrification delivers strong local air-quality benefits and, in most contexts, substantial climate gains, but net outcomes depend on grid carbon intensity, charging time profiles, battery production, and end-of-life pathways, making managed charging and circularity pivotal complements. Connectivity and cooperative control improve energy efficiency primarily through coordination effects such as traffic smoothing, eco-routing, and platooning, yet benefits are non-linear and sensitive to penetration rates and infrastructure interoperability. Automation offers efficiency and safety co-benefits but exhibits the widest uncertainty because induced demand, empty travel, and mode substitution can offset per-vehicle improvements. AI-driven fleet optimization can reduce empty miles and extend component life, although computational and hardware overhead and rapid obsolescence can introduce trade-offs. We identify persistent gaps in comparability, non-exhaust emissions assessment, causal evaluation at scale, and equity-aware impact metrics,

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and propose a research and policy agenda emphasizing integrated Life Cycle Assessment (LCA) system modeling, standardized reporting, interoperable data governance, and demand management to secure durable environmental gains.

Keywords: Eco-Innovation; Smart Vehicles; Vehicle Electrification; Connected and Automated Mobility; Life-Cycle Sustainability

1. Introduction

Transportation is simultaneously a foundation of economic activity and a leading source of environmental pressure. Road, rail, aviation, and maritime systems enable mobility and trade, yet they also generate greenhouse gas emissions, local air pollutants, noise, and material demands that accumulate across vehicle production, operation, and end-of-life [1,2]. In many countries, the transport sector remains among the most difficult to decarbonize because it is tightly coupled to fossil energy, long-lived capital stock, dispersed infrastructure, and behavioral routines that shape travel demand. The pressure on mobility convenience and the increasing demand to move goods and people freely is exacerbated by fast urbanization, e-commerce, freight movement growth, and growing expectations. It is on this ground that the concept of eco-innovation, which reduces the environmental impact but still creates economic and social value, has taken center stage, on which the re-evaluation of how transportation systems can be taken to the sustainable level without affecting performance, safety, or accessibility has been taken into consideration [3].

In the meantime, digitalization is the technological transformation in the transport sector. Cars are getting networked, more automated, and electrified; they are part of data-intensive ecosystems that also comprise intelligent infrastructure, cloud computing, edge computing, and platform-based mobility services. These innovations tend to be marketed as part of the so-called smart mobility, but these effects on the environment are neither homogeneous nor universal. A connected vehicle is capable of saving on energy consumption by achieving smoother driving and optimizing routes, yet can also allow more vehicle kilometers to be covered in case convenience improves and the cost reduces. Electrified powertrains can eliminate tailpipe emissions, but life-cycle benefits depend on electricity generation mixes, charging behavior, and battery supply chains. Autonomous driving may improve traffic flow and safety, but it may also introduce new energy and material burdens through sensors, computation, and induced demand. The key issue is therefore not whether smart vehicle technologies are environmentally beneficial in principle, but how, when, and under what governance conditions they become meaningful instruments of eco-innovation [4–7].

This review links smart vehicle technologies to environmental sustainability outcomes through the mediating mechanisms of eco-innovation. Smart vehicle technologies are considered broadly to include electrified powertrains and vehicle–grid interfaces; vehicle connectivity and cooperative systems (e.g., V2X); automation and advanced driver-assistance systems; and data-driven or AI-enabled optimization across vehicles and fleets. These technologies interact with infrastructure (charging networks, roads, communication systems), energy systems (generation, grid management, storage), and institutions (standards, incentives, data governance) [8]. Environmental sustainability is treated as multi-dimensional, encompassing climate metrics, local air quality, noise, and resource and material footprints, as well as distributional concerns that shape who experiences. Automation could enhance safety benefits and harms. Eco-innovation is understood as a spectrum of technological, organizational, and systemic innovations that improve environmental performance while enabling viable adoption and diffusion pathways. In transportation, eco-innovation is rarely a single device or feature; it is typically a bundle, a combination of technology, operational practice, infrastructure, and policy capable of reshaping both supply (vehicle efficiency, fuels, logistics) and demand (routing, occupancy, mode choice) [9].

A growing body of research highlights the promise of smart vehicle technologies for environmental improvement. Electrification and smart charging can reduce operational emissions and facilitate renewable integration when charging aligns with low-carbon generation and grid constraints. Connectivity enables real-time traffic management and cooperative driving, potentially smoothing stop–and–

go patterns that waste fuel and increase emissions. Predictive cruise control and eco-driving assistance can decrease energy consumption by matching the speed profiles to the roadway and predicted traffic. AI-based logistics and fleet telematics will have the opportunity to reduce empty miles, improve asset utilization, and last-mile delivery, opening an opportunity to cut freight-based emissions without cutting services. However, these advantages depend much on context and are typically counterbalanced by antagonistic effects, and that has caused mixed results in the literature and confusion among policymakers and practitioners [8,10,11].

The selection of system boundaries is one of the sources of inconsistency. A lot of analyses focus on tailpipe emissions or the energy consumption per vehicle, whereas life-cycle assessments include vehicle manufacturing, battery production, electricity generation, maintenance, and end-of-life treatment [5,12]. A technology with lower operational energy could still result in higher overall environmental impact when it is based on carbon-intensive materials, regular replacement of hardware, or energy-intensive computation. The other source is context dependence. Even the same electric vehicle can be associated with quite different life-cycle emissions based on the local grid mix, climate (heating and cooling loads), driving patterns, and charging infrastructure. Similarly, the efficiency of connected and automated driving in terms of emissions reduction is dependent on the level of traffic, the rate of penetration, the shape of roads, and the implementation of cooperative infrastructure. One-third of the source is behavioral and economic response. In case smart features decrease the perceived cost of travel, enhance comfort, or reduce time stress, they will be capable of spurring more travel, longer trips, or shifts in mode towards low-carbon alternatives, including public transportation, walking, and bicycling. Platform-based mobility and delivery services are capable of enhancing convenience, but are also associated with empty miles and aggravated congestion unless designed and managed to internalize externalities [13].

These tensions suggest that smart vehicle technologies function less like deterministic solutions and more like general-purpose enablers. They create new capabilities, sensing, decision-making, communication, and control that can be steered toward sustainability or away from it, depending on how systems are designed, governed, and used. This is precisely where an eco-innovation framing adds explanatory power. Eco-innovation highlights mechanisms such as efficiency optimization, substitution, coordination and sharing, dematerialization, and circularity, and it emphasizes diffusion and adoption: an eco-innovative solution is not only environmentally superior under ideal conditions, but also viable in markets and institutions, scalable across diverse contexts, and aligned with social goals [14].

Several eco-innovation mechanisms map naturally onto smart vehicle capabilities. Efficiency optimization is the most direct mechanism: smart control of acceleration, braking, and thermal management can reduce energy consumption; cooperative driving and traffic smoothing can reduce congestion-related waste; predictive maintenance can extend component life and reduce material consumption [15]. Substitution refers to replacing high-carbon energy carriers with low-carbon ones through electrification or hydrogen, but it also includes substituting resource-intensive operational practices with data-enabled alternatives such as consolidated routing and dynamic dispatch. Vehicles that can communicate with other vehicles, as well as infrastructure, will make coordination and sharing possible and facilitate platooning, intersection management, harmonize speed, and other smoother fleet interactions. Dematerialization is manifested in the ownership/service turnover and hardware-intensive upgrades to software-defined vehicles, but these tendencies may equally drive obsolescence unless handled with responsibility. Circularity is linked to battery second-line approaches, recycling, design-for-repair, and modular systems that could be enhanced without replacement [16,17].

These mechanisms are not fully technical to be realized. They rely on policies and the institutions that define incentives, access to data, interoperability, and accountability. Smart charging can mitigate emissions in case it is synchronized with the supply of renewable energy and grid configurations, but it might boost peak demand and related emissions in case incentives motivate simultaneous charging at high-carbon hours. The efficiency of V2X-based traffic is reliant on shared standards, cybersecurity guarantees, and roadside unit and Internet infrastructure investments. It may make the drive safer and smoother, but still, automation requires regulatory openness, liability frameworks, and moral values to ensure that the masses of people are on their guard without pursuing perverse motives to increase travel demand. Eco-innovation is, in other words, by definition socio-technical: the product of the interaction between technological capability and policy formation, market structures, and usage [18].

Evidence base remains fragmented in the different areas of investigation and is usually incomparable across the fields of study, even with the scalding advancement of research. The studies are varied in transportation engineering, energy systems, computer science, environmental evaluation, economics, and policy, and tend to adopt different assumptions and measurements. Without including upstream emissions or induced demand, engineering studies can claim fuel savings as a result of certain control measures. Energy analysis can be used to model the effects of Electric Vehicles (EVs) on the grid without considering the dynamics of congestion or traveling. Mobility-service studies can be dedicated to the efficiency of operations, and they can neglect the material effects on life-cycle and distributional results. Moreover, sustainability indicators can be instantaneous fuel use, life-cycle CO_2 equivalent emissions, citywide air quality indicators, and localized exposure estimates. The methodologies can be simulation and scenario modeling, pilots, and quasi-experimental studies based on observational data. Counterfactual baselines, rebound assumptions, and sensitivity analyses are often not transparently reported in many studies, limiting the generalizability and policy applicability [19,20].

There are also uneven distributions of trade-offs and distributional impacts. Environmental sustainability is commonly boiled down to one climate indicator, but in reality, the tradeoff between opposing goals of climate, air quality, noise, land use, safety, and equity has to be negotiated. EV implementation could increase air quality in cities at the expense of electricity production and battery chain supply. Autonomous mobility can also minimize collisions and traffic congestion, as well as augment vehicle kilometers flown by more convenient and empty repositioning actions. Freight optimization can reduce emissions and focus traffic and exposures in certain neighborhoods. The question of equity: who can afford smart vehicles, who enjoys the benefits of infrastructure improvements, who is vulnerable to traffic jams or to higher pollution levels- is becoming the cornerstone of sustainability transitions, but not adequately reflected in most evaluations [21–23].

There is more complexity due to scaling. Most of the reported advantages occur in a controlled or pilot context and cannot be sustained with large-scale deployment, heterogeneous user behavior, or mixed fleets. Scaling would need interoperable standards, strong cybersecurity and privacy measures, data governance structures to facilitate coordination and protect rights, and infrastructure investment that meets system-level objectives. When these conditions are not present, the smart vehicle technologies can end up scattered in ways that bring comfort and commercial benefits without meeting the environmental goals [9,24].

To fill these gaps, this review is a synthesis of the available research on eco-innovation in transportation by directly connecting smart vehicle technologies to environmental sustainability effects through a rigorous framework of analysis [25]. Instead of listing the technologies separately, the review focuses on a cause-and-effect chain of smart vehicle capability, eco-innovation mechanism, and sustainability impact, assessed by suitable life-cycle and system boundaries, and taking into consideration the behavioral and governance conditions. The synthesis is structured around four guiding questions: which technologies demonstrate the most evidence of benefits to the environment and how those benefits differ by context; what mechanisms can bring about sustainability and what complementary infrastructure or policy is needed; what trade-offs and rebound effects are repeated across studies and how they should be considered; and what research and policy gaps best limit efforts to make impact at scale [10,26–28].

The article continues with a description of the review design and analytical framework, and elaborates on an evolution of a taxonomy of smart vehicle technologies that match the processes of eco-innovation, synthesis of evidence regarding sustainability impacts and their conditions of boundary, and analysis of enablers and barriers; policy, infrastructure, market adoption, and measurement challenges to define the real-world outcomes. The conclusion of the review takes an integrative approach to these insights with a tailored research and practice agenda in order to have the next generation of smart vehicles development deliver quantifiable and fair environmental sustainability benefits.

2. Review Design and Analytical Framework

The article has a structured review design in the sense that it synthesizes the role of smart vehicle technologies in eco-innovation of transportation and, consequently, quantifiable environmental sustainability results. Since the subject is multidisciplinary, involving transportation engineering, energy systems, environmental evaluation, computer science, and policy, this review is intended to combine incoherent evidence with remaining transparency and reproducibility. The section will include the description of the review protocol, the process of the literature identification and selection, the method of the quality of the studies, and the method of analyzing the data in order to relate technologies to the eco-innovation processes and effects on the environment [29–31].

2.1. Review Approach and Rationale

The review should be structured as a synthesis that is guided by theory. Systematic means having a documented search strategy, having clear eligibility criteria and having traceable screening processes. Theory-guided is an application of an analytical framework, which connects smart vehicle capabilities with eco-innovation processes and sustainability performances within the context of systems boundaries of relevance. Such a hybrid method is correct since the empirical background comprises quantitative impact research and conceptual or methodological research papers that influence the definition and measurement of impacts. Unless the systematic review is purely qualitative and gives all studies the same level of relevance, a systematic review would risk obscuring the dependence on context and effects on boundaries, and the narrative review would risk selection bias. The review will strive to achieve a balance between breadth, rigor, and interpretability by incorporating systematic identification and a clear organizing structure [32].

In addition to peer-reviewed sources, grey literature was systematically identified and screened to capture practical and policy-relevant insights. Sources included government reports, NGO (Non-Governmental Organizations) publications, white papers, and conference briefs that focus on smart vehicle deployment, regulatory frameworks, and urban mobility outcomes. Documents were selected based on relevance to environmental impacts, policy interventions, equity, or technological performance. This approach complements academic studies and ensures that actionable lessons and emerging practices are captured, even if not yet reported in peer-reviewed journals.

2.2. Information Sources and Search Strategy

The literature search will be aimed at collecting peer-reviewed articles published in journals and conference papers, usually indexed in major citation databases. Multidisciplinary databases containing Web of Science Core Collection and Scopus are searched, and discipline-specific databases are added where necessary to address such technical areas as vehicle automation, connectivity, and battery systems. The search strategy employs parallel database queries, which are then deduplicated to minimize database-specific blind spots.

Search strings will be built on three groups of concepts, including: smart vehicle technologies, eco-innovation or innovation mechanisms, and environmental sustainability outcomes. The technology category contains the words connected, electrification, intelligent or connected vehicles, V2X communications, autonomous driving, AI-enabled control, telematics, and fleet optimization. Regarding innovation, it has eco-innovation, sustainability-oriented innovation, green innovation, and system innovation and mechanism terms, which include optimization, coordination, sharing, and circularity. Life-cycle emissions, energy consumption, air quality, criteria pollutants, noise, resource use, and material footprints belong to the outcomes group. These themes intersect with each other to select the studies that are retrieved using the sets of rules of proximity and binary operators. To enhance relevance, transportation context terms included in the search consist of terms like mobility, freight, logistics, traffic flow, and intelligent transportation systems [25,33,34].

The temporal scope is selected to reflect the acceleration of connected, automated, and electrified vehicle research, while still capturing foundational work in eco-driving, traffic smoothing, and life-cycle assessment. The final scope is reported explicitly in the manuscript, including the date of the last search, to support reproducibility and to clarify the currency of the evidence base.

2.3. Eligibility Criteria and Study Selection

Eligibility criteria are defined a priori to ensure that included studies directly inform the research questions. Studies are included when they analyze, measure, or model a smart vehicle technology (or a closely coupled vehicle–infrastructure capability) and link it to at least one environmental sustainability outcome. Outcomes may be direct, such as changes in energy use, greenhouse gas emissions, or air pollutant emissions, or indirect, such as network-level congestion changes that affect emissions. Studies are also included when they develop methods that substantially shape environmental evaluation in this domain, such as life-cycle assessment frameworks for electric vehicles, emissions modeling for connected and automated traffic, or causal inference designs for mobility service impacts [35].

Exclusion criteria remove studies that mention smart mobility only tangentially, do not specify a vehicle technology component, or discuss sustainability without measurable or clearly defined indicators. Articles focused exclusively on non-vehicle digital systems without a vehicle technology linkage are excluded unless they directly govern vehicle behavior at scale, as in corridor-level cooperative control systems. Non-peer-reviewed sources can be included selectively when they provide essential standards context (e.g., communication protocols) or policy baselines, but such inclusions are treated as contextual rather than primary evidence and are clearly labeled as such [36].

The selection process proceeds in stages. Titles and abstracts are screened first to remove clearly irrelevant records, followed by full-text screening to confirm eligibility against the criteria. Screening decisions are documented, and reasons for exclusion at the full-text stage are recorded to enable a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-style reporting of the selection flow. Where ambiguity exists, the study is retained for full-text review to minimize false exclusions, and the final decision is made based on whether the paper provides a defensible link between a smart vehicle technology and environmental outcomes [37].

2.4. Quality Appraisal and Risk-of-Bias Considerations

Because of the methodological heterogeneity of the literature, quality appraisal is structured around internal validity and transparency as opposed to one scoring rubric. In case of empirical studies, it specifically focuses on whether the design can be used to interpret causally or whether the research outcomes are correlational. Simulation and modeling research is evaluated in accordance with the clarity of assumptions, the suitability of baselines and counterfactuals, as well as the sensitivity analysis. In the case of life-cycle assessment studies, appraisal focuses on defining the system boundaries, choice of functional units, data provenance, treatment of electricity mix, temporal dynamics, and end-of-life assumptions of important components like batteries. In the context of traffic and emissions modeling, the appraisal is concerned with the representativeness of driving cycles, emissions model calibration, and whether the fleet composition and penetration rate of the technology are realistically addressed [38,39].

Reporting completeness is considered a fundamental quality criterion across the types of studies. Those studies that are not explicit in determining the important parameters, i.e., grid carbon intensity, penetration rates, and boundary conditions, are not automatically eliminated, but their conclusions are given a heavy weight in the synthesis. This will enable the review to maintain coverage without making uncertainty implicit, which is imperative to a Science Citation Index (SCI)-standard article meant to inform both research and policy.

2.5. Data Extraction and Coding Scheme

The data extraction procedure was made to address what is being described in the studies and how the findings describe the underlying mechanisms. In each study that we included, we had to note the most important details, including the location of the study, the mode or sector in which the study was conducted, the type of road environment (either urban streets or highways), and the nature of analysis that was carried out by either individual vehicles, fleets, or platform-based services. Technologies were split into two levels: first by their particular implementations (predictive cruise control, cooperative adaptive cruise control, managed charging, or platooning) and then by their themes, including electrification and energy systems, connectivity and cooperation, automation and control, data-driven optimization, as well as fleet or service bundles. In order to ensure transparency and consistency in all disciplines, we outlined our review protocol, eligibility criteria, and a coding framework in **Table 1**. This framework formed the basis of categorizing technologies, mechanisms, and sustainability results during the entire review [40,41].

Environmental outcomes are extracted with attention to units and comparability. Where possible, outcomes are normalized to functional units commonly used in the field, such as per vehicle-kilometer, per passenger-kilometer, or per ton-kilometer. They are also interpreted at the system level when studies report corridor, city, or fleet impacts. The extraction also records whether outcomes are operational, well-to-wheel, or full life-cycle, and whether the study incorporates non-exhaust emissions, noise, or material footprint indicators. Finally, the extraction captures mediating factors that determine impact magnitude, such as electricity mix, temperature and climate, traffic density, technology penetration rates, user behavior adaptation, and policy constraints [42].

Table 1. Review protocol, eligibility, and coding framework.

Component	Operational Definition in This Review	Implementation Details to Report	Output in This Paper
Review type	Structured, theory-guided systematic synthesis	Databases, timeframe, last search date	PRISMA-style flow + narrative synthesis
Core constructs	Smart vehicle tech; eco-innovation mechanisms; sustainability outcomes	Definitions and boundary conditions	Unified analytical framework
Inclusion criteria	Vehicle technology + link to at least one environmental outcome	Peer-reviewed; transport context; measurable indicator	Final corpus size (n)
Exclusion criteria	No vehicle component; no defined outcome; purely conceptual without relevance	Screening reasons	Transparent scope limits
Boundary classification	Operational vs. well-to-wheel vs. life-cycle	Electricity mix treatment, end-of-life assumptions	Comparable evidence buckets
Context coding	Mode, geography, road type, fleet/private, penetration	Study setting and deployment maturity	Evidence stratification
Methods coding	Simulation, field trial, observational causal, LCA, hybrid	Validation, sensitivity analysis	Quality-weighted synthesis
Outcome coding	GHG (greenhouse gas), energy, air quality, noise, materials/circularity, equity	Functional unit and metrics	Cross-domain evidence map

2.6. Evidence Synthesis Strategy

The synthesis uses a configurational approach that emphasizes "what works, for whom, and under what conditions," rather than assuming that a single pooled effect size is meaningful across contexts. Where studies are sufficiently comparable in technology definition, boundary conditions, and outcome metrics, results are summarized quantitatively in terms of ranges and central tendencies reported in the literature. However, formal meta-analysis is treated as conditional on adequate homogeneity and is not presumed as the default because many studies differ in system boundaries, baseline assumptions, and context.

To ensure interpretability, the synthesis is organized around the technology-to-impact pathway. Evidence is first summarized within technology categories, then reassembled by sustainability outcome domain to highlight cross-cutting patterns and trade-offs. Findings are contextualized by identifying moderators, such as grid carbon intensity for electrification or penetration rate thresholds for cooperative driving benefits. Contradictory findings are treated as informative signals of boundary-condition effects rather than as noise, and are analyzed by tracing differences in assumptions, modeling frameworks, or measured contexts [43].

2.7. Analytical Framework Linking Technology, Eco-Innovation Mechanisms, and Outcomes

A central contribution of the review is an analytical framework that structures the evidence into a causal chain. The first element of the chain is smart vehicle capability, defined as the ability to sense, communicate, decide, and actuate in ways that alter energy use, emissions, or resource flows. The second element is the eco-innovation mechanism that translates capability into environmental performance. Mechanisms include efficiency optimization, substitution toward lower-carbon energy carriers, coordination and sharing that improve system utilization, dematerialization through software-enabled functionality and mobility services, and circularity through life-extension and end-of-life recovery.

The third element is sustainability outcomes, defined across multiple dimensions: climate impacts (greenhouse gases across appropriate boundaries), energy demand, air quality and pollutant emissions, noise, and material and resource footprints. The framework explicitly accommodates multi-scale effects by recognizing that impacts can occur at the vehicle level, network level, and system-of-systems level, which includes the grid and built environment. This is essential because some technologies generate minimal benefit per vehicle but substantial benefit at scale through coordination, while others yield per-vehicle gains that are diluted or reversed by behavioral responses such as increased travel demand [44,45]. The analytical framework used to structure the review linking smart vehicle capabilities to Eco-innovation mechanisms and environmental sustainability outcomes is shown in **Figure 1**. This framework underpins the taxonomy in Section 3 and the evidence synthesis in Sections 4 and 5.

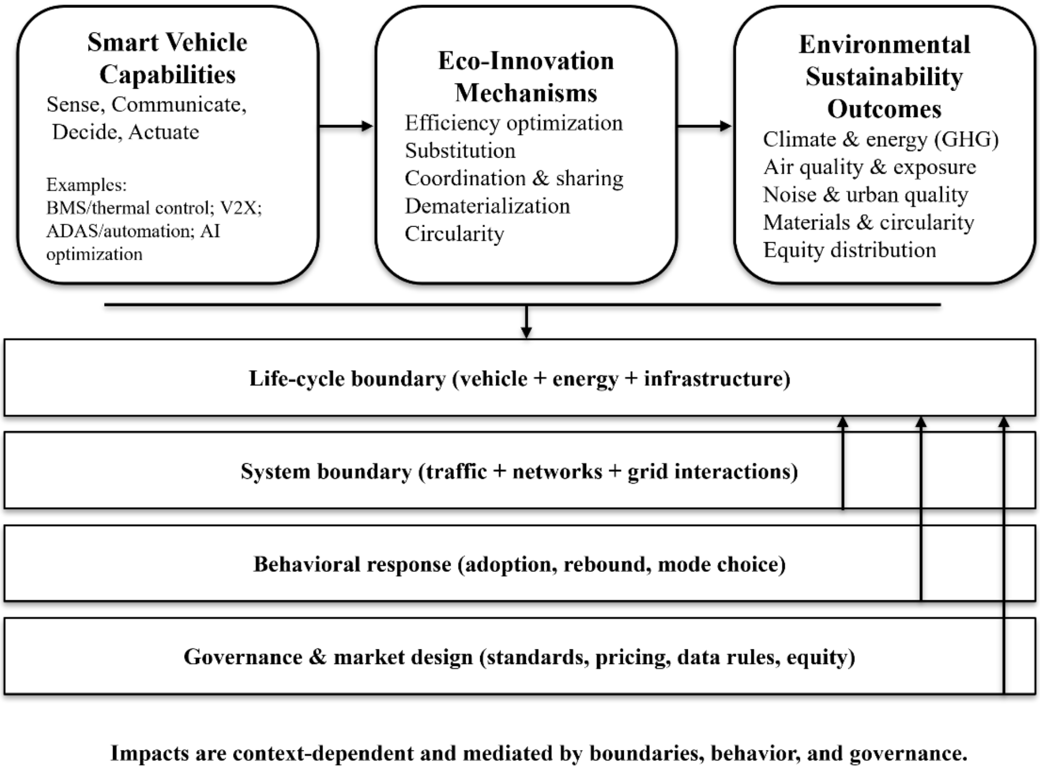

Figure 1. Conceptual framework linking smart vehicle technological capabilities to eco-innovation mechanisms and multi-dimensional environmental sustainability outcomes across life-cycle, system, behavioral, and governance boundaries.

The framework also treats context and governance as conditioning layers rather than externalities. Infrastructure readiness, standards interoperability, cybersecurity and privacy rules, pricing and incentives, and market adoption pathways are modeled as determinants of whether the eco-innovation mechanism activates and whether net benefits persist. In practice, this means that the review does not interpret a technology as inherently sustainable, but as sustainable under a definable set of conditions that can be influenced by design and policy.

2.8. Methodological Limitations and Robustness Steps

No review design can eliminate all sources of bias, especially in a rapidly evolving technological domain. Publication bias is possible if studies with favorable environmental outcomes are more likely to be published or cited, while negative or null results remain underreported. Database coverage bias may occur if relevant engineering conference proceedings or regional journals are unevenly indexed. To mitigate these issues, the search is conducted across multiple databases, forward and backward citation tracking is applied to key papers, and the synthesis explicitly records when evidence is drawn from simulations rather than measured deployments.

The second limitation is on comparability. Direct numerical comparison can be unreliable or even misleading due to variations in the definitions of the functional units of study, system boundaries, and baseline scenarios in a study. To overcome this, the review groups are based on the type of boundaries, explicitly state main assumptions, and indicate the dependence of interpretations on certain circumstances. The third constraint is related to the fast development of smart vehicle technologies and electricity systems that can make empirical estimates obsolete in a short period of time. As a way of remaining relevant, the review also prioritizes research with clear parameter settings and sensitivity analyses, which enables readers to modify the findings to suit the changing circumstances. All these measures combine to form a review method that is both transparent and reproducible and is adaptable to publish in SCI-standard journals, though it is elastic enough to incorporate evidence across disciplines and methodological views [46].

3. Taxonomy of Smart Vehicle Technologies for Eco-Innovation

The environmental contribution of smart vehicle technologies cannot be assessed meaningfully without a clear taxonomy that distinguishes what is being implemented, how it operates, and which eco-innovation mechanism it activates. In the literature, "smart mobility" is often used as an umbrella term that mixes powertrain change, digital connectivity, automation, and service reconfiguration, sometimes obscuring causal attribution and complicating comparison across studies. This section, therefore, develops a technology taxonomy oriented toward eco-innovation, grouping technologies by the core capability they add to the vehicle system and the pathway through which that capability can translate into environmental performance. The taxonomy recognizes that many real-world applications are not single technologies but integrated bundles, and that the same enabling technology can produce different environmental outcomes depending on operational context, infrastructure coupling, and behavioral response [47,48].

3.1. Electrified Powertrains and Vehicle–Energy Interfaces

Electrified powertrains represent the most visible technological shift in contemporary transportation eco-innovation because they directly alter the energy carrier and enable deep reductions in tailpipe emissions [49]. Battery electric vehicles, plug-in hybrid vehicles, and fuel cell electric vehicles are typically discussed as distinct categories, but from an eco-innovation perspective, their relevance is better understood through the degree to which they enable substitution away from fossil fuels and the extent to which they can be coordinated with low-carbon energy systems. The environmental outcomes associated with electrification depend not only on drivetrain efficiency but also on upstream electricity generation, charging behavior, and the material intensity of energy storage systems. Consequently, research in this domain increasingly treats the vehicle as a flexible energy asset rather than an isolated consumer of energy [50].

A defining element of "smart" electrification is the vehicle's interface with the grid and with distributed energy resources. Managed charging, time-of-use response, and vehicle-to-home or vehicle-to-grid concepts extend electrification from a product innovation into a system innovation by enabling temporal and spatial shifting of demand. This capability can support renewable integration, reduce peak loads, and potentially lower marginal emissions, but it can also create new system stress if charging demand clusters are under misaligned incentives. In addition, electrified vehicles rely heavily on battery management systems and thermal control, which are themselves smart subsystems that influence energy efficiency, range, and battery degradation. As a result, the electrification category in this taxonomy includes not only drivetrain choice, but also smart charging control, battery health optimization, and energy-aware thermal management, all of which shape environmental performance across operational and life-cycle boundaries [51].

3.2. Connected Vehicles and Cooperative Communication Systems

Connectivity expands the vehicle's capability to perceive and respond to its environment beyond onboard sensors by exchanging information with other vehicles, infrastructure, and digital services. Vehicle-to-vehicle and vehicle-to-infrastructure communications can enable cooperative behaviors that improve traffic efficiency and safety, and can also increase the precision of routing, speed control, and energy management. Regarding the perspective of eco-innovation, the main way through which connectivity functions is by boosting coordination. It is used to have vehicles, traffic lights, and fleets communicate with each other to minimize system-wide waste such as stop-and-go traffic, unnecessary idling, and redundant trips. Connection is another aspect that transforms the way information operates in the transportation systems. Real-time availability will assist drivers and operators to make more intelligent route decisions, circumvent congested parts, and embrace eco-routing strategies that will seek to reduce the consumption of energy rather than time. In freight, connectivity allows continuous tracking and movement of dispatch, which could decrease empty miles and enhance consolidation of loads. The mobility of passengers allows navigation services, real-time tolling interconnection, and communication with mobility platforms [52]. However, because connectivity can also reduce generalized travel costs by increasing convenience and reliability, it may stimulate additional travel demand. The environmental effect of connected vehicle systems, therefore, depends on whether connectivity is embedded in governance structures that internalize externalities and align individual optimization with system-level sustainability goals.

3.3. Automation, ADAS (Advanced Driver Assistance Systems), and Eco-Driving Control

Advanced driver-assistance systems and automation change the way vehicles are operated, with some systems being advisory systems that change human driver control, and others being automated control, which changes or fully removes human driver control. Green-wise, the technologies are often related to easier driving, better speed control, and less energy loss due to the elimination of rough acceleration and braking. Examples of such a category of eco-innovation include eco-driving support, predictive cruise control, and intelligent speed adaptation, which take advantage of control algorithms and anticipatory information to optimize energy use without necessarily altering the carrier of energy.

The major difference in the given category is between the automation that is performed at the individual vehicle level primarily and the one based on the global interaction of the system. Automation on the vehicle level may enhance efficiency by ensuring a smooth and efficient pattern of driving, but it is often constrained by the traffic and road environments, and when motorists take over. Greater benefits can arise when cooperative automation, including cooperative adaptive cruise control or vehicle platooning, is used to provide stable traffic flow and aerodynamic drag reduction among vehicle platoons that are closely spaced, particularly in freight transport. Such benefits, however, are subject to such variables as the level of adoption, the interactions between the automated and non-automated vehicles, and supportive infrastructure. Greater automation also brings more general behavioral and systemic issues: with travel becoming less uncomfortable and stress-inducing, individuals might decide to travel more or be further compensated by some of the efficiency benefits. In the end, automation of the environment is subject to environmental potential, which is pegged on balancing technological advances with careful demand management, pricing mechanisms, and planning provisions to avert such rebound effects [53].

3.4. AI-Enabled Optimization, Data Analytics, and Cyber-Physical Control

The development of smart vehicles is heavily influenced by artificial intelligence and the optimization of data, which is why the systems would be able to predict and adapt to the surroundings of the complex driving scenario and learn [54]. Within the context of sustainability studies, AI can be considered in two distinct perspectives, namely, as an internal layer on vehicles, which improves energy management, perception, and control, or as a systems layer on a wider level, where fleets, charging networks, and traffic can be coordinated. The most relevant eco-innovation process associated with AI is its capability to enhance efficiency in the context of uncertainty. The predictive models can predict the traffic pattern, driver behavior, weather, battery, and demand, making more intelligent decisions that reduce energy consumption and emissions than reactive ones [55].

The AI can be found inside the car to assist with predictive energy management, predicting battery health, estimating battery energy consumption along a route, and predictive thermal control. Such capabilities not only maximize the efficiency of the operation, but also increase the lifetime of the components, bridging the gap between the material benefits of increased durability and the material benefits of consuming less energy daily. On a fleet-level, AI aids in dispatch management, demand prediction, and dynamic rebalancing, which may decrease empty miles and augment utilization, especially in shared mobility and logistics. Nevertheless, AI also brings along with it its environmental considerations. The energy and hardware needs of sensing and computation, the lifecycle impact of the regular changes of sensors, and the hardware infrastructure of cloud services can be material at scale. The overall net sustainability of AI-enabled systems then lies in the question of whether the level of computational overhead is minimal compared to the operational savings, and whether the design of systems does not create obsolescence induced by hardware, which raises material throughput [56,57].

3.5. Smart Fleet Operations and Service-Based Mobility as Technology Bundles

Many of the strongest eco-innovation effects in transportation arise not from isolated vehicle technologies but from integrated operational models in which vehicles, platforms, and infrastructure function as a coordinated system. Fleet electrification combined with telematics, optimized routing, and managed charging exemplifies such a bundle, frequently delivering larger system-level benefits than any single component. In freight, integrated bundles can support load consolidation, warehouse coordination, dynamic routing, and driver behavior management. In transit, bundles can support energy-efficient scheduling, depot charging optimization, and real-time headway management. In ride-hailing and shared mobility, bundles can support pooling, dynamic pricing, and multimodal integration, though the sustainability outcomes depend strongly on platform incentives and regulatory constraints [58].

Service-based models also reshape the innovation locus from the vehicle product to the mobility function. When mobility is delivered as a service, environmental performance can improve through higher utilization and right-sizing of vehicles for trips, provided that the service reduces reliance on private vehicles and complements rather than substitutes for public transit and active modes. Conversely, if service models increase total vehicle kilometers traveled through empty repositioning, fragmented trip patterns, or substitution away from high-occupancy modes, environmental impacts can worsen. The eco-innovation relevance of service bundles, therefore, depends on governance, pricing, and integration with land-use and public transport systems. In this taxonomy, fleet and service bundles are treated as a distinct category because they operationalize smart vehicle capabilities at scale and make the sustainability outcome highly sensitive to institutional design. **Figure 2** provides a visual assessment of the smart vehicle technology taxonomy, illustrating how major technology groups relate to distinct eco-innovation pathways [47,59].

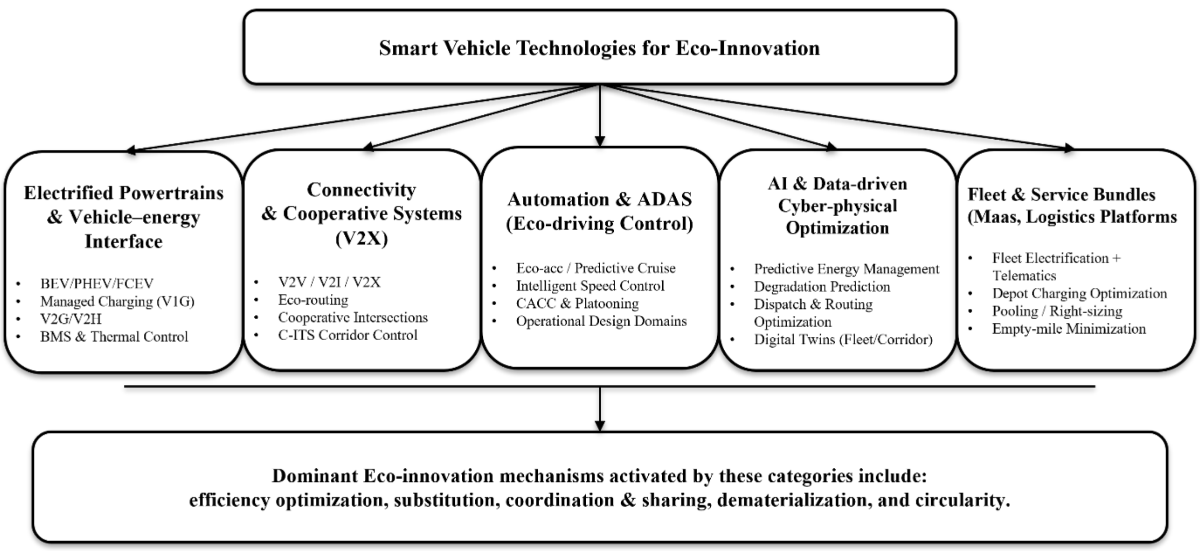

Figure 2. Taxonomy of smart vehicle technologies for eco-innovation, highlighting major technology categories, representative applications, and dominant innovation mechanisms.

3.6. Enabling Infrastructure and Interoperability Requirements

Although this review focuses on vehicle technologies, the taxonomy must explicitly acknowledge that many "smart" functions are inseparable from enabling infrastructure and interoperability standards. Vehicle electrification depends on charging networks and grid capacity; smart charging depends on communication protocols, metering, and pricing structures; V2X capabilities depend on roadside units, spectrum allocation, and cybersecurity; and automated driving depends on digital mapping, lane markings, and safety validation ecosystems. In eco-innovation terms, these infrastructure elements can be understood as complements that determine whether vehicle-level capabilities can translate into system-level environmental improvements [60].

Interoperability plays a particularly important role because eco-innovation benefits from coordination across diverse actors. Without interoperable standards, cooperative driving may remain fragmented, managed charging may be limited to proprietary ecosystems, and mobility platforms may be unable to coordinate efficiently with public infrastructure goals. Cybersecurity and privacy protection are also enabling conditions rather than peripheral concerns, because a lack of trust can suppress adoption and because security failures can undermine the reliability needed for cooperative efficiency gains. For this reason, the taxonomy treats enabling infrastructure and interoperability not as an external backdrop but as a core layer that conditions the effectiveness of smart vehicle eco-innovation pathways [61].

3.7. Implications of the Taxonomy for Subsequent Synthesis

The taxonomy identified in this section gives a uniform framework for synthesizing environmental evidence in Section 4 and analyzing scaling conditions in Section 5. The taxonomy can be used to assign the effects of technologies and to make more straightforward comparisons across research that applies dissimilar assessment techniques by categorizing technologies based on the ability and mechanism of eco-innovation [62]. This point of view also helps explain why the findings of the empirical studies tend to diverge. The same mechanism can cause mixed results based on the boundaries of a system or user behavior, whereas similar technologies might cause different mechanisms based on their implementation. The analysis of the rest of the review is developed according to this framework by connecting technological categories to the areas of the outcome and determining the contextual elements that influence overall environmental benefits and the research gaps that prevent the conclusion on the sustainability performance in real life. **Table 2** depicts a systematic taxonomy of smart vehicle technologies based on the core capabilities and eco-innovation pathways, which were revealed in the literature, forwarding representative implementations to predominant eco-innovation mechanisms and sustainability pathways. This taxonomy serves as a standard of reference for later interpretation of empirical evidence [63,64].

Table 2. Taxonomy of smart vehicle technologies and eco-innovation mechanisms.

Technology Category	Typical Implementations	Primary Eco-Innovation Mechanism(s)	Key Enabling Conditions	Dominant Sustainability Pathways
Electrified powertrains & vehicle–grid	BEV (Battery Electric Vehicle)/PHEV (Plug-in Hybrid Electric Vehicle)/FCEV (Fuel Cell Electric Vehicle); smart charging; V2G (Vehicle-to-Grid)/V2H (Vehicle-to-Home); BMS (Battery Management System)/TMS (Thermal Control System)	Substitution; efficiency optimization; system integration	Charging access; grid capacity; tariff design; standards	Tailpipe elimination; time-shifted low-carbon charging; reduced degradation
Connectivity & cooperation (V2X)	V2V (Vehicle-to-Vehicle)/V2I (Vehicle-to-Infrastructure); eco-routing; cooperative intersection; C-ITS (Cooperative Intelligent Transport Systems)	Coordination; utilization gains	Interoperability; roadside units; data governance; cybersecurity	Traffic smoothing; reduced idling; network-level efficiency
Automation & ADAS	Eco-ACC (Eco-Adaptive Cruise Control); PCC (Predictive Cruise Control); CACC (Cooperative Adaptive Cruise Control); platooning; automation levels	Efficiency optimization; coordination (at scale)	Mixed-fleet rules; safety validation; infrastructure quality	Smoother speed profiles; lower drag (platoons); possible induced demand

Table 2. *Cont.*

Technology Category	Typical Implementations	Primary Eco-Innovation Mechanism(s)	Key Enabling Conditions	Dominant Sustainability Pathways
AI/data-driven control	Predictive energy management; degradation prediction; dispatch optimization	Efficiency optimization; circularity support	Data access; model robustness; compute architecture	Reduced empty miles; extended component life; optimized charging/dispatch
Fleet/service bundles	Fleet electrification + telematics + routing + charging; MaaS (Mobility as a Service)/pooling	Coordination; dematerialization; utilization gains	Pricing; integration with transit; regulation	Higher occupancy/utilization; reduced redundant trips or increased empty miles

4. Environmental Sustainability Impacts and Evidence Synthesis

This section synthesizes the empirical and modeling evidence on how smart vehicle technologies influence environmental sustainability outcomes. The synthesis is organized by outcome domain rather than by technology category because different technologies often affect the same environmental indicator through distinct mechanisms, and because trade-offs across indicators are a defining feature of transportation eco-innovation. Across the literature, the most robust findings are those that specify system boundaries and contextual conditions clearly, since the same technology can yield opposite results under different electricity mixes, traffic states, adoption pathways, and behavioral responses. Accordingly, the synthesis emphasizes not only the direction of reported impacts, but also the conditions under which impacts are most consistently observed and the reasons for discrepancies across studies [65].

4.1. Climate and Energy Outcomes across Operational, Well-to-Wheel, and Life-Cycle Boundaries

Climate impacts are most frequently evaluated through changes in energy consumption and greenhouse gas emissions, but comparability depends on whether studies measure operational impacts only, well-to-wheel effects, or full life-cycle footprints. Operational assessments typically report energy use per vehicle-kilometer or fuel consumption changes attributable to control strategies such as eco-ADAS, predictive cruise, or cooperative driving. These studies often find measurable reductions in energy demand under conditions where speed variability and stop-and-go driving are major contributors to inefficiency. Benefits are generally amplified in congested or unstable traffic, where smoothing reduces frequent acceleration events, while gains are smaller on uncongested highways, where baseline driving is already steady [66].

When the boundary expands to well-to-wheel or full life-cycle, electrification and vehicle–grid coordination become central. The literature consistently shows that tailpipe emissions reductions from electrification are immediate and large in local terms, but net climate benefit depends on electricity generation carbon intensity, charging time profiles, and the marginal rather than average emissions of electricity supply. Managed charging is frequently identified as a leverage point because it can align demand with lower-carbon generation and reduce peak reliance on carbon-intensive peaking plants, although the magnitude of benefit varies with grid structure and pricing regimes. Conversely, unmanaged charging can shift emissions temporally without reducing them, and may increase system emissions if it exacerbates peak demand in regions where marginal generation is carbon-intensive. These findings highlight that it is not solely the efficiency of the various electrified vehicle drivetrains that dictate the environmental performance of these cars, but rather that the dynamics of the energy system and user charging habits co-determine the environmental performance of these vehicles [67].

According to life-cycle analysis, sometimes the manufacturing phase, particularly of batteries, can be a major part of the total climate footprint of a car. This is especially so in areas where power consumed during operation is already low-carbon, and those vehicles that cover relatively fewer kilometers in a year. Consequently, the fleet context is a significant factor: since high-use fleets can distribute manufacturing emissions across a large number of miles, leading to better overall life-cycle performance, whereas low-use personal cars are more likely to have a slower carbon payback.

The literature on the life-cycle also identifies some areas of improvement. It is possible to change the balance towards less environmental impact through extending battery life, improving recycling, and decreasing the quantity of raw materials needed. Smart battery control and predictive maintenance also lead to indirect gains through lessening degradation, enabling second-life applications, and delaying replacements, connecting digital control policies with climatic results of the life-cycle. The degree of this benefit, however, is determined by whether increased battery health in the field actually increases service life in the field or just permits increased usage that may increase overall travel and nullify some of the gains [68,69].

A recurring theme across climate studies is the importance of demand-side response. Many evaluations implicitly assume fixed travel demand, yet smart mobility can alter demand by changing generalized travel costs. Automation and platform-based services are the clearest sources of potential induced demand through improved comfort, reduced time costs, and the proliferation of empty repositioning trips. Studies that incorporate these behavioral dynamics often find that per-kilometer efficiency gains can be partially or fully offset at the system level if total vehicle kilometers traveled rise substantially. This does not imply that smart technologies are climate-negative by default, but it indicates that net climate outcomes depend on aligning technology deployment with complementary measures such as pricing, occupancy incentives, and integration with high-capacity public transport.

4.2. Air Quality and Exposure: Tailpipe, Non-Exhaust Emissions, and Spatial Distribution

The effects of air quality are commonly measured in terms of criteria pollutant emissions, e.g., nitrogen oxide and particulate matter, and in terms of exposure-oriented measures that indicate when and where the emissions take place. Electrification has the general impact of lowering tailpipe emissions and potentially producing significant co-benefits of local air quality, particularly in crowded urban or high-traffic settings. Current studies are pointing more and more to the fact that the effects of air quality are not only determined by the volume of pollution generated, but also by its location and distribution. Since emissions will no longer be tailpipe, but power plants, the impact of these emissions on the population will depend on the location of the power plants, the extent of emission control implemented by the power plants, the atmospheric conditions around the power plant, and the exposure of the immediate population. Literature review. Studies that consider non-vehicle emissions usually discover that urban air quality is enhanced through electrification, even with upstream emissions. The level of that improvement, however, differs greatly based on the electricity grid and the location of generation facilities [70].

Non-exhaust emissions, such as particles from brakes, tires, and road surfaces, have also become a major uncertainty and a potential trade-off. Regenerative braking can significantly reduce brake wear and its related particles, but the added weight of electric vehicles can lead to more tire and road wear, potentially offsetting some benefits. The overall balance depends on vehicle weight, driving patterns, and braking behavior. Smart control and traffic smoothing may reduce harsh braking events and could therefore reduce non-exhaust emissions in stop–go environments, but empirical evidence remains less consistent than for operational energy metrics because measuring non-exhaust emissions in real-world conditions is complex and standardized methods are still evolving. This is a central gap in the literature because non-exhaust particulate matter becomes relatively more important as tailpipe emissions decline [70].

For connected and automated systems, air quality outcomes often depend on traffic flow changes and route allocation. Speed harmonization, cooperative intersection management, and platooning can reduce idling and acceleration-related emissions, but benefits may be unevenly distributed spatially if routing optimization shifts traffic toward particular corridors. Freight optimization is a particularly salient case: reducing total mileage and improving load factors can lower emissions, yet changes in delivery routing and depot siting can concentrate exposures in specific neighborhoods. The literature increasingly calls for combining emissions modeling with exposure assessment to avoid characterizing air quality impacts solely through aggregate emissions totals.

4.3. Material Footprints, Resource Demand, and Circularity Outcomes

Material and resource impacts are central to evaluating whether smart vehicle technologies constitute eco-innovation rather than simple emission shifting. Electrification and digitalization introduce new material demands, including critical minerals for batteries and rare earth elements, and semiconductors for electronics and sensing. Life-cycle literature consistently identifies battery production as a hotspot for both greenhouse gas emissions and resource-related impacts, and it highlights supply risks and ethical concerns in upstream extraction. These concerns do not negate the sustainability potential of electrification but indicate that eco-innovation must include strategies for material efficiency, supply chain transparency, and end-of-life recovery [47].

The impacts of smart vehicle technologies on material footprints are interrelated in a number of ways. Firstly, enhanced battery management, thermal control, and predictive maintenance would be able to prolong the life of critical parts, which reduces replacement and total material consumption. Condition-based maintenance is also possible because of connectivity and sophisticated diagnostics; that is, parts are replaced only when they are needed, no unnecessary waste is generated, and remanufacturing can also be supported. Moreover, the software-defined vehicle architectures can reduce the frequency of hardware improvements, as they can be enhanced with new features by software modifications instead of physical modifications.

Simultaneously, conflicting forces are mentioned in the literature. The constant demand for a stronger sensing and computing ability, especially to assist a higher degree of automation, may heighten the number and complexity of electronic parts. This tendency can contribute to the accelerated hardware replacement with the development of sensor technologies. If business models continue to promote frequent hardware refreshes, overall material impacts could rise even as vehicles become more energy efficient. Circularity outcomes are, therefore, highly contingent on governance and design choices. Studies that model high recycling rates, effective second-life battery pathways, and design-for-disassembly assumptions tend to report substantially improved life-cycle sustainability metrics. In contrast, pessimistic assumptions about recycling efficiency, second-life feasibility, or collection rates can reduce the net benefit of electrified and digitally intensive vehicle systems. The evidence suggests that circularity is not a passive consequence of technological change but a co-designed system outcome that requires standards, reverse logistics infrastructure, and market mechanisms for recovered materials [47,71].

Equity and distributional effects remain critical considerations in evaluating the sustainability of smart vehicle technologies. Although limited, emerging evidence highlights several patterns. Access to AV (autonomous vehicle) and shared mobility services often favours urban, higher-income populations, potentially exacerbating mobility inequities, while suburban and low-income communities may experience reduced accessibility. Shared mobility services can deliver environmental benefits unevenly, with air quality improvements concentrated in higher-density urban areas. Additionally, incentive programs such as tax credits or subsidies may disproportionately benefit wealthier early adopters, underscoring the need for equity-sensitive policy design. Integrating these considerations into environmental assessments is essential to ensure that the deployment of smart vehicle technologies does not inadvertently reinforce existing social disparities. Notably, cities such as Los Angeles and New York have begun pilot programs to monitor equity impacts, providing preliminary lessons for inclusive mobility governance.

4.4. Noise, Congestion, and Broader Urban Environmental Quality

Noise and congestion are often treated as secondary outcomes, yet they meaningfully shape urban environmental quality and public acceptance. Electrified vehicles generally reduce powertrain noise at low speeds, which can improve urban soundscapes, although at higher speeds, tire–road noise dominates and the advantage diminishes. The literature also notes a safety-related dimension, since lower noise can increase risk for pedestrians and cyclists in certain contexts, leading to acoustic vehicle alert system requirements that may reduce noise benefits. Consequently, noise outcomes depend on speed distribution, street design, and the specific acoustic profiles mandated by regulation [72,73].

Congestion-related impacts are closely tied to connected and automated driving claims. Traffic smoothing through cooperative adaptive cruise control, platooning, and coordinated signal timing can reduce stop–go conditions and stabilize flow, producing energy and emissions co-benefits. However, congestion impacts are not uniformly positive. If automation increases road capacity, it can reduce congestion in the short run but may induce additional travel demand over time, eroding both congestion relief and environmental gains. Platform-based mobility services can also change congestion patterns by adding circulating vehicles and repositioning trips, even as they increase convenience. The evidence therefore suggests that smart vehicle technologies can improve traffic efficiency but that long-run outcomes depend on whether demand growth is managed through pricing, curb management, occupancy incentives, and land-use alignment.

Urban environmental quality also includes safety and public realm impacts. Some studies treat safety improvements as a co-benefit that can enable shifts to active modes if streets become safer, while others warn that increased vehicle dominance can suppress walking and cycling. Although safety is not an environmental indicator in a narrow sense, it interacts with sustainability through mode choice and through the political feasibility of reallocating street space to low-carbon mobility. In this sense, eco-innovation in transportation is as much about shaping the mobility ecosystem as it is about improving vehicle efficiency [74].

4.5. Trade-Offs, Rebound Effects, and Uncertainty Drivers

Across outcome areas, trade-offs and rebound effects consistently emerge as key reasons why studies reach different conclusions. Rebound effects occur when efficiency gains lower the effective cost of travel, leading to increased mobility that partially offsets emissions reductions. In the context of smart vehicles, these effects can take several forms: more travel due to greater comfort or productivity in automated vehicles, higher vehicle availability and ease of use through on-demand platforms, and expanded freight activity made possible by lower delivery costs. The most significant change is the emergence of empty miles; that is, car journeys with no passengers or cargo (e.g., repositioning in ride-hailing fleets, deadheading in freight, or zero-occupancy travel in autonomous transport) [75]. The studies that consider those empty miles usually indicate vastly different emission results of a system on a system-wide basis than results of studies that simply consider the per-trip efficiency.

The unpredictability of the outcomes is also enhanced by variations in the modeling assumptions and the fast-changing technology and energy systems. The success of the outcomes is largely influenced by the quality of cooperative systems adoption, the ability to adapt behavior fast, the quality of grid decarbonization, and battery manufacturing and recycling. Results can also change based on methodological decisions, e.g., baseline definition, functional unit, and geographic scope, sometimes turning a net effect into positive or negative. All these findings point to the significance of transparent reporting and integrated assessment systems that would attach life-cycle analysis to system-level travel demand and exposure modeling [76].

4.6. Integrative Interpretation and Implications for Evidence Mapping

When the evidence is interpreted through an eco-innovation lens, several integrative conclusions emerge. Technologies that directly improve operational efficiency, such as eco-driving control and traffic smoothing, tend to yield relatively consistent per-vehicle energy savings but smaller absolute climate impacts unless deployed at scale and paired with broader decarbonization of energy supply. Electrification tends to deliver strong local air quality benefits and, in most contexts, substantial climate benefits, but its life-cycle performance is highly sensitive to energy and material system conditions, making smart charging and circularity strategies essential complements. Connectivity and AI-driven optimization can generate system-level gains through coordination and utilization improvements, especially in fleets and logistics, yet they also create pathways for increased travel demand and spatial redistribution of externalities. Automation has the widest range of projected outcomes: it can support smoother driving and safer roads, but it also poses the greatest rebound risk if it reduces travel costs and enables large volumes of low-occupancy or empty travel [77,78].

These patterns motivate the structure of the subsequent section on enablers and barriers. The literature suggests that the environmental sustainability of smart vehicle technologies is not only a question of technical performance but also of governance, infrastructure, and market design that determine whether eco-innovation mechanisms translate into net system benefits. Section 5, therefore, examines the policy, infrastructure, adoption, and measurement conditions that appear most decisive in turning smart vehicle capabilities into scalable and equitable environmental outcomes [79]. To synthesize the heterogeneous findings across outcome domains and system boundaries, **Table 3** summarizes the direction, consistency, and contextual sensitivity of reported environmental impacts for each technology category.

Table 3. Evidence matrix linking technologies to environmental outcomes (with confidence and boundary conditions).

Technology Category	Climate (GHG)	Energy Use	Air Quality	Noise/Urban Quality	Materials/Circularity	Main Boundary Conditions and Moderators
Electrification & vehicle–grid	Net ↓ (context-dependent)	↓	Tailpipe ↓; upstream varies	Low-speed ↓	Mixed: ↑ materials; circularity can ↓	Grid carbon intensity (marginal/time-varying), charging timing, battery production, recycling rates, vehicle utilization
Connectivity & cooperation (V2X)	↓ (often non-linear)	↓	↓ via smoother traffic	Contextual	Neutral to mixed	Penetration thresholds, interoperability, corridor design, routing spillovers, induced demand risk
Automation & ADAS	Uncertain (↓ per-km; ↑ VKT—vehicle kilometers traveled, possible)	↓ per-km	Mixed	Mixed	↑ sensors/compute possible	Induced demand, empty travel, mode substitution, operational design domain, fleet composition
AI & optimization	↓ (stronger in fleets)	↓	↓ If VKT/idle is reduced	Contextual	Potential ↓ via life extension	Data access, model quality, organizational adoption, compute overhead, hardware upgrade cycles
Fleet/service bundles	Strongly context-dependent	Mixed to ↓	Mixed to ↓	Mixed	Mixed	Pricing, pooling rates, empty miles, integration with transit, regulation, demand growth

5. Enablers, Barriers, and Governance for Scaling Eco-Innovation

Synthesized evidence in Section 4 suggests that smart vehicle technologies can be used to promote environmental sustainability, though actualized gains are much dependent on the context of deployment and institutional circumstances that define the beginning, operation, and integration of systems. Transportation eco-innovation is not solely an issue of technological performance; rather, it is a socio-technical change that requires combined effort on the part of public policy, investment in infrastructure, market creation, organizational capacity, and behavioral legitimation. This section summarizes the key enablers and obstacles that are repeated throughout the literature and how governance set-ups can result in either a net environmental benefit at scale, given smart vehicle capabilities [80–83].

5.1. Policy and Regulatory Frameworks Shaping Environmental Outcomes

The role of policy in the realization of whether smart vehicle innovation would result in actual eco-innovation is central since it limits the technological advance on the way it is moving, as well as the context within which these technologies are applied [84]. Emissions of vehicles and fuel consumption, zero-emission vehicle requirements, and carbon pricing systems can all help to direct markets to electrified powertrains and to promote the elimination of high-emission vehicles. But once policies are too narrow on tailpipe emissions, they may have the impact of generating biased incentives that fail to consider upstream electricity generation emissions, non-exempt particulate emissions, and a larger burden of material life-cycle. The recent literature, in turn, recommends policy frameworks, which clearly state boundaries of the system and initiate such measures as incentives to controlled charging, mandatory consideration of the life-cycle impacts, and such standards, which would encourage durability and repairability of products instead of the quick hardware replacement [85].

In the case of connected and cooperative systems, regulatory frameworks can apply to both technical feasibility and environmental performance. The choices of the spectrum distribution, the standards of communications, and data-sharing regulations define whether cars and infrastructure can organize their work successfully. Unless there are clear interoperability requirements, market fragmentation will ruin any potential efficiencies and entrap gains within proprietary ecosystems. Cybersecurity and safety policies are also important in developing the trust of the people, which is a critical factor that is known to influence adoption rates and the magnitude required to provide cooperative systems with network-level beneficial environmental results. The policy issues within the automation field go beyond this to liability, certification issues, and limitations in operations. The impact of these governance structures on the speed of the adoption of automated technologies and the usage of these technologies directly impacts the trends in low-occupancy travel or vehicle repositioning, which can erode sustainability objectives [86,87].

Another policy aspect is the management of the total travel demand. Since the efficiency benefits of smart vehicles can be rebounded, the environmental benefits of smart vehicles frequently rely on strategies to minimize unnecessary travel and promote increased occupancy. Pricing of congestion, curb space management, low-emission zones, parking reform, and incentives to shared or multimodal transport are commonly mentioned as effective supplements. The technology policy and demand management interaction is of particular concern to platform-based and even potential autonomous mobility services, where the growth due to convenience might otherwise surpass system-level sustainability benefits.

5.2. Infrastructure Readiness and System Integration Constraints

Infrastructure can be viewed as a fundamental backbone of smart vehicle technologies, as well as a possible chokepoint that can reduce their uptake or change their effect on the environment [88]. The availability, reliability, and geographic dispersion of charging stations have a strong impact on both consumer acceptance and fleet transition decisions in the case of electrification. However, the issue is not as simple as the installation of chargers. The voltage of the grid and local distribution capacity are what determine the potential of electrification, resulting in more actual cleaner energy consumption or, instead, a redistribution of demand to the carbon-intensive peak generating stations. Surveys are pointing towards the necessity of ensuring that the planning of charging infrastructure is made coherent with the rest of the power system planning, with an important focus on the concentration of electrified fleets around depots and logistics hubs. Stressors such as managed charging, demand response, and on-site generation of renewable energy can assist in alleviating these strains, although they depend on hardware, software, and institutional alignment that is uneven among regions [89].

Connectivity and cooperative driving require both digital and physical infrastructure, roadside units, communication networks, and effective maintenance systems, with the help of stable roadway conditions. Sensing and control systems are not reliable in a lot of places due to the decayed lane markings, uncoordinated signage, and unmatched coordination of the traffic lights. Due to this, the environmental payoffs observed in pilot-programmed controlled environments might not be readily scaled unless there is massive roadway modernization. This brings in equity and governance issues, as the upgrades to infrastructure are expensive and can be clustered in different regions; they may put benefits in richer areas or on other freight corridors that are given priorities due to economic, rather than environmental, factors [90].

Institutional interoperability is also required to carry out system integration. The providers, manufacturers of vehicles, utilities, and mobility platforms often have different objectives, infrastructures, and data systems. In the absence of a common set of standards and governance structures, system-wide coordination opportunities are limited, and the results are locally optimized but globally inefficient. More and more interoperability per se is recognized in the literature as a pillar to sustainability, and as such, all coordination-based eco-innovations, such as cooperative speed harmonization, optimal charging, and efficient fleet dispatching, can be effective across multiple actors and networks [91].

5.3. Market Adoption Dynamics and Organizational Capabilities

Scalability of eco-innovation relies on the methods of the diffusion of technologies in markets and organizations, and whether this diffusion maintains or increases environmental advantages. The overall cost of ownership is also one of the key variables when it comes to electrification, particularly in connection with fleets that have foreseeable routes and are used extensively. Such savings in fuel and maintenance can be used to counter increased upfront expenditures. Nonetheless, large-scale implementations are usually hindered by the uncertainty regarding the residual value, battery deterioration, charging battery delays, and the dependability of the existing infrastructure. Such risks can hold transitions up even when it is evident that they will benefit the environment. Individual preferences, perceived risk, and information gaps are the determinants of adoption in consumer markets, whereas the factors influencing adoption in fleets are the procurement cycles, operational constraints, and risk management capacity [92].

In the case of connected and automated systems, the adoption is based on trust, which is typically based on the safety, reliability, and usefulness, as well as the integration with existing workflows. When these systems can be incorporated into performance management systems and provide quantifiable savings, fleet operators are more likely to accept technologies such as telematics, eco-driving assistance, and routing optimization. However, the transition may pose the following organizational issues, such as opposition to change by drivers, labor issues, and additional experience requirements in data analytics and cybersecurity. Studies are also beginning to indicate that organizational capability, i.e., data use, change management, and partnership management skills are a silent factor in whether intelligent technologies become sustainable eco-innovations or isolated pilot projects.

Mobility services based on platforms make everything more complicated. Since platforms are market share-driven and performance-based on service, their effect on the environment is highly centered on pricing systems and regulation policies. In the absence of incentives, platforms may drive up the number of kilometers covered by vehicles by over-supply, empty seats, and competing with transit. Nonetheless, policies to pool, combine platforms with established transit, and the external cost in terms of prices can contribute to changing travel to low-carbon modes and increased use. The bigger point here is that market adoption in itself is not a guarantee of eco-innovation, and efficient incentive regimes and governance mechanisms are needed to match the technological development with the sustainability objectives [93].

5.4. Behavioral Responses, Acceptability, and Distributional Considerations

Human behavior forms a very critical direct connection between technological potential and environmental outcome. Any technological advancements that make travel more comfortable, reduce the uncertainty of travel time, or enable individuals to utilize the time spent on traveling can contribute to an increase in travel involuntarily by reducing the perceived cost of travel. Efficiency gains can be compensated to some extent by this growth in demand. Behavior further determines the effects of electrification, by charging habits, route choice, and openness towards participating in managed charging schemes. Studies continue to discover that even managed charging incentives that are well designed can fail in cases where the end user perceives them as a hassle, or where there is a lack of trust in utilities and information systems. Similarly, eco-driving systems have the potential to produce quantifiable energy savings, although their effectiveness over the long term will depend on how drivers react to the feedback, whether incentives are consistent with their motivation, and whether the organizations will promote a culture that will help maintain the change in behavior [94].

Equity is directly related to acceptability. The advantages of smart vehicle systems frequently benefit early adopters, who tend to be wealthier, whereas the downsides of infrastructure disturbances, spillover effects on traffic, or even proximity to freight operations are likely to endanger underprivileged groups out of proportion. As much as electrification is inclined towards air quality in urban centers, the upsurge in effects in mining and manufacturing are often found in areas that have weaker environmental protection. Also, mobile-driven systems generate privacy and surveillance issues that can have a higher burden on the marginalized. This is why there is a growing need in the literature to have eco-innovation evaluations that contain equity-sensitive measures that describe who gains, who incurs the expenses, and how the infrastructure and data decisions are managed [95].

Public acceptance is also influenced by the workforce. The automation and platform-based business model are changing the working conditions of drivers and logistics workers, which are posing new social and economic issues. When these changes are viewed as a threat to livelihoods, they can be met with resistance, slackening the adoption of technology or leading to regulatory backlash. On the other hand, transition policies that put more emphasis on training of workers, labor protection, and involving all stakeholders can enhance legitimacy and assist in increasing the adoption of innovations that can be of benefit to the environment [96].

5.5. Data Governance, Cybersecurity, and Trust as Enabling Conditions

A great number of intelligent vehicle eco-innovations rely on the successful data exchange and on-the-fly coordination. Data governance, literally, the policies that regulate access to which data, under what circumstances, and with what responsibility, can therefore be essential. The full potential of connected mobility is beyond reach without definite mechanisms that will ensure privacy, commercial confidentiality, and social good are balanced. As it is observed consistently, decentralized ownership of data and proprietary platforms may impede the cooperation of traffic management, coordinate charging strategies, and interconnected multimodal planning. Instead, these efficiencies can be transformed through a well-designed data governance model like data trusts, standardized APIs (Application Programming Interface), or public-private data partnerships that do not affect the required protections and safeguards.

Cybersecurity is also an essential prerequisite and not a fringe technical issue. The security breaches may undermine security by interfering with the operation of vital mobility services and destroying the confidence of the people. Environmentally, poor cybersecurity will hinder the implementation of connected systems to allow network-level efficiency gains. Furthermore, security standards affect the design of hardware and software architecture, determining the material and energy consumption throughout the life cycle. Such strategies as security-by-design, reporting of their incidents, and powerful certification systems can thus be perceived as facilitators of sustainability, as they will assist in making sure that digital coordination infrastructure is not only secure, but scalable and contributes to the stable deployment of eco-innovations [97].

5.6. Measurement, Reporting, and Standardization Challenges in Scaling Evaluations

More than massive implementation is needed to scale smart vehicle eco-innovation, but it also needs stable methods of measuring environmental performance and utilizing that data to inform policy and investment. One of the ongoing problems with the literature is the inability to provide standard measures and reporting practices that would allow researchers to make their studies comparable and synthesize significant results. The variation in defining functional units, baselines, and boundaries of researchers makes results difficult to interpret and may allow people to use only positive results. Even in the studies of electrification, such as how to treat grid emissions (average versus marginal, or static versus time-varying), one can get quite different conclusions depending on whether to treat the results as average or marginal. To enable automation and connectivity, the assumptions regarding the saturation of technology, driver habits, and the initial traffic state can change the outcomes of reported findings to negative. Equally, the non-uniformity in the accounting of empty miles and induced demand during the fleet and platform analysis persists in compromising comparability among the studies [98].

To fill in these gaps, the increased disclosure of assumptions and systematic sensitivity analyses is demanded by numerous researchers nowadays. There is an increased recommendation of hybrid assessment methods that combine the life-cycle assessment with real-life operational data. Natural and quasi-experimental designs can be particularly effective in testing platform and policy interventions, whereas long-term field trials are important in testing cooperative and automated systems. However, one of the most challenging governance restrictions is access to data. Even the data from most of the operations is in the possession of private companies, and the public agencies do not usually have the authority, infrastructure, or technical capacity to access and analyze the data. It implies that measurement standardization efforts and data governance should be co-led: in the absence of powerful institutions to facilitate data sharing, transparency, and open approaches, scaling decisions could be informed by incomplete evidence or short-term measures of performance.

In the literature, a general trend can be found whereby smart vehicle technologies can only be regarded as true eco-innovations when they are implemented as a system-level approach. The local benefits of electrification are most easily and tangibly immediate, though to achieve its full climate potential, one should think of managed charging, decarbonization of the grid, and material circularity. The ability to be connected and use data to achieve higher efficiency through better coordination and utilization requires these to be interoperable, data governance to be strong, and investments in supporting infrastructure. Automation offers highly efficient opportunities but also has serious rebound risks, and demand control, occupancy rewarding, and functional restraint are essential to achieving sustainable results. Fleet and platform-based models are scalable and potentially create systemic benefits, yet raise the significance of governance- since platform incentives are equally likely to expand as well as diminish aggregate vehicle activity and environmental externalities. This scaling pathway is outlined in **Figure 3** with a major focus on the most salient governance and system levers that can define whether smart vehicle innovations will result in long-term environmental benefits [9].

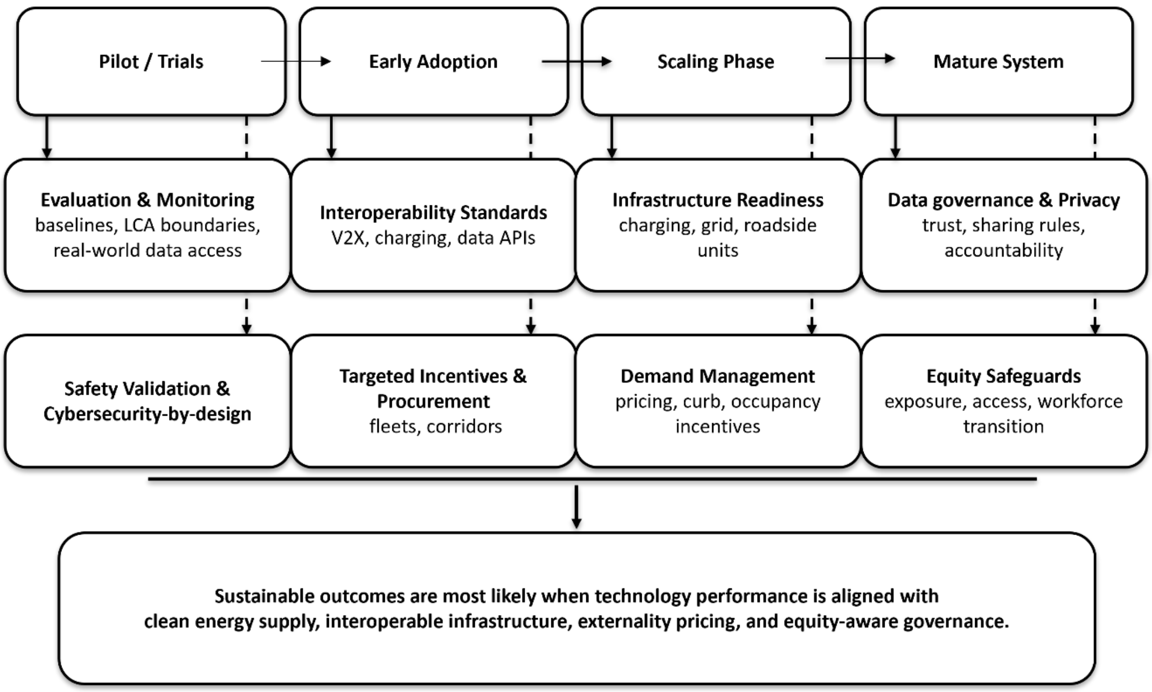

Figure 3. Conceptual pathway from pilot deployment to system-scale adoption of smart vehicle technologies, showing key governance, infrastructure, and market levers shaping environmental outcomes.

These conclusions imply that the policy and technology must go through a transformation in unison and not independently. Sustainable scaling requires that both governance systems and technological systems are designed simultaneously, the behavior is expected to rise in response, it is ensured that there is definite accountability regarding system-wide effects, and market incentives are aligned with performance on the environment, both on a life-cycle basis and on an exposure basis. To support the sustainable deployment of smart vehicle technologies, **Table 4** provides practical recommendations across policy, infrastructure, market adoption, and measurement domains. These recommendations are complemented with illustrative examples of successful implementations. For instance, market adoption can be accelerated through targeted incentives such as Norway's electric vehicle purchase subsidies, which have led to EVs representing over 80% of new car sales in certain regions. Infrastructure readiness is exemplified by the Netherlands' nationwide smart-charging network, which ensures high interoperability and grid optimization. Policy interventions such as London's low-emission zones demonstrate how regulatory frameworks can reduce urban emissions while encouraging adoption of clean vehicle technologies. Finally, for measurement and monitoring, cities like Singapore and Los Angeles have implemented real-time air quality monitoring coupled with mobility data to evaluate the environmental outcomes of smart mobility interventions. These examples provide actionable guidance for cities and governments seeking to operationalize recommendations [98–101].

Table 4. Recommendations for sustainable deployment of smart vehicle technologies, supplemented with illustrative examples of successful policies, infrastructure initiatives, market adoption strategies, measurement practices, and equity-focused interventions.

Domain	Key Recommendations	Actionable Examples/Implementation
Policy & Governance	Establish regulatory frameworks, incentives, and standards for deployment	London's Low-Emission Zone; Singapore's AV pilot regulatory framework
Infrastructure	Deploy interoperable charging networks, V2X communication, and smart-grid integration	Netherlands smart-charging network; California EV charging corridors
Market Adoption	Encourage adoption through subsidies, procurement programs, and public-private partnerships	Norway EV purchase subsidies; municipal fleet electrification in Shenzhen
Measurement & Monitoring	Implement real-time emissions and mobility monitoring for evaluation	Singapore urban mobility dashboards; Los Angeles air quality monitoring linked to shared mobility usage
Equity Considerations	Design incentives and deployment strategies to ensure inclusive access	Pilot programs monitoring AV access in low-income neighborhoods; fare integration for underserved communities

6. Conclusion

This review set out to clarify how eco-innovation in transportation can be advanced by smart vehicle technologies, and under what conditions these technologies translate into measurable environmental sustainability gains. Across electrification, connectivity, automation, and AI-enabled optimization, the evidence indicates that "smartness" is best understood as a set of enabling capabilities, sensing, communication, prediction, and control—rather than as a guarantee of sustainability. Environmental outcomes are shaped by the eco-innovation mechanisms these capabilities activate, the boundaries used to evaluate impacts, and the socio-technical context in which technologies diffuse.

Several synthesis insights emerge consistently from the literature. First, electrification remains the most direct route to large local environmental co-benefits through elimination of tailpipe emissions, and in most contexts, it offers substantial climate advantages as grids decarbonize. However, the magnitude and robustness of climate benefit depend on upstream electricity dynamics, charging behavior, and life-cycle factors, especially battery production and end-of-life management. Smart charging, vehicle–grid integration, and battery health optimization, therefore, function as core eco-innovation complements to electrified powertrains rather than optional add-ons. Second, connected vehicle technologies and cooperative systems tend to generate environmental benefits primarily through coordination mechanisms that reduce stop–and–go traffic, improve routing, and support higher utilization in fleet operations. These gains are most credible when evaluations account for penetration thresholds, mixed-fleet interactions, and spatial redistribution effects, since coordination benefits are often non-linear and can be unevenly distributed across corridors and communities. Third, automation and advanced driver assistance can improve energy efficiency through smoother control and can deliver important safety co-benefits, but they also introduce the widest uncertainty in net environmental outcomes because of induced demand and empty travel. Without demand management, occupancy incentives, and operational constraints, rebound effects can erode or overwhelm per-vehicle efficiency improvements. Fourth, AI and data-driven optimization can strengthen eco-innovation by improving predictive control, maintenance, and dispatch efficiency, especially in high-utilization fleets, yet net benefits depend on whether computational and hardware overhead remain modest relative to operational savings and whether design choices avoid accelerating obsolescence and material throughput.

A cross-cutting conclusion is that eco-innovation in smart mobility is most effective when technologies are deployed as coordinated bundles that link vehicles, infrastructure, and institutions. The strongest evidence for durable sustainability improvement appears in contexts where (i) clean energy supply and managed charging align vehicle electrification with low-carbon electricity, (ii) interoperable connectivity enables system-level coordination rather than isolated optimization, (iii) governance frameworks price or constrain externalities to prevent induced travel from dominating outcomes, and (iv) circularity strategies and durability-oriented design reduce material burdens associated with batteries and electronics. Conversely, environmental performance is most fragile when studies or deployments narrow the assessment boundary to tailpipe or per-vehicle metrics, treat travel demand as fixed, or overlook the spatial distribution of impacts and exposure.

The review reveals that there are a number of persistent gaps that restrain scientific agreement as well as confidence in policymaking. The empirical base is still uneven in terms of regions and modes of transport, and the research environment is still mostly characterized by simulations and small-scale pilots, but not long-term and real-life assessments. Comparability is also limited by inconsistent reporting of the important parameters, including (but not limited to) functional units, baseline definitions, and boundary conditions, particularly those of grid emissions (average versus marginal, static versus time-varying), non-exhaust PM (Particulate Matter), and empty mileage, attributed to platform-based mobility. The importance of material and circularity has become a fundamental component of sustainability evaluation, but there is a lack of reliable and standardized information about battery supply chains, recycling efficiency, and the obsolescence of electronic parts. Moreover, equity and distributional effects are recognized, although they are not formally integrated in environmental analysis, and even though they are critical to legitimacy and clarity in terms of who gains and who incurs costs.

These gaps in evidence lead to an evident research and practice agenda. Further research needs to implement combined appraisal frameworks connecting life-cycle assessment with system-level travel demand and traffic modelling, and clearly capture behavioral and rebound effects, and broaden air quality analysis to encompass exposure-based and non-exhaust emissions. The field would also be methodologically improved by the use of standard reporting conventions, open and reproducible tools and shared datasets that can allow meaningful cross-study comparison, without breaching privacy protection. Practically, governance and infrastructure should not be seen by policy-makers and industry leaders as peripheral aspects of eco-innovation, but rather as core elements. The role of managed charging programs, interoperability standards, cybersecurity and data governance systems, demand management measures, and their applicability have crucial roles to play in ultimate environmental outcomes. Equity-sensitive planning that is based on distributional metrics, community engagement, and transition support of the workforce should be built in at the initiation so that sustainability gains would be long-term and socially appropriate.

To sum up, intelligent vehicle technologies have immense opportunities to hasten environmental sustainability, although only in the case of their development and implementation along specific eco-innovation trajectories, balancing technical capacity to clean energy systems with coordinated infrastructures and prudent governance. The move to sustainable mobility is not a mere issue of replacing smarter vehicles into already existing tendencies; it is a more profound change whereby vehicles, infrastructure, markets, and institutions are co-evolving. To realize such a change requires the shift of a limited efficiency agenda towards coordinated, open, equity-based approaches to change that can convert technological advancements into testable, system-wide environmental benefits.

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Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Novizayanti, D., Prasetio, E.A., 2021. Orchestrating innovation network: Case of sustainable transportation technology. International Journal of Sustainable Transportation Technology. 4(1), 35–41.

[2] Liu, J., Meng, H., Xu, H., et al., 2025. Economic–environmental coordination and influencing factors under dual-carbon goal: A spatial empirical evidence from China's transport sector. Environment, Development and Sustainability. 27(1), 531–569.

[3] Rehman Khan, S.A., Ahmad, Z., Sheikh, A.A., et al., 2022. Digital transformation, smart technologies, and eco-innovation are paving the way toward sustainable supply chain performance. Science Progress. 105(4), 00368504221145648.

[4] Sharma, B., Gupta, M., Jeon, G., 2024. Smart Cities: Blockchain, AI, and Advanced Computing. CRC Press: Boca Raton, FL, USA.

[5] Ankathi, S.K., Bouchard, J., He, X., 2024. Beyond tailpipe emissions: Life cycle assessment unravels battery's carbon footprint in electric vehicles. World Electric Vehicle Journal. 15(6), 245.

[6] Kannangara, M., Bensebaa, F., Vasudev, M., 2021. An adaptable life cycle greenhouse gas emissions assessment framework for electric, hybrid, fuel cell and conventional vehicles: Effect of electricity mix, mileage, battery capacity and battery chemistry in the context of Canada. Journal of Cleaner Production. 317, 128394.

[7] Xue, X., Yan, Z., Prada, D.N., et al., 2025. Life Cycle Economic and Environmental Assessment for Emerging Heavy-Duty Truck Powertrain Technologies in China: A Comparative Study of Battery Electric, Fuel Cell Electric, and Hydrogen Combustion Engine Trucks. Environmental Science & Technology. 59(4), 2018–2030.

[8] Abdelkader, G., Elgazzar, K., Khamis, A., 2021. Connected vehicles: Technology review, state of the art, challenges and opportunities. Sensors. 21(22), 7712.

[9] Taiebat, M., Brown, A.L., Safford, H.R., et al., 2018. A review on energy, environmental, and sustainability implications of connected and automated vehicles. Environmental Science & Technology. 52(20), 11449–11465.

[10] Aldhanhani, T., Abraham, A., Hamidouche, W., et al., 2024. Future trends in smart green IoV: Vehicle-to-everything in the era of electric vehicles. IEEE Open Journal of Vehicular Technology. 5, 278–297.

[11] Hossain, M.S., Kumar, L., Haj Assad, M.E., et al., 2022. Advancements and future prospects of electric vehicle technologies: A comprehensive review. Complexity. 2022(1), 3304796.

[12] Das, P.K., Bhat, M.Y., Sajith, S., 2024. Life cycle assessment of electric vehicles: A systematic review of literature. Environmental Science and Pollution Research. 31(1), 73–89.

[13] Roy, S., Majumder, S., De, K., et al., 2025. Electric Vehicles and Environmental Sustainability: Integrating Material, Energy, and Emission Flows in a System-Level LCA. Sustainable Development. 34(1), 851–872.

[14] Rajagopal, 2020. Eco-Innovation and technology. In Sustainable Businesses in Developing Economies: Socio-Economic and Governance Perspectives. Palgrave Macmillan: Cham, Switzerland. pp. 203–233.

[15] Liu, Z., Han, S., Yao, M., et al., 2023. Exploring drivers of eco-innovation in manufacturing firms' circular economy transition: An awareness, motivation, capability perspective. Annals of Operations Research. 355, 147–182.

[16] Rabuni, M.F., Hizaddin, H.F., Hashim, N.A., 2025. Hydrogen as a clean energy carrier—Transitioning to low-carbon economies. In: Kurniawan, T.A., Prasad, M.N.V. (Eds.). Accelerating the Transition to a Hydrogen Economy. Elsevier: Amsterdam, The Netherlands. pp. 177–208.

[17] Zhao, Y., Pohl, O., Bhatt, A.I., et al., 2021. A review on battery market trends, second-life reuse, and recycling. Sustainable Chemistry. 2(1), 167–205.

[18] Cheng, L., Tan, C., Meng, X., et al., 2025. Evolutionary Game Theory for Sustainable Energy Systems: Strategic Bidding, Carbon Pricing, and Policy Optimization for Clean Energy Development. Smart Energy System Research. 1(2), 10006.

[19] Mueller, K.L., Lauvaux, T., Gurney, K.R., et al., 2021. An emerging GHG estimation approach can help cities achieve their climate and sustainability goals. Environmental Research Letters. 16(8),

084003.
[20] Carnevale, C., Ferrari, F., Guariso, G., et al., 2018. Assessing the economic and environmental sustainability of a regional air quality plan. Sustainability. 10(10), 3568.
[21] Yang, Z., Huang, H., Lin, F., 2022. Sustainable electric vehicle batteries for a sustainable world: Perspectives on battery cathodes, environment, supply chain, manufacturing, life cycle, and policy. Advanced Energy Materials. 12(26), 2200383.
[22] Lyu, W., Hu, Y., Liu, J., et al., 2024. Impact of battery electric vehicle usage on air quality in three Chinese first-tier cities. Scientific Reports. 14(1), 21.
[23] Liang, X., Zhang, S., Wu, Y., et al., 2019. Air quality and health benefits from fleet electrification in China. Nature Sustainability. 2(10), 962–971.
[24] Vegni, A.M., Biagi, M., Cusani, R., 2013. Smart Vehicles, Technologies and Main Applications. In: Galati Giordano, L., Reggiani, L. (Eds.). Vehicular Technologies: Deployment and Applications. InTechopen: London, UK.
[25] Indiran, L., Fu, C., Fahim, N.A., et al., 2025. Eco-innovation methodologies: A literature review. Discover Sustainability. 6(1), 1143.
[26] Díaz-García, C., González-Moreno, Á., Sáez-Martínez, F.J., 2015. Eco-innovation: Insights from a literature review. Innovation. 17(1), 6–23.
[27] Vermesan, O., John, R., Pype, P., et al., 2021. Automotive intelligence embedded in electric connected autonomous and shared vehicles technology for sustainable green mobility. Frontiers in Future Transportation. 2, 688482.
[28] Nanan, P.B., Annapareddy, V.N., Komaragiri, B.V., et al., 2022. Emerging Technologies in Smart Computing, Sustainable Energy, and Next-Generation Mobility: Enhancing Digital Infrastructure, Secure Networks, and Intelligent Manufacturing. Mathematical Statistician and Engineering Applications. 71(4), 16749–16773.
[29] Passaro, R., Quinto, I., Scandurra, G., et al., 2023. The drivers of eco-innovations in small and medium-sized enterprises: A systematic literature review and research directions. Business Strategy and the Environment. 32(4), 1432–1450.
[30] Chaparro Banegas, N., 2024. Driving Sustainable Development: Eco-Innovation Systems and Public Policies [PhD Thesis]. Universitat Politècnica de València: Valencia, Spain.
[31] Hamdouna, M., Khmelyarchuk, M., 2025. Technological Innovations Shaping Sustainable Competitiveness—A Systematic Review. Sustainability. 17(5), 1953.
[32] Foo, Y.Z., O'Dea, R.E., Koricheva, J., et al., 2021. A practical guide to question formation, systematic searching and study screening for literature reviews in ecology and evolution. Methods in Ecology and Evolution. 12(9), 1705–1720.
[33] Harari, M.B., Parola, H.R., Hartwell, C.J., et al., 2020. Literature searches in systematic reviews and meta-analyses: A review, evaluation, and recommendations. Journal of Vocational Behavior. 118, 103377.
[34] Vamsi, T.M.N., Pratibha, L., 2024. Learning processes for the internet of autonomous vehicles and intelligent transportation systems. In: Singh, P., Kumar, S., Gupta, S.K. (Eds.). Wireless Ad-hoc and Sensor Networks. CRC Press: Boca Raton, FL, USA. pp. 87–111.
[35] Grote, M., Williams, I., Preston, J., et al., 2016. Including congestion effects in urban road traffic CO2 emissions modelling: Do Local Government Authorities have the right options? Transportation Research Part D: Transport and Environment. 43, 95–106.
[36] Gillis, D., Semanjski, I., Lauwers, D., 2015. How to monitor sustainable mobility in cities? Literature review in the frame of creating a set of sustainable mobility indicators. Sustainability. 8(1), 29.
[37] O'Dea, R.E., Lagisz, M., Jennions, M.D., et al., 2021. Preferred reporting items for systematic reviews and meta-analyses in ecology and evolutionary biology: A PRISMA extension. Biological Reviews. 96(5), 1695–1722.
[38] Nordelöf, A., Poulikidou, S., Chordia, M., et al., 2019. Methodological approaches to end-of-life modelling in life cycle assessments of lithium-ion batteries. Batteries. 5(3), 51.
[39] Akasapu, U., Hehenberger, P., 2023. A design process model for battery systems based on existing life cycle assessment results. Journal of Cleaner Production. 407, 137149.
[40] Pollock, D., Peters, M.D.J., Khalil, H., et al., 2023. Recommendations for the extraction, analysis, and presentation of results in scoping reviews. JBI Evidence Synthesis. 21(3), 520–532.
[41] Peters, M.D.J., Godfrey, C., McInerney, P., et al., 2022. Best practice guidance and reporting items for the development of scoping review protocols. JBI Evidence Synthesis. 20(4), 953–968.
[42] Cox, B., 2018. Mobility and the Energy Transition: A Life Cycle Assessment of Swiss Passenger Transport Technologies Including Developments Until

2050 [PhD Thesis]. ETH Zurich: Zürich, Switzerland.
[43] Olawolu, W., Sinfield, J.V., 2025. Towards a Typology of Technological Impact: Defining and Measuring Applicability, Pervasiveness, and Significance of High Impact Technologies. Available from: https://discovery.researcher.life/article/towards-a-typology-of-technological-impact-defining-and-measuring-applicability-pervasiveness-and-significance-of-high-impact-technologies/68e0e8d313143ca8ad9c7da2fa5d2d48 (cited 2 January 2026).
[44] Türkeli, S., Kemp, R., 2018. Changing patterns in eco-innovation research: A bibliometric analysis. In: Horbach, J., Reif, C. (Eds.). New Developments in Eco-Innovation Research. Springer: Cham, Switzerland. pp. 13–54.
[45] Cao, Y., Qu, Y., Guo, L., 2023. Identifying critical eco-innovation practices in circular supply chain management: Evidence from the textile and clothing industry. International Journal of Logistics Research and Applications. 26(11), 1462–1483.
[46] Dwan, K., Gamble, C., Williamson, P.R., et al., 2013. Systematic review of the empirical evidence of study publication bias and outcome reporting bias—An updated review. PLoS One. 8(7), e66844.
[47] Aprile, M.C., 2025. Innovation and Environment: Definition and Adoption of Eco-innovation. In: Aldieri, L. (Ed.). Technological Evolution: How Innovations are Changing Our Future. Springer: Cham, Switzerland. pp. 1–26.
[48] Carrillo-Hermosilla, J., Kiefer, C.P., del Río, P., 2019. Taxonomy and dimensions of eco-innovation from a resource-based perspective. In: Boons, F., Mcmeekin, A. (Eds.). Handbook of Sustainable Innovation. Edward Elgar Publishing: Cheltenham, UK. pp. 78–100.
[49] Lewis, A.M., Kelly, J.C., Keoleian, G.A., 2014. Vehicle lightweighting vs. electrification: Life cycle energy and GHG emissions results for diverse powertrain vehicles. Applied Energy. 126, 13–20.
[50] Hu, X., Han, J., Tang, X., et al., 2021. Powertrain design and control in electrified vehicles: A critical review. IEEE Transactions on Transportation Electrification. 7(3), 1990–2009.
[51] Mwasilu, F., Justo, J.J., Kim, E., et al., 2014. Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration. Renewable and Sustainable Energy Reviews. 34, 501–516.
[52] Butt, F.A., Chattha, J.N., Ahmad, J., et al., 2022. On the integration of enabling wireless technologies and sensor fusion for next-generation connected and autonomous vehicles. IEEE Access. 10, 14643–14668.
[53] Reimer, B., 2014. Driver assistance systems and the transition to automated vehicles: A path to increase older adult safety and mobility? Public Policy & Aging Report. 24(1), 27–31.
[54] Tong, W., Hussain, A., Bo, W.X., et al., 2019. Artificial intelligence for vehicle-to-everything: A survey. IEEE Access. 7, 10823–10843.
[55] Shanmugapriya, N., 2025. An Edge-Enabled Cyber-Physical Framework for Real-Time Reservoir Surveillance and Optimization Using Autonomous Sensor Networks and AI-Based Analytics. International Journal of Computer Science and Engineering Innovations. 1(1), 9–17.
[56] Islam, S.N., Biswas, A., Chowdhury, A.K., 2023. AI-enabled cyber-physical power systems: Review of smart grid security, optimization, and decision support. Applied IT & Engineering. 1(1), 1–9.
[57] Usmani, U.A., Sulaiman, S., Watada, J., 2024. Intelligent Integration of IoT and Cyber-Physical Systems: Empowering the Next Generation of AI-Enabled Smart Environments. In Proceedings of the 2024 8th International Conference on Computing, Communication, Control and Automation (ICCUBEA), Pune, India, 23–24 August 2024; pp. 1–9.
[58] Cisterna, C., 2023. Membership and Mobility Bundles Choice in Mobility-as-a-Service [PhD Thesis]. Université du Luxembourg: Luxembourg, Luxembourg.
[59] Cao, Y., Cui, J., Liu, S., et al., 2023. A holistic review on e-mobility service optimization: Challenges, recent progress, and future directions. IEEE Transactions on Transportation Electrification. 10(2), 3712–3741.
[60] Ayoade, I.A., Longe, O.M., 2024. A comprehensive review on smart electromobility charging infrastructure. World Electric Vehicle Journal. 15(7), 286.
[61] Biswas, P., Rashid, A., Habib, A.K., et al., 2025. Vehicle to Grid: Technology, Charging Station, Power Transmission, Communication Standards, Techno-Economic Analysis, Challenges, and Recommendations. World Electric Vehicle Journal. 16(3), 142.
[62] Lucarelli, C., Mazzoli, C., Rancan, M., et al., 2020. Classification of sustainable activities: EU taxonomy and scientific literature. Sustainability. 12(16), 6460.
[63] Lucas, R.M., German, S., Metternicht, G., et al., 2022. A globally relevant change taxonomy and evidence-based change framework for land monitoring.

Global Change Biology. 28(21), 6293–6317.
[64] Xavier, A.F., Naveiro, R.M., Aoussat, A., et al., 2017. Systematic literature review of eco-innovation models: Opportunities and recommendations for future research. Journal of Cleaner Production. 149, 1278–1302.
[65] Cooke, S.J., Cook, C.N., Nguyen, V.M. et al., 2023. Environmental evidence in action: On the science and practice of evidence synthesis and evidence-based decision-making. Environmental Evidence. 12(1), 10.
[66] Rahman, M.M., Canter, C., Kumar, A., 2015. Well-to-wheel life cycle assessment of transportation fuels derived from different North American conventional crudes. Applied Energy. 156, 159–173.
[67] Sovacool, B.K., Axsen, J., Kempton, W., 2017. The future promise of vehicle-to-grid (V2G) integration: A sociotechnical review and research agenda. Annual Review of Environment and Resources. 42(1), 377–406.
[68] Aichberger, C., Jungmeier, G., 2020. Environmental life cycle impacts of automotive batteries based on a literature review. Energies. 13(23), 6345.
[69] Wang, Q., Liu, W., Yuan, X., et al., 2018. Environmental impact analysis and process optimization of batteries based on life cycle assessment. Journal of Cleaner Production. 174, 1262–1273.
[70] Habre, R., Girguis, M., Urman, R., et al., 2021. Contribution of tailpipe and non-tailpipe traffic sources to quasi-ultrafine, fine and coarse particulate matter in southern California. Journal of the Air & Waste Management Association. 71(2), 209–230.
[71] Bleischwitz, R., 2009. Eco-Innovation-Putting the EU on the Path to a Resource and Energy Efficient Economy. In Proceedings of the Workshop at the ITRE Committee of the European Parliament, Brussels, Belgium, 6 October 2009.
[72] Chiarini, B., D'Agostino, A., Marzano, E., et al., 2020. The perception of air pollution and noise in urban environments: A subjective indicator across European countries. Journal of Environmental Management. 263, 110272.
[73] Lercher, P., 2018. Noise in cities: Urban and transport planning determinants and health in cities. In: Nieuwenhuijsen, M., Khreis, H. (Eds.). Integrating Human Health into Urban and Transport Planning: A Framework. Springer: Cham, Switzerland. pp. 443–481.
[74] Desfor, G., Keil, R., 2004. Nature and the City: Making Environmental Policy in Toronto and Los Angeles. University of Arizona Press: Tucson, AZ, USA.
[75] Font Vivanco, D., Freire-González, J., Galvin, R., et al., 2022. Rebound effect and sustainability science: A review. Journal of Industrial Ecology. 26(4), 1543–1563.
[76] Segovia-Martin, J., Creutzig, F., Winters, J., 2023. Efficiency traps beyond the climate crisis: Exploration–exploitation trade-offs and rebound effects. Philosophical Transactions of the Royal Society B. 378(1889), 20220405.
[77] Saleem, M.A., Eagle, L., Low, D., 2021. Determinants of eco-socially conscious consumer behavior toward alternative fuel vehicles. Journal of Consumer Marketing. 38(2), 211–228.
[78] Felder, M., De Marchi, M., Dallasega, P., et al., 2025. Smart Routing for Sustainable Supply Chain Networks: An AI and Knowledge Graph Driven Approach. Applied Sciences. 15(14), 8001.
[79] Nichols, S.J., Peat, M., Webb, J.A., 2017. Challenges for evidence-based environmental management: What is acceptable and sufficient evidence of causation? Freshwater Science. 36(1), 240–249.
[80] Islam, N., Mammadov, A., 2024. Eco-Innovation: Adoption, Barriers, Enablers and Performance Outcomes. Elsevier BV: Amsterdam, The Netherlands.
[81] Hojnik, J., Ruzzier, M., 2016. Drivers of and barriers to eco-innovation: A case study. International Journal of Sustainable Economy. 8(4), 273–294.
[82] Marti, L., 2025. Heterogeneity in Green Markets: Barriers and Drivers Shaping Eco-Innovation Outcomes. Sustainable Development. 1–16. DOI: https://doi.org/10.1002/sd.70507
[83] Jansson, C., Carlberg, C., 2019. Barriers to Eco-Innovation: A Qualitative Study on Large Manufacturing Companies [Master's Thesis]. Uppsala University: Uppsala, Sweden.
[84] Leitner, A., Wehrmeyer, W., France, C., 2010. The impact of regulation and policy on radical eco-innovation: The need for a new understanding. Management Research Review. 33(11), 1022–1041.
[85] Lindsey, R., Tikoudis, I., Hassett, K., 2023. OECD Environment Working Papers, No. 211: Distributional Effects of Urban Transport Policies to Discourage Car Use: A Literature Review. OECD Publishing: Paris, France.
[86] Press, D., 2007. Industry, environmental policy, and environmental outcomes. Annual Review of Environment and Resources. 32(1), 317–344.
[87] Peuckert, J., 2014. What shapes the impact of environmental regulation on competitiveness? Evidence from Executive Opinion Surveys. Environmental

Innovation and Societal Transitions. 10, 77–94.

[88] Paradoulakis, A., 2024. Sustainable Mobility, Climate Change and Geopolitics [Master's Thesis]. University of Piraeus: Piraeus, Greece.

[89] Sumitkumar, R., Al-Sumaiti, A.S., Kumar, R., et al., 2025. Requirement of integration of renewable energy sources (RES) with charging infrastructure. In: Kumar, A., Bansal, R.C., Kumar, P., et al. (Eds.). Handbook on New Paradigms in Smart Charging for E-Mobility. Elsevier: Amsterdam, The Netherlands. pp. 197–224.

[90] Mittal, V.K., Sangwan, K.S., 2014. Prioritizing barriers to green manufacturing: Environmental, social and economic perspectives. Procedia CIRP. 17, 559–564.

[91] Agbaje, P., Anjum, A., Mitra, A., et al., 2022. Survey of interoperability challenges in the internet of vehicles. IEEE Transactions on Intelligent Transportation Systems. 23(12), 22838–22861.

[92] Karakaya, E., Hidalgo, A., Nuur, C., 2014. Diffusion of eco-innovations: A review. Renewable and Sustainable Energy Reviews. 33, 392–399.

[93] Hellström, T., 2007. Dimensions of environmentally sustainable innovation: The structure of eco-innovation concepts. Sustainable Development. 15(3), 148–159.

[94] Wei, Y., Wu, S., Tesemma, Z., 2018. Re-orienting technological development for a more sustainable human–environmental relationship. Current Opinion in Environmental Sustainability. 33, 151–160.

[95] Kaiser, N., Barstow, C.K., 2022. Rural transportation infrastructure in low-and middle-income countries: A review of impacts, implications, and interventions. Sustainability. 14(4), 2149.

[96] Ashford, N.A., Hall, R.P., 2011. The importance of regulation-induced innovation for sustainable development. Sustainability. 3(1), 270–292.

[97] Khattak, Z.H., 2024. Cybersecurity vulnerability and resilience of cooperative driving automation for energy efficiency and flow stability in smart cities. Sustainable Cities and Society. 106, 105368.

[98] Park, M.S., Bleischwitz, R., Han, K.J., et al., 2017. Eco-innovation indices as tools for measuring eco-innovation. Sustainability. 9(12), 2206.

[99] Khan, M.S., Hasan, Z., 2022. Thermo-Economic Modeling of Hydrogen Energy Integration in Smart Factories. ASRC Procedia: Global Perspectives in Science and Scholarship. 2(1), 257–288.

[100] Nguyen, B., Cranney, L., Bellew, B., et al., 2021. Implementing food environment policies at scale: What helps? What hinders? A systematic review of barriers and enablers. International Journal of Environmental Research and Public Health. 18(19), 10346.

[101] Xue, X., Dhumras, H., Thakur, G., et al., 2025. Integrating artificial intelligence and sustainable materials for smart eco innovation in production. Scientific Reports. 15(1), 36942.