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A Review of Sociotechnical Transitions and Institutional Change Dynamics for Sustainable Urban Mobility

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ABSTRACT

Urban mobility systems are undergoing profound socio-technical transitions driven by technological innovation, sustainability imperatives, and evolving governance structures. This review article synthesizes emerging research on three interrelated domains: electrification of public transport fleets, integration of autonomous and connected vehicle technologies, and institutional change in urban mobility governance. The article highlights how electrification initiatives reshape operational models and cost structures in public transport networks, how autonomous vehicle pilots challenge existing regulatory and planning frameworks, and how institutional design and governance capacity condition the success of these transitions. Situating these developments within socio-technical transition theory, the review emphasizes the multi-level interactions between niche innovations, regime dynamics, and broader landscape pressures. By integrating technological, institutional, and policy perspectives, the article provides actionable insights for policymakers, practitioners, and researchers seeking to navigate the complexities of sustainable urban mobility.

1. Introduction

Urban transport systems are increasingly recognized as complex socio-technical assemblages, where technological innovations, institutional frameworks, and social practices interact to shape mobility outcomes. The concept of socio-technical transitions, particularly as articulated in the multi-level perspective (MLP), provides a useful lens for analyzing these dynamics. Transitions occur through interactions between niche[1] innovations, established regimes, and broader landscape pressures such as climate change and urbanization [1, 2]. In the context of urban mobility; electrification, automation, and institutional change represent three interdependent domains of transformation that are reshaping the future of cities.

Electrification of public transport fleets has emerged as a cornerstone of sustainable mobility strategies. Recent studies demonstrate that while electric buses significantly reduce greenhouse gas emissions, they also require adjustments in scheduling, fleet size, and cost structures. For example, charging strategies directly affect fleet scheduling and service reliability [3]. Similarly, lifecycle cost

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assessments must incorporate infrastructure and energy system impacts to ensure feasibility [4]. More recently, the financial and operational challenges of large-scale electrification have been examined [5]. The results of these studies underscore that electrification is not merely a technological substitution but a systemic transition requiring institutional and financial adaptation.

Parallel to electrification, the integration of autonomous and connected vehicle technologies is reshaping urban mobility landscapes. Autonomous shuttles and shared automated electric vehicles (SAEVs) are being piloted in cities worldwide, raising questions about safety, governance, and integration with existing transport systems. Research emphasizes that autonomous vehicles can improve traffic sustainability but require robust governance frameworks to manage risks [6]. A recent UK review highlights the gap between policy ambition and institutional capability, showing that while the government has set ambitious targets for connected and automated vehicle deployment, regulatory readiness and safety assurance mechanisms remain limited [7]. These studies highlight that automation is not a purely technical challenge but one deeply embedded in governance and policy contexts.

Institutional and governance frameworks play a decisive role in shaping the trajectory of urban mobility transitions. UN-Habitat's Global Report on Human Settlements [8] stresses that even well-designed policies cannot succeed without fit-for-purpose institutions capable of directing, managing, and resourcing implementation. More recent scholarship emphasizes collaborative governance models, where municipalities, operators, and citizens co-design sustainable mobility schemes, highlighting the prevalence of governance-driven democratization models that shape stakeholder integration [9]. Likewise, the "CalmMobility paradigm underlines participatory and adaptive governance as essential for managing uncertainty in urban mobility transitions [10]. Institutional adaptability and stakeholder integration are essential for resilience in the face of technological disruption. These three domains, electrification, automation, and institutional change are not isolated. Their interactions create new synergies and tensions. For instance, electrification and automation together raise questions about workforce adaptation, as bus drivers may face both technological displacement and new skill requirements. Financing models for electrification may also need to account for automation-related infrastructure, such as digital connectivity and safety systems. Moreover, institutional change is both a prerequisite and a consequence of technological transitions: governance frameworks must adapt to manage new risks, while technological innovations often catalyze institutional reform.

Beyond technological and institutional dimensions, socio-technical transitions in urban mobility also involve cultural narratives and public imaginaries. How societies envision the future of transport whether through discourses of "smart cities," "green mobility," or "digital disruption" shapes both policy ambition and public acceptance. These imaginaries act as landscape pressures, influencing regime actors to adopt certain pathways while marginalizing others. For instance, the framing of electrification as a climate imperative has accelerated investment, while automation is often promoted through narratives of efficiency and innovation. Recognizing the role of cultural imaginaries ensures that transitions are understood not only as technical or institutional processes but also as deeply social and discursive phenomena [11].

While existing studies have examined electrification, automation, and governance in urban mobility largely as separate domains, there remains a lack of integrative reviews that analyze how these transitions interact as part of broader socio-technical change. This article fills that gap by synthesizing technological, institutional, and policy perspectives into a unified framework, highlighting cross-cutting dynamics that are often overlooked in single-issue studies. The article is structured as follows: Section 2 explains the methodology for literature review; Section 3 introduces multi-level perspective as a useful conceptual framework and its relevance to urban mobility; Section 4 reviews operational, financial, and infrastructural challenges of electric bus deployment; Section 5 examines socio-technical issues in autonomous and connected vehicle integration; Section 6 analyzes evolving governance models and stakeholder participation; Section 7 discusses the cross-cutting themes and tensions across these domains by offering a comparative synthesis, and finally, Section 8 concludes the study by offering policy recommendations and directions for future research.

2. Methodology for Literature Review

This article adopts a structured literature review approach to synthesize research on electrification, automation, and governance in urban mobility transitions. The review was designed to capture both foundational studies in socio-technical transition theory and recent empirical work on transport innovations. To ensure comprehensiveness, multiple academic databases were consulted, including Scopus, Web of Science, and Google Scholar, supplemented by targeted searches of Springer, Elsevier, Taylor & Francis, and IEEE repositories. Grey literature such as policy reports from UN-Habitat, the International Transport Forum, and national transport agencies was also included to capture practice-oriented perspectives. Search strings combined keywords such as "socio-technical transitions," "multi-level perspective," "urban mobility," "electrification," "autonomous vehicles," and "governance." Boolean operators were used to refine results (e.g., "electrification AND buses," "automation AND governance"). The initial search yielded approximately 450 sources published between 2000 and 2025. After screening abstracts for relevance, 180 sources were retained for full review. Inclusion criteria required that studies explicitly address either (a) electrification of public transport fleets, (b) autonomous or connected vehicle integration, or (c) governance and institutional change in mobility systems. Exclusion criteria eliminated articles focused solely on private car adoption, technical engineering without policy context, or speculative commentary lacking empirical grounding.

The review process followed a thematic coding strategy. Sources were categorized into three domains electrification, automation, and governance while cross-cutting themes such as equity, institutional adaptation, and socio-technical imaginaries were coded across domains. This allowed for both vertical analysis within each domain and horizontal synthesis across domains. Case studies were identified as particularly valuable for illustrating how transitions unfold in practice; therefore, empirical examples from China, Singapore, Norway, the UK, and the US were prioritized. The review also sought to balance Global North and Global South perspectives, though the literature remains unevenly weighted toward high-income contexts.

Finally, the review approach was guided by the objective of producing actionable insights for policymakers and practitioners. Rather than treating electrification, automation, and governance as isolated topics, the methodology emphasized integrative analysis, situating each within the multi-level perspective (MLP). This ensures that the findings not only advance academic debates but also provide practical guidance for managing transitions in complex urban mobility systems.

3. Multi-Level Perspective (MLP) as a Conceptual Framework

Understanding transitions in urban mobility requires a conceptual lens that can capture the interplay between technological innovation, institutional adaptation, and societal pressures. The multi-level perspective (MLP) offers such a framework, distinguishing between niche innovations, regime structures, and landscape forces. Niches are protected spaces where radical technologies such as electric buses or autonomous shuttles emerge, regimes represent the entrenched systems of infrastructure, regulation, and user practices, and landscapes encompass broader pressures like climate change, demographic shifts, and public expectations. The strength of the MLP lies in its ability to explain how innovations move from experimental niches into mainstream regimes when aligned with landscape pressures [12].

Applied to urban mobility, this framework highlights how electrification, automation, and governance reforms are not isolated phenomena but interconnected processes. Electrification introduces niche innovations in battery technology and charging infrastructure that challenge diesel-based regimes. Studies of electric bus operations demonstrate that charging strategies directly affect fleet scheduling and service reliability. For example, interactive optimization of overnight charging and vehicle scheduling can significantly improve operational efficiency and reduce service disruptions [13]. Feasibility analyses highlight the importance of charging infrastructure and energy supply integration [14]. Lifecycle cost assessments further demonstrate that electrification requires systemic changes in infrastructure and energy systems to ensure feasibility. The economic viability of electric buses depends heavily on supportive policy frameworks and charging infrastructure investment [15].

Automation represents another niche innovation, with pilot projects for autonomous shuttles and shared automated electric vehicles testing regulatory flexibility and institutional readiness. Autonomous vehicles can improve traffic sustainability but require robust governance frameworks to manage risks [6]. Recent studies highlight the persistent gap between policy ambition and institutional capability in the deployment of connected and automated vehicles. While governments set ambitious targets for automation, regulatory frameworks and safety assurance mechanisms remain underdeveloped [16].

Governance reforms represent the institutional dimension of socio-technical transitions, shaping how technological innovations are embedded in practice. Emerging models of collaborative and adaptive governance emphasize the importance of stakeholder participation, institutional flexibility, and co-design. Transport policy requires new forms of governance that move beyond hierarchical control toward more networked and participatory arrangements [17]. The role of collaborative governance is key in fostering innovation and legitimacy in public policy, where inclusive processes are particularly vital in contexts of uncertainty such as sustainable mobility transitions [18]. Governance frameworks must also adapt to disruptive technologies in transport, where institutional agility and stakeholder integration are essential for resilience [19]. These perspectives demonstrate that governance is not merely a backdrop to technological change but an active driver of transition pathways, determining how innovations are scaled, legitimized, and sustained.

The multi-level perspective provides a useful starting point for understanding how technological innovations interact with established urban mobility systems and broader societal pressures. However, the review suggests that the conventional distinction between niches, regimes, and landscapes is insufficient on its own to capture the particular dynamics of contemporary urban mobility transitions. Electrification, automation, and institutional change interact across these levels, while governance plays a critical role in mediating the relationship between experimentation and regime transformation. Figure 1 synthesizes these relationships into an integrated framework for sustainable urban mobility transitions. The framework conceptualizes transition as an iterative process of experimentation, learning, institutionalization, and regime transformation rather than as a linear process of technological substitution.

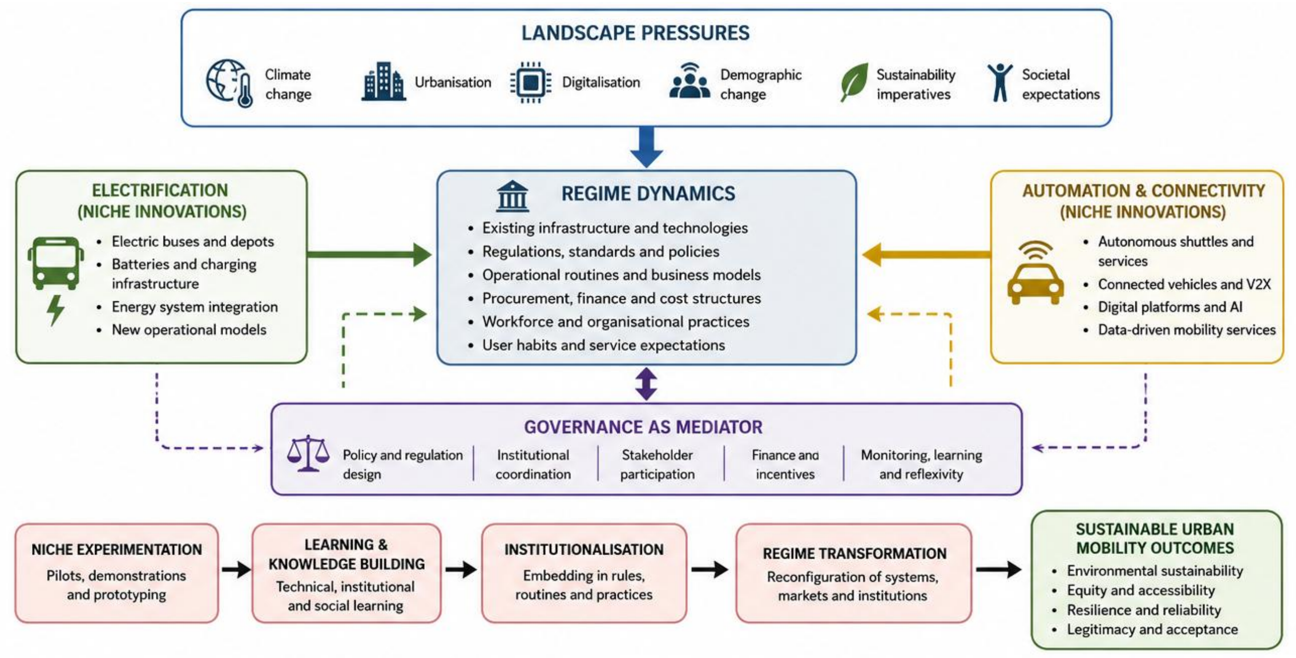

Fig. 1. An integrated multi-level framework for socio-technical transitions in urban mobility

4. Bus Fleet Electrification

Electrification of bus fleets represents a classic case of niche innovation within the multi-level perspective. Electrification is not a linear technological upgrade but a socio-technical transition requiring alignment across niches, regimes, and landscapes. Electric bus pilots, infrastructure planning, governance reforms, and financing mechanisms all illustrate how systemic coordination is necessary to embed electrification within urban mobility systems.

Protected pilot projects and early deployments allow electric buses to develop in spaces shielded from the dominant diesel regime. Energy consumption patterns vary significantly across routes, requiring adaptive scheduling and infrastructure strategies [20], underlining how niche experimentation interacts with regime practices, as operational routines must be reconfigured to accommodate new technological characteristics. At the regime level, institutional and infrastructural inertia often slows diffusion. An evaluation of the costs and operations of full fleet electrification across German transport networks show that electrification increased total costs and required more vehicles and drivers [21]. This reflects regime-level challenges of procurement, financing, and workforce adaptation. Landscape pressures such as climate imperatives and urban air quality targets accelerate transitions. Electric bus adoption is often driven by environmental mandates, but success depends on aligning charging infrastructure with grid capacity [22]. This illustrates how landscape forces create urgency for change, while regime-level energy systems must adapt to accommodate niche technologies. Governance mechanisms mediate between niches and regimes. An analysis of stakeholder dynamics in electric bus adoption shows that coordination among operators, municipalities, and energy providers is essential for scaling up deployment [23]. Within socio-technical transition theory, this highlights governance innovation as a bridge between niche experimentation and regime adaptation.

Shenzhen, China, provides the most prominent example of large-scale bus fleet electrification. By 2017, the city had converted its entire fleet of over 16,000 buses to electric, supported by strong government subsidies, coordinated planning with energy utilities, and extensive charging infrastructure [3]. This case illustrates how niche innovations can rapidly diffuse into regime practices when aligned with landscape pressures such as air quality mandates and national industrial policy. However, scholars note that Shenzhen's success relied heavily on state capacity and financial support, raising questions about replicability in cities with weaker governance or limited resources [24, 25].

Electrification also illustrates how socio-technical transitions reshape actor networks and institutional roles. Bus electrification requires new forms of collaboration between transport operators, energy utilities, and municipal authorities. Integrating electric buses into urban transport systems demands coordination across multiple sectors, particularly to balance charging demand with grid stability [26]. Within the MLP, this reflects how niche innovations trigger regime-level reconfigurations in institutional responsibilities. Electrification also highlights the importance of learning processes and knowledge diffusion. Transitions are accelerated when lessons from pilot projects are shared across networks, enabling cities to avoid repeating costly mistakes [27]. Electrification underscores the uneven geography of transitions. While wealthier cities can mobilize resources for infrastructure and fleet replacement, smaller municipalities often struggle to adopt electric buses without external support. This unevenness reflects the socio-technical nature of transitions: niches may thrive in certain contexts but fail to diffuse widely unless regime and landscape conditions align.

Another socio-technical dimension is the role of uncertainty and experimentation. Transitions are inherently contested processes where technological pathways are negotiated among diverse actors [28]. In the case of electric buses, uncertainty about battery lifespans and charging standards reflects niche instability, while regime actors such as transport authorities must adapt procurement and maintenance practices to accommodate evolving technologies. Electrification also underscores the importance of social acceptance and user practices. Studies of passenger perceptions in Oslo reveal that public support for electric buses is shaped not only by environmental benefits but also by service reliability and comfort [29]. Within the MLP, this reflects how regime-level user practices and expectations must adapt alongside technological change, ensuring that innovations are embedded in everyday mobility routines.

Electrification also raises important questions about long-term system resilience. While early pilots demonstrate feasibility, scholars caution against technological lock-in, where cities commit to specific battery chemistries or charging standards that may become obsolete. This risk underscores the need for adaptive procurement strategies and modular infrastructure investment [30]. Furthermore, electrification intersects with broader energy transitions: the sustainability of electric buses depends on the decarbonization of electricity grids. In regions where electricity generation remains fossil-fuel intensive, the environmental benefits of electrification are diminished, highlighting the systemic nature of transitions. Policymakers must therefore integrate transport electrification with energy system decarbonization to maximize climate benefits.

5. Automation

Automation in urban mobility represents a niche innovation within the multi-level perspective, where pilot projects and experimental deployments test the viability of autonomous shuttles and connected vehicles. User acceptance of automated shuttles in European trials depends on perceptions of safety and reliability, highlighting how niche experiments provide crucial learning spaces [31]. These pilots are often shielded from mainstream operations, allowing uncertainties to be managed before confronting regime-level constraints. Within socio-technical transition theory, such niches are essential for building momentum and legitimacy for disruptive technologies.

At the regime level, automation challenges established practices of regulation, liability, and workforce organization. Widespread adoption of autonomous vehicles would require significant changes to insurance frameworks and safety standards, reflecting the inertia of regime institutions [32]. Integrating autonomous shuttles into existing transport systems demands new operational models and regulatory oversight. In socio-technical transition terms, this shows that entrenched regimes resist niche innovations, even when technological progress is rapid, underscoring the importance of institutional adaptation in socio-technical transitions.

Landscape pressures such as congestion, climate imperatives, and demographic change create urgency for automation. Public opinion on automated driving is shaped by broader societal concerns about safety, efficiency, and sustainability [33]. These landscape forces push regimes to adapt, even as uncertainties remain about technological readiness. In the MLP framework, automation reflects the classic dynamic where external pressures accelerate change, but regime institutions must evolve to accommodate niche technologies. Governance innovation is central to bridging niches and regimes in automation. Adaptive governance frameworks are needed to manage uncertainty and ensure safety in autonomous vehicle deployment [6]. This includes stakeholder participation, iterative regulation, and flexible standards that evolve alongside technological development. Within socio-technical transition theory, governance thus acts as a mediator, shaping how niche experiments are scaled and embedded in regime structures.

Automation also underscores the contested nature of socio-technical transitions. Autonomous vehicle policies often neglect equity considerations, with gaps in addressing access for disadvantaged groups and potential labor displacement [34]. This highlights that transitions are not purely technical but involve negotiation among diverse actors with competing interests. Within the MLP, this reflects how niche innovations must align not only with regime institutions and landscape pressures but also with societal values and expectations.

Singapore has emerged as a global leader in autonomous vehicle experimentation, establishing regulatory sandboxes and pilot zones for autonomous shuttles. The government’s proactive approach includes adaptive regulation, strong public communication, and partnerships with technology firms [6]. These pilots demonstrate how governance innovation can bridge niche experimentation and regime adaptation, while also highlighting the importance of anticipatory regulation in managing uncertainty. Singapore’s case underscores that automation is not only a technical challenge but also a governance experiment in balancing innovation with safety and public trust.

Finally, automation demonstrates the uneven geography of transitions. The transition to autonomous vehicles unfolds differently across contexts, with high-income countries advancing pilot projects and regulatory frameworks while lower-income regions face barriers related to infrastructure, governance capacity, and public trust [35]. This divergence reflects how niche innovations can thrive in supportive environments but struggle to diffuse when regime institutions lack resources or alignment. Moreover, landscape pressures such as global competition and climate imperatives may accelerate adoption in some regions, while others remain locked into conventional mobility systems, reinforcing uneven transition pathways.

Automation also introduces new forms of socio-technical risk. Scholars highlight the potential for algorithmic bias in decision-making systems, where autonomous vehicles may inadvertently reproduce inequalities in safety or accessibility [36]. Moreover, automation challenges existing labor relations, requiring proactive strategies for workforce reskilling and social protection [37]. The contested politics of automation reveal that transitions are not merely about technological feasibility but about negotiating social contracts between governments, industries, and citizens. Addressing these risks requires governance frameworks that are anticipatory, inclusive, and reflexive, ensuring that automation contributes to sustainable and equitable mobility rather than exacerbating existing divides [38].

6. Governance and Institutional Change

Governance reforms represent the institutional dimension of socio-technical transitions, shaping how technological innovations are embedded in practice. Within the multi-level perspective, governance operates primarily at the regime level, mediating between niche experimentation and landscape pressures. Transport governance must move beyond hierarchical control toward more networked and participatory arrangements, reflecting the need for institutional flexibility in the face of disruptive technologies [17]. This illustrates how regime institutions must adapt to accommodate niche innovations such as electrification and automation, rather than simply reinforcing existing practices. Collaborative governance models are increasingly recognized as essential for managing uncertainty in mobility transitions. Collaborative innovation in the public sector fosters legitimacy and resilience, particularly when diverse stakeholders are engaged in co-design processes [18]. Within socio-technical transition theory, this demonstrates how governance innovation can accelerate niche diffusion by aligning regime institutions with landscape imperatives such as climate targets and public demand for sustainability. In this sense, governance acts as a bridge between experimentation and institutionalization, ensuring that innovations are not confined to pilot projects but embedded in mainstream systems.

London illustrates how governance reforms can shape transition pathways through institutional innovation. The introduction of the congestion charge in 2003, later expanded into the Ultra Low Emission Zone (ULEZ), reflects a governance model that integrates regulatory instruments with public engagement. London's governance capacity anchored in the Greater London Authority and Transport for London enabled adaptive policymaking and stakeholder integration. This case demonstrates how governance frameworks can act as regime-level mediators, embedding sustainability objectives into everyday mobility practices while maintaining legitimacy through transparency and consultation.

Governance also plays a critical role in shaping transition pathways by determining which innovations are scaled and embedded. Governance frameworks must adapt to disruptive technologies like smart mobility, with an emphasis on institutional agility and stakeholder integration [19]. Regime structures can either enable or constrain niche innovations, depending on the degree of institutional openness and adaptability. For example, rigid procurement rules or fragmented regulatory oversight can stall transitions, while adaptive governance can create enabling environments for systemic change.

Equity considerations further highlight the contested nature of governance in socio-technical transitions. Autonomous vehicle policies often neglect equity implications, leaving gaps in access for disadvantaged groups [34]. This underscores that governance is not merely a technical exercise but a normative process, shaping whose interests are prioritized in transition pathways. Societal values at the landscape level influence regime adaptation and niche diffusion, ensuring that transitions are evaluated not only in terms of efficiency but also in terms of fairness and inclusivity.

Institutional change is also driven by landscape pressures such as climate imperatives, digitalization, and globalization. Urban governance mediates global pressures and local responses, with some cities acting as experimental niches while others remain locked into conventional regimes

[39]. This unevenness highlights that socio-technical transitions are context-specific, requiring governance frameworks that are sensitive to local institutional capacities and landscape pressures. In practice, this means that governance reforms must be tailored to the political, economic, and cultural conditions of each city or region, rather than relying on one-size-fits-all solutions.

Governance reforms illustrate the importance of institutional learning and reflexivity. Sustainability transitions are inherently political, requiring institutions to learn from experimentation and adapt policies over time. Therefore, regime actors must remain open to feedback from niche experiments and landscape pressures, adjusting governance frameworks as transitions unfold. Reflexive governance thus becomes a critical mechanism for ensuring that socio-technical transitions remain adaptive, inclusive, and resilient in the face of uncertainty.

Institutional change also involves the reconfiguration of power relations. As new actors such as technology firms and energy utilities enter the mobility arena, traditional transport authorities must renegotiate their roles. This raises questions about accountability, transparency, and democratic oversight. Without careful governance design, transitions risk being captured by corporate interests, undermining public legitimacy [40]. Conversely, inclusive governance models that embed citizen participation can enhance trust and resilience. Comparative studies show that cities with strong traditions of participatory governance are better able to integrate disruptive technologies while maintaining social legitimacy [41]. This highlights governance not only as a technical mediator but as a democratic safeguard in socio-technical transitions.

7. Comparative Synthesis

The preceding sections have examined electrification, automation, and governance as distinct dimensions of urban mobility transitions. Yet socio-technical transition theory and the multi-level perspective (MLP) remind us that these processes are deeply interconnected, unfolding not in isolation but through overlapping pathways of technological innovation, institutional adaptation, and societal pressure. A comparative synthesis reveals how each dimension interacts across niches, regimes, and landscapes, shaping the trajectory of mobility systems in complex and sometimes contradictory ways.

The three transition domains examined in this review differ in their technological characteristics and immediate challenges, but they share important socio-technical dynamics. Electrification primarily involves the reconfiguration of vehicle, energy and operational systems, while automation introduces new regulatory, safety and workforce challenges. Governance and institutional change cut across both domains by shaping how innovations are coordinated, regulated and embedded within existing mobility systems. Table 1 compares these three domains across their position within the multi-level perspective, landscape pressures, regime challenges, actors, governance requirements, and principal risks and enabling mechanisms.

Three domains shown in Table 1 should not be understood as independent transition pathways. Although electrification and automation originate largely as technological innovations within protected or experimental niches, their diffusion depends on changes to established infrastructures, operational routines, regulatory frameworks and organisational practices. Governance therefore occupies a distinctive position as a mediating process that can facilitate or constrain the movement of innovations from niches into established regimes. The comparison also highlights the importance of contextual factors: financial resources, institutional capacity, regulatory readiness and stakeholder coordination influence the extent to which similar innovations can be successfully scaled across different urban contexts.

Table 1
Comparative characteristics of socio-technical transitions in urban mobility

Dimension	Bus fleet electrification	Autonomous and connected mobility	Governance and institutional change
Primary innovation/change	Electric buses, batteries and charging infrastructure	Autonomous shuttles, connected vehicles and digital/AI systems	Collaborative, adaptive and reflexive governance
MLP position	Niche innovation challenging diesel-based regimes	Niche innovation challenging established mobility and regulatory regimes	Regime-level institutional adaptation
Main landscape pressures	Climate change, air-quality targets and decarbonisation	Congestion, climate imperatives, demographic change and technological competition	Climate change, digitalisation, globalisation and societal expectations
Key regime challenges	Scheduling, procurement, infrastructure, financing and grid integration	Regulation, liability, safety standards and workforce organisation	Institutional rigidity, fragmented oversight and hierarchical governance
Main actors	Transport operators, municipalities and energy utilities	Governments, regulators, technology firms, operators and citizens	Municipalities, operators, citizens, regulators, technology firms and energy utilities
Key governance requirements	Coordination of transport, energy and finance	Adaptive regulation, safety assurance and anticipatory governance	Participation, co-design, institutional flexibility and reflexivity
Main risks and tensions	Financial viability, technological lock-in, service reliability and uneven capacity	Safety, equity, labour displacement, algorithmic bias and public trust	Accountability, corporate influence, legitimacy and unequal participation
Key enabling mechanisms	Infrastructure and institutional coordination	Regulatory experimentation and stakeholder participation	Institutional learning and adaptive governance
Main learning mechanisms	Pilot projects, charging strategies and fleet management	Safety protocols, user acceptance and regulatory experimentation	Stakeholder feedback and policy adaptation
Spatial/contextual dependency	Financial and infrastructure capacity	Regulatory and institutional readiness	Political, economic and institutional capacity
Potential transition outcome	Low-emission public transport systems	Integrated and potentially automated mobility services	Legitimate, adaptive and resilient mobility governance

Electrification illustrates how niche innovations in battery technology and charging infrastructure must be integrated into regime-level operations and energy systems. Automation, by contrast, highlights the disruptive potential of digital technologies and artificial intelligence, which challenge regulatory frameworks and workforce structures. Governance reforms cut across both, mediating between experimentation and institutionalization, and determining whether innovations are scaled, legitimized, and embedded. Taken together, these transitions demonstrate that technological change alone is insufficient; institutional and social dimensions are equally decisive in shaping outcomes.

At the niche level, electrification pilots, autonomous shuttle trials, and collaborative governance experiments provide protected spaces for learning and innovation. These niches generate knowledge, test new practices, and build legitimacy. Yet their success depends on regime adaptation. For electrification, this means reconfiguring scheduling, procurement, and grid integration. For automation, it requires new liability frameworks, safety standards, and operational models. For governance, it involves institutional flexibility, stakeholder participation, and reflexivity. Without regime adaptation, niches remain isolated experiments, unable to diffuse into mainstream systems.

Landscape pressures provide the overarching drivers of change. Climate imperatives, urbanization, digitalization, and societal demand for sustainability create urgency for transitions. Electrification is propelled by air quality mandates and decarbonization targets. Automation is accelerated by demographic change, congestion, and global competition in technology. Governance reforms are shaped by broader societal values, including equity, inclusivity, and democratic participation. These landscape forces push regimes to adapt, but they also create uneven geographies of transition, with some cities and regions advancing rapidly while others remain locked into conventional systems. Beyond the differences between electrification, automation and governance, the literature reveals a set of cross-cutting mechanisms that shape transition pathways across all three domains. These include institutional adaptation, stakeholder integration, learning and experimentation, equity, uncertainty, power and legitimacy, spatial unevenness, and reflexivity. Identifying these mechanisms is important because they help explain why technological feasibility alone does not necessarily result in successful system-wide transition. Table 2 synthesizes how these mechanisms manifest across the three domains and identifies their broader implications for socio-technical change.

A comparative perspective also highlights the contested nature of transitions. Electrification raises questions about financial viability and social acceptance, automation provokes debates about equity, access, and labor displacement, and governance reforms confront tensions between efficiency and inclusivity. These contestations reflect the political character of socio-technical transitions, where diverse actors negotiate competing interests and values. Within the MLP, this underscores that transitions are not linear or predetermined but contingent, shaped by the alignment or misalignment of niches, regimes, and landscapes.

The synthesis also reveals how transitions unfold unevenly across geographies and institutional contexts. Electrification has advanced rapidly in cities with strong climate policies and financial resources, while smaller municipalities struggle to mobilize investment. Automation pilots are concentrated in high-income regions with robust regulatory frameworks, leaving lower-income contexts at risk of exclusion. Governance reforms similarly vary, with some cities embracing collaborative and adaptive models while others remain tied to hierarchical, rigid structures. This unevenness illustrates the importance of context-sensitive governance, capable of mediating global pressures and local realities.

Another dimension of synthesis is the role of learning and reflexivity. Transitions are accelerated when lessons from pilot projects are shared across networks, enabling cities to avoid repeating costly mistakes. Electrification benefits from knowledge diffusion about charging strategies and fleet management. Automation advances through shared insights on safety protocols and user acceptance. Governance reforms evolve through reflexive processes that incorporate feedback from stakeholders and adapt policies over time. Within socio-technical transition theory, this highlights the importance of institutional learning as a mechanism for scaling innovations across regimes.

Finally, the synthesis underscores that transitions are systemic, requiring coordination across technological, institutional, and societal domains. Electrification, automation, and governance are not separate pathways but interdependent processes. Electric bus deployment depends on governance frameworks for financing and stakeholder coordination. Autonomous vehicle adoption requires governance innovation to manage uncertainty and ensure equity. Governance reforms themselves are often catalyzed by technological disruptions, forcing institutions to adapt to new realities. In this way, the three dimensions form a mutually reinforcing triad, illustrating the systemic nature of socio-technical transitions in urban mobility.

The comparative synthesis also reveals the importance of sequencing and timing in transitions. Electrification, automation, and governance reforms do not unfold simultaneously; rather, they interact in complex temporal patterns. For example, electrification may need to precede automation to ensure that autonomous fleets are sustainable, while governance reforms often lag behind technological experimentation. Misalignment in sequencing can create systemic inefficiencies, such as deploying autonomous vehicles before regulatory frameworks are ready or investing in electrification without adequate grid decarbonization. Recognizing the temporal dynamics of transitions allows policymakers to design phased strategies that align technological innovation with institutional readiness and societal acceptance.

The integrated framework also highlights the importance of sequencing and feedback in socio-technical transitions. Innovations do not automatically diffuse from experimental settings into established mobility systems; rather, diffusion depends on learning, institutional adaptation, and the ability of governance arrangements to respond to emerging technological and societal conditions. The comparative synthesis identifies experimentation, learning, governance adaptation, regime reconfiguration, and system-level diffusion as interconnected stages of this process. Figure 2 illustrates this transition pathway and the feedback mechanisms that connect these stages.

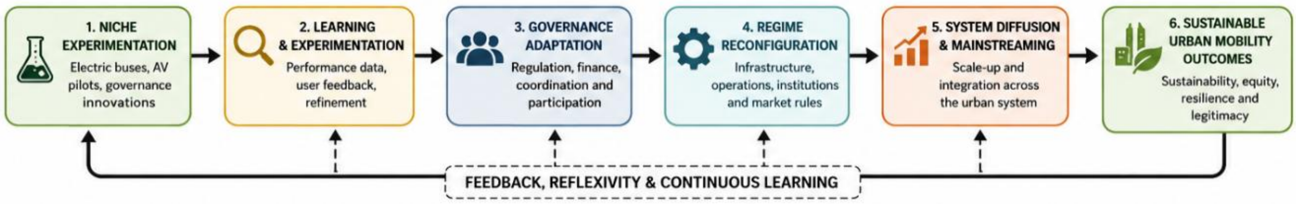

Fig. 2. Transition pathways and feedback loops in urban mobility systems

Figure 2 emphasizes that transition pathways are neither linear nor predetermined. Niche experiments generate technical, institutional, and social learning, which can inform subsequent governance adaptation and regime reconfiguration. Successful reconfiguration can enable innovations to diffuse and become embedded across the wider urban mobility system. At the same time, experience from implementation generates feedback that can lead to further experimentation, regulatory adjustment, and institutional learning. This reflexive process is particularly important under conditions of technological uncertainty, where regulatory frameworks, operational practices, and stakeholder expectations may need to evolve alongside innovation. The figure therefore highlights learning and reflexivity as continuous mechanisms linking technological experimentation with long-term institutional and system transformation.

8. Conclusions and Policy Recommendations

The comparative analysis of electrification, automation, and governance demonstrates that urban mobility transitions are not linear technological upgrades but complex socio-technical processes. Within the multi-level perspective, niches provide spaces for experimentation, regimes embody institutional inertia and operational routines, and landscapes exert external pressures such as climate imperatives and societal demand for sustainability. The interplay of these levels reveals that successful transitions depend on systemic coordination across technological, institutional, and social domains.

Electrification highlights the importance of aligning technological innovation with regime adaptation. Pilot projects and early deployments show that electric buses can deliver environmental benefits, but their diffusion requires integration with energy systems, procurement frameworks, and financial mechanisms. Policymakers must therefore prioritize long-term investment strategies, support adaptive scheduling and charging infrastructure, and ensure that equity considerations are embedded in deployment plans.

Automation underscores the disruptive potential of digital technologies, challenging regulatory frameworks, liability structures, and workforce arrangements. Pilot projects demonstrate technical feasibility, but scaling requires governance innovation to manage uncertainty, ensure safety, and address equity concerns. Policy frameworks must anticipate labor displacement, guarantee accessibility for disadvantaged groups, and establish adaptive regulatory standards that evolve alongside technological development.

Governance emerges as the critical mediator of transitions. Institutional reforms determine whether innovations remain confined to niches or diffuse into mainstream systems. Collaborative governance models, reflexive learning, and participatory processes are essential for building legitimacy and resilience. Policymakers must embrace governance as a normative process, balancing efficiency with inclusivity, and ensuring that transitions reflect societal values as well as technical imperatives.

From a policy perspective, three overarching recommendations can be drawn: (i) Electrification and automation cannot succeed without governance frameworks that align procurement, regulation, and financing with innovation; (ii) policies must address access, affordability, and labor impacts to ensure that transitions do not exacerbate existing inequalities, and (iii) institutions must remain open to feedback, learn from experimentation, and adjust policies as transitions unfold, recognizing that uncertainty is inherent in socio-technical change.

Future research should therefore adopt a more integrative lens, examining how electrification, automation, and governance reforms co-evolve across different urban contexts. Comparative studies between Global North and Global South cities can illuminate how resource constraints, institutional capacities, and cultural imaginaries shape divergent transition pathways. Longitudinal research is also needed to track how governance frameworks adapt over time, particularly in response to technological uncertainty and societal contestation. By embedding these perspectives, scholarship can provide more actionable insights for policymakers and practitioners, ensuring that urban mobility transitions are not only technologically feasible but also socially legitimate and institutionally resilient. Finally, interdisciplinary approaches that bridge engineering, social science, and policy analysis are needed to capture the systemic nature of transitions. By combining technical feasibility studies with institutional analysis and societal perspectives, future scholarship can provide more holistic and actionable guidance for policymakers and practitioners.

Ultimately, the synthesis reveals that electrification, automation, and governance are mutually reinforcing dimensions of a systemic transition toward sustainable urban mobility. Policymakers and practitioners must therefore move beyond siloed approaches, embracing integrated strategies that coordinate technological innovation, institutional reform, and societal engagement. Only through such systemic alignment can urban transport systems achieve the dual goals of sustainability and equity in the face of accelerating global pressures.

Author Contributions

The author conceptualized the study, designed the methodology, conducted the literature review, and synthesized findings into the manuscript. All sections of the paper, including case study analysis, comparative synthesis, and policy recommendations, were written and revised by the author.

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Data Availability Statement

No new data were created or analyzed in this study. Data sharing is not applicable to this article. All sources used in the literature review are publicly available through academic databases and institutional repositories.

Conflicts of Interest

There are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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