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Socio-technical Transitions for Sustainable Mobility in Cities: Taking Stock, Looking Ahead

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ABSTRACT

Socio-technical transitions in mobility and transport are complex processes. They involve the transformation of entire mobility systems, including technologies, infrastructures, regulations, and social practices. A significant socio-technical transition has been going on in mobility over the last decades with major trends including the shift to electric vehicles (EVs), the development of connected and automated vehicles (CAV), and the shift to sustainable mobility including public transport, cycling, and walking. These transitions are not just about technological innovations but also involve changes in policies, market structures, and social practices. They require coordinated efforts from various stakeholders, including governments, businesses, and civil society. This paper provides a comprehensive overview of the development and progress of socio-technical transition framework in the area of mobility over the last decades, with a special emphasis on the multi-level perspective. The paper also reviews the conceptual underpinnings, current issues, and future research areas with regards to socio-technical transitions for mobility.

1. Introduction

Mobility systems are currently undergoing significant transformations driven by technological changes, environmental concerns, and changing societal expectations. Socio-technical transitions are brought about through systemic changes involving new technologies, infrastructures, policies, and social behaviours [1]. In recent decades, key drivers such as electrification, digitalisation, and automation have changed the regime of mobility eco-systems in such a way that this transformation could be better examined with a multi-level perspective (MLP) framework, which highlights the interaction between niche innovations, socio-technical regime, and broader landscape changes [2]. Efforts to accelerate the transition to sustainable mobility further contributed to these system-wide transformations in the area of mobility. Therefore, there is a greater need for a holistic, multi-

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stakeholder approach to drive the transition to sustainable mobility systems that balance technological innovation with social and environmental concerns.

Mobility is a fundamental component of modern economies and societies, facilitating trade, transportation of goods and people, and urban, regional, and national development [3]. However, current mobility systems are a major contributor to global carbon emissions, air pollution, and resource depletion. The rapid urbanisation as well as rising demand for mobility services place significant pressure on existing mobility infrastructures, which makes the shift towards a sustainable mobility system crucially imperative. Socio-technical transitions in mobility systems refer to paradigmatic changes including technological advancements, institutional transformations, policy shifts, and behavioural changes [4]. These transitions are influenced by various developments including climate policies, economic incentives, and technological breakthroughs such as electric vehicles (EVs), autonomous mobility, and digital mobility platforms.

The Multi-Level Perspective (MLP) is a widely used analytical framework for conceptualising and understanding socio-technical transitions [5]. The MLP conceptualises these transitions as the result of dynamic interactions among three levels: 1) ‘niche innovations’ consisting of emerging technologies, experimental initiatives, and alternative mobility solutions that challenge dominant mobility systems (e.g. EVs, hydrogen fuel cell vehicles, on-demand mobility services, autonomous vehicles, etc.); 2) ‘socio-technical regime’ representing the established mobility systems, including infrastructure, regulatory and governance frameworks, industry standards, and user behaviours (e.g. internal combustion engine vehicles (ICE) vehicles, road-based freight transport, car-centric urban planning); 3) ‘socio-technical landscape’ encompassing external and long-term changes such as climate change, global energy crises, urban sprawl, and geopolitical events which have the potential to destabilise existing regimes and create opportunities for niche innovations to break through. The MLP framework is useful to explain why certain mobility transitions succeed while other fail and disappear. Successful transitions typically happen when niche innovations gain momentum, align with wider social changes, and receive institutional acceptance [6]. However, incumbent actors, political interests, and infrastructural lock-ins often create barriers for transition.

Key drivers of socio-technical transitions in mobility systems include technological innovations, environmental and regulatory measures, changing customer preferences, and economic /market forces [7]. Advancements in battery technology, vehicle automation, and smart mobility solutions are the most outstanding examples of technological innovations that reshape mobility systems. The decrease in battery costs has accelerated the adoption of EVs, making them more accessible to consumers. Artificial intelligence (AI) and the internet of things (IoT) are enhancing connectivity, enabling real-time data-driven decision making in areas of real-time traffic management, vehicle-to-infrastructure communication, and autonomous driving capabilities [8]. City-wide zero-emission fleet targets, carbon-taxes, fuel efficiency standards, and subsidies for EV adoption are examples of regulatory measures driving transitions in mobility systems. Shared mobility options such as ridesharing, bike-sharing, and public transport, mobility-as-a-service (MaaS) platforms, remote working are examples of changing customer preferences influencing mobility transitions. Major automakers like Tesla, Volkswagen, and Toyota are heavily investing in electric and autonomous vehicles, signaling a shift in industry dynamics. Meanwhile, oil companies are diversifying into renewable energy, considering that the future of mobility is moving away from fossil fuels.

This paper aims to give a comprehensive overview of the development and progress of socio-technical transition framework in the area of mobility over the last decades. The paper also reviews how socio-technical transitions unfold in the mobility eco-system, what factors facilitate or hinder these transformations, and what policies can be implemented to achieve sustainable mobility solutions. The study also utilises the multi-level perspective (MLP) framework to examine how mobility innovations interact with existing mobility regimes and wider socio-political contexts. Through an analysis of emerging trends and case studies in the area of mobility, this paper aims to contribute to the ongoing discourse on sustainable mobility futures. Section 2 provides a theoretical overview of the Multi-Level Perspective (MLP) to analyse mobility transitions. Section 3 discusses the key drivers of socio-technical transitions, including technological, regulatory, and social factors. Section 4 presents examples of case studies about socio-technical transitions to sustainable mobility, highlighting different approaches. Section 5 explores the barriers and challenges to sustainable mobility transitions. Section 6 discusses future trends and innovations in mobility transitions. Finally, Section 7 concludes with policy implications, recommendations and future research and planning directions.

2. Theoretical Framework: The Multi-Level Perspective (MLP)

A theoretical framework is needed to understand socio-technical transitions in mobility that gives an account of how technological innovations come about, get into relationship with existing systems, and transform an entire eco-system. The Multi-Level Perspective (MLP), developed by Frank Geels [4], is one of the most widely used frameworks in socio-technical transition studies. MLP frames socio-technical transition as a dynamic change process taking place across three intertwined levels: niche innovations, socio-technical regimes, and the socio-technical landscape. This section explains each level and how they interact with one another in the context of mobility transitions.

2.1. Niche Innovations (Micro-Level)

The niche level consists of emerging technologies, experimental projects, and alternative mobility solutions that challenge the dominant mobility system [9]. Innovations such as electric vehicles (EVs), hydrogen fuel cells, autonomous vehicles, and digital mobility platforms are examples of niche developments. These developments often start as small-scale experiments and trials, supported by various startups, research agencies, and government funds. Successful niche initiatives can gain traction, improve in efficiency, and achieve market competitiveness over time [10]. They eventually challenge and transform existing mobility systems. For example, Tesla’s emergence in the early 2000s as a niche player in electric mobility was first dismissed by the automative industry. However, Tesla gradually gained market influence through technological improvements and strong branding, eventually accelerating the global EV transition.

2.2. Socio-technical Regime (Meso-Level)

The regime level represents the existing dominant mobility system, including its established technologies, infrastructures, policies, business models, and user behaviours. The regime is often resistant to change due to path dependencies accumulated over time, vested interests, and regulatory structures. Although there have been various challenges against the dominant mobility system over recent decades, it can still be characterised by a widespread reliance on internal combustion engine (ICE) vehicles and fossil fuel infrastructure, car-centric urban planning which prioritises roads over public transport, and an established automative and oil industries having a strong influence on policy decisions [11]. Change at the regime level is often challenging and difficult given the economic and political incentives of the regime actors such as large automobile manufacturers, oil companies, and transport policymakers to maintain the status quo. However, as niche innovations and external (landscape) pressures build up and intensify, regime-level transformations become possible.

2.3. Socio-technical Landscape (Macro-Level)

The landscape level consists of wider external pressures that influence and shape the overall conditions for transitions. In the context of mobility, there pressures include climate change and environmental crises, which are pushing for decarbonisation, geopolitical shifts triggering oil price volatility and energy security concerns, urbanisation and demographic trends, increasing demand for sustainable mobility, and economic shifts like the growing competitiveness of renewable energy and electric mobility solutions. These landscape pressures destabilise the existing mobility regime, creating 'windows of opportunity' for niche innovations to scale up. For example, city targets for fully electrified bus fleets accelerated the electrification of bus fleets across the cities [12]. Another example is the increasing concerns around air pollution in megacities like Beijing, Delhi, and Mexico City in recent decades that led to stricter emission regulations, accelerating the adoption of electric buses and low-emission zones [13].

MLP gives an account of socio-technical transitions as a dynamic, multi-phase, and multi-actor process where niche innovations gradually gain traction and challenge the dominant regime. Geels and Schot [14] identified four possible transition pathways: 1) 'transformation pathway' by which the regime adopts niche innovations gradually in response to landscape pressures (e.g. traditional automakers such as Volkswagen and Ford transitioning to electric mobility due to regulatory pressures), 2) 'reconfiguration pathway' by which innovations are integrated into the existing system, but the overall regime remains stable (e.g. the rise of ride-sharing apps such as Uber and Lyft alongside conventional transport modes), 3) 'technological substitution' by which the old system is entirely replaced by new technologies (e.g. the transition from horse-drawn carriages to automobiles in the 20th century), 4) 'collapse and rebuilding' by which the existing regime fails, and a new system emerges (e.g. a potential scenario where fossil fuel infrastructure becomes obsolete, and green mobility solutions become dominant).

Currently, the mobility eco-system is experiencing a hybrid transition, where multiple pathways are unfolding simultaneously. While some incumbent actors (e.g. Toyota, BMW) are integrating EV technology into their existing models (taking the transformation pathway), new disruptors (e.g. Tesla, Waymo) are driving more radical changes through technological substitution.

The MLP provides a comprehensive framework for examining socio-technical transitions in transport. By examining the interactions between niche innovations, socio-technical regimes, and landscape pressures, the MLP helps explain why some transitions succeed while others face resistance. In the context of mobility, the transition from fossil-fuel-based mobility to electric, autonomous, and shared mobility models is occurring through a complex interplay of technological advancements, policy interventions, and societal preferences. Understanding these dynamics is crucial for policymakers, industry stakeholders, and urban planners aiming to develop sustainable mobility policies.

3. Key Drivers of Socio-Technical Transitions for Mobility

The transition toward sustainable mobility is driven by technological advancements, environmental concerns, policy measures, economic shifts, and changing consumer behaviours [15].

These factors interact in various ways, shaping the pace and direction of mobility transitions. This section explores the key forces driving socio-technical changes in mobility.

Technological innovations and advancements play a key role in transforming mobility systems by enabling cleaner, more efficient, and intelligent mobility solutions [16]. The most outstanding innovations include electric vehicles, hydrogen fuel cells, autonomous vehicles (AVs), and mobility-as-a-service (MaaS). Improvements in battery efficiency, range, and cost have made EVs more competitive with internal combustion engine (ICE) vehicles. According to BloombergNEF [17], the price of lithium-ion batteries has dropped significantly over the last decade, though it increased in 2022 for the first time, reducing EV production costs and increasing affordability. Major automakers like Tesla, Volkswagen, and Toyota are investing heavily in EV technology, accelerating market penetration. While still in the early adoption phase, hydrogen-powered vehicles offer a promising solution for long-haul freight and heavy-duty transport. Countries such as Japan, Germany, and South Korea are investing in hydrogen refuelling infrastructure to support wider adoption. AI-powered self-driving technology, also called 'autonomous vehicles (AVs)', has the potential to enhance road safety, optimise traffic flow, and reduce congestion. Companies like Waymo, Tesla, and Baidu are leading the development of AVs, testing autonomous ride-hailing and delivery services. The digital integration of ride-sharing, e-scooters, bike-sharing, and public transport into app-based platforms, also known as Mobility-as-a-service (MaaS), is reshaping urban mobility. Services and apps such as Uber, Lyft, and Citymapper improve efficiency and reduce reliance on private car ownership. These technological innovations are disrupting the conventional mobility regime, forcing industries, policymakers, and consumers to adapt to new mobility models.

The climate crisis and environmental degradation are major catalysts for mobility transitions. The mobility sector is responsible for approximately 25% of global CO2 emissions [18], making it a critical area for decarbonisation. The Paris Agreement (2015), for example, is a key environmental driver whereby countries committed to reducing greenhouse gas emissions (GHG) are implementing policies to phase out fossil fuel vehicles. The European Union (EU) has announced a ban on new petrol and diesel car sales by 2035. Air pollution and public health concerns are another example of key environmental driver for mobility transitions. Vehicle emissions contribute to poor air quality and respiratory diseases, particularly in urban areas. Cities like London, Paris, and Beijing have introduced low-emission zones (LEZs) and congestion pricing to reduce pollution. Extreme weather events and climate-related disruptions such as heatwaves, floods, and wildfires are pushing governments to develop resilient and sustainable mobility infrastructure. As awareness of climate change grows, governments and consumers are prioritising low-carbon mobility solutions to reduce environmental impact.

Regulatory and policy measures play a crucial role in accelerating socio-technical transitions. Key regulatory drivers include emission standards such as CO2 regulations that push automakers to develop zero-emission vehicles and improve fuel efficiency. Financial subsidies and incentives for EV buyers, tax breaks, and investment in EV charging infrastructure are increasing adoption rates. For instance, Norway's strong EV incentives have led to over 80% of new car sales being electric [19]. Bans on ICE vehicles are helping to phase out petrol and diesel cars. For example, the UK plans to ban new ICE vehicle sales by 2030, while France and Germany aim for 2035. Another example of policy measures is growing investment in public transport whereby metro networks, electric buses, and high-speed rail have been promoted mass transit over private car usage. These policy interventions create a regulatory push for sustainable mobility while discouraging high-emission mobility options.

Economic and market forces are also reshaping mobility transitions through market competition, cost reductions, and shifts in consumer preferences. Declining costs of EVs is an example of market forces that shape the consumer preferences. As production scales up, EV prices are approaching parity with gasoline cars. EVs are anticipated to become cheaper than ICE vehicles by 2027 due to technological improvements [20]. Automakers, technology firms, and energy companies are investing in clean transport such as EV production, battery recycling, and renewable energy integration. Companies like Tesla, BYD, and Rivian are competing to dominate the EV market. Fluctuating fuel prices and geopolitical conflicts (e.g. the Russia-Ukraine war) have highlighted the need for energy diversification and transport electrification. As green technologies become more cost-effective, the economic case for sustainable mobility solutions continues to strengthen.

Changing customer preferences, attitudes, and behaviours are also influencing socio-technical transitions. Young generations including Millennials and Gen Z are less likely to own and use a car, preferring shared and digital mobility as well as public transport [21]. Post-pandemic trends in hybrid and remote working have reduced daily commuting, reducing car dependency in urban areas [22]. The rise of ride-hailing, car-sharing, and micro-mobility services have shifted the mobility landscape from conventional mass transit options towards on-demand mobility models [23]. In line with these developments, cities are adapting by redesigning urban spaces to be more pedestrian and cyclist-friendly, promoting sustainable mobility habits.

4. Three Case Examples for Socio-technical Transitions to Sustainable Mobility

Examining real-world examples of socio-technical transitions provides valuable insights into how different factors interact in shaping mobility transitions. This section presents three representative examples of case studies from Norway, China, and the Netherlands, highlighting different approaches to sustainable mobility transitions.

Norway is widely regarded as the world’s most successful case of electric vehicle (EV) adoption. As of 2023, over 82% of new car sales in Norway are electric [24]. Several factors contributed to this rapid electrification. The strong government incentives played a major role in adopting EVs in a greater scale. The Norwegian government introduced generous subsidies, including zero VAT and import taxes on EVs, free parking, and access to bus lanes [25]. These policies significantly reduced the total cost of ownership of EVs, making them more attractive than ICE vehicles. Norway built a nationwide EV charging network, ensuring that charging stations are easily accessible, even in rural areas [26]. Strong environmental awareness and early adoption by consumers also encouraged the uptake of EVs. In terms of regulatory changes, Norway set a goal to phase out petrol and diesel cars by 2025, creating a clear roadmap for industry and consumers.

China leads the world in electric public transport, particularly in electric buses and shared mobility services. The city of Shenzhen, for example, has successfully transitioned its entire public bus fleet to electric vehicles [27]. The key success factors include significant state investment, local policy mandates, strategic industrial growth, and integration with smart city initiatives. The Chinese government subsidised EV production and invested in battery manufacturing to achieve economies of scale, making electric buses cost-competitive compared to other propulsion technologies [28]. Cities like Shenzhen introduced strict policies requiring public transport operators to replace diesel buses with electric ones [29]. China also leveraged its transport electrification as an opportunity to become a global leader in EV production, with companies like BYD, NIO, and XPeng driving innovation [30]. Chinese cities have integrated real-time traffic monitoring, AI-driven public transport scheduling, and digital payment systems, to integrated EVs with the smart city initiatives to improve efficiency. China’s model demonstrates how state-led policies and large-scale industrial coordination can accelerate mobility transitions.

Unlike Norway and China, the Netherlands has focused on reducing car dependence by promoting cycling and public transport. Today, over 27% of all trips in the Netherlands are made by bicycle [31]. The key factors driving this transition include urban planning prioritising cyclists and pedestrians, integration with public transport, government and municipal investments, and cultural and behavioural factors. Dutch cities have been designed with dedicated bike lanes, traffic-calming measures, and car-free zones to make cycling safer and more convenient [32]. Train stations are equipped with large bike parking facilities, allowing seamless multi-modal transport [33]. The Dutch government continuously invests in cycling infrastructure, including bike highways connecting cities [34]. Cycling is also deeply embedded in Dutch culture, supported by policies that prioritise active mobility over car usage [35]. The Netherlands' approach highlights the importance of urban planning and behavioural shifts in sustainable mobility transitions.

Three example case studies above illustrate different socio-technical transition strategies. Whereas Norway demonstrates the power of financial incentives and regulatory clarity, China shows the effectiveness of large-scale government-led industrial policies. On the other hand, the Netherlands highlights the role of urban planning and cultural change in shaping mobility habits. Each country has taken a different approach, yet all have made significant progress in ensuring sustainability, improving mobility efficiency, and reshaping mobility eco-systems.

5. Barriers and Challenges to Sustainable Mobility Transitions

Despite the growing momentum towards sustainable mobility systems, several technological, economic, political, and social barriers continue to slow down transitions. Understanding these barriers and challenges is crucial for policymakers, businesses, and researchers aiming to accelerate the transition to sustainable mobility.

Although advancements in electric, autonomous, and shared mobility have been significant, several technological barriers remain such as limitations in EVs, hydrogen fuel-cell efficiency, uncertainties around autonomous vehicle adoption, and integration of smart mobility systems. While lithium-ion battery costs have decreased, challenges related to energy density, charging speed, and raw material availability persist [36]. EVs still have limited range compared to ICE cars, and charging infrastructure remains inadequate in many regions. On the other hand, hydrogen-powered mobility technologies have the potential to decarbonise long-haul trucking, shipping, and aviation, but high production costs and energy inefficiencies hinder widespread adoption [37]. As for autonomous vehicles (AV), although AV technology is advancing, issues related to safety, ethical decision-making, and regulatory approval slow down large-scale deployment [38]. In terms of the integration of smart mobility systems, while Mobility-as-a-service (MaaS) platforms improve urban mobility, challenges related to data privacy, cybersecurity, and interoperability between different mobility networks must be addressed. Without overcoming these technological barriers, the transition to a fully sustainable mobility system is likely to remain slow and fragmented.

Another significant barrier to socio-technical transitions to sustainable mobility are the economic and financial constraints. The high upfront costs of electric and hydrogen vehicles, infrastructure investments, and research & development (R&D) present financial challenges for the industry and government. Although EV prices are declining, they are still more expensive upfront than ICE vehicles in many markets [39]. Infrastructure investment needs are another barrier to sustainable mobility transitions. Charging stations, hydrogen refuelling stations, and high-speed rail networks require significant public and private funding. Countries with economies reliant on oil production and automobile manufacturing face resistance to rapid decarbonisation efforts. The transition to new mobility solutions can also be disruptive, making some investors hesitant to fund projects without clear long-term returns. Without financial incentives and long-term policy commitments, private sector engagement in mobility transitions may remain limited.

Government policies play a key role in shaping mobility transitions; however, political and regulatory challenges can create roadblocks. Key challenges in this area include inconsistent policies across regions, resistance from the fossil fuel industry, slow policy implementation, and geopolitical risks in supply chains. While some countries have clear transport decarbonisation goals, others lack coherent strategies or have weak enforcement mechanisms. Oil and gas companies lobby against climate policies, delaying reforms and EV adoption. Even in progressive regions, the process of passing climate-friendly regulations, securing funding, and deploying infrastructure can be time-consuming. On the other hand, the production of lithium, cobalt, and rare earth metals for EV batteries is concentrated in a few countries, raising concerns about supply chain stability and geopolitical tensions [40]. Strong regulatory frameworks and international cooperation are essential to overcoming these political and regulatory challenges.

Consumer preferences and cultural factors significantly influence mobility transitions, and social and behavioural resistance can be a barrier to these transitions. The most common barriers in this area include range anxiety and charging concerns, car ownership culture, workforce transition challenges, misinformation and public scepticism. Many consumers hesitate to switch to EVs due to concerns about charging speed, station availability, and battery life [41]. In many countries, private car ownership is still a status symbol, making it difficult to shift toward shared and public transport solutions [42]. The shift to electric and autonomous mobility disrupts traditional industries, impacting jobs in automative manufacturing, oil refining, and transportation services, and this leads to significant workforce transition challenges [43]. Additionally, conflicting reports about EV battery sustainability, autonomous vehicle safety, and the viability of alternative fuels contribute to public hesitation and scepticism [44]. Raising awareness and shifting social attitudes toward sustainable mobility are critical for long-term success in achieving transition.

Overcoming these barriers necessitates stronger government policies to enforce emission regulations and support green infrastructure as well as greater investment in R&D to improve battery technology, hydrogen efficiency, and smart mobility systems. Public awareness campaigns to encourage sustainable mobility habits and countering misinformation help address public scepticism and hesitation. International cooperation to secure critical raw materials and standardise regulations is critical to change the regulatory landscape affecting sustainable mobility transitions. By addressing these challenges, societies can accelerate the shift towards a cleaner, more efficient, and accessible mobility future.

6. Future Trends and Innovations in Mobility Transitions

The future of mobility is being shaped by emerging technologies, shifting policies, and evolving consumer behaviours. As sustainability becomes a global priority, innovative solutions are being developed to create cleaner, smarter, and more efficient mobility solutions. The future of mobility will be greatly shaped and transformed by electric, hydrogen, and autonomous mobility solutions, alongside urban redesigns and policy innovations that prioritise sustainability. This section gives an overview of the key trends that will drive the next phase of socio-technical transitions in mobility.

Electric vehicles (EVs) are expected to dominate future mobility systems due to falling battery costs, improved range, and expanding charging networks. Next-generation battery technology with lithium-ion batteries being replaced by solid-state batteries offers higher energy density, faster charging times, and longer lifespan. Companies like Toyota and QuantumScape are leading research in this field. This is being complemented by the advancements in ultra-fast charging infrastructure. Emerging ultra-fast chargers (350 kW and above) allows EVs to be charged in under 10 minutes, making them more efficient than gasoline refuelling. Improvements in vehicle-to-grid (V2G) technology are expected to accelerate the transition to electric mobility. EVs will store and supply energy back to the grid, balancing electricity demand and reducing reliance on fossil fuels. Countries like Denmark and the Netherlands are piloting V2G programmes. The expansion of electric aviation and shipping is another key development fostering the transition to electric mobility. Companies like Airbus and Rolls-Royce are developing electric and hybrid aircraft [45], while shipping companies like Maersk are investing in green hydrogen and battery-powered vessels [46]. These advancements are expected to make EVs more practical, affordable, and widely adopted in various mobility sectors.

Whereas EVs dominate passenger mobility, hydrogen fuel cells are expected to play a crucial role in long-haul mobility, aviation, and shipping. Companies like Hyundai, Nikola, and Alstom are launching hydrogen-powered freight trucks and trains, reducing emissions in industries where electrification is challenging [47]. Green hydrogen production is being enhanced by advancements in electrolysis technology, which enables large-scale hydrogen production using renewable energy sources [48]. This is supplemented with advances in hydrogen infrastructure, and countries like Germany, Japan, and the USA are investing heavily in hydrogen refuelling stations, ensuring availability for commercial fleets [49]. As production costs decrease, hydrogen will become a viable clean fuel for sectors that cannot rely solely on batteries.

Autonomous vehicles and AI-driven mobility are set to transform mobility, increasing safety, efficiency, and accessibility. Companies like Waymo, Tesla, and Baidu are refining Level 4 and Level 5 autonomous vehicles, which could eliminate human error in driving [50]. Cities are experimenting with driverless buses and robo-taxis, potentially reducing costs and improving accessibility for the elderly and disabled. Advancements in AI-Powered traffic management such as AI-driven traffic lights help optimise traffic lights, predict congestion, and reduce emissions by dynamically adjusting routes. Although regulatory approval and safety concerns remain key challenges, autonomous mobility is expected to become mainstream within next 10-15 years.

Urban mobility innovations such as Mobility-as-a-Service (MaaS), 15-minute cities, electric micromobility help cities prioritise sustainable and efficient mobility solutions. Integrated MaaS platforms will allow users to seamlessly switch between e-scooters, bicycles, ride-sharing, and public transport through a single app. Cities like Helsinki and Singapore are leading MaaS implementations. Urban planners are designing cities where residents can access work, shops, and recreation within a 15-min walk or bike ride, reducing car dependency [51]. Shared e-bike and e-scooter services are also expanding rapidly, especially in dense urban areas. These innovations will make cities less car-dependent and more pedestrian-friendly, improving air quality and public health.

7. Conclusions and Implications for Future Mobility Planning and Research

The transition toward sustainable, low-carbon, and efficient mobility systems is one of the most critical socio-technical challenges of the 21^{st} century. Driven by technological advancements, environmental concerns, and changing mobility patterns, this transition requires a coordinated effort between governments, industries, and society. Throughout this paper, we have explored the key drivers of mobility transitions, emerging innovations, barriers to progress, and policy interventions necessary for accelerating change.

The main insights from this study highlight several essential trends and challenges. The most significant of these trends are the technological innovations reshaping transport. Advancements in EVs, hydrogen fuel cells, autonomous mobility, and artificial intelligence are transforming mobility systems, making them cleaner, smarter, and more efficient. Another key highlight is the socio-technical transitions requiring systematic change as mobility transition is not just about technology, but it also involves new policies, infrastructure investments, behavioural shifts, and economic restructuring [52]. Due to this multi-dimensional nature of socio-technical transitions, barriers must be addressed for widespread adoption. High costs, regulatory hurdles, resistance from fossil fuel industries, and public scepticism remain significant obstacles to achieving large-scale transitions. Therefore, policy interventions are critical. Strong government policies, including zero-emission mandates, financial incentives, infrastructure investments, and carbon pricing mechanisms are key to drive rapid and equitable change. Sustainability and equity should also go hand in hand. Future mobility planning must prioritise accessibility, affordability, and social equity to ensure that the transition benefits all communities, including low-income and rural populations.

Mobility planners and policymakers should also consider several strategic priorities to ensure a smooth and accelerate transition. For example, integrating multi-modal mobility systems is crucial. Future mobility systems should focus on seamless connectivity between public transport, cycling, walking, and shared mobility options. Cities should invest in MaaS platforms that allow users to combine different modes of mobility efficiently. Additionally, urban planning should also prioritise compact, walkable neighbourhoods, high-quality public transport, and extensive cycling infrastructure. The 15-minute city model, implemented in Paris and Barcelona, can serve as a blueprint for reducing traffic congestion and emissions.

Developing resilient and flexible mobility networks is another key strategic priority. Climate change poses risks to mobility infrastructure, including rising sea levels, extreme weather events, and heatwaves. Future mobility planning should focus on climate adaptation strategies, such as green infrastructure, flood-resistant mobility networks, and smart traffic management systems. Mobility transitions also require global cooperation in areas such as standardising EV charging networks and hydrogen infrastructure, coordinating aviation and maritime decarbonisation policies, and securing sustainable supply chains for battery materials and alternative fuels. Governments and industry should also provide affordable mobility solutions for marginalised communities and develop workforce retraining programmes for industries affected by mobility decarbonisation. This needs to be supported with public education campaigns to build trust in new technologies like EVs, hydrogen, and autonomous mobility.

The coming decades will be critical for shaping the future of mobility. While significant progress has been made, urgent action is still required to meet global climate targets and create mobility systems that are sustainable, accessible, and resilient. By embracing bold and forward-thinking mobility strategies, societies can achieve net-zero emissions, improved urban mobility, and long-term economic benefits. The success of this transition depends on collaborative efforts across multiple sectors, ensuring that future mobility systems serve both people and the planet.

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