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Editorial

Future transportation: An integrated research agenda on system, technology, equity, and sustainability

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Abstract: We are living through a pivotal era of mobility transformation. This integrated research agenda, developed by some of the co-editors-in-chief of the Transportation Research journal series, identifies critical directions across four interconnected pillars. First, reimagining the future urban mobility systems requires orchestration of microtransit ecosystems and low-altitude operations into ground-air cooperative networks. Second, core enabling technologies must advance verifiable autonomous intelligence, hierarchical vehicle-road-cloud control, and decoupled development platforms to ensure safety and scalability. Third, translating data abundance into actionable insights demands rigorous methods for data fusion and bias correction, alongside sustained commitment to granular equity, accessibility, and mobility justice. Fourth, sustainability hinges on coherent policy instruments and equitable emissions allocation across passengers, cargo, and infrastructure. Across these pillars, technological innovation must be coupled with systemic integration, equitable governance, and rigorous sustainability metrics to build resilient, low-carbon, and human-centric mobility systems for the future.

Keywords: future transportation systems; microtransit; low-altitude mobility; autonomous driving; mobility justice; data-driven policy; emissions allocation

Introduction

We are living through a pivotal era of mobility transformation, driven by the confluence of technological revolutions, pressing climate imperatives, and evolving societal expectations. These forces are fundamentally reshaping how people and goods move—challenging long-standing paradigms and opening new frontiers across urban, ground, and low-altitude transportation systems (Gao et al., 2025). In light of these profound shifts, several co-editors-in-chief of transportation journals, i.e. Communications in Transportation Research, Journal of Intelligent and Connected Vehicles, and Transportation Research Part A\C\E) have convened to identify and articulate critical research directions where transformative progress is both urgently needed and imminent in the coming decade.

Our inquiry is organized around four interconnected pillars. First, we examine the systemic reimagining of urban mobility, focusing on the integration of microtransit ecosystems and the orchestration of scalable low-altitude operations—two domains that together reconfigure how people and goods move within and across cities (Section 1).

Second, we delve into the core enabling technologies and architectures, highlighting the need for verifiable, socially-coordinated autonomous intelligence, the hierarchical control frameworks required for large-scale vehicle-road-cloud integration, and the development of ubiquitous operating systems and heterogeneous development platforms that can support a decoupled, scalable autonomous driving ecosystem (Section 2).

Third, we address the foundational role of data and analytics, exploring the journey from data abundance to actionable and equitable insights—a challenge that spans technical issues of data fusion and bias, as well as deeper questions of accessibility, mobility justice, and the translation of analytical findings into practice (Section 3).

Fourth, we confront the imperative of sustainability and impact quantification, examining the policy and governance instruments needed to accelerate low-carbon transitions—including pricing mechanisms, regulatory mandates, public investment, and behavioral interventions—alongside the development of transparent, equitable methodologies for allocating transportation emissions across passengers, cargo, and infrastructure (Section 4).

Collectively, these pillars outline a comprehensive research agenda. Across these domains, technological innovation must be seamlessly coupled with systemic integration, equitable governance, and rigorous sustainability metrics to build resilient and human-centric mobility systems for the decades ahead.

Section 1: Reimagining Urban Mobility Systems—Integrated Microtransit Ecosystems and Low-Altitude Operations

This section addresses the first pillar of our agenda: the systemic reimagining of urban mobility across ground and air layers. It examines two interconnected domains that together reconfigure how people and goods move within and across cities.

1.1 The Integrated Microtransit Ecosystem

The future of urban public transportation lies not in a single monolithic solution, but in the intelligent coordination of multiple services into a seamless, user-centric ecosystem. A primary research frontier is the evolution and maturation of microtransit—a dynamic, on-demand shared service bridging the gap between fixed-route buses and ride-hailing vehicles (Zhang et al., 2023), as shown in Figure 1. The critical challenge is to design systems that maximize social utility by enhancing accessibility, reducing congestion, and promoting equity, while achieving financial sustainability and operational efficiency.

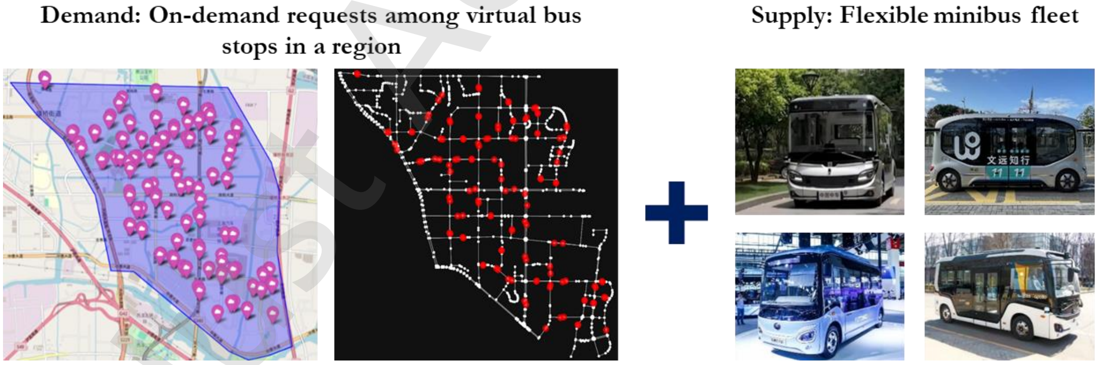

Figure 1. The operational mode in a microtransit ecosystem

(1) Algorithmic Core and Operational Efficiency. Research must first address the algorithmic core of profitable and efficient microtransit. This involves advancing real-time routing and matching algorithms that consolidate ride-pooling requests from diverse platforms (e.g., ride-hailing apps, municipal portals) into high-occupancy journeys. The goal is to minimize detours and wait times, making pooled services competitively attractive against solo rides. To improve economic viability, studies should explore integrated mobility-as-a-service subscriptions, dynamic pricing models for premium services, and public-private partnership frameworks

where public agencies provide infrastructure and regulatory oversight while private operators manage fleet and tech platforms, alongside standardized data governance. Moreover, the spatiotemporal imbalances between mobility demand and supply may lead to inefficiencies and low quality of service. Vehicle rebalancing—dispatching idle vehicles to high-demand areas—is a solution for efficient fleet management, though multiple challenges arise due to extra empty kilometers traveled, driver compliance, and increased emissions (Guan and Bao, 2024).

(2) Vehicle Platform Transformation. Simultaneously, the vehicle platform itself is transforming. The convergence of electrification and automated driving technology creates an opportunity to deploy autonomous electric shuttles and minibuses in carefully bounded operational design domains, such as campuses, airport districts, business parks, and lower-complexity urban corridors. Research should focus on the phased integration of autonomous electric minibuses into microtransit fleets. Key areas include vehicle-to-everything (V2X) communication for priority at intersections and safe interaction with vulnerable road users, and fleet management systems that optimally dispatch and charge vehicles based on predictive demand. These automated, zero-emission vehicles promise significant long-term operational cost savings, 24/7 availability, and a drastic reduction in the urban transport carbon footprint.

(3) Systemic Integration and Multimodal Ecosystem. The growth of the ride-hailing industry over the past decade has indeed provided passengers with more flexible mobility options, but it has also sparked debates about its potential impact on public transport ridership. Ride-hailing services' convenience and accessibility can be particularly valuable in areas where public transport options are limited or insufficient. Ultimately, success hinges on systemic integration. Future research must develop unified digital platforms that offer multimodal trip planning, booking, and payment, presenting microtransit as a reliable first/last-mile connector to major transit corridors, with efforts to regulate competition in areas of high-quality public transport. Furthermore, embedding these services into urban planning—via dedicated pickup points, traffic priority measures, and coordinated land-use policies—is essential. The objective is a resilient, adaptive shared-transport ecosystem where microtransit, traditional public transport, and active mobility coalesce, offering an affordable, convenient, and low-carbon mobility mode.

1.2 Scalable and Safe Low-Altitude Mobility

Low-altitude mobility is emerging as a new transport layer, propelled by advances in electric vertical take-off and landing (eVTOL) aircraft and drones (Zhao et al., 2026). The maturation of their technology has unlocked new pathways for smart city operations, as unmanned aerial vehicles are increasingly shaping the future of urban mobility, logistics, and infrastructure monitoring (Yang et al., 2024). A critical research direction is how to move from small-scale demonstrations to safe, scalable, and socially legitimate passenger and logistics services that complement, rather than compete destructively with, existing ground networks (Wang et al., 2022). The central question is not whether the urban sky can be used, but under what operational, regulatory, and social conditions it can create public value.

(1) Technological Standardization and Automation. For low-cost, large-scale deployment, the paramount research thrust is technological standardization and automation. In logistics, this means developing highly automated, beyond-visual-line-of-sight drone fleets for package delivery. Research must tackle swarm orchestration algorithms for efficient parcel sorting and routing, autonomous battery swaping or charging infrastructure, and the design of low-noise, safe aircraft for dense environments. For air taxis, the path to affordability involves scaling manufacturing, extending vehicle and component lifespans, and creating highly automated systems to minimize human oversight needs (Lv et al., 2024).

(2) Airspace Management and Traffic Control. Unmanned aerial vehicle (UAV) operations can utilize urban transport networks by including a third-dimensional space for additional mobility alternatives. However, several new operational issues and questions are being raised as traffic congestion may form in constrained urban airspace as the number of aircraft grows. Moreover, in current aviation operations, aircraft are individually controlled under rigid individual operations with limited capacity and safety constraints, while future aircraft can be aggregately controlled under flexible aircraft flow operations. Given the high complexity of individual movements of aircraft in three-dimensional space, traffic control strategies should be revisited and designed with hierarchical control approaches and connection with ground transport, to control flows in specific regions. While there are some similarities between urban ground traffic systems and UAV systems, there are also additional challenges that require revisiting both the network modeling and control of both layers in the era of automation and communication.

(3) Layered Digitalized Airspace Management. The cornerstone of integration is a layered, digitalized airspace management system, often conceptualized as the Urban Air Mobility (UAM) Traffic Management (UTM) (Piscopo et al., 2025). This system must dynamically deconflict flight paths for diverse users (drones, air taxis, emergency services) up to approximately 600 meters altitude. Research is urgent in the following aspects: creating secure, interoperable communication protocols (5G/6G, satellite); developing AI-powered dynamic geofencing and conflict resolution tools; and integrating UTM with traditional Air Traffic Control for seamless corridor transitions (Wang et al., 2025). Physical integration requires studying vertiport and vertistop networks—their optimal locations atop transit hubs, parking garages, and buildings to facilitate smooth intermodal transfers—and designing them to

minimize community impact.

(4) Safety, Security, and Socio-Technical Acceptance. Finally, enabling high-frequency, high-density operations while ensuring safety is a multifaceted challenge. It requires rigorous research into airworthiness certification for novel eVTOL designs under high-utilization scenarios, cyber-physical security for the entire navigation and communication grid, and real-time safety monitoring systems capable of predicting and mitigating failures. Furthermore, comprehensive socio-technical studies on public acceptance, noise mitigation, visual intrusion, and equitable access are vital for sustainable implementation. The vision is a layered, regulated, and automated "highway-in-the-sky" that complements ground congestion, offering rapid long-distance connections and agile logistics, governed by a fail-safe principle where safety is embedded in every layer of the system's design and operation.

Section 2: Core Enabling Technologies—Verifiable Autonomy, Hierarchical Control, and Decoupled Development Platforms

This section addresses the second pillar of our agenda: the core enabling technologies and architectures that underpin advanced mobility systems. It covers verifiable autonomous intelligence, hierarchical control frameworks for vehicle-road-cloud integration, and the development of ubiquitous operating systems and heterogeneous development platforms.

2.1 Advancing Autonomous Driving: Verifiable, Efficient, and Socially-Coordinated Intelligence

The integration of Vision Language Models (VLM) and Vision Language Action (VLA) architectures marks a decisive shift from traditional modular pipelines to unified, reasoning-capable policies in autonomous driving. While these foundation models promise enhanced generalization and human-like interpretability, their deployment into safety-critical vehicular platforms over the next five years faces three fundamental bottlenecks.

(1) Computational Latency and Hardware Efficiency. The primary engineering roadblock is computational latency and the demand for hard real-time performance. The massive parameter counts of VLA models introduce significant inference delays, often exceeding the sub-100 ms threshold required for high-speed reactive control. Bridging this gap requires a move away from "brute-force" computation toward hardware-aware efficiency. Future research must prioritize knowledge distillation to compress the reasoning capabilities of teacher models into lightweight edge-deployable versions, alongside the use of Mixture-of-Experts (MoE) architectures. By leveraging model sparsity, MoE-based systems can selectively activate only relevant neural pathways, drastically reducing floating-point operations while maintaining the depth of

understanding necessary for complex environments.

(2) Neuro-Symbolic Dilemma: Neural Flexibility vs. Formal Safety Verification. Secondly, a critical conflict exists between neural flexibility and formal safety verification. Pure end-to-end generative models are inherently non-deterministic "black boxes," making them currently uncertifiable by automotive safety standards. Future research must resolve the "neuro-symbolic dilemma"—the challenge of embedding a symbolic safety kernel within a neural architecture. Resolving this requires designing a hybrid system in which the neural VLA stack outputs a structured "Chain-of-Thought" plan that is then audited by a symbolic, rule-based verifier. Bridging the gap between the creative reasoning of generative AI and the zero-tolerance requirements of traffic safety remains a primary hurdle for regulatory acceptance.

(3) Standardization of Machine-Human Social Intelligence and Cooperative Protocols. Last but not least, the industry faces the standardization of machine-human social intelligence and cooperative protocols (Dong et al., 2025). Beyond solo vehicle operation, future systems must parse the "unwritten rules" of the road, such as pedestrian gestures, police hand signals, and social norms, into a standardized, ontology-driven language (Tang et al., 2025). The challenge is twofold: achieving robust alignment between visual gestures and linguistic intent across diverse cultures, and establishing a low-latency, universal "traffic phraseology" for V2X (Vehicle-to-Everything) communication. Without a canonical framework for inter-agent coordination, the deployment of large-scale fleets will likely suffer from "coordination paralysis," where conflicting AI intents lead to gridlock rather than the seamless, collective intelligence envisioned for the future transport ecosystem.

2.2 Hierarchical Safety Control Architecture for Vehicle-Road-Cloud Integration

The realization of robust, large-scale vehicle-road-cloud (VRC) integrated systems necessitates a fundamental shift from vehicle-centric safety paradigms toward multi-layered, cross-domain safety assurance frameworks (Gao et al., 2024). Beyond safety, hierarchical coordination enables substantial efficiency gains: cloud-based cooperative controllers can orchestrate multi-vehicle trajectory optimization to form stable platoons, reducing aerodynamic drag and improving fuel economy; coordinated speed regulation helps suppress shockwave propagation, alleviating phantom congestion and increasing traffic throughput across network corridors (see an example in Figure 2). A critical frontier is the development of elastic arbitration mechanisms that can dynamically reconcile conflicting control commands—balancing individual safety imperatives with collective efficiency objectives—across reactive, deliberative, and network-connected hierarchies in complex, dynamically evolving failure scenarios.

(1) Multi-Source Uncertainty and Cascading Risks. The core technical challenge involves

managing the propagation of multi-source uncertainty through the control stack. Traditional fail-safe designs assume isolated and predictable failure modes, whereas VRC systems face cascading risks arising from simultaneous occurrences such as sensor degradation, communication latency, algorithmic bias, and infrastructure malfunctions. Research must advance multi-tier functional safety architectures that implement graduated responses: reflexive collision avoidance at the vehicle layer, predictive trajectory replanning at the edge computing layer, and coordinated flow optimization at the cloud layer. Central to this approach is a safety sandbox arbitration kernel—a formally verified mediator that evaluates control proposals against dynamically computed safe operational envelopes, enabling provably safe trajectory selection even when upstream algorithms generate suboptimal or conflicting outputs.

(2) Multi-Tier Functional Safety Architectures. Equally critical is the co-design of physical and digital infrastructure to support such hierarchical control. This requires rigorous demand analysis to determine the minimum necessary roadside sensing density, computational capacity, and communication reliability for safety-critical arbitration. Future research must bridge algorithmic coordination with infrastructure economics, establishing cost-benefit models that can guide phased rollout strategies. The ultimate objective is a certifiable, scalable VRC framework in which safety and efficiency emerge not from perfect prediction, but from verified, elastic coordination across all system layers.

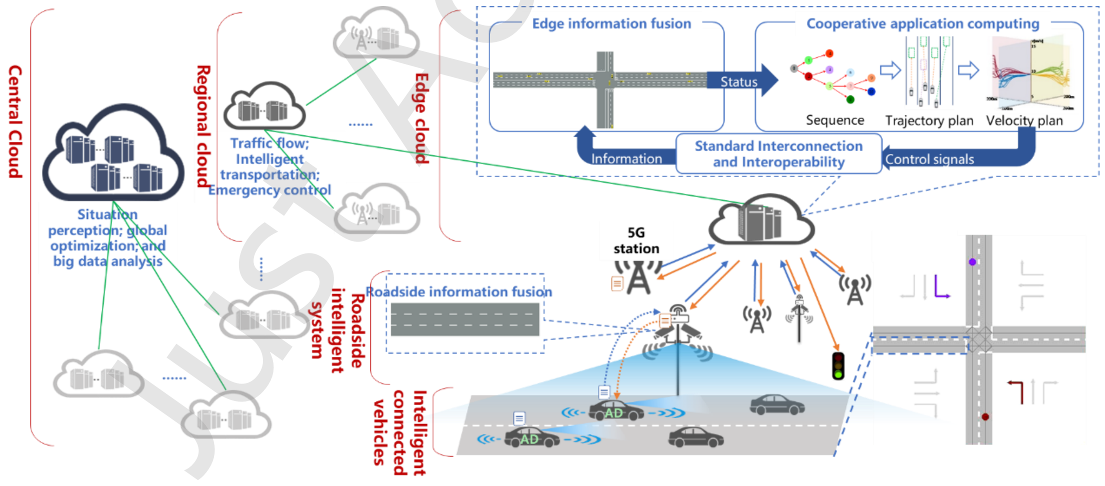

Figure 2. A Vehicle-Road-Cloud architecture

2.3 Ubiquitous Operating Systems and Heterogeneous Development Platforms for Autonomous Driving

The autonomous driving industry faces a fundamental productivity crisis stemming from deep coupling between algorithms and hardware platforms, which forces redundant engineering, drives up costs, and fragments the ecosystem. Achieving sustainable maturation requires a paradigm shift toward layered, decoupled architectures—separating foundational platform services from differentiated application algorithms—and establishing development toolchains agnostic to hardware heterogeneity.

(1) Ubiquitous Operating System (uOS) for Hybrid Intelligence. The core research imperative is to construct a ubiquitous operating system (uOS) for vehicle-road-cloud environments capable of reconciling hybrid intelligence paradigms. Unlike monolithic software stacks, the uOS must seamlessly integrate deterministic rule-based services (e.g., traffic regulation compliance), end-to-end neural perception-decision models, and multimodal large language model agents for contextual reasoning. This calls for novel middleware architectures, including tree-structured microservice orchestration, operator-level decomposition, and low-rank adaptation techniques for fine-tuning large language models (LLMs).

(2) Hardware Abstraction and "Write Once, Deploy Anywhere". Crucially, the uOS must abstract heterogeneous accelerators—such as compute unified device architecture (CUDA) graphics processing units (GPUs) and specialized artificial intelligence (AI) chips from different manufacturers—through unified hardware abstraction layers. This enables algorithm deployment, dynamic workload scheduling, and resource management independent of the underlying silicon, achieving a "write once, deploy anywhere" capability essential to breaking vendor lock-in and fostering innovation.

(3) Integrated Development Platforms for Decoupled Algorithm Design. Complementing the runtime environment, future research must deliver integrated development platforms that are both model-driven and data-driven, fully decoupling algorithm design from implementation. Such platforms should merge symbolic reasoning engines, graphical application modeling interfaces, and neural architecture search tools into a unified workflow. For LLM-based agents, the platform must support closed-loop pipelines encompassing fine-tuning on driving scenarios, adversarial testing in simulation, and iterative refinement—ultimately enabling automatic translation from high-level agent specifications to deployable code.

(4) Distributed Intelligence and Strategic Outcome. This vision extends to distributed intelligence, where cloud-hosted foundation models distill knowledge to lightweight vehicle-edge models via federated learning, with dynamic computational offload mechanisms balancing latency and accuracy. The strategic outcome is a decoupled and standardized ecosystem where infrastructure providers, algorithm developers, and vehicle original equipment manufacturers (OEMs) collaborate through open interfaces, reducing duplication, accelerating innovation, and democratizing access to advanced autonomous driving capabilities.

Section 3: From Data Abundance to Equitable and Actionable Insights

This section addresses the third pillar of our agenda: the foundational role of data and analytics in transforming transportation systems. It spans technical issues of data fusion, bias, and reproducibility, as well as deeper questions of accessibility, equity, and mobility justice.

3.1 Data Reconciliation, Bias, and Reproducibility

Transportation has entered an era of unprecedented data availability—a development that once raised expectations that long-standing challenges, such as demand estimation, would be rendered obsolete by data collection alone. However, experience has shown that while emerging and revolutionary data sources solve certain problems, they also introduce new complexities. A primary challenge is the need for data reconciliation and fusion across scales and sources. For instance, researchers must integrate novel passively collected data—from mobile phones, Global Navigation Satellite Systems (GNSS), smart cards, etc. (see Figure 3)—with traditional survey data. Another significant hurdle lies in managing temporal and spatial misalignment between disparate data streams.

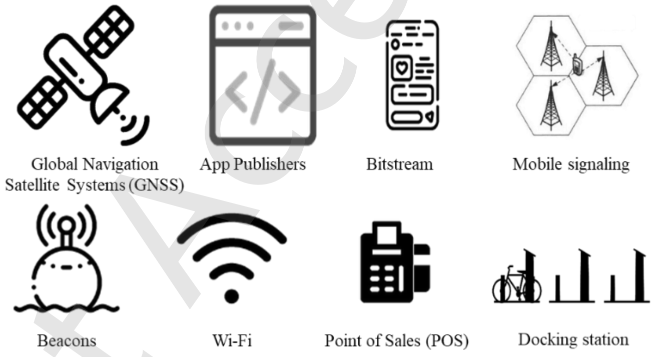

Figure 3. Typical mobility data sources for transportation systems

A downstream question, therefore, is how researchers can translate heterogeneous data into robust, transferable, and policy-relevant knowledge. Issues of data quality, bias, and representativeness emerge as central concerns. It is well recognized that big data often carries systematic biases, such as coverage gaps, socio-demographic skew, and urban bias. Consequently, it is critical to develop and refine methods to assess, correct, or explicitly model bias and uncertainty within both the data and its applications. In an era where no single dataset is entirely complete or neutral, even the concept of "ground truth" requires re-evaluation.

As a result, the importance of standardization, interoperability, and reproducibility has grown considerably. As applications scale from local to regional or global levels, the absence of common data standards across cities, countries, and platforms becomes a pressing issue.

Reproducibility and transparency are also vital in a research environment increasingly reliant on proprietary or restricted datasets. Here, open and public data play a significant role (Mahajan et al., 2022). Scientific journals, including Communications in Transportation Research, are increasingly mandating that data and code be made available to the public, while platforms such as ETS-Data (https://ets-data.sciopen.com/home) provide persistent, citable access to datasets.

Returning to the question of whether sufficiently high-quality data can eliminate the need for modeling, the scientific community stands at a crossroads. While data-driven and machine-learning models typically outperform traditional models in metrics, such as accuracy, precision, and recall, they often lack the capacity to support causal, policy-relevant inference. Significant efforts across multiple fields are therefore underway to develop explainable machine learning models that offer both predictive superiority and capacities for explanation and causal reasoning. Delving further, considerations of reliable and trustworthy artificial intelligence add further complexity to these discussions.

Beyond technical aspects, researchers cannot overlook issues of governance, access, and ethics. Data ownership, privacy regulations (Qin et al., 2025)—such as the European General Data Protection Regulation (GDPR)—and other legal constraints limit scientific access. For example, while high-resolution mobility data enables more effective analysis, its use may raise ethical concerns regarding the identifiability of vulnerable populations. Moreover, trade-offs between open science and commercial viability often hinder scientific progress, as entities restrict data access to maintain a competitive advantage, thereby limiting researchers' ability to advance knowledge.

A promising direction for addressing many of these challenges is synthetic data generation. Synthetic data have been used in transportation research for decades; one clear example is population synthesis, where simulation and optimization techniques generate synthetic populations that replicate macroscopic properties of real populations for use in transportation simulations (Farooq et al., 2013). More recently, synthetic trajectory datasets have been created for various mobility applications (Kim & Jang, 2024). A key advantage of synthetic datasets is their inherent privacy preservation, as they do not seek to replicate individual trajectories.

3.2 Granular Equity, Accessibility, and Mobility Justice

The increasing availability of high-quality, high-resolution data, as noted previously, offers significant positive implications, enabling researchers to refine foundational concepts such as accessibility and equity. For decades, accessibility studies have predominantly relied on single aggregate measures. Advances in data, algorithms, and computational power now facilitate a shift towards distributional analyses, capturing group- and mode-specific accessibility to diverse opportunities—including jobs, education, and healthcare. This granular perspective allows researchers to incorporate nuanced considerations like time poverty, reliability, and safety into their assessments.

Beyond these initial advances, deeper analysis can profoundly influence transportation policy, particularly in identifying and correcting inequitable impacts of transport investments. It is increasingly feasible to evaluate the distributional effects of pricing schemes, electrification, automation, and climate-related policies such as low-emission zones. For instance, an accessibility-centered spatial equity evaluation by Abouelela et al. (2024) suggests that to make e-scooters a competitive mode in disadvantaged areas, priority should be given to urban structural solutions—such as land-use densification and mixed-activity promotion—over simply increasing vehicle availability, which alone may not achieve the desired outcome. Ignoring such nuances risks reinforcing existing inequalities and misallocating resources that could otherwise address root causes.

A persistent challenge is the "invisibility" of vulnerable populations—including low-income, elderly, disabled, rural, and migrant groups—due to their underrepresentation in mobility data. Researchers must actively develop methods to uncover and fill these data gaps. Quantifying such gaps is a first step, raising awareness among decision-makers and prompting policy adjustments. However, this remains a partial remedy. A more fundamental solution requires pioneering inclusive data collection methods that prevent exclusion from the outset.

To meaningfully advance these issues, researchers must integrate equity objectives into transport models historically optimized for efficiency. Balancing multiple objectives can foster evidence-based policies that are both effective and just. Yet, accurately measuring these concepts scientifically is only the beginning. For real-world impact on disadvantaged groups, insights must reach and inform policymakers. Equity, accessibility, and mobility justice metrics need to be translated into planning, appraisal, and regulatory frameworks. Two major challenges in this process are (i) researchers distilling complex findings into clear, concise policy briefs, and (ii) educating policymakers on the value of evidence-based approaches and the tangible impacts of equity-focused concepts.

Section 4: Sustainability and Impact Quantification—Policy Pathways and Transparent Emissions Allocation

This section addresses the fourth pillar of our agenda: the imperative of sustainability and impact quantification. It examines two interconnected domains — the policy and governance instruments that can accelerate sustainable transportation transitions, and the establishment of transparent, equitable methods for allocating transportation emissions across passengers, cargo, and infrastructure use.

4.1 Building Policy and Governance for Sustainable Transportation Transitions

Achieving a sustainable transportation system requires not only technological innovation but also a coherent portfolio of policies and governance mechanisms that steer adoption, shape behavior, and internalize environmental externalities. While vehicle electrification, automation, and shared mobility offer technical pathways, their real-world sustainability outcomes depend critically on the regulatory and economic context in which they are deployed (Zhao et al., 2025). This subsection outlines key policy instruments and governance challenges for accelerating the transition toward low-carbon, equitable, and resilient mobility.

(1) Pricing and market-based instruments. Carbon pricing, congestion charging, and low-emission zones (LEZs) are among the most direct tools to reflect the social cost of transport emissions. It is worthwhile to evaluate the effectiveness and distributional impacts of these measures across different urban and regional contexts. Dynamic road pricing, which varies by time, location, and vehicle emissions, can further align incentives with real-time congestion and pollution levels. Studies should also explore the integration of mobility-as-a-service (MaaS) platforms with pay-as-you-drive carbon fees, enabling seamless, price-based modal shifts.

(2) Regulatory mandates and technology standards. Governments can accelerate sustainable transitions through zero-emission vehicle mandates, fuel economy standards, and phase-out dates for internal combustion engines. However, such top-down regulations must be carefully designed to avoid unintended consequences, such as increased vehicle prices that exclude lower-income households or rebound effects where efficiency gains lead to more travel. There needs the investigation on the interplay between regulatory stringency, industrial competitiveness, and consumer acceptance, drawing on cross-country comparisons.

(3) Public investment and infrastructure planning. Sustainable transport cannot scale without dedicated public funding for charging networks, high-quality public transit, cycling lanes, and pedestrian zones. We need to develop frameworks for cost-benefit analysis that go beyond travel time savings and include carbon abatement, air quality improvements, and health co-benefits. Priority should be given to investments that serve underserved communities and bridge the “last-mile” gap. Public-private partnerships can leverage private capital while ensuring public accountability.

(4) Behavioral interventions and demand management. Policies that rely solely on prices or mandates often face political resistance. Complementary behavioral tools — such as

personalized travel feedback, gamification, eco-driving training, and workplace commute programs — can shift travel choices at lower political cost. Research shall quantify the effectiveness and cost-effectiveness of nudges in different cultural and institutional settings, and explore how they interact with traditional policy instruments.

(5) Multi-level governance and policy integration. Transportation policy operates across local, regional, national, and international levels. Inconsistent or conflicting policies (e.g., a city's LEZ vs. a national fuel subsidy) undermine effectiveness. Research shall examine how to achieve policy coherence across levels, including mechanisms such as national framework laws with local implementation flexibility, interjurisdictional coordination bodies, and harmonized emissions standards for freight corridors. Furthermore, transport policies should be integrated with land-use, housing, and energy policies to avoid siloed decision-making and leverage synergies — for instance, linking transit-oriented development with charging infrastructure.

4.2 Establishing Equitable and Transparent Methods for Allocating Transportation Emissions

As transportation systems diversify and decarbonization commitments intensify, the question of how emissions are measured, attributed, and governed has moved from a technical detail to a central policy and research frontier. Current accounting approaches are often too aggregate, too static, or too mode-specific to guide operational decisions, public policy, or user choice. A research agenda is the development of transparent, equitable, and practically implementable methods for allocating emissions across passengers, cargo, and infrastructure use.

At the heart of this challenge lies the need to move beyond system-level aggregates toward attribution at the level of individual trips, shipments, and users. Such granularity is essential for enabling informed choices—whether for a traveler comparing modes, a shipper selecting a logistics provider, or a public agency designing low-emission zones or carbon pricing mechanisms. However, achieving this granularity requires resolving fundamental questions about how to assign emissions from shared vehicle trips, multi-modal journeys, supply chain segments, and common infrastructure assets such as ports, corridors, and charging networks. Existing carbon calculators offered by transportation companies are often inconsistent, lack transparency in their calculation methods, and may be flawed.

Temporal and spatial heterogeneity add further complexity. Marginal emissions vary with congestion, route choice, vehicle utilization, time of day, and the underlying energy mix. A robust allocation framework must therefore move beyond static, average-based estimates and incorporate dynamic, context-sensitive principles that reflect actual operational conditions. At the same time, such frameworks must remain transparent and auditable to ensure credibility and avoid strategic manipulation.

A particularly challenging dimension is the treatment of non-revenue or repositioning movements—empty container hauls, ferry crossings without passengers, or vehicle deadhead miles. These movements generate real emissions that are necessary for service provision but are not directly attributable to any single cargo or passenger unit. Whether such emissions are allocated to the preceding load, the following load, or treated as systemic overhead involves normative judgments that significantly affect the perceived carbon intensity of individual shipments or trips. Research must therefore develop principled approaches that balance fairness, incentive alignment, and practical feasibility. Recent work has begun to explore principled allocation approaches (Shangguan et al., 2025; Tian et al., 2024).

Beyond technical methodology, emissions allocation is inherently a matter of equity and governance. Different allocation rules distribute carbon burdens—and potentially mitigation costs—differently across income groups, regions, supply-chain actors, and transportation-disadvantaged populations. Future research must systematically examine how alternative accounting frameworks affect vulnerable groups, small carriers, rural communities, and users with limited mobility options. This distributional lens is essential to ensure that decarbonization policies do not inadvertently reinforce existing inequalities.

Finally, emissions allocation must be linked to real-world governance and incentive structures. To be useful for policy and investment decisions, allocation methods must be interoperable across modes and jurisdictions, auditable by third parties, and sufficiently simple to operationalize without sacrificing rigor. Research should explore how standardized carbon-accounting frameworks can support a range of applications—from internal carbon pricing within logistics firms, to consumer-facing labeling, to regulatory instruments such as low-emission zones, fleet procurement standards, and infrastructure appraisal. Measurement, reporting, and verification protocols must be designed to build trust among operators, regulators, and the public, while enabling the innovation and flexibility needed to adapt to evolving technologies and operational practices.

In the long term, a mature emissions-allocation framework should not only provide accurate attribution but also guide operational choices, investment priorities, and behavioral change toward deep and equitable decarbonization. Achieving this requires sustained interdisciplinary effort, combining transportation engineering, environmental accounting, economics, and equity analysis to build methods that are both analytically rigorous and socially legitimate.

5 Conclusions

The transformation of transportation systems over the coming decade will be defined not by isolated technological breakthroughs but by the ability to integrate innovation across multiple domains into coherent, equitable, and sustainable mobility ecosystems. This research agenda has articulated four interconnected pillars that together form a comprehensive framework for guiding future inquiry: reimagining urban mobility through integrated ground and air networks; advancing core enabling technologies that prioritize safety, scalability, and interoperability; transforming data abundance into actionable and equitable insights; and pursuing sustainability through deep vehicle-grid integration and transparent emissions allocation.

Across these pillars, a unifying theme emerges: technological innovation, no matter how advanced, cannot succeed in isolation. True progress will require systemic integration, rigorous governance, and an unwavering focus on equity and human-centered design. The research directions identified here—spanning algorithmic development, infrastructure co-design, data standards, and policy frameworks—represent the collective priorities of the transportation research community. Pursuing this integrated agenda will be essential to building resilient, low-carbon, and just mobility systems for the future.

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