

A Future in Motion: Reimagining Public Transport with Diverse Autonomous Vehicles

Muhammad Aamir Cheema[†], Muhammad Ali Babar[‡], Mohammed Eunus Ali[†], Mohammad Goudarzi[†], Walid G. Aref[§]

{aamir.cheema,eunus.ali,mohammad.goudarzi}@monash.edu, ali.babar@adelaide.edu.au, aref@purdue.edu

[†]Faculty of Information Technology, Monash University, Australia

[‡]Faculty of Sciences, Engineering and Technology, University of Adelaide, Australia

[§]Department of Computer Science, Purdue University, USA

ABSTRACT

Public transportation plays a vital role in supporting sustainable, accessible, environment-friendly, and equitable urban mobility. However, challenges such as poor first- and last-mile connectivity, limited service coverage, and inefficient use of space continue to limit its effectiveness and uptake. Autonomous vehicles (AVs) offer new opportunities to address these limitations by enhancing flexibility, improving access, and complementing existing transit systems. This vision paper explores how a diverse fleet of AVs, including cars, shuttles, pods, scooters, and buses, can be integrated into public transport to form an adaptive, multimodal, and data-driven mobility ecosystem. We outline key research directions spanning fleet coordination, spatial deployment, infrastructure planning, and intelligent transportation platforms. We highlight the need for interdisciplinary research at the intersection of spatial computing, transportation systems, artificial intelligence, and urban data infrastructure. Our aim is to inform and inspire future efforts toward building autonomous mobility systems that are efficient, inclusive, and future-ready.

CCS CONCEPTS

• Information systems → Spatial-temporal systems; • Computing methodologies → Planning and scheduling; • Applied computing → Transportation.

KEYWORDS

Autonomous Vehicles, Public Transport, Urban Mobility, Sustainability

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1 MOTIVATION

Challenges in Public Transport. Public transportation systems are crucial to achieving sustainable urban mobility. They offer accessible, efficient, and environmentally friendly travel options that help reduce congestion, lower emissions, and improve equity. However, despite their benefits, these systems face several persistent challenges that hinder their effectiveness and limit their usage. A major issue is poor first- and last-mile connectivity — the gap between a traveler’s origin or destination and the nearest transit stop [29]. According to a McKinsey study, transit usage drops by 90% when commuters must walk more than half a mile to reach a station [3]. When facing these inconveniences, many residents either drive to transit stations or use private vehicles for the entire journey. This widespread reliance on single-occupancy cars leads to increased traffic congestion, higher emissions, and inefficient use of urban road space, particularly along common travel routes.

Additionally, the lack of diverse mobility options limits the ability to match vehicle types to specific trip needs such as smaller, energy-efficient vehicles (e.g., scooters, mopeds, bikes) for short or solo journeys. This mismatch leads to higher emissions, under-utilized vehicle capacity, and missed opportunities to create a more adaptable and sustainable transportation ecosystem that accommodates a variety of user requirements and trip purposes. The widespread use of private vehicles in cities has also led to a significant demand for parking, and thus resulting in large areas of urban land being allocated for this purpose.

Transforming Transport with Autonomous Vehicles (AVs). AVs offer a transformative opportunity to address many of these longstanding challenges in public transport. Their ability to operate without human drivers, often with greater precision and safety, allows for more flexible, efficient, and user-centered mobility solutions. AVs can significantly enhance first- and last-mile connectivity by providing on-demand services that connect homes, workplaces, and community hubs to nearby transit stations [19]. They can help reduce the need for car ownership, decrease personal car usage, reduce traffic congestion, and lower greenhouse gas emissions, particularly when deployed as part of shared or pooled services [14]. Furthermore, by integrating AVs into public transit systems and reducing reliance on private car ownership, cities can substantially lower parking demand. This, in turn, opens opportunities to reclaim valuable urban space for housing, green infrastructure, or other community-focused developments [32].

To fully unlock these benefits, it is important to consider a diverse range of AV types, each suited to specific trip patterns, service roles, and urban contexts. Rather than relying solely on autonomous cars



or buses, cities can improve efficiency and responsiveness by incorporating smaller vehicles, e.g., scooters and bikes for short trips, pods and shuttles for neighborhood-scale travel, and high-capacity AV buses for major corridors [12]. This “right-sizing” approach helps match vehicle capabilities to user needs, reducing energy use, avoiding underutilized capacity, and enhancing the overall user experience.

While traditional vehicles and human-operated rideshare services can provide similar functions, AVs offer distinct advantages that make them especially valuable for system-wide integration. They can operate continuously without driver fatigue or labor constraints, reposition autonomously to meet shifting demand, and be coordinated centrally as part of a real-time, data-driven platform. These capabilities allow finer-grained fleet optimization, better coverage in low-demand areas, and more consistent service.

The Need for Careful AVs Integration and Coordination. Despite their promise, AVs deployed without careful planning may worsen existing urban challenges. Several studies have warned that poorly integrated AV services could worsen congestion and emissions by increasing empty vehicle travel (deadheading) [22], duplicating existing services, and undermining public transit [4, 29]. For example, on-demand AVs operating independently of transit networks may prioritize convenience over efficiency, leading to fragmented services and higher vehicle miles traveled. Without spatial coordination, AVs may cluster in high-demand areas, leaving low-income or less dense neighborhoods underserved. And without shared platforms, pricing, or scheduling integration, riders may face friction when switching between modes.

These risks highlight the importance of a system-level approach in which diverse AV types are coordinated with one another and with broader public transport infrastructure. The goal is not simply to add AVs to existing networks, but to weave them into a cohesive, multimodal, and data-driven mobility ecosystem. To fully realize their transformative potential, AVs must be thoughtfully coordinated with public transport and other urban infrastructure in ways that enhance efficiency, accessibility, and sustainability. Achieving this vision presents complex research challenges that range from multimodal routing for heterogeneous fleets, to spatial deployment strategies, to real-time data fusion across platforms and services. This vision paper makes the case for deeper interdisciplinary research at the intersection of spatial computing, transportation systems, artificial intelligence, and intelligent urban infrastructures. By outlining a set of high-impact research directions, we aim to spark new ideas and collaborations that advance the development of coordinated, adaptive, and inclusive AV-integrated intelligent mobility systems.

2 RESEARCH GAPS

Research on designing techniques for integrating AVs into public transport systems is still in a preliminary stage. Much of the current work [2, 10, 18, 24, 25] focuses on conceptual studies or simulation-based analyses that evaluate the potential benefits of AVs, e.g., reduced congestion [5, 28], lower emissions [16, 28], improved accessibility [5, 23], and more efficient land use [23]. While these studies have helped establish the value of AV integration, there remains a need for advanced routing algorithms, fleet coordination

techniques, and deployment strategies that can support scalable, practical integration with public transport systems.

A second gap concerns the limited consideration of diverse AV types. Most existing studies focus on a single mode—typically autonomous cars or buses [11, 26]—and overlook the potential of deploying a heterogeneous AV fleet including cars, buses, shuttles, pods, scooters, and bikes. This narrow scope fails to address the need for “right-sizing” mobility: using the most appropriate AV type for different trip lengths, demand levels, and urban environments. As a result, there is insufficient understanding of how diverse AVs can be coordinated to complement one another and integrate seamlessly with existing transit services.

A third gap lies in the lack of research on how to operationalize multi-type AV fleets. Questions around determining the optimal mix of vehicle types, siting charging infrastructure, and orchestrating real-time routing and scheduling remain largely unaddressed—especially in scenarios with fluctuating demand, limited energy availability, and equity constraints. These operational challenges are particularly complex when aiming to align AV services with public transport goals and performance metrics.

The spatial database community is well-positioned to help bridge these gaps. Effective AV integration requires managing and analyzing large volumes of dynamic, location-based data to support decisions on AV routing, scheduling, and infrastructure placement. Spatial indexing, real-time query processing, and spatiotemporal analytics can enable intelligent assignment of AVs, prediction of mobility patterns, and optimization of multimodal connectivity. By contributing scalable, data-driven tools and algorithms, the spatial data community can help transform high-level AV integration strategies into deployable, responsive transport systems. In the era of AI, the spatial database community is uniquely positioned to lead the development of shared geospatial intelligence platforms, empowering autonomous agents to reason, learn, and coordinate in dynamic environments—paving the way for seamless integration of multimodal AVs into public transportation systems.

3 VISION AND RESEARCH DIRECTIONS

To fully harness the potential of diverse AVs in public transportation, we envision a unified, intelligent mobility network in which heterogeneous AVs operate in coordination with each other and with existing transit modes. Realizing this vision will require progress across multiple technical and operational dimensions. The research directions outlined below address some representative open challenges and opportunities in this space but are not an exhaustive list. Our goal is to inspire the research community, particularly those working in spatial databases and urban mobility, to explore these and other promising avenues that can help shape the future of integrated autonomous transportation.

3.1 Adaptive Fleet and Mobility Management

3.1.1 Dynamic Fleet Routing and Scheduling. Unlike traditional public transport systems built on fixed schedules and routes, autonomous mobility networks must be highly adaptive, multimodal, and responsive to real-time demand, traffic, and infrastructure constraints [15]. At the heart of this challenge lies the need for intelligent routing and scheduling algorithms that can dynamically

allocate vehicles of different types, e.g., autonomous shuttles, buses, scooters, and pods based on rider needs, local congestion, and system-level priorities. These algorithms must account for heterogeneity in vehicle capacity, speed, energy range, and service roles. For example, AVs might operate as first-mile connectors during peak hours and shift to delivery or standby services during off-peak times. During large events, autonomous buses could manage long-haul routes while smaller AVs handle local distribution. Achieving this requires coordination platforms that can assign and adjust vehicle roles in real time based on live spatial data.

3.1.2 Seamless Multimodal Integration. Equally important is multimodal integration [20], ensuring that AV services augment rather than replace traditional transport. For users, seamless connections between AVs and buses, trains, or trams are essential. This demands synchronized scheduling (e.g., ensuring an AV arrives just before a train departs) and optimized transfer infrastructure, such as curbside pickup zones near stations. Integrated trip-planning platforms—embedded in Mobility-as-a-Service (MaaS) [31] apps—can help orchestrate multimodal journeys by solving dynamic shortest-path problems across changing conditions and modes. These platforms must leverage spatial data systems to combine static (e.g., infrastructure maps) and dynamic (e.g., vehicle and train locations) data and enable real-time multimodal queries such as: “Find the fastest combination of scooter + tram + shuttle to reach destination B by 9:00 AM.”

3.2 Spatial Deployment and Optimization

3.2.1 Service Area and Fleet Optimization. A central challenge in AV integration is determining where and how services should operate. Which neighborhoods should be served by autonomous shuttles, pods, or buses? What is the optimal number of vehicles of each type, and where should they be stationed, repositioned, or staged throughout the day—including designated pick-up and drop-off hubs? These planning decisions can be framed as facility-location or coverage optimization problems that balance service quality, operational efficiency, and equity. For instance, hub locations may be chosen to ensure that most residents are within a five-minute walk or ride, while prioritizing access in historically underserved or low-density areas. Fleet sizing and composition must similarly align with varying mobility needs across different communities, ensuring that service is not just concentrated in high-demand or high-income areas.

3.2.2 Infrastructure Siting and Accessibility Planning. Supporting infrastructure—such as charging stations for electric AVs, maintenance depots, and staging areas for idle vehicles—must be sited with care [8]. These decisions involve spatial trade-offs: minimizing travel detours for vehicles, leveraging electrical grid capacity, and ensuring accessibility in areas where infrastructure investment has traditionally lagged. Planning must go beyond efficiency to explicitly consider equity [9]: for example, ensuring that outer suburbs and lower-income neighborhoods are not left without charging or pick-up facilities. The spatial data and urban computing communities can contribute by identifying infrastructure gaps and optimizing siting plans to support inclusive urban mobility.

3.2.3 Simulation-Driven Evaluation and Equity Assurance. Urban simulations [33] and digital twins [1, 30] offer a powerful tool for testing deployment strategies under realistic conditions. By simulating traffic, energy usage, and rider behavior, planners can evaluate the impact of different configurations on metrics such as wait times, accessibility, and network load. These simulations produce rich spatiotemporal datasets that, when paired with spatial databases and analytical tools, enable the detection of service gaps and inequities. For example, planners can identify neighborhoods with long wait times or limited access to AV services and adjust deployment accordingly. Equity can be embedded directly into simulation objectives—ensuring that the benefits of AV technology extend across all communities, including those that have historically faced transport disadvantage. This data-driven approach enables cities to make more informed and inclusive decisions about where to deploy infrastructure and how to allocate AV resources fairly [7].

3.3 AI-Driven Mobility Platform

3.3.1 Spatiotemporal Data and AI-Driven Decision Making. Realizing the vision of coordinated, multimodal, and adaptive autonomous transport requires an intelligent, data-driven platform [21] capable of integrating data, queries, and decision-making across diverse mobility modes. At the heart of this vision is the need for research at the intersection of spatiotemporal data management and AI—effectively building the “brain” of a heterogeneous AV transit system. Such a platform must continuously ingest real-time data streams from AV locations, passenger requests, public transit schedules, and traffic sensors. This data must be processed with high reliability and low latency to support time-sensitive decisions like dispatching vehicles, rerouting traffic, or adjusting service schedules.

On top of the data infrastructure, analytics and optimization engines are needed to support operational intelligence. Predictive models trained on historical and live data can forecast travel demand, traffic congestion, or service delays. Prescriptive models can recommend dynamic actions such as rebalancing vehicle distribution or adapting fares in real time. Combining machine learning with spatiotemporal reasoning enables advanced capabilities such as traffic flow prediction using graph neural networks and dispatch optimization via reinforcement learning.

3.3.2 Agentic Intelligence for Distributed Coordination. Recent advances in agentic AI [13] provide a new paradigm for mobility management. Rather than relying solely on centralized control, agentic approaches empower autonomous agents—each representing an individual vehicle, control center, or user group—to plan, coordinate, and act based on local context and shared system goals. These agents can adapt to changes in demand, infrastructure availability, or network conditions in real time, making independent yet cooperative decisions.

This distributed approach enables the system to become more scalable, resilient, and adaptive. Agents can negotiate trade-offs—such as minimizing wait times versus maximizing coverage—and coordinate actions like routing, pick-up location adjustments, or load balancing. The transition from passive, data-driven automation to active, goal-driven coordination opens up exciting opportunities for intelligent, collaborative AV systems.

3.3.3 AI-Powered Dashboards. We envision future city operations centers overseeing entire mobility ecosystems through interactive dashboards powered by AI [17]. These systems would monitor AVs and public transit in real time, detect congestion patterns, and assess service coverage. In response to disruptions—such as a subway line going offline—the platform could automatically deploy AVs and reassign routes using multi-vehicle routing algorithms, spatial optimizers, and real-time data fusion to maintain service levels.

Real-world initiatives like the Jacksonville Ultimate Urban Circulator (U2C)¹ already signal this direction. The U2C project aims to convert a monorail system into a flexible fleet of autonomous shuttles that can operate both as coordinated virtual trains and as independent on-demand vehicles. This hybrid model blurs the boundary between fixed-route transit and dynamic mobility, emphasizing the need for intelligent, adaptive coordination.

3.4 Leveraging AVs Beyond Transport Support

While the primary goal of integrating diverse AVs into public transport is to improve accessibility, sustainability, and flexibility, these vehicles can also offer value beyond peak commuting times. During off-peak hours, weekends, or overnight periods, AVs often remain idle. Leveraging this idle capacity opens up opportunities to improve system efficiency, reduce costs, and support broader urban functions. This section outlines several example applications where AVs can extend their impact beyond traditional transport services."

3.4.1 Dual-Use AVs for Urban Logistics and Services. One promising use case is urban logistics. AVs that transport passengers during peak hours could be repurposed to handle last-mile deliveries [27], such as groceries, packages, or medical supplies, during low-demand periods. This dual-use model reduces the need for separate delivery fleets, optimizes road usage, and provides an additional revenue stream. By dynamically switching between passenger and cargo modes, AVs can support time-sensitive deliveries while minimizing deadheading [22]. Moreover, this flexibility allows cities to better utilize existing vehicle infrastructure, particularly in areas underserved by conventional freight services. As e-commerce and home delivery continue to rise, integrating logistics into AV operations could play a key role in reducing urban congestion and improving service equity.

3.4.2 AVs as Energy Assets and Mobile Sensors. Another opportunity lies in energy systems. Electric AVs can function as distributed energy storage units through vehicle-to-grid (V2G) integration. When not in motion, their batteries can store excess energy from renewable sources, and discharge it back into the grid during peak demand. This can help balance energy supply and demand, reduce emissions, and support grid resilience, as highlighted in a recent vision paper [6].

AVs can also contribute to urban sensing and data collection. Equipped with cameras and sensors, they can be used to monitor infrastructure conditions, map road surfaces, detect environmental hazards, or support emergency response planning. Some AVs could even serve temporary community functions, e.g., mobile clinics, pop-up libraries, or digital inclusion hubs in under-served areas.

3.4.3 AV Fleets for Emergency and Resilience Operations. Beyond these routine functions, AV fleets offer unique advantages for resilience and emergency management. During natural disasters, pandemics, or public transit disruptions, autonomous vehicles can be rapidly redeployed to support evacuation routing, deliver critical supplies, or transport essential workers. Their ability to operate continuously and without direct human intervention makes them ideal for high-risk or dynamically changing environments. These scenarios demand intelligent systems that can reprioritize vehicle usage, respond to hazards in real time, and coordinate across multiple agencies. The spatial data community can support these efforts by developing tools for emergency routing, hazard mapping, and rapid fleet reconfiguration based on live geospatial data.

These secondary applications make AV fleets more versatile and economically viable, while also raising new research challenges around real-time task allocation, scheduling, and prioritization. The spatial database community can play a key role in enabling these multi-role capabilities by developing efficient spatial-temporal models and systems to support intelligent, adaptive decision-making.

4 CONCLUSION

Autonomous vehicles offer a powerful opportunity to improve the sustainability, accessibility, and responsiveness of urban transportation. Realizing this potential requires more than technological progress—it demands thoughtful integration of diverse AV types into the broader mobility ecosystem. When strategically embedded within a multimodal, data-driven system, heterogeneous AV fleets can address longstanding transport challenges such as poor first- and last-mile access, underutilized capacity, and high emissions. Moreover, their capabilities can extend beyond transport, supporting urban logistics, energy systems, sensing, and emergency response during off-peak periods.

This vision paper advocates for a shift in how AV integration is conceived and studied. We argue that heterogeneous AV fleets, when thoughtfully matched to trip contexts and user needs, can complement public transit, improve coverage, and enable more efficient use of infrastructure and energy. By leveraging idle AV capacity during off-peak hours, cities can also support logistics, energy grid resilience, emergency response, and urban sensing—expanding the role of AVs beyond transport alone. Achieving this vision raises significant research challenges. From designing scalable routing and scheduling algorithms to developing spatiotemporal data platforms and AI-powered coordination strategies, these problems span the disciplines of transportation, spatial computing, and intelligent infrastructure. We highlight a set of representative directions where interdisciplinary collaboration is essential.

By articulating this integrated and multi-functional vision for AVs, we aim to spark new research and policy conversations. The path forward lies not just in advancing autonomous technologies, but in building mobility systems that are intelligent, adaptive, and attuned to the evolving needs of cities and their communities.

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¹<https://u2c.jtafla.com/>

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