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# Community-based ultra-flex autonomous mobility system: A framework for advancing urban transportation spatial equity

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**Abstract** Urban transportation systems exhibit structurally spatial inequity, characterized by inadequate service in non-central areas and persistent first/last-mile challenges, disproportionately impacting vulnerable populations. While existing solutions like Community-Based Transportation (CBT), micromobility, ride-hailing, micro-transit, and Autonomous Shuttle Buses (ASB) offer partial remedies, they often suffer from limitations such as scale constraints, cost barriers, technological immaturity, or profit-driven biases. To overcome these systemic shortcomings, this paper proposes and elaborates on the Community-Based Ultra-Flex Autonomous Mobility System (CBUAMS), a novel, integrated socio-technical framework explicitly designed to advance urban transportation spatial equity. Crucially, CBUAMS is envisioned not as an isolated system but as a complementary and synergistic component. It is designed for seamless integration with existing urban transportation modes to enhance overall network efficiency and accessibility. CBUAMS is founded on three core pillars—community-based operations, ultra-flex service—and an adapted autonomous mobility system, and achieves equity goals through

synergistic, multi-dimensional strategies: 1) Spatial restructuring via a “Three-Ring Model” (Core, Coordination, External Rings) that redefines the community as the basic unit for mobility planning and prioritizes local circulation; 2) Equity-oriented technological innovation, featuring a proposed Community-Based Autonomous Driving Classification (C-ADC) tailored for community contexts and costs, and low-cost, inclusive Vehicle-to-Everything (V2X) deployment strategies to ensure broad accessibility; and 3) Polycentric community governance through a “government-enterprise-community” tripartite model that fosters collaboration, responsiveness, and sustainability. This research details the conceptual underpinnings, operational mechanisms, key technological components, and inherent engineering management challenges of CBUAMS. By offering a holistic, integrated approach that confronts systemic inequities, CBUAMS presents a promising new paradigm and practical blueprint with significant potential to redefine urban accessibility, enhance transportation equity, and contribute to a more sustainable and just city future.

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## 1 Introduction

Urban transportation systems, serving as fundamental pillars of modern socio-economic functioning, profoundly influence residents' quality of life, social participation, and economic opportunity equality (Pereira et al., 2017; Gao et al., 2023; Ritchie et al., 2024). However, traditional transportation planning paradigms, long dominated by an efficiency-first principle focused on high-density, high-demand corridors (Hendren and Niemeier, 2006; Murray et al., 2024; Wong et al., 2024),

and often failing to integrate and measure social equity objectives robustly (Manauagh et al., 2015), have systematically overlooked the travel needs of low-density areas, service peripheries, and specific community groups—particularly vulnerable populations such as the elderly, low-income individuals, and people with disabilities. This oversight has fostered in deep-seated structural spatial inequity in the distribution of urban transportation resources and service provision (Gössling, 2016; Potter et al., 2023). Manifesting acutely as the first/last-mile (FMLM) problem, this inequity significantly restricts mobility freedom and life possibilities for residents in non-hotspot areas, thereby exacerbating societal inequalities (Chen et al., 2022; Li and Wei, 2023; Mun et al., 2024).

To address this challenge, academia and practitioners have explored various solutions. Community-Based Transportation (CBT), which often refers to locally organized, non-profit, or volunteer-driven services tailored to meet specific community mobility needs, especially for underserved groups, demonstrates grassroots resilience but is frequently constrained by funding, technology, and standardization challenges (Mulley et al., 2018; Hosford et al., 2024). Micromobility options (e.g., shared bikes and e-scooters) enhance flexibility but struggle to overcome deployment biases toward high-demand areas and cannot meet the needs of all population segments (Kopplin et al., 2021; Shaheen et al., 2020; Wang and Lindsey, 2019). Ride-hailing offers convenience but faces high cost barriers and persistent spatial mismatches between supply and demand, limiting its universal accessibility (Hussin et al., 2021; Winter et al., 2021). On-demand microtransit aims to merge the advantages of shared mobility and public transportation; however, issues of service area selectivity, driven by profitability pressures and the digital divide, persist (Rossetti et al., 2023; Dong et al., 2025). Autonomous Shuttle Buses (ASB) have garnered significant attention, promising cost reduction and enhanced flexibility (Cai et al., 2023; Cohen and Shaheen, 2018; Li et al., 2024a). However, substantial challenges remain regarding technological maturity, operational models, deployment costs, and integration with existing systems; without proper guidance, their deployment might replicate or even worsen existing inequities (Rossetti et al., 2023; Khavarian-Garmsir et al., 2023). These solutions share a fundamental limitation: they cannot provide a systemic framework integrating community-specific spatial and social contexts, equity-oriented technological pathways, and effective multi-stakeholder collaborative governance mechanisms. Consequently, they struggle to address the structural inequity rooted in planning paradigms. This reflects “market-government double failure” in providing equitable transportation at the community level (Stiglitz, 2010; Murray et al., 2024).

To bridge this systemic gap, this research proposes and elaborates on an innovative framework named Community-Based Ultra-Flex Autonomous Mobility System (CBUAMS). CBUAMS is conceptualized as a community-centric, integrated, and equity-oriented socio-technical system, designed with the core philosophy of elevating the community to the basic unit of transportation planning, operation, and governance, explicitly aiming to advance urban transportation spatial equity. To achieve this goal, CBUAMS constructs a comprehensive solution built upon three core pillars and systematically addresses service gaps through the following three interconnected core strategies:

**(1) Spatial restructuring:** Employing an innovative “Three-Ring Model” (Core Ring, Coordination Ring, External Ring) to mitigate over-reliance on traditional transportation corridors, prioritizing convenient and efficient circulation intra/inter-communities, and fostering balanced resource deployment at the local level.

**(2) Equity-oriented technological innovation:** Moving beyond the traditional SAE International (SAE) J3016 levels of driving automation (SAE International, 2016) to propose a “Community-Based Autonomous Driving Classification” (C-ADC) that is more suited to complex community environments and sensitive to service needs and cost-effectiveness. Advocating for low-cost, widely deployable, and inclusive community-level Vehicle-to-Everything (V2X) strategies to ensure technological advancements benefit all community members.

**(3) Polycentric community governance:** Establishing an innovative “Government-Enterprise-Community” tripartite collaborative governance framework that clearly defines rights, responsibilities, and interests, leveraging grassroots structures like community grid management to enhance responsiveness, effective resource coordination, and system sustainability.

This paper details the conceptual underpinnings, operational mechanisms, key technological components, and inherent implementation challenges of CBUAMS. Through this integrated approach encompassing spatial, technological, and governance dimensions, CBUAMS holds significant potential to overcome the limitations of existing solutions, offering a novel theoretical lens and practical blueprint for tackling urban transportation spatial inequity, ultimately contributing to a more equitable, inclusive, and sustainable urban future.

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature on transportation inequity issues. Section 3 introduces an equity-focused evaluation framework and positions CBUAMS within it. Section 4 details the three core strategies of CBUAMS for enhancing spatial equity: spatial restructuring, technological innovation, and community governance. Section 5 addresses the key enabling technologies and the engineering management challenges associated with the

implementation of CBUAMS. Section 6 summarizes the main contributions and discusses future research directions, as well as potential implementation roadmaps.

## 2 Literature review

The seminal study by Cervero and Kockelman (1997) summarizes that successfully establishing a city requires three key elements: sufficient population and employment density, diverse land use, and transportation-friendly urban design. The interplay of these elements shapes the overall urban structure, which in turn profoundly influences the spatial equity of transportation services (Levine, 2013; Heyer et al., 2020). Otherwise, cities will eventually fall into a vicious cycle characterized by traffic congestion and urban sprawl, ultimately undermining the benefits of urban agglomeration (Graham, 2007; Wong et al., 2020). Transportation equity and justice have gradually gained attention among researchers over the past few decades (Pereira et al., 2017). Gössling (2016) argues that transportation inequity is evident in at least three dimensions: exposure, space, and time. Within spatial inequity, the accessibility of transportation facilities is crucial, referring to residents' inability to use certain transportation modes due to cost or spatial constraints (Chen et al., 2022; Gössling, 2016).

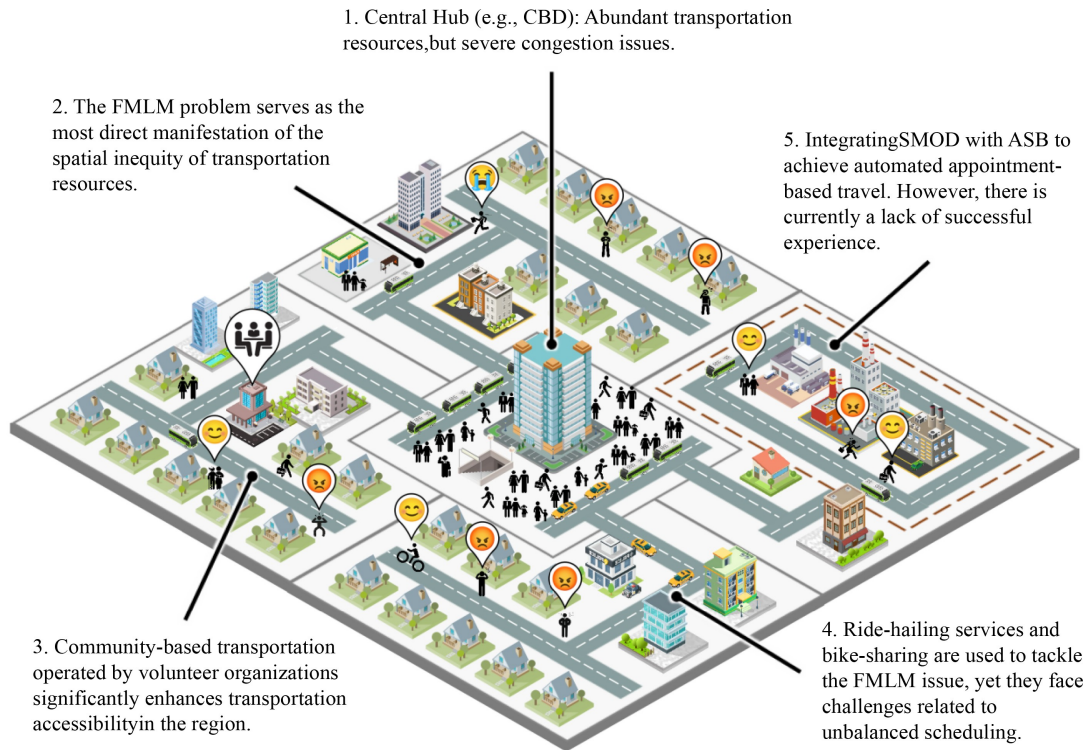
Urban public transportation aims for universality and inclusivity, playing a vital role in urban mobility while emphasizing social equity and the fair distribution of resources (Hensher et al., 2020; Kuo, et al., 2023). Examples include traditional buses and subways. However, transportation policies have prioritized efficiency for a long time (Hendren and Niemeier, 2006; Murray et al., 2024; Swanstrom and Banks, 2009; Wong et al., 2020). Existing transportation systems predominantly adopt a radial distribution model that prioritizes service to transportation corridors with dense populations and frequent economic activities (e.g., main roads connecting employment centers, commercial districts, and entertainment hubs), a characteristic often exacerbated by underlying urban structures and planning paradigms that can impede equity-focused reforms (Levine, 2013). However, it neglects the travel demands of non-hotspot areas (Murray et al., 2024; Potter et al., 2023). The direct reason is that investments in transportation resources in densely populated areas yield clearer returns, which makes planners reluctant to allocate resources to sparsely populated regions (Chiquetto et al., 2022; Martens, 2016). As a result, high-capacity transportation networks—such as subways, light rail, and bus lines—are heavily concentrated in hotspot areas, while broader ordinary communities face service gaps. This leads to a disconnect between public service provision and the heterogeneous needs of communities, ultimately resulting in an uneven spatial

distribution of public transportation resources. This spatial disparity is further compounded by dynamic urban transformations, such as the outward migration of vulnerable populations to suburban areas that often lack commensurate transportation investment and are inadequately addressed by current regional planning metrics (Heyer et al., 2020). Transportation policymakers strive to maintain equity through fare policies and service planning (Davis and Jha, 2011; Wang et al., 2021). Examples include subsidizing affordability and increasing service frequency to cover diverse travel needs. However, transportation resources are often disproportionately allocated to high-income neighborhoods and commercial centers. Empirical studies show that public facilities and transportation accessibility in non-hotspot areas are generally lower, and residents usually express lower satisfaction with public transportation, hindering social opportunities and participation (du Toit and de Casanova, 2025; Li and Wei, 2023; Mun et al., 2024).

The FMLM problem is a concrete manifestation of this accessibility dilemma (Fig. 1). This is particularly evident in how FMLM disproportionately affects non-hotspot areas, serving as a direct manifestation of spatial inequity in resource distribution (Fig. 1, Block 2), unlike central areas which may have direct transit access (Fig. 1, Block 1). Ironically, FMLM obscures the underlying issue of uneven spatial distribution of transportation resources, as it suggests accessibility challenges at both ends of a trip. In reality, however, only residents in non-hotspot areas face extra time costs when traveling to nearby transit hubs, whereas subway systems often provide direct access to the basements of popular shopping malls (Fig. 1, Block 1). Systemic transportation inequity has spurred new mobility demands, prompting various organizations, governments, and businesses to make significant efforts to address the issue. This section revisits five shared mobility approaches: (1) community-based transportation, (2) micromobility including shared bikes, e-scooters, and e-mopeds, (3) ride-hailing, (4) shared on-demand microtransit, and (5) autonomous shuttle buses.

### 2.1 Community-based transportation

This structural gap catalyzes a community-based transportation approach, wherein residents spontaneously organize to fulfill their unmet travel needs (Mulley et al., 2018; Murray et al., 2024) (Fig. 1, Block 3). Currently, CBT lacks a clear definition. Previous studies have employed various terms to describe transportation services outside traditional systems, including flexible and alternative transportation services (Hosford et al., 2024). These services often share the following common characteristics: (1) They provide customized services in response to the needs of marginalized or vulnerable groups within a fixed area, usually without standardized



**Fig. 1** Schematic diagrams of the FMLM problem and its current solutions. The surrounding areas depicted, particularly those highlighted by annotations 2–5, represent various non-hotspot residential or peripheral community zones where FMLM challenges and different mobility solutions are examined.

operating procedures and publicly available data; (2) Individuals or non-profit organizations operate them with a certain degree of public welfare nature; (3) They typically use vans, small trucks, or minibuses, encouraging or exclusively offering carpooling services. For example, the Collingwood Neighborhood House Seniors' Shuttle in Vancouver, a non-profit urban community service for the elderly (Hosford et al., 2024); and the Bürgerbus operated by volunteer associations in Germany, Austria, and other countries (Jeekel, 2018). Due to the lack of support from governments, large enterprises, and organizations, CBT has long been constrained by a shortage of funding and technology, lacking the ability and motivation to standardize, unify, and expand its systems and services (Hosford et al., 2024). It is also institutionally unprotected, without mature insurance services to safeguard its operations, and often operates in a regulatory gray area that is difficult to monitor (Valenzuela et al., 2005). This limits these services to specific communities and particular groups of people. However, the emergence of CBT reveals that the pursuit of transportation equity and accessibility is inevitable (Hosford et al., 2024; Martens, 2016).

## 2.2 Micromobility

Micromobility, including bike-sharing and its alternatives, has been widely recognized as an effective means

of alleviating spatial inequities in transportation resources (Kopplin et al., 2021; Tavassoli and Tamannaie, 2020) (Fig. 1, Block 4). Introducing bike-sharing in cities can bring a range of impressive benefits, including reducing travel time, expanding public transportation coverage, alleviating traffic congestion, and reducing energy consumption and air and noise pollution (Tavassoli and Tamannaie, 2020). There are generally two operating models: the “docked” system, where bicycles are picked up and returned at designated stations, and the “dockless” system, where users can pick up and return bicycles at any location. Although both types have advantages and disadvantages, there is no evidence to suggest that one is superior to the other (Tavassoli and Tamannaie, 2020). Research has shown that bike-sharing has a significant impact on public transportation, particularly rail transit (Yang et al., 2018), and helps reduce private car travel (Mugion et al., 2018).

However, this is not the ultimate solution to the problem. On the spatial side, the deployment of shared bicycles and e-bikes prioritizes areas with high travel demand and higher economic levels (Wang and Lindsey, 2019). Frequent rebalancing activities are also required to meet imbalanced demand (Machavarapu and Ram, 2022). On the other hand, these transportation modes cannot serve all citizens, such as the elderly and children. Their operating range is limited, and they cannot function in adverse weather conditions.

### 2.3 Ride-hailing services

Some studies advocate integrating ride-hailing services (on-demand door-to-door car-hailing services) with public transportation to facilitate seamless travel from transit stations to destinations (Hussin et al., 2021; Zhang and Khani, 2021; Guan and Bao, 2024) (Fig. 1, Block 4). These individual mobility-on-demand (MOD) services offer significant advantages in terms of flexibility and convenience (Ahmed and Hyland, 2023; Hussin et al., 2021). Users need to make a reservation on their mobile phones and can then board a dedicated transportation service at a nearby pick-up point. This enhances the accessibility of transportation services, especially for individuals in urban fringe areas (Ahmed and Hyland, 2023). A well-functioning ride-hailing service system can also reduce the number of private cars on the road, alleviate congestion, and contribute to environmental protection (Acheampong et al., 2020).

However, the high operating costs of ride-hailing services preclude them from being a solution to the problem of spatial inequity of transportation resources. Ride-hailing matching systems are far from the envisioned efficiency and instead face more severe spatial inequity issues. Numerous empirical studies have demonstrated that ride-hailing drivers tend to concentrate in high-demand areas to maximize their income. This can lead to an oversupply of vehicles in some areas and an undersupply in others, ultimately resulting in supply and demand imbalance (Dong et al., 2024; Lei and Ukkusuri, 2023; Li et al., 2024b; Winter et al., 2021). This phenomenon, where market efficiency diverges from social equity goals, underscores a fundamental challenge: the profit motive inherent in market mechanisms does not naturally align with the objective of providing equitable access to all citizens, regardless of their location's profitability. While ride-hailing has significantly expanded mobility options for many, attempting to ensure equitable coverage in low-demand areas solely through market-based ride-hailing could lead to systemic oversupply and inefficiency in high-demand areas or across the entire system. Therefore, ride-hailing services can only serve as a supplement and cannot fundamentally solve the problem of spatial inequity.

### 2.4 Shared mobility-on-demand microtransit

In recent years, a solution for short-distance travel based on Shared Mobility-on-Demand (SMOD) has emerged. To address the declining public transportation ridership and compete with established individual MOD services like ride-hailing, an increasing number of public transportation agencies have attempted to add flexible microtransit to their fixed-route service packages to provide SMOD services (Rossetti et al., 2023; Wang et al., 2019; Wang et al., 2021) (Fig. 1, Block 5). For example, the

Kutsuplus project in Helsinki is well-known (Haglund et al., 2019). Microtransit is usually operated or coordinated by public transportation agencies, using routing and matching technologies similar to shared ride-hailing services like UberPool or Shared Lyft. It provides shared rides within the service area using vans, minivans, or minibuses (Rossetti et al., 2023). Numerous surveys have shown that these short-distance SMOD door-to-door services are quite popular for daily short trips (Abe, 2021; Rossetti et al., 2023). Lucken et al. (2019) summarized that current microtransit services mainly serve five purposes: FMLM, low-density areas, off-peak hours, medical transportation, and paratransit. This overlaps with CBT, focusing on short-distance daily travel, using van-like vehicles, and supplementing public transportation insufficiencies. The main difference is that the service targets shift from specific marginalized or vulnerable groups to all ordinary urban residents.

Despite the expectation that on-demand microtransit will optimize urban transportation (Hensher et al., 2020), it still harbors inequity risks. First, its operational logic is constrained by the transportation corridor—that is, resources are concentrated in high-density economic corridors to pursue economies of scale (Murray et al., 2024; Potter et al., 2023), ultimately forming a radial transportation distribution. This fundamentally conflicts with the distributed community-centered concept advocated by the 15-min city (Khavarian-Garmsir et al., 2023), leading to service desertification in non-hotspot areas. Second, microtransit faces the issue of clustering in high-demand areas, similar to ride-hailing services (Winter et al., 2021). Therefore, rebalancing scheduling is also indispensable, which may lead to vehicle idling, exacerbating traffic congestion (Martin and Minner, 2021). Third, younger, higher-income, and more educated communities are more willing and financially capable of trying new types of transportation (Dong et al., 2025; Li and Wei, 2023).

In summary, although microtransit can flexibly adjust to passenger needs, it cannot solve the inequity problem in transportation resource distribution, manifesting as a market-government double-failure dilemma (Stiglitz, 2010). Whether it is public transportation planned by the government or transportation operated by private enterprises, it is difficult to escape the constraint of pursuing profit maximization and truly meet the travel needs of all users (Murray et al., 2024; Potter et al., 2023). Limited resources are always oversupplied in profitable areas, leading to resource scarcity in other areas, and problems such as traffic congestion and inconvenient travel persist (Martin and Minner, 2021).

### 2.5 Autonomous shuttle buses

Autonomous shuttle buses (ASB), as a type of connected and automated vehicles (CAV), have garnered significant

attention (Iclodean et al., 2020; Li et al., 2024a) (Fig. 1, Block 5). ASB operate without drivers and allow for extended service hours, reduced fares, and ultimately lower operational costs (Cai et al., 2023; Chehri and Mouftah, 2019; Kidmose, 2024; Rahman and Thill, 2023). Being entirely electric, ASB promote vehicle electrification, reduce fuel consumption, and contribute to environmental sustainability (Cai et al., 2023; Mouratidis and Serrano, 2021). By integrating with SMOD, ASB offer more flexible end-to-end travel services, which are particularly friendly to vulnerable groups such as the elderly and children (Dong et al., 2025; Mouratidis and Serrano, 2021). ASB are generally conceived to accommodate 8-12 passengers and equipped with sensors (e.g., radar and cameras) that enable communication with surrounding infrastructure and other vehicles, providing autonomous driving services at or above Level 3 (Iclodean et al., 2020; SAE International, 2016).

Recent studies have proposed using ASB for urban short-distance transportation to address spatial imbalances in transportation resources. Khavarian-Garmsir et al. (2023) argued that ASB could enhance the connectivity of transportation networks, making the concept of the 15-min city possible. Through surveys, Dong et al. (2025) demonstrated that urban residents were willing to use ASB to commute to nearby buses or metro hubs. Liu et al. (2025) showed that autonomous shuttles could significantly reduce the need for vehicle re-balancing and alleviate traffic congestion, making them a viable solution for suburban FMLM demands. Currently, there is no unified operating model for ASB, which can be broadly categorized into the following four types:

(1) Fixed-route operation. ASB run on fixed routes, similar to traditional bus lines, with either a set departure schedule or reservation support, allowing passengers to board directly at designated stops. Successful projects are already operational in the regions of Kista and Barkarby, Sweden (Hatzenbühler et al., 2020) and in Vantaa, Finland (Koskela, 2018).

(2) Operation within a specific enclosed area. ASB usually provide services within a particular enclosed area, such as industrial parks, scenic spots, and university campuses, to address local transportation needs. For instance, the “Ride the Future” project deployed ASB within the campus of Linköping University in Sweden (Larsson et al., 2023).

(3) Dynamic On-Demand Ridesharing. ASB offer door-to-door ridesharing services based on real-time passenger demands. Passengers book their trips through a mini-program or app, and the vehicles respond accordingly (Meshkani and Farooq, 2022).

(4) Mobility-as-a-Service (MaaS). ASB are integrated as part of MaaS, where passengers can use a single platform or app to combine various transportation modes and achieve a seamless travel experience (Hensher et al., 2020; Hasselwander et al., 2022).

Research combining SMOD with ASB has grown recently (Israel and Plaut, 2024; Li et al., 2024a; Rich et al., 2023). Integrating autonomous driving technology with on-demand travel concepts is a future trend, which can improve travel efficiency and flexibility, reduce travel costs, and enhance traffic safety.

The rational application of ASB has the potential to effectively address the inequity of the spatial distribution of urban transportation resources. However, a significant engineering gap remains in deploying ASB in urban environments. The real-time accuracy of high-definition maps is hard to guarantee, and erroneous information can lead to reduced positioning accuracy (Chen et al., 2024). There is also a lack of successful cases and proven operational plans (Rossetti et al., 2023). The SAE standard for autonomous driving only classifies the technology from a functional perspective, which cannot provide effective guidance in complex real-world scenarios. Other barriers to its widespread adoption include the potential reduction of employment opportunities for bus drivers, the absence of laws for liability allocation, and the significant initial capital investment required. Although the combination of SMOD and autonomous driving technology is an inevitable trend, ensuring their stable and regulated operations in cities, and possibly supplementing or even replacing existing public transportation systems, remains a challenging issue.

## 2.6 Summary

The preceding analysis reveals that while diverse shared mobility solutions exist, single-dimensional technological innovations or isolated institutional adjustments are insufficient to overcome the structural spatial inequities in urban transportation systems. Public transportation, often constrained by efficiency goals and concentrated investment in high-demand corridors, falls short of adequately serving the distributed needs of communities. Conversely, while offering flexibility and leveraging technology, private sector-driven mobility solutions are heavily influenced by profit motives, leading to deployment biases that favor high-demand, higher-income areas and create cost barriers for vulnerable populations. This results in a market-government double failure in addressing transportation equity (Stiglitz, 2010; Murray et al., 2024).

These existing solutions address symptoms (FMLM as an isolated problem) rather than the underlying structural issue of inequitable resource distribution and service design. Despite their merits, the solutions collectively fail to bridge the crucial gaps:

- The unique spatial and social context of diverse community environments.
- The application of appropriate, context-aware, and equity-oriented technology.
- The establishment of effective, multi-stakeholder governance mechanisms capable of balancing efficiency

with social goals.

Confronting these systemic limitations, this research proposes and elaborates on the novel CBUAMS framework, specifically designed to address transportation spatial inequity through a holistic, integrated socio-technical system approach. Its core lies in redefining “community” as the fundamental unit for transportation planning and operation, integrating advanced automation technologies adapted for community scenarios, ultra-flexible service design to ensure high coverage and responsiveness, and innovative multi-party governance leveraging community resilience and local resources. This integration aims to create a community-based, high-coverage, and short-response-time shared autonomous on-demand travel service that directly counteracts the biases of traditional corridor-based systems and profit-driven models.

### 3 Transportation equity and CBUAMS

The evaluation of transportation services has centered on efficiency as the core metric (Wong et al., 2020), closely linked to transportation planning paradigms focused on optimizing capacity or operational profit. However, as previously discussed, this efficiency-prioritizing approach can lead to an uneven distribution of transportation resources across space, potentially creating or exacerbating challenges like FMLM and undermining social equity. This study constructs an evaluation framework centered on equity to assess the social value of various shared mobility modes, including CBUAMS. Inspired by Wong et al. (2020), we divide transportation equity into two dimensions: Spatial Equity and Economic Equity. While research exists on quantifying transportation equity (Oswald and Mohammed, 2016; Berke et al., 2024; Xu et al., 2024), this study provides a qualitative and conceptual analysis framework to lay the foundation for subsequent arguments. Within the framework of this study, these concepts are defined as follows:

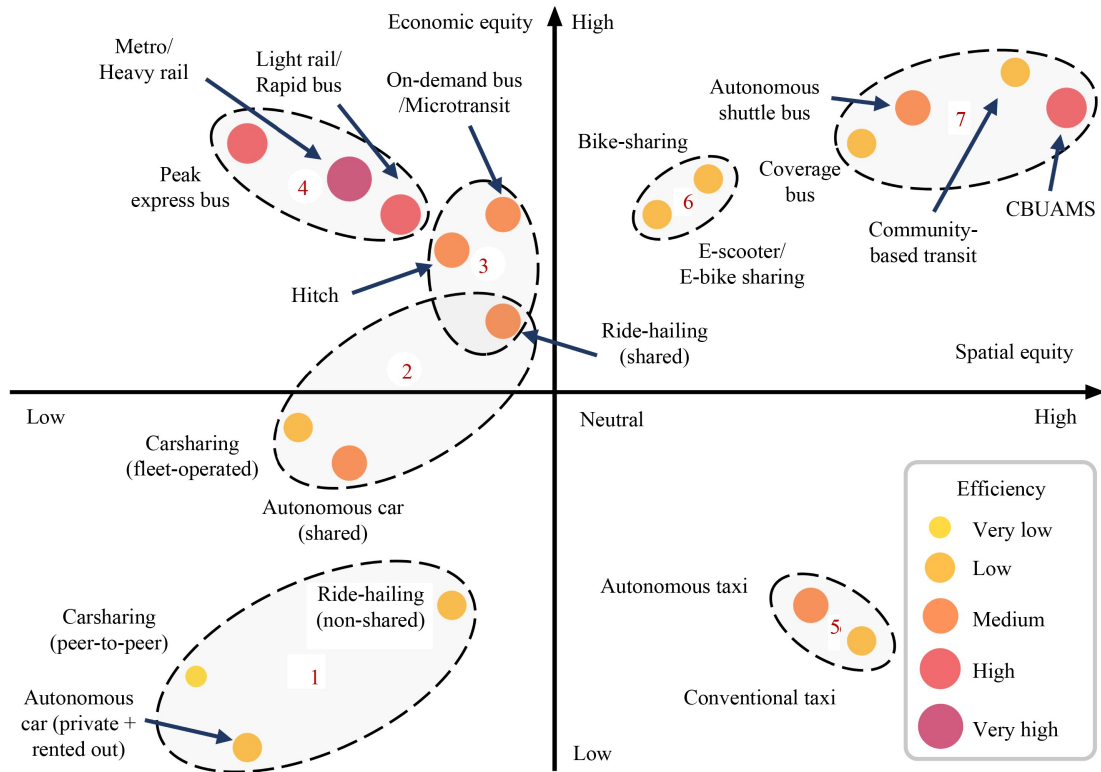
**Spatial equity** within the context of this study refers to the equitable distribution of opportunities for all individuals, regardless of their geographic location within a service area, to access transportation services with a consistent and acceptable level of quality. This extends beyond mere service presence or ‘wide distribution’ to encompass equality in key service attributes that users experience. Crucially, high spatial equity means that users in different locations (e.g., downtown vs. suburbs, urban core vs. peripheral areas) experience comparable ease of access, similar and predictable response/wait times, reliable service availability (minimizing service gaps or ‘deserts’), and consistent service quality (e.g., vehicle availability, and likelihood of successful booking). It implies that the system is designed and operated not just to cover a large area, but to ensure that the burden of accessing the service (in terms of time, effort,

and reliability) is not disproportionately borne by residents of certain areas, particularly those that may be less profitable for market-driven services.

**Economic equity** refers to the extent to which the costs (e.g., fares, time costs) and benefits (e.g., convenience, accessibility improvements) of the transportation service are fairly distributed among user groups with different income levels, payment capacities, or socioeconomic backgrounds. It focuses on affordability and whether economic barriers exist that might exclude or disadvantage certain groups. High economic equity means pricing and potential subsidy mechanisms ensure that low-income or economically vulnerable groups can afford and benefit from the service. Potential quantitative assessment dimensions include: affordability metrics (e.g., fare-to-income ratio, and cost comparison with alternative modes), fairness of pricing mechanism (e.g., dynamic pricing impact assessment, and fare reasonableness for long-distance/low-density trips), subsidy and assistance effectiveness (e.g., target group coverage rate, and subsidy usage distribution), and payment inclusivity (e.g., proportion of non-digital payments).

It is important to distinguish “spatial equity” from the commonly used concept of “accessibility” in transportation planning. Accessibility is typically defined as the ease with which an individual can travel from one location to another (Jones, 1981), emphasizing the ability to reach destinations. In contrast, spatial equity focuses on the equitable distribution of transportation service resources, which concerns equal access to and initiation of service use. For example, regardless of where one lives within a community, one can conveniently hail a car or find a shared bike. Although the two concepts are related (high spatial equity can enhance overall accessibility), their focus differs. The former concerns the geographical balance of service provision, while the latter concerns the convenience of travel outcomes. Furthermore, efficiency remains an indispensable dimension for measuring transportation system performance. In this study, efficiency primarily refers to the effective passenger transportation volume completed by a specific mode per unit of time (e.g., passenger kilometers or number of trips served), reflecting its overall transportation capacity and resource utilization rate.

Based on these three dimensions—spatial equity, economic equity, and efficiency—we have plotted a bubble chart (Fig. 2) for a qualitative comparison of CBUAMS and other mainstream shared mobility modes. In the chart, spatial equity and economic equity form the two-dimensional axes, with higher positions on the axes representing better equity performance. The size and color intensity of the bubbles represent qualitative level of efficiency (categorized as Very Low, Low, Medium, High, or Very High). A total of 20 shared mobility modes are discussed. The vast majority of these have already been implemented in real life (e.g., ride-hailing services,



**Fig. 2** The positioning of various common and envisioned shared transportation modes based on spatial equity and economic equity, with efficiency represented by different colors and sizes of spots corresponding to qualitative levels from Very low to Very high. This figure is intended for qualitative comparative purposes only. The axes and bubble sizes represent relative qualitative levels rather than precise quantitative measurements.

bike-sharing, and subway), and a small portion is expected to see large-scale application after autonomous driving technology matures (e.g., autonomous taxis, and shared autonomous cars), alongside CBUAMS proposed in this study. Transportation modes with similar characteristics have been grouped within dashed circles and numbered to facilitate identification and discussion.

In Quadrant 3 at the bottom left, Category 1 includes three transportation modes: carsharing (peer-to-peer), autonomous car (private + rented out), and ride-hailing (non-shared). While some of these modes, particularly non-shared ride-hailing, have achieved widespread adoption in many urban areas, their fundamental operational models present inherent challenges in systemically improving overall transportation efficiency and achieving equitable service distribution (Courcoubetis et al, 2024). Crucially, “widespread adoption” or “broad geographic coverage” should not be conflated with the achievement of true spatial equity as defined in this study (see beginning of Section 3). As discussed in our literature review (e.g., Sections 2.3), non-shared ride-hailing often faces significant spatial inequity issues, such as an oversupply of resources in high-demand “hotspots” at the expense of underserved peripheral areas, alongside high economic thresholds for users (Dong et al., 2024; Lei and Ukkusuri, 2023; Winter et al., 2021). This spatial imbalance, driven

by market dynamics, limits their ability to serve as a standalone solution for comprehensive transportation equity.

Category 2 can be seen as an upgrade of Category 1 enabled by advancements in information technology. (Autonomous) carsharing shifts from peer-to-peer operation to fleet-based operation, allowing users to rent and return vehicles at widely distributed parking lots, similar to bike-sharing. This also reduces the maintenance cost per vehicle due to more standardized management, lowers the economic threshold, and increases usage rates and efficiency. Ride-hailing services that allow carpooling can significantly reduce the empty running rate, thereby lowering travel costs (Du et al., 2022).

Ride-hailing (shared) also belongs to Category 3. This category represents the basic form of SMOD, characterized mainly by carpooling. It includes ride-hailing (shared), hitch, and the recently popular on-demand bus/microtransit. The characteristic of these services is that the dispatch platform often optimizes travel routes based on multiple travel demands to provide shared door-to-door services for multiple people. They can reduce operating costs and passenger fares when implemented on a large scale. On-demand bus/microtransit, in particular, plans routes in real-time, which can further reduce operating costs and improve economic equity. In terms of spatial equity, although these three transportation modes can improve

spatial equity through door-to-door services compared to previous ones, economically developed areas tend to have more abundant infrastructure and transportation resources (Wang et al., 2024).

Category 4 in the upper left Quadrant 2 represents traditional transportation modes serving high-demand transportation corridors with high accessibility, including metro/heavy rail, light rail/rapid bus, and peak bus. These are primarily operated by governments or state-owned enterprises, providing high-capacity and stable public services for high-demand public corridors. The subway is a typical example. On the one hand, these transportation modes have the highest efficiency and meet most travel demands. On the other hand, the high initial investment and operating costs mean they can only serve high-demand areas in cities, leading to unequal resource distribution, specifically manifested as the FMLM problem. Since governments or state-owned enterprises primarily operate these transportation modes, they are often part of social welfare, with relatively affordable fares, thus demonstrating a high level of in economic equity.

In Quadrant 4, there is only one set, Category 5, which includes conventional and envisioned autonomous taxis. The characteristics of these transportation modes are wide coverage, high service unit prices, and serious empty running problems. Although autonomous driving technology can reduce driver costs, it cannot completely solve the problem of empty running. However, it is crucial to acknowledge that their potential for high spatial equity is not guaranteed. A purely profit-driven platform may still allocate its fleet to high-demand, profitable areas, potentially failing to improve or even exacerbating existing spatial inequities, especially given the enhanced control provided by AV technology. Therefore, the positioning in Fig. 2 represents an idealized scenario where autonomous taxi services are assumed to be regulated or designed to prioritize broader service coverage over pure profit maximization. Due to the persistent empty running problem, it remains difficult to reduce costs and improve efficiency. As a result, most people believe in combining autonomous driving technology with SMOD to provide efficient, sustainable, and resilient transportation services (Hu et al., 2024).

Quadrant 1 consists of two categories. The first category, Category 6, includes micromobility that serves individuals only, namely bike-sharing and e-scooter/e-bike sharing. These modes are characterized by their wide distribution, convenience, and relatively low cost (Kopplin et al., 2021; Tao and Zhao, 2023). However, their application has revealed significant shortcomings. First, bike-sharing and similar services are more concentrated in high-frequency usage hotspots, with non-hotspot areas still facing insufficient resource allocation (Dong et al., 2023). Second, they face rebalancing challenges because travel demands between central and peripheral areas are inconsistent (Yu et al., 2020). Third, they

cannot meet the needs of vulnerable groups such as the elderly and children (Tao and Zhao, 2023). Therefore, it is clear that while these transportation modes can alleviate spatial inequity to some extent, they cannot completely solve the problem.

The other category in Quadrant 1 is Category 7, which includes coverage bus, ASB, CBT, and CBUAMS. These modes are characterized by their wide distribution on urban feeder roads, large coverage, affordable fares to ensure accessibility for urban residents of different income levels, and operations similar to buses. The coverage bus, as one of the most common transportation modes in cities, covers most major destinations in the city and provides a basic public transportation service for urban residents. On this basis, ASB integrates autonomous driving technology and on-demand travel technology to reduce operating costs and provide more flexible and user-friendly bus services. As a transportation mode spontaneously organized by residents to provide short-distance travel services for local residents, CBT has achieved a high level of spatial and economic equity. However, due to the lack of technical and financial support, its efficiency is limited by funding and technology (Hosford et al., 2024). CBUAMS envisioned in this study retains the community self-organization resilience of CBT, relies on autonomous driving and advanced information technologies to meet a large number of short-distance, high-frequency travel demands in cities, and significantly improves its efficiency while ensuring spatial and economic equity, realizing an efficient, sustainable, fair, and user-friendly future urban vision.

To further dissect the distinctions among these modes and more intuitively highlight the potential of CBUAMS in addressing the challenges of existing transportation services concerning equity and service coverage, we constructed Table 1. This table aims to conduct a systematic comparative analysis of CBUAMS against representative transportation modes from the different quadrants of Fig. 2 across multiple key dimensions, thereby more clearly revealing the unique advantages and design philosophy of CBUAMS.

Considering interpretability and readability, Table 1 does not include all transport modes depicted in Fig. 2. We selected CBUAMS and four typical transport modes representing the characteristics of the four quadrants in Fig. 2 for comparison: Coverage bus (representing traditional modes with high spatial and economic equity in the first quadrant), Conventional taxi (representing modes with high spatial but low economic equity in the second quadrant), Ride-hailing (non-shared) (representing modern modes performing poorly in both spatial and economic equity in the third quadrant), and Metro/Heavy rail (representing modes with high economic equity but spatial equity largely confined to corridors in the fourth quadrant). Comparing CBUAMS with these representative

**Table 1** Multi-dimensional comparative analysis of CBUAMS and representative transportation modes

Mode	Spatial equity	Economic equity	System efficiency	Service flexibility	Vulnerable user service	Community empowerment & governance
CBUAMS	Very high	Very high	High	Very high	High	Very high
Coverage bus	High	High	Medium	Low	Medium	Low
Metro/Heavy rail	Low	High	Very high	Very low	Medium	Very low
Ride-hailing (non-shared)	Low	Low	Low	High	Medium	Very low
Conventional taxi	High	Low	Low	Medium	Medium	Very low

Note: The comparative analysis in Table 1 reveals the characteristics and differences of various transportation modes across the six key dimensions.

modes allows for a more effective positioning of its value.

The comparison in Table 1 is based on the following six core dimensions:

- **Spatial equity:** As previously defined, measuring the balanced distribution of service resources across geographical space.

- **Economic equity:** As previously defined, focusing on service affordability and the fair distribution of cost-benefits among different income groups.

- **System efficiency:** As previously defined, primarily referring to the effective passenger throughput per unit of time.

- **Service flexibility:** Refers to the ability of a transport service to respond to users' dynamic demands and adapt to different travel scenarios (e.g., time, route, pick-up/drop-off points). High flexibility means the service can better meet personalized, real-time travel needs.

- **Vulnerable user service:** Measures the performance of a transport service in meeting the travel needs of specific groups such as the elderly, people with disabilities, and low-income individuals, including accessibility, ease of use, safety, and accommodation of special requirements.

- **Community empowerment and governance:** Assesses the degree of community participation in the planning, operation, supervision, and feedback of transport services, and whether the governance structure can effectively incorporate community opinions, safeguard community interests, and promote service sustainability.

Regarding Spatial Equity, CBUAMS is designed to fill service gaps with its community-based, on-demand nature, thus aiming for very high spatial equity. Taxi services, in theory, also offer comprehensive network access. Coverage bus achieves high potential for broad geographical coverage through extensive fixed-route networks; however, these networks, while widespread, may still fall short in addressing granular, off-route demands in less densely populated or non-corridor areas. In contrast, non-shared ride-hailing often exhibits lower effective spatial equity due to its business model, which tends to over-concentrate services in high-demand urban centers and during peak hours, leading to service deserts or unreliable availability in other areas. Metro systems,

while highly efficient within their designated corridors, inherently offer limited accessibility to, and thus create spatial inequities for, areas and trips outside these specific routes.

In terms of Economic Equity, CBUAMS aims to provide universally affordable services, aligning it with bus (often supported by affordable fares and subsidies) and metro (which typically offers relatively affordable fares for its capacity) in the high economic equity category. This contrasts sharply with the higher-cost non-shared ride-hailing, characterized by dynamic surcharges and market-driven pricing, and taxi services, which are generally expensive and lack subsidies, making them less friendly to low-income groups.

Concerning System Efficiency, metro demonstrates very high efficiency due to its large capacity, high speed, punctuality, and operation on dedicated rights-of-way. CBUAMS, through intelligent dispatch optimization and shared modes, aims for higher efficiency than conventional buses, which might experience high peak capacity but low off-peak utilization leading to moderate overall resource use. Both non-shared ride-hailing and taxi services often suffer from low system efficiency due to significant deadheading mileage and, in the case of ride-hailing, potentially contributing to rather than alleviating congestion.

Service Flexibility is a core strength of CBUAMS. Its on-demand, dynamic routing characteristics far exceed the fixed routes and schedules of buses and metros. While non-shared ride-hailing also offers high door-to-door, on-demand convenience, CBUAMS aims to match this convenience while addressing associated equity issues. Taxi services offer some flexibility through street-hail or phone booking, but typically less instantly or conveniently than modern app-based on-demand services.

For Vulnerable User Service, CBUAMS is intrinsically designed with the goal of serving all community residents, placing a particular emphasis on vulnerable groups, thereby continuing the foundational spirit of CBT. This philosophy is expected to translate into more humanized and tailored operational methods, potentially formulated by local service organizations deeply familiar with community needs. Furthermore, CBUAMS envisions

the integration of comprehensive accessible facilities, including, for example, more user-friendly applications and vehicles equipped to accommodate diverse needs. This approach seeks to overcome systemic barriers, such as the limited last-mile accessibility of conventional bus stops (where CBUAMS aims for more precise pick-up/drop-off) and the digital divide that can exclude certain users from app-dependent ride-hailing services. While taxis can be used without smartphones, their cost remains a barrier for many vulnerable users. Metro stations are generally accessible, but transfers can be challenging for some individuals.

Most critically, in the Community Empowerment and Governance dimension, the “government-enterprise-community” tripartite collaborative governance model proposed for CBUAMS gives it a unique advantage. It aims for deep community involvement and effective response to real needs. This fundamentally differs from the predominantly government-led models of traditional public transportation (like buses and metros, which typically have specialized, centralized management with low direct community participation in operations) and the enterprise-dominated models of commercial mobility platforms (like ride-hailing and taxi industries, where community voice in governance is often weak or non-existent).

In summary, the comparative analysis in [Table 1](#), supported by the detailed dimensional discussion, preliminarily substantiates CBUAMS’s comprehensive potential in balancing objectives of equity, efficiency, flexibility, and community participation, providing strong support for it as an innovative framework aimed at systematically enhancing urban transportation spatial equity.

This chapter systematically established an evaluative framework prioritizing transportation equity, meticulously defining Spatial Equity and Economic Equity, alongside considerations for System efficiency, Service flexibility, Vulnerable user service, and Community empowerment and governance. An initial broad qualitative comparison using a bubble chart ([Fig. 2](#)) analyzed 20 distinct shared mobility modes, categorizing them to reveal prevalent challenges among existing systems in achieving comprehensive spatial and economic equity, particularly in the equitable distribution of service resources and addressing FMLM issues.

To further crystallize the distinct advantages of CBUAMS, a more focused, multi-dimensional comparative analysis was subsequently presented in [Table 1](#). This table, along with its detailed accompanying discussion, systematically evaluates CBUAMS against representative existing transport modes across the six defined dimensions. The analysis robustly demonstrated CBUAMS’s significant potential not only to substantially enhance spatial and economic equity but also to offer superior service flexibility and dedicated vulnerable user service. Most critically, it highlighted CBUAMS’s unique strength

in fostering community empowerment and governance through its proposed tripartite model. These findings collectively underscore CBUAMS’s promise as an innovative framework capable of addressing the multifaceted limitations of current transportation modes. The next section will delve into the specific mechanisms and operational strategies through which CBUAMS aims to realize these comprehensive benefits and effectively overcome these identified shortcomings.

## 4 Improving transportation equity through CBUAMS

Undoubtedly, relying on transportation corridors to construct urban public transportation networks has significantly promoted urban development. By connecting economic nodes with high-density residential areas and establishing corridors, there is a substantial boost to urban revitalization and densification along the corridors. Ensuring the accessibility and service level of these corridors through public infrastructure investment maintains the basic operation of urban transportation systems ([Chiquetto et al., 2022](#); [Martens, 2016](#); [Venter, 2016](#)). Meanwhile, some private companies or individuals provide complementary shared transportation modes to enhance the accessibility of urban transportation systems, which constitutes the current layout of urban shared transportation. This model demonstrably achieves a certain macro-level system efficiency by concentrating resources on high-demand routes. However, in recent years, the spatial inequity crisis inherent in this corridor-centric development model has increasingly attracted attention ([Murray et al., 2024](#); [Pereira et al., 2017](#); [Potter et al., 2023](#); [Venter, 2016](#)). This crisis manifests not only as inadequate service in non-corridor areas, persistent FMLM challenges, and reduced accessibility for residents in peripheral or less dense communities, but also potentially leads to inefficiencies in local circulation as short-distance trips may be forced onto congested arterial roads or remain unserved. The traditional corridor model, by its nature, struggles to provide granular, equitable, and efficient mobility solutions within and between diverse communities. Simply increasing the supply of transportation resources cannot solve this problem. For example, Braess’ paradox points out that in a transportation network, merely increasing supply, such as adding a new road, can lead to increased travel times for all travelers ([Steinberg and Zangwill, 1983](#)). Therefore, a strategic shift is needed — from relying solely on centralized corridors to embracing a model that complements them with distributed community networks, as advocated by CBUAMS. This approach can fundamentally optimize travel patterns and resource allocation at the community level. This section will elaborate on how CBUAMS can change the current dilemma and build a more equitable

and efficient urban travel system through spatial restructuring, technological innovation, and community governance.

#### 4.1 Spatial restructuring: Complementing centralized corridors with distributed community networks

Inspired by CBT, CBUAMS adheres to “community as the smallest equity unit.” It advocates using autonomous driving technology and on-demand travel mechanisms to complete numerous short-distance shuttle tasks locally. This approach enhances the accessibility and spatial equity of the transportation system. The feasibility of this concept is discussed through the following two points:

**(1) Fractal cities can make the most efficient use of public transportation infrastructure.** As discussed earlier, radial transportation corridors lead to spatial inequity in the distribution of transportation resources. Typological studies of cities, which classify urban layout forms, have conducted more detailed research. Burke et al. (2022) categorized common urban development models into four major types and ten subtypes. An analysis of 24 global cities with over 8,000 geographical units below the municipal level revealed that urban typology has a significant impact on the accessibility of urban facilities, with fractal cities being found to be the most efficient in utilizing physical infrastructure. The spatial structure of fractal cities exhibits self-similarity, meaning that similar spatial layout patterns exist at different scales, with Barcelona being a typical example. In poly-centric, self-similar urban types, each amenity is often closer to residents than in other types of layouts. In fractal cities, various facilities overlap, making it easier for people to access each amenity. Enhancing the fractal nature of urban layouts may help achieve the goal of the “15-minute city” concept, which emphasizes proximity and equal access to daily needs. In contrast, the street networks and spatial distribution characteristics of radial cities, such as Beijing and Paris, lead to an inequitable distribution of service facilities, failing to achieve the goal of a 15-min living circle.

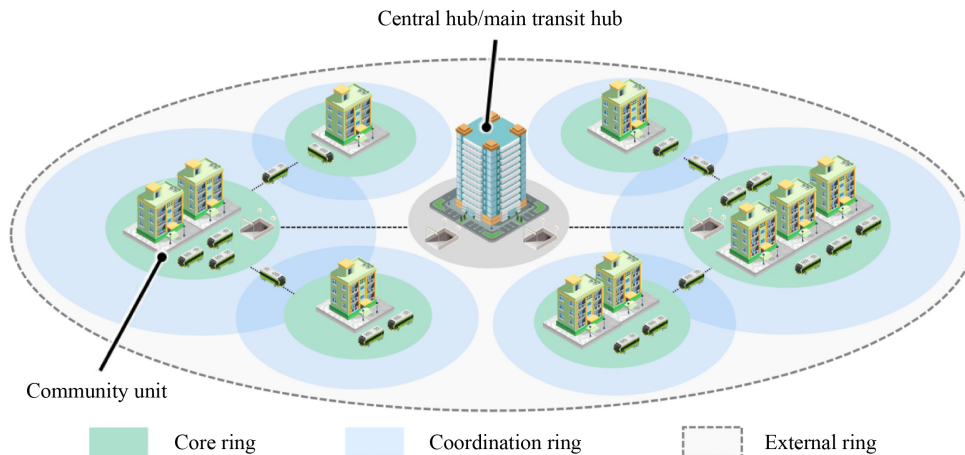
**(2) Meeting high-frequency short-distance travel demands is expected to reduce the load on transportation systems.** Many empirical studies have shown that short-distance travel accounts for a significant proportion of urban travel (Liu et al., 2023; Schwarz et al., 2024; Xue et al., 2024). Using data from Hangzhou, Liu et al. (2023) showed that most trips were within 3 km. Xue et al. (2024) analyzed shared bicycle data and found that many users’ travel times were concentrated 10–20 min, with a clear characteristic of short-distance commuting. Schwarz et al. (2024) analyzed data from the 2019 Enquête mobilité des personnes (people’s mobility survey) and found that the proportion of survey participants whose short car trips were all less than 5 km was 23.4%, with an average length of 2.42 km. However, there is

currently a lack of short-distance travel modes that balance efficiency and comfort. Research using taxi GPS data has shown that shorter travel distances lead to more circuitous routes and lower travel efficiency (Yang et al., 2020). Many residents give up using shared bicycles in extreme temperatures and switch to cars or ride-hailing services (Qian et al., 2025; Xue et al., 2024). This suggests that a short-distance shuttle transportation mode balancing efficiency and comfort would be beneficial. It could reduce the demand for motor vehicle travel, alleviate traffic congestion, and reduce carbon emissions.

To systematically elaborate on how CBUAMS can achieve enhanced spatial equity and system efficiency by addressing the aforementioned limitations of the traditional “transportation corridor” model at the community scale, we propose the “Three-Ring Model” as a novel spatial organization framework specifically for CBUAMS in Fig. 3. This model is conceptualized not as a replacement for corridors, but rather as a complementary framework for spatial organization. It organizes urban space into a distributed, multi-level network based on communities, aiming to achieve a more balanced distribution of mobility resources and optimize their use, particularly for local travel needs that corridors often fail to serve adequately.

**(1) Core ring.** The foundational layer of the model is depicted by the green-shaded areas surrounding community buildings in Fig. 3. It represents the basic service unit of CBUAMS, typically corresponding to one or several adjacent residential communities. Each Core Ring possesses a dedicated “Community Resource Pool,” namely, a localized fleet of autonomous vehicles (Section 5.2). Its primary function is achieving self-sufficiency for intra-community travel, prioritizing residents’ short-distance, high-frequency travel needs within the ring (e.g., commuting within the community, shopping, school trips, and connecting to nearby public transportation stations) (Sun, 2019; Xiong et al., 2024). This local focus, supported by community-based operations and governance (Section 4.3), minimizing residents’ reliance on external (potentially inequitable) systems for basic mobility needs, ensuring basic mobility accessibility and equity, and establishing the foundation for the “community as the smallest equity unit.”

Unlike the traditional corridor model, which often leaves intra-community travel underserved or forces residents to make lengthy trips to access corridor services, the Core ring prioritizes universal basic mobility within the community itself. By establishing a dedicated “Community Resource Pool,” it ensures that all residents, including vulnerable populations (e.g., elderly, disabled, low-income), have direct and equitable access to essential short-distance travel for daily needs (e.g., local shops, schools, clinics) regardless of their proximity to major transport corridors. This focus on local self-sufficiency directly tackles the FMLM problem at its origin/destination within the community, offering a more granular equity



**Fig. 3** Schematic diagram of the “Three-Ring Model” for CBUAMS spatial organization. The central high-rise building depicts the Urban center hub, serving as the city’s primary node for activity and transportation. Surrounding community units are serviced by their local Core ring, which handles intra-community transit and access. The Coordination ring is responsible for managing connections between community units and coordinating services directed toward the Urban center hub. Finally, the External ring delineates the overall operational boundary of the system.

than corridor-based systems alone can provide.

By efficiently handling a high volume of short-distance, high-frequency trips internally using appropriately sized CBUAMS vehicles (Section 5.2), the Core ring reduces the need for these trips to spill onto major arterial roads designed for longer-distance travel. This not only alleviates congestion on the main corridors, allowing them to function more efficiently for their intended purpose, but also minimizes inefficient empty vehicle miles and circuitry often associated with using corridor-based public transport or private vehicles for very short local hops. This localized operation enhances overall system efficiency by right-sizing services to local demand.

(2) **Coordination ring.** Surrounding and overlapping multiple Core rings, as represented by the light blue shaded areas in Fig. 3. While fundamentally representing a mechanism layer for resource scheduling and service coordination, its spatial representation in the figure highlights the zone of interaction and potential resource sharing between adjacent or related communities (Core rings). This layer facilitates “Multi-Community Interconnection.” The Coordination ring mechanism is activated when a single Core Ring’s resource pool cannot meet peak demand or residents require medium-to-short distance travel across community boundaries (visualized by vehicles moving between Core rings or toward shared connection points in the figure). Vehicle resources are flexibly shared and optimized across Core rings through pre-defined inter-community collaboration protocols and dynamic scheduling algorithms managed by the CBUAMS platform (Section 5.2.1). This enhances overall resource utilization efficiency and resilience to demand fluctuations within the community cluster, preventing Core rings from becoming isolated resource islands, and

is a crucial element for achieving broader, inter-community scale spatial equity.

The Coordination Ring extends spatial equity beyond individual communities by facilitating resource sharing and service connectivity between adjacent Core rings, areas often poorly served by direct corridor-to-corridor links or infrequent orbital routes in traditional systems. This proactive coordination ensures a more balanced service level across a cluster of communities, mitigating the “service desert” phenomenon often found between major corridors and preventing communities from becoming isolated “mobility islands” solely reliant on often indirect corridor connections.

From an efficiency perspective, this inter-community coordination allows for dynamic load balancing and optimized fleet utilization across a wider operational area. Instead of each community independently over-provisioning vehicles for peak demand (a common issue if relying on isolated local solutions), resources can be shared intelligently. This is more efficient and responsive than relying solely on fixed-route corridor services to handle diverse and often unpredictable inter-community travel patterns, which may not align perfectly with corridor orientations or fixed schedules. The CBUAMS platform (Section 5.2.1) managing this ring can thus reduce overall fleet requirements and idle times compared to uncoordinated local services or less flexible corridor systems.

(3) **External ring.** The outermost dashed line boundary in Fig. 3 represents the External ring. It delineates the operational boundary and interaction interface between the CBUAMS community cluster, comprising multiple interconnected Core and coordination rings. It also defines the broader “Urban Macro-Transportation Network” (e.g., subways, major bus routes, connections to the city center, like the central high-rise building

depicted in the figure). Its design adheres to the “asymmetric coupling” principle: On one hand, CBUAMS provides efficient FMLM shuttle services; on the other hand, through carefully designed operating ranges and scheduling rules, it prevents CBUAMS’s community-centric vehicle resources from being excessively siphoned off by the demands of the main urban network, thus safeguarding the stability and equity of local community services. External Ring aims to achieve an organic integration between the community mobility system and the overall urban transportation system, rather than simple replacement or assimilation.

The External Ring defines the critical interface with the broader ‘Urban Macro-Transportation Network’, typically comprised of high-capacity corridors such as metro lines, Bus Rapid Transit (BRT) systems, major bus routes, and regional rail connections. By providing efficient, reliable, and demand-responsive FMLM shuttle services to and from designated stations and interchanges of these existing public transportation modes (e.g., metro station entrances, key bus terminals, and park-and-ride facilities), CBUAMS ensures that residents from all participating communities, even those geographically distant from corridor stations, have fair and convenient access to city-wide mobility options. This targeted FMLM service directly expands the catchment area of these established public transportation corridors, making them more accessible and attractive to a wider population, thereby enhancing their ridership and overall operational efficiency. The ‘asymmetric coupling’ principle is crucial here: it safeguards local community service equity by preventing CBUAMS resources from being entirely absorbed by corridor demand, a common risk if FMLM services are not managed with a community-first priority.

This seamless integration enhances the efficiency of the entire urban transportation network. CBUAMS acts as an effective “last-mile distributor and first-mile collector” for the corridors, expanding their effective catchment area and potentially increasing their ridership and operational efficiency. This synergy allows high-capacity corridors to operate optimally for longer-haul trips, while CBUAMS efficiently manages the distributed local access. This reduces the inefficient use of private vehicles, taxis, or overly circuitous feeder buses for FMLM connections, thereby alleviating congestion around transit hubs and optimizing passenger journey times. The organic integration avoids the inefficiencies of a poorly coordinated or disconnected multi-modal system.

Collectively, the “Three-Ring Model,” as a complement to existing corridor infrastructure, forms a distributed, multi-level, internally and externally coordinated, community-oriented mobility network.

**Enhanced Spatial Equity:** By spatially anchoring the service focus at the community level (Core Ring), it ensures baseline mobility access is distributed more equitably than corridor systems alone. By enabling

inter-community collaboration (Coordination Ring), it reduces service disparities between communities. By managing the coupling with the macro-transportation network (External Ring), it extends equitable access to city-wide services for all community residents. Thus, this model systematically addresses the spatial equity challenges often unaddressed by purely traditional transportation models.

**Improved System Efficiency:** The model contributes to overall system efficiency by optimizing local trips within Core Rings (reducing corridor congestion and inefficient short trips on main roads), by improving fleet utilization and responsiveness through the Coordination Ring’s resource sharing, and by streamlining FMLM transfers and enhancing the catchment of corridors via the External Ring (making the entire multi-modal system more efficient). It provides a clear spatial organization framework for realizing the intertwined goals of “high accessibility,” “equity,” and “efficiency” advocated by CBUAMS, embodying the “spatial restructuring” strategy - focused on community-level optimization and integration - within the “space-technology-institution” trinity equity empowerment framework.

#### 4.2 Technological innovation: Equity-oriented design principles

In Section 4.1, we discussed that spatial restructuring to establish a distributed community network (represented by the “Three-Ring Model”) forms the foundational framework for CBUAMS to achieve spatial equity. Emerging technologies provide favorable support for realizing this vision, especially autonomous vehicles and V2X communications (Cai et al., 2023; Iclodean et al., 2020). However, technology is not value-neutral (Milakis and van Wee, 2020). Traditional technological development paths primarily focus on efficiency or profit. Consequently, they often overlook potential social equity impacts and may even inadvertently exacerbate the digital divide and unequal resource distribution (Martens, 2016; Pereira et al., 2017). For example, deploying high-level ASB primarily in high-density, high-value areas may seem technologically and commercially rational, but it could further marginalize communities with weak infrastructure and lower purchasing power, which contradicts the goal of enhancing overall transportation equity. Therefore, the technological innovation strategy of CBUAMS follows equity-oriented design principles. The aim is to ensure that the benefits of technological progress can be shared by all community members, especially those who are disadvantaged in the existing transportation system (such as the elderly, people with disabilities, low-income individuals, and residents in underserved areas) (Milakis and van Wee, 2020). This means that the selection of technology, the definition of functions, deployment strategies, and the establishment of standards

should all prioritize equity as a core consideration, rather than merely being adjuncts to efficiency, cost, or technological advancement.

This section elaborates explicitly on how CBUAMS embodies equity-oriented principles in two key technological areas: First, by critiquing the limitations of existing autonomous driving classification standards and proposing a new standard that is more suitable for community scenarios and conducive to equitable deployment; second, by designing and promoting a low-cost, widely deployable V2X communication solution aimed at feasibly bringing safety and efficiency improvements to a broader range of communities at an affordable cost. Through these specific technological strategies, CBUAMS strives to build a future community travel system that is intelligent, efficient, and truly fair and inclusive.

#### 4.2.1 Transformation of community-based autonomous driving classification Standards

The most widely accepted classification of autonomous driving technology currently comes from SAE International's J3016 standard, which primarily focuses on vehicle automation capabilities and the role of the driver (SAE International, 2016). Although the SAE classification scheme has certain practicality, for instance, it provides a basis for common terminology across domains and functions (e.g., policymakers, engineers, researchers) (Noy et al., 2018), its limitations become apparent when directly applied to CBUAMS, which centers on equity and inclusivity. The SAE standard is essentially technology-centric. It focuses on what the vehicle “can do” but fails to adequately address service needs under specific Operational Design Domains (ODD), deployment costs, and equitable accessibility in different community environments.

To more precisely guide the design, deployment, and operation of CBUAMS and align its technological development path with equity goals, this study proposes a community service-oriented and equity-driven autonomous driving classification standard, C-ADC, referred to as three levels: C1, C2, and C3. Crucially, C-ADC is not intended to replace the foundational SAE standard. Instead, it can be understood as a specialized application and contextual extension of SAE capability descriptions. C-ADC achieves this by meticulously

defining the service model, safety requirements, and cost-effectiveness considerations specifically tailored for vehicles operating within diverse community ODDs. This approach thereby guides differentiated, sustainable, and equitable deployment strategies. The core components of C-ADC are detailed in Table 2.

1) **C1-basic guarantee.** Its core equity goal is to provide basic travel services at the lowest cost and with the highest safety assurance, ensuring universal accessibility, especially for vulnerable groups within the community (Core Ring), meeting their needs for safe and reliable short-distance travel. This is the technological foundation for realizing the concept of “community as the smallest equity unit.” It typically operates at extremely low speeds (e.g., < 15–20 km/h) in highly restricted ODD (e.g., quiet internal community roads, low-speed mixed-traffic areas, and fixed/semi-fixed routes), heavily relying on high-precision maps and simple roadside perception assistance, and through low-cost V2X or sensors. The design prioritizes collision avoidance and passenger safety over travel efficiency. Technologically, this level's capabilities are indicative of SAE L3 +, specifically tailored for such highly restricted ODDs where the system manages all aspects of the dynamic driving task but may still require a fallback-ready user under certain predefined conditions, or operates so simply that fallback is to a safe stop. It aims to significantly reduce technological complexity and hardware costs, enabling widespread deployment in communities with relatively weak infrastructure and limited budgets, thus achieving the bottom-line equity of basic services.

2) **C2-core coverage.** Under the premise of ensuring safety and controlling costs, it provides more flexible and efficient on-demand travel services to meet the vast majority of daily travel needs of community residents (within the Core Ring and Coordination Ring), achieving equity in service quality and coverage. Operating at medium-low speeds (e.g., < 30–50 km/h), ODD expand to more complex environments within the community, such as main roads and intersections, capable of handling common traffic flows and weather conditions. It requires stronger onboard perception capabilities (such as LiDAR and camera fusion) and benefits from V2X collaboration (see Section 4.2.2) to enhance safety and efficiency. This aligns with indicative SAE L4 + capabilities, signifying that the automated driving system can perform all driving

**Table 2** Core comparison of CBUAMS community-based autonomous driving classification

Level	Core fairness goal	Primary scenario/ODD	Key Tech/Cost focus	Role in CBUAMS	Indicative SAE level correspondence
C1	Universal access, ensure basic travel	Internal community, very low-speed, fixed routes	Lowest cost, high safety, simple tech	Equity foundation	SAE L3 + (Highly restricted ODD)
C2	Equity in quality and coverage, meet daily needs	Main community roads, on-demand travel	Balance performance/cost/efficiency, V2X	Main service fleet	SAE L4 + (Community adapted)
C3	Continuity & reliability, response to abnormalities	Edge/complex/emergency scenarios	High adaptability, redundancy, advanced tech	Resilience guarantee	SAE L4 + (Resilience for edge cases)

tasks and monitor the driving environment within its defined ODD without human intervention, specifically adapted for these community scenarios in terms of ODD and service model. It balances technological performance, operational efficiency, and deployment costs. It is intended to be the mainstay of the CBUAMS fleet, gradually reducing costs through scaled application and technological optimization to make high-quality services accessible to more residents.

3) **C3-resilience and expansion.** The goal is to enhance the overall system's reliability and resilience, ensuring that the system can maintain basic services or transition safely under non-ideal conditions (such as severe weather, temporary traffic control, partial sensor failure, and edge cases beyond the regular ODD), guaranteeing the continuity of travel and sense of security for all users, and avoiding service disruptions and inequities due to system vulnerabilities. Technologically, C3 relies on robust capabilities indicative of SAE L4 + (potentially touching upon aspects considered for L5 in specific resilience functions), demonstrating a high degree of autonomy to ensure resilience for edge cases and handle a wider range of abnormal conditions. It has stronger environmental adaptability and fault response mechanisms, such as degrading operation, safely pulling over, requesting remote assistance, or switching to a more conservative operating mode. It requires advanced decision-making and planning capabilities and cloud collaboration support to handle complex and unexpected situations. It poses very high demands on both technology and cost. Typically, it does not require large-scale deployment but serves as a necessary redundancy and supplement, deployed at key nodes or on-demand to deal with emergencies and ensure the bottom line of service equity and reliability.

In summary, this C1-C3 community-based classification standard, by integrating the capabilities of autonomous driving technology with the specific service needs of communities (especially equity needs), provides a differentiated, phased, and cost-controlled technological deployment framework for CBUAMS. It allows communities with different resource endowments to choose appropriate level combinations according to their own situations. For example, prioritizing the widespread adoption of C1, gradually introducing C2, and configuring a small amount of C3), thus avoiding the "all-or-nothing" technological gap and truly embedding equity into the implementation of autonomous driving technology.

#### 4.2.2 Low-cost, inclusive V2X communication for equitable deployment

V2X communication technology is the cornerstone for the safe and efficient collaborative operation of CBUAMS. Through real-time information exchange, V2X enables effective connections between vehicles,

infrastructure, pedestrians, and cloud management platforms within the system, achieving beyond-line-of-sight perception, collaborative decision-making, and control, thereby significantly enhancing traffic safety and operational efficiency (Elsayed et al., 2023; Pearre and Ribberink, 2019; Li et al., 2024b; Chang et al., 2024). However, traditional V2X technologies, whether based on Dedicated Short-Range Communications (DSRC) or Cellular V2X (C-V2X), often face challenges of high equipment costs and complex network deployment (Qian et al., 2024). In traditional road scenarios, civilian autonomous vehicles can afford substantial investments in sensors, computing units, communication modules, control systems, and power supplies to provide the best autonomous driving experience (Qian et al., 2024). However, directly applying these solutions to community settings is not only economically unfeasible but also exacerbates the "digital divide" between communities due to inequity deployment, contradicting the inclusive service goals of CBUAMS.

Therefore, to ensure the feasibility and equity of CBUAMS, we explore an alternative path. This requires us first deeply to analyze the unique characteristics of community traffic environments: the widespread coexistence of pedestrians and vehicles, narrow roads, frequent obstructions to line of sight (such as buildings, parked vehicles, and green belts), and the predominantly short-distance, high-frequency travel patterns of residents (Liu et al., 2023; Peters et al., 2022; Schwarz et al., 2024; Sharifi, 2019). Based on these insights, CBUAMS adopts an equity-oriented, low-cost, inclusive V2X implementation strategy. This strategy does not aim for one-step full-function coverage but focuses on core safety and collaborative needs in community environments. It aims to achieve broader and more equitable V2X coverage at a lower cost through innovative technical approaches and deployment models. CBUAMS primarily employs the following three core strategies:

##### (1) Layered deployment prioritizing urgent needs.

In resource-constrained community environments, pursuing full-function, full-coverage V2X deployment is impractical and cost-prohibitive (Qian et al., 2024). Therefore, CBUAMS adopts a layered deployment strategy. The basic layer expands the deployment scope as much as possible through low-cost solutions, prioritizing the most core and urgent safety needs. For example, it provides basic collision warnings at key intersections or areas with obstructed visibility, perception, and alert capabilities for vulnerable road users such as pedestrians and cyclists, and supports simple operational status or intent broadcasts between vehicles (Hejazi and Bokor, 2024; Huang et al., 2022). This tier uses the most cost-effective technical solutions to ensure the broadest range of vehicles and residents benefit, safeguarding basic operational safety and efficiency. The enhanced layer is deployed at identified high-accident spots, densely

populated human-vehicle interaction areas (e.g., school entrances, community centers, and bus stops), or specific complex intersections, with more functional and higher-performance V2X equipment or integrated perception systems. These areas may require low latency, high data throughput, or complex collaborative perception and decision-making capabilities (e.g., cooperative lane changes, and precise merging) (Khan et al., 2022). By optimizing resource allocation through a layered strategy, limited investments are prioritized to address the most prominent pain points, ensuring the broad accessibility of basic functions while providing necessary performance enhancements at key nodes. It avoids the problem of overall cost escalation to meet the needs of a few extreme scenarios, representing a pragmatic path to achieve cost control and maximize effectiveness.

**(2) Flexible technology selection and lightweight solutions.** When selecting technologies, it is essential to avoid “technological determinism” and the over-pursuit of advanced technologies. Instead, a pragmatic and cost-effectiveness-first approach should be adopted, flexibly choosing or combining the most suitable technologies based on the specific needs and budget constraints of community scenarios. Qian et al. (2024) proposed a segmented path-planning solution for resource-constrained industrial parks, determining the next driving direction based on the relative positions of the current vehicle location and target location. Since it does not require complex map construction and positioning algorithms, it avoids the reliance on expensive radar systems, reducing system resource demands. CBUAMS also needs to innovate in community scenarios, breaking down technological barriers to make V2X functionality accessible to communities and serve a broad user base.

**(3) Infrastructure reuse to lower deployment costs.** Besides equipment, constructing infrastructure for V2X deployment (e.g., new poles, trenching for cabling, and power supply) constitutes a significant portion of costs. The cost of deploying new infrastructure, such as fiber-optic cables, is high, with installation costs often exceeding the cost of the fiber itself. For example, deploying a 1,000-km-long cable may cost approximately \$20 million (Winzer et al., 2020). To reduce this expenditure, CBUAMS emphasizes reusing existing public infrastructure in communities. Miniaturized, low-power roadside units (RSUs), perception devices (cameras, radar), or communication antennas are directly installed on existing streetlight poles, traffic signal poles, surveillance poles, and even the facades of some buildings throughout the community. This approach eliminates the need to construct many physical support structures specifically for V2X deployment and leverages the existing power supply lines on these poles to power V2X devices. For data backhaul, priority is given to utilizing public Wi-Fi that may cover the community, existing fiber-optic networks, or collaborating with operators to use cellular

network base stations to reduce or avoid the need to lay new communication cables (Nagel and Meyer, 1999; Winzer et al., 2020). If a community already has intelligent systems (such as smart security, smart lighting, and environmental monitoring), active efforts should be made to share and integrate resources with these systems to create synergies and further spread construction and maintenance costs (Ceglia et al., 2020). By maximizing the reuse of existing facilities, CBUAMS can significantly reduce engineering costs, accelerate deployment speed, and enhance economic feasibility. In this way, CBUAMS substantially lowers the barrier to V2X deployment, making it no longer a “luxury” for a few advanced communities but a practical solution that can serve various communities, including old and underdeveloped ones. This is the core embodiment of achieving technological inclusivity and extending the benefits of safety and convenience to a broader range of residents.

Overall, the layered deployment strategy of CBUAMS ensures that resources are focused on core needs, while flexible technology selection and exploration of lightweight solutions reduce system complexity and per-unit costs. The reuse of existing infrastructure maximizes the reduction of fixed investment. These three strategies form an innovative path for low-cost, broad-coverage, and sustainable V2X deployment in the complex community environment, supporting the inclusive service goals of CBUAMS.

#### 4.3 Community governance: A tripartite governance mechanism involving government, enterprises, and communities

Given CBUAMS’s nature as a quasi-public good providing essential mobility services within communities, its successful and equitable governance requires moving beyond traditional single-agent models (government, enterprise, or community acting alone). Each single-agent approach faces inherent limitations: government-led models can suffer from bureaucracy and lack of innovation; pure enterprise dominance risks prioritizing profit over social equity; and solely community-run initiatives often struggle with scalability, funding, and technological complexity (Burch and Di Bella, 2021; Eras-Almeida and Egado-Aguilera, 2019; Hosford et al., 2024; Jeekel, 2018). Therefore, an innovative governance framework emphasizing multi-party participation, clear responsibilities, and collaborative complementarity is essential to effectively balance multiple goals like efficiency, equity, safety, and sustainability (Stiglitz, 2010; Murray et al., 2024).

Inspiration for effective local coordination and grassroots engagement can be drawn from models like China’s community grid management (Tang, 2020). While traditionally focused on top-down administration, its structure of dividing communities into manageable units and

assigning personnel provides a potential organizational basis for localized service feedback collection, resource coordination within the community, and facilitating direct interaction between service providers and residents (Mittelstaedt, 2023; Wu et al., 2024). Adapting this concept, CBUAMS governance leverages a community-level organizational layer to ensure resident needs are effectively captured, feedback loops are established, and local resources or support can be mobilized. This empowers the community to transition from passive recipients to active participants in shaping their mobility service.

Building upon this foundation and resonating with Elinor Ostrom's concept of Polycentric Governance (Ostrom, 2010), which suggests that diverse, overlapping governing bodies at different scales can be more effective and adaptable than monolithic systems, CBUAMS proposes a tripartite "Government-Enterprise-Community" social governance framework. This model aims to clearly define the boundaries of rights and responsibilities for the three main entities to foster synergy, leverage their respective comparative advantages, and address the critical engineering and management challenges inherent in deploying and operating such a complex system. Table 3 summarizes the core roles and responsibilities for each party.

#### 4.3.1 Inspiration from grid management and governance transformation

The community grid management model (Tang, 2020) divides communities into grids and coordinates government bodies (sub-district/neighborhood committees), residents (owners' committees), and grid officers, offering valuable insights into refined management and resource coordination (Mittelstaedt, 2023; Wu et al., 2024). However, CBUAMS requires shifting from traditional top-down "management" toward modern "governance," emphasizing multi-stakeholder collaboration, feedback, and consultation. Adapting the grid structure, the focus should be on leveraging it to effectively gather resident needs, establish feedback loops, and coordinate internal

community resources. This transforms the community from passive recipients into active participants, laying the groundwork for the proposed tripartite (government-enterprise-community) governance framework.

Based on the above analysis, this study concludes that ideal localized governance should carry three key functions: **1) To become a standardized way for community residents to express specific and differentiated travel needs.** For example, the travel needs of elderly residents to specific destinations (e.g., hospitals, and markets) during non-peak hours, or parents' needs for school pick-up and drop-off services for their children, can be effectively collected and reflected through the grid system; **2) To build a routine, low-threshold feedback mechanism for service quality and problem consultation:** regularly organize tripartite symposiums involving neighborhood committees, owners' committees, and enterprise representatives to fully discuss operational issues raised by residents, such as vehicle cleanliness, punctuality, driving smoothness, and even data privacy concerns; **3) To promote the effective coordination of internal community resources:** within the grid, jointly discuss the most suitable locations for shared charging piles or vehicle parking spots; organize volunteers through the grid to provide simple vehicle usage guidance, report facility damage information, etc., to support the smooth operation of CBUAMS.

Integrating governance functions into the grid structure fundamentally transforms the role of the community and its members. They shift from passive recipients or objects of management to active participants, advisers, and supervisors who substantially influence their community's travel services. This model blends the localization adaptability and resilience of community-based approaches (like CBT) with the advantages of government-led models in ensuring basic equity and order. Using the grid's deliberation mechanism enables the community to collaboratively address practical issues (such as poor intersection visibility) with operators and relevant departments. This core shift from "management" to "governance" lays a crucial community foundation for

**Table 3** Roles and responsibilities of key stakeholders in CBUAMS

Responsible entity	Core rights and responsibilities	Key considerations/constraints	Reference
Government	Fair regulation Standard setting Strategic guidance Financial support Ultimate responsibility	Ensuring baseline equity Cross-domain coordination Avoiding over-intervention	Eras-Almeida & Egido-Aguilera (2019); Davis & Jha (2011); Wang et al. (2021); Boin & Hart (2003)
Enterprise	Technology provision Efficient operation Data management Service innovation	Social responsibility Data ethics Fair algorithms Service sustainability	Burch & Di Bella (2021); Zheng & Xu (2023); Mentsiev et al. (2023)
Community	Demand expression and definition Daily participation and supervision Culture building Preliminary mediation	Representativeness Capacity building Incentive mechanisms Avoiding "Not-In-My-Backyard" effects	Jeekel (2018); Ostrom (2010); Tang (2020)

the tripartite governance model with clearly defined responsibilities.

#### 4.3.2 Engineering and management aspects of tripartite governance

Implementing and sustaining CBUAMS requires addressing fundamental engineering management questions concerning resource allocation, operational control, risk management, and stakeholder coordination within the defined tripartite structure.

**Funding model (Who pays):** The financial sustainability of CBUAMS is critical, especially given the high initial investment in autonomous vehicles and potentially V2X infrastructure, and the need to ensure affordability (economic equity), which may lead to operational deficits in low-demand areas. A blended funding model is likely necessary. Government plays a crucial role by potentially providing initial capital subsidies for infrastructure deployment (e.g., V2X RSUs on public poles, charging stations), offering operational subsidies to cover losses in serving less profitable community zones or providing discounted fares to vulnerable groups, or leveraging public-private partnership (PPP) frameworks where the government contributes assets or policy support while the enterprise provides technology and manages operations (Li and Akintoye, 2003). Enterprises are responsible for the direct investment in the vehicle fleet and technology development, seeking operational efficiencies to minimize costs. The community might contribute indirectly through local infrastructure provision (e.g., designated parking areas within residential compounds) or potential local taxation/fees, though direct financial contribution should be minimized to ensure economic equity.

**Operational responsibility (Who runs it):** The enterprise is the primary entity responsible for the day-to-day technical operation of the CBUAMS fleet, including vehicle dispatch, maintenance, charging, platform management, and ensuring compliance with safety standards (Hosford et al., 2024). However, this operation occurs under the regulatory oversight of the government (monitoring safety, service quality KPIs) and the direct feedback and supervision of the community (Li and Akintoye, 2003). The community governance body acts as a crucial interface, collecting resident feedback on service performance, cleanliness, punctuality, and driverless interaction (if applicable), and channeling this feedback to the enterprise and government for resolution.

**Liability and risk management (Who takes responsibility):** This is a significant engineering and legal challenge for autonomous systems. A clear and comprehensive liability framework must be established, potentially through government legislation or detailed contractual agreements within a PPP (Li and Akintoye, 2003). This framework must define the responsibilities of the technology provider (enterprise) for system failures, the operator

(enterprise) for operational errors, the infrastructure owner (government/community) for infrastructure-related issues affecting safety (e.g., faulty V2X units), and even the user in cases of misuse. Mechanisms like mandatory insurance coverage specifically tailored for autonomous shared mobility are essential. The tripartite model facilitates risk identification (community feedback on hazardous spots, enterprise reporting technical issues) and mitigation coordination (government enacting regulations, enterprise updating software, community requesting infrastructure fixes).

**Incentive mechanisms (Why participate):** The government is incentivized by tangible improvements in urban mobility, leading to reduced congestion and associated economic losses, lower emissions contributing to environmental targets, and significantly enhanced social equity, particularly for underserved communities, which translates into higher public satisfaction and improved governance legitimacy. It can incentivize enterprises through subsidies, favorable operating licenses, or data-sharing agreements that are tied to achieving these societal benefits. The enterprise is incentivized by both direct economic returns, such as operational revenues and performance-based subsidies (balanced with clear equity mandates), and significant strategic benefits, including gaining a first-mover advantage in the burgeoning community autonomous mobility market, accumulating invaluable operational data and technological expertise, and enhancing its corporate social responsibility (CSR) profile and brand reputation. It can be incentivized to serve less profitable areas through targeted subsidies or cross-subsidization models that still ensure overall business viability. The community is incentivized by direct and substantial improvements to their daily lives through access to convenient, affordable, and reliable mobility, which can significantly reduce travel burdens and expand access to essential services (e.g., healthcare, education and employment), and enhance overall quality of life. Active participation in governance, leading to services that genuinely reflect local needs (e.g., tailored stop locations, service hours responsive to community activities), fosters a strong sense of ownership and empowerment, making CBUAMS a truly community-centric asset. Utilizing the community grid structure can help organize and channel this participation effectively, ensuring that community benefits are maximized and sustained (Wu et al., 2024).

#### 4.4 Summary

This section systematically explains how CBUAMS enhances spatial equity in urban transportation by overcoming the inherent spatial inequity of the traditional “transportation corridor” model. CBUAMS proposes a more systematic and fundamental solution. Its core lies in constructing an empowerment framework integrating

space, technology, and governance:

1) **Spatial restructuring.** Advocating for the “community as the smallest equity unit,” this section detailed the “Three-Ring Model” (Core, Coordination, External Rings). This model complements and optimizes the traditional centralized corridor approach by building a distributed, multi-level community travel network. It shifts the service focus spatially to the community, prioritizing high-frequency short-distance travel needs. Crucially, compared to relying solely on corridor models, this restructuring enhances spatial equity by providing granular local access and service consistency within communities. Furthermore, it improves overall system efficiency not only by optimizing local resource use and reducing corridor congestion from short trips, but also by streamlining multi-modal integration through effective FMLM connections to existing public transportation networks. This strategic integration transforms CBUAMS into a vital component that enhances the functionality and reach of the entire urban transportation ecosystem.

2) **Technological innovation.** The section emphasizes the principle of “equity-oriented” technology design. Specifically, we propose C-ADC, a more suitable standard for community scenarios. It also advocates for low-cost, inclusive V2X communication strategies. These strategies include tiered deployment, flexible technology selection, and infrastructure reuse. The aim is to ensure that technological progress benefits a broader range of communities and people. This strategy helps avoid exacerbating inequity caused by the digital divide and provides key technological support for realizing spatial equity.

3) **Community governance.** The section analyzes the limitations of single governance models. Drawing on grid management experience, it proposes a tripartite governance framework: “government, enterprises, and communities.” The framework is based on Ostrom’s (2020) polycentric governance theory. It clarifies the boundaries of rights, responsibilities, and collaborative mechanisms among entities. It emphasizes the community’s core role in demand expression, local supervision, and culture building. This governance innovation seeks to balance efficiency and equity. It ensures that spatial restructuring and technological innovation operate sustainably. This means responding to real community needs and balancing all parties’ interests. Ultimately, it provides institutional guarantees for the system’s resilience and adaptability.

In summary, CBUAMS is not merely a new transportation technology or service model but a comprehensive solution promoting spatial equity in transportation. Through spatial reconstruction, cautious technological innovation, and collaborative governance, these three aspects support each other and are all essential. Together, they strive to make CBUAMS an efficient, intelligent, and community-oriented mobility system that effectively promotes the fair distribution of transportation resources and enhances the travel well-being of all residents,

especially vulnerable groups. This lays a solid theoretical and practical foundation for achieving a more equitable, inclusive, and resilient urban transportation future.

## 5 Key technological components and challenges

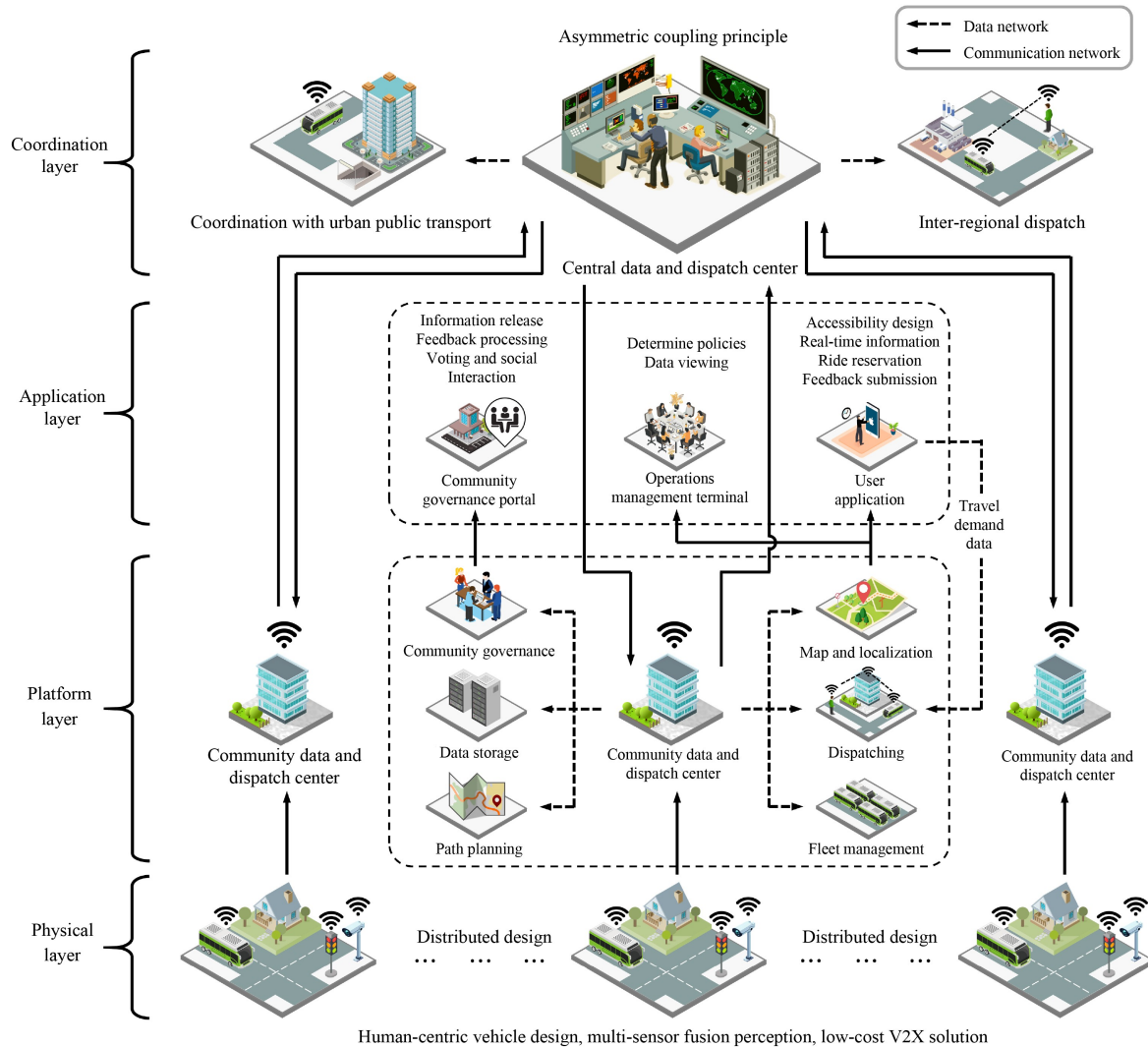
The previous section elaborated on the conceptual framework of CBUAMS and its potential for enhancing community mobility equity, inclusion, and resilience. This section shifts focus from ‘what’ to ‘how’, delving into the core technical challenges. Fig. 4 presents the overall system architecture of CBUAMS, depicting a layered socio-technical system comprising Coordination, Application, Platform, and Physical Layers. Understanding this architecture provides the foundation for analyzing the operational mechanisms and technological requirements. This section delves into the core technical components and challenges, focusing on three key areas corresponding to crucial layers: first, the physical layer’s environmental perception and human-centric interaction capabilities (including autonomous vehicles and smart infrastructure); second, the platform layer’s core services supporting efficient and equitable operations (e.g., data management, path planning, and intelligent dispatching); and third, the application layer’s accessible application and interaction design for all users.

As shown in Fig. 4, we focus on analyzing three key technological areas: first, the environmental perception and human-centric interaction capabilities of vehicles at the Physical Layer; second, the core platform service technologies at the Platform Layer that support efficient and equitable operations (such as data management, path planning, and intelligent dispatching); and third, the accessible application and interaction design for all users at the Application Layer. For each area, we will identify key technological elements and the main obstacles faced during their implementation, exploring the critical steps from concept to execution.

### 5.1 Physical environment perception and interaction

The successful operation of CBUAMS fundamentally depends on its core physical components: a fleet of autonomous vehicles capable of reliable environmental perception and intelligent interaction, supported by essential community smart infrastructure (Ignatious and Khan, 2022). Compared to highways or arterial roads, community environments present unique challenges (Liu et al., 2023; Peters et al., 2022; Schwarz et al., 2024; Sharifi, 2019). These include:

- **Complex and constrained geometry:** Narrow roads, frequent curves, lack of clear lane markings, and numerous physical obstructions (buildings, fences, parked cars, vegetation) create severe line-of-sight blockages and



**Fig. 4** CBUAMS System architecture.

dynamic blind spots, particularly at intersections and pedestrian crossings. This directly impacts sensor perception range and effectiveness.

- **High density of diverse and unpredictable agents:** Communities host a high density of vulnerable road users (VRUs), including pedestrians, cyclists, children, elderly individuals, and pets, who often exhibit random, unpredictable, and non-rule-following behaviors (e.g., jaywalking, sudden changes in direction, cycling on sidewalks). Accurately detecting, tracking, and predicting the intent of these agents is critical and technically challenging.

- **Intensive mixed traffic interaction:** Vehicles, non-motorized vehicles, and pedestrians frequently occupy and share the same physical space, requiring sophisticated interaction, negotiation, and yielding behaviors from the autonomous vehicle, rather than simple rule-based driving.

- **Non-standardized/degraded infrastructure:** Traffic signs and road markings may be inconsistent, damaged,

or absent, complicating perception and navigation relying on such features.

- **Low-speed, High-interaction scenarios:** While speeds are low, the frequency and complexity of interactions per unit distance are high, demanding fine-grained, low-latency perception and responsive control.

Consequently, CBUAMS's physical layer requires highly adaptive and robust technologies. The challenge lies in balancing absolute safety with avoiding excessive conservatism that leads to low traffic efficiency.

### 5.1.1 Autonomous driving technology adapted for community environments

On the hardware side, CBUAMS vehicles possess precise spatio-temporal modeling and understanding capabilities for the community environment. This necessitates deploying advanced multi-modal fusion perception systems (e.g., high-resolution LiDAR, wide-angle

cameras, millimeter-wave radar, and ultrasonic sensors). Fusing data from these diverse sensors enhances the system's robustness to individual sensor limitations and environmental variability, improving the fine-grained recognition and intent prediction of common objects within communities (Ignatiou and Khan, 2022).

For localization and mapping, achieving centimeter-level accuracy is required for safe operation in tight community spaces (Durrant-Whyte and Bailey, 2006; Ignatiou and Khan, 2022). This relies on fusing data from global navigation satellite systems (potentially with real-time kinematic corrections), inertial measurement unit, and especially perception-based methods like visual odometry (VO) and LiDAR simultaneous localization and mapping (SLAM). Given the dynamic nature of community environments, vehicles must support real-time local mapping and dynamic object tracking, integrating with or providing updates to high-definition (HD) community maps. The challenge lies in balancing the high costs associated with high-performance sensor suites, compute platforms, and HD map maintenance with service affordability. Furthermore, achieving good scene generalization is a major technical hurdle, enabling the system to operate reliably across communities with diverse layouts and characteristics.

Behavior prediction and decision-making algorithms should be tailored for low-speed, high-interaction community scenarios. This involves sophisticated VRU behavior prediction that considers potential deviations from traffic norms, robust multi-agent interaction planning that can perform yielding, negotiation, and smooth maneuvers (like slow passing in narrow sections), and control algorithms designed for passenger comfort during frequent acceleration/deceleration and steering, paying special attention to users with mobility impairments. Balancing absolute safety with practical efficiency is a key optimization challenge.

### 5.1.2 Community smart infrastructure and V2X collaboration

Considering the inherent limitations of vehicle-only perception, particularly concerning blind spots and predicting the behavior of obscured agents, deploying community smart infrastructure and leveraging V2X communication is crucial (Gyawali et al., 2020; Huang et al., 2023). RSUs equipped with sensors (cameras, radar, LiDAR) can be strategically deployed at critical nodes like blind intersections, sharp corners, pedestrian crossings near schools or community centers, and areas with high VRU activity. These RSUs can detect objects or events beyond the vehicle's line of sight and transmit this information (via V2I) to approaching CBUAMS vehicles, enabling early warnings or informing cooperative maneuvers. Vehicle-to-Pedestrian (V2P) and Vehicle-to-

Cloud (V2C) communication can also facilitate warnings for vulnerable users (e.g., alerts on their mobile devices) or transmit information about vehicle status and intentions.

However, implementing V2X in community settings faces challenges beyond traditional road networks. Key technical requirements include low latency for safety-critical messages (e.g., collision warnings requiring < 100ms end-to-end latency) and high reliability (> 99.9% message delivery). Network challenges in communities include signal attenuation and multipath effects caused by dense buildings, interference from numerous Wi-Fi and Bluetooth devices, and ensuring continuous coverage despite physical obstructions. Technical solutions involve utilizing the PC5 direct communication mode of C-V2X for low-latency V2V/V2I (Miao et al., 2021), leveraging edge computing located within or near the community to process V2X data locally and reduce backhaul latency, potentially utilizing network slicing (in 5G/6G networks) to prioritize V2X traffic, and conducting detailed wireless propagation analysis during deployment to optimize RSU placement and density.

Crucially, to ensure equitable deployment and avoid concentrating V2X benefits solely in privileged areas, CBUAMS relies on the low-cost, inclusive V2X implementation strategies discussed in Section 4.2.2. This means prioritizing layered deployment (deploying basic, low-cost V2X widely first), adopting flexible technology selection (considering cost-effective wireless options where feasible), and critically, maximizing infrastructure reuse (Tsigidinos et al., 2025). Mounting RSUs, sensors, and antennas on existing streetlights, traffic poles, and building facades, and leveraging existing power and potentially network connections, significantly reduces the civil engineering and cabling costs—often the most expensive part of V2X deployment. This engineering strategy is vital for making community-level V2X economically feasible for a broader range of communities, ensuring that the safety and efficiency benefits of collaborative autonomy are not exclusive. Interoperability between potentially diverse equipment vendors and maintaining these distributed infrastructure elements are ongoing challenges.

### 5.2 Core platform services

CBUAMS's core operation relies not only on the physical layer's vehicle autonomy and infrastructure but also on a powerful platform layer for intelligent resource scheduling, service management, and data handling. This layer is the central nervous system, connecting users, vehicles, and the community governance structure. It is responsible for receiving user requests, optimizing fleet operations, performing order matching, route planning, managing vast amounts of operational and spatial data, and support-

ing community-level oversight. The goal is to meet diverse community mobility needs efficiently while achieving high efficiency, fairness, and sustainability (Feng et al., 2021; Ge et al., 2023; Asudeh et al., 2023).

### 5.2.1 Vehicle dispatching and optimization

Efficient vehicle dispatching and optimization are paramount for realizing CBUAMS's "Ultra-Flex Service" and ensuring operational efficiency. Community travel patterns, characterized by short distances, high frequency, and dynamic, often uneven spatio-temporal distribution, pose complex scheduling challenges. The dispatch system must handle a diverse stream of requests, including pre-bookings, immediate on-demand hails, and requests for accessible vehicles, while optimizing multiple, often conflicting objectives. These objectives include minimizing passenger waiting times, minimizing empty vehicle miles, maximizing fleet utilization, ensuring equitable service distribution across all community zones, and prioritizing requests based on user needs or urgency (Asudeh et al., 2023).

The platform requires sophisticated algorithms capable of real-time, dynamic dispatching. This relies on accurate short-term demand prediction for different vehicle types and request origins/destinations within fine-grained community grids (Chow et al., 2024; Wang et al., 2023). Prediction models can leverage historical data, real-time traffic/event information, and contextual factors using techniques like time series analysis, machine learning, and spatial statistical models.

The core dispatch logic solves a complex dynamic ride-pooling or vehicle routing problem with time windows and capacity constraints. Algorithms from operations research (e.g., mixed-integer programming, constraint programming) and machine learning (e.g., deep reinforcement learning) perform real-time matching of requests to vehicles and optimize routes considering current vehicle status, network conditions, and future predicted demand (Chen et al., 2021; Lee et al., 2024).

**Embedding equity in dispatch:** Achieving equity is not secondary but a core optimization objective. The dispatch algorithm must explicitly incorporate fairness considerations. This can be done by:

- Including penalties in the objective function for metrics related to inequity, such as the standard deviation of waiting times across different community zones, or prolonged service gaps in less dense areas.
- Setting hard constraints to ensure a minimum level of service or maximum waiting time in all designated service areas, even during low-demand periods.
- Implementing a priority system that gives precedence to requests from vulnerable users (e.g., requiring wheelchair access), medical appointment trips, or pre-booked essential travel, ensuring these needs are met reliably (Arias-Molinares and García-Palomares, 2020;

Hensher et al., 2020).

**Seamless multi-modal connection:** Seamless Multi-modal Connection: The CBUAMS platform is designed to facilitate seamless connections with other transportation modes. This is achieved by optimizing vehicle arrival and departure times for FMLM segments connecting to stations and hubs of existing public transportation systems (e.g., metro, bus, and rail), allowing users to plan complete journeys and minimize transfer waits (Yang et al., 2024). Ideally, the platform would leverage real-time data feeds from these public transportation services (e.g., live arrival and departure information, and service disruptions) to dynamically adjust CBUAMS shuttle schedules, providing users with highly coordinated and reliable intermodal transfers. This capability is crucial for enhancing the attractiveness of integrated multi-modal trips.

**Robustness and "anti-pressure" handling:** Community demand can be volatile, with significant surges during peak hours (morning/evening commute), adverse weather, or special community events. The dispatch system must be robust and resilient to these demand fluctuations, possessing "anti-pressure" capabilities. Key mechanisms include:

- Using demand forecasts to proactively reposition idle vehicles to anticipated high-demand zones before peaks occur (Lee et al., 2024).
- Activating the Coordination Ring's resource sharing mechanism, allowing the platform to dynamically borrow vehicles from less busy Core Rings or a shared reserve pool to bolster service in congested areas.
- Implementing a system where, during extreme peak load, the platform adjusts service parameters or prioritizes urgent/pre-booked trips, while communicating these temporary changes to users.
- Maximizing the efficiency of each vehicle by dynamically grouping multiple passengers with compatible routes, significantly increasing throughput per vehicle during busy periods.

These capabilities require advanced algorithms and robust computational infrastructure capable of handling high volumes of real-time data and complex optimization calculations under strict time constraints.

### 5.2.2 Data anonymization and community governance

CBUAMS operations will generate large amounts of sensitive data concerning user behavior and community dynamics. This imposes strict requirements for data security, privacy protection, and community governance (Murthy et al., 2019; Zhuang et al., 2018). The platform employs reliable data anonymization techniques like differential privacy and k-anonymity to protect individual privacy. This analysis supports service optimization, demand forecasting, and urban planning (Murthy et al., 2019). Furthermore, adopting a distributed data storage

architecture can significantly enhance security. Decentralized storage reduces the risk of single points of failure and large-scale breaches (Zhuang et al., 2018).

The CBUAMS platform design integrates community governance principles as a community-based system. This means the platform needs to provide transparent operational information (while protecting privacy) and establish effective community feedback mechanisms. Clear data access protocols ensure that enterprises require explicit community authorization before accessing or using aggregated community-level data. Balancing the strength of privacy protection with data usability remains a significant task for researchers and engineers (Bhumi-ratana and Bishop, 2009). Challenges include designing secure and reliable data storage and access control mechanisms to prevent leaks or misuse. Another challenge is building easy-to-understand and participatory digital governance tools to foster trust and cooperation between the platform operator and the community.

### 5.3 Application and interaction interfaces

The ultimate value of CBUAMS is realized through user interface and interaction design, which must be convenient, reliable, and dignified for all community residents, especially vulnerable groups. Achieving high user acceptance and satisfaction directly impacts the system's social benefit. Universal accessibility is not merely a compliance requirement but a fundamental design principle (Friedman and Bryen, 2007; Henry, 2007; Tyler, 2002). Design requires optimizations for the diverse needs of target users:

- **Simplified Workflow:** Streamlined interfaces and booking processes with minimal steps and clear visual/audio cues to reduce cognitive load, particularly for users less familiar with digital technology.
- **Multi-modal Interaction:** Full support for voice commands and voice output for users with visual impairments or mobility issues that make typing difficult. Inclusion of large fonts, high-contrast color schemes, and adjustable text spacing. Providing trip information (e.g., vehicle location, ETA, and route guidance) through multiple channels simultaneously (e.g., visual map, audio announcements, and haptic feedback like vibrations).
- **Personalized profiles and needs:** Allowing users to easily create profiles and preset specific mobility needs or preferences, such as requiring a wheelchair accessible vehicle, needing assistance with boarding/alighting, or preferred pickup/drop-off locations within allowed zones. This information must be clearly communicated to the dispatch system and potentially to any human support staff (Tyler, 2002).
- **Non-smartphone access:** Recognizing that not all residents, particularly among the elderly or low-income, may own or be proficient with smartphones, alternative access methods are crucial for ensuring economic and

digital equity. This could include dedicated phone-based booking services, community kiosks or service points where residents can book trips with assistance from staff, or providing simple, dedicated hardware tokens for booking and identification.

Building user trust in autonomous vehicles, especially for less tech-savvy users, is paramount. The application interface should provide clear, real-time status updates, easily accessible information about safety protocols, estimated time of arrival, and simple ways to contact remote assistance or emergency services if needed.

Key technical and design challenges include: developing interfaces that are adaptable to a wide spectrum of accessibility needs and digital literacy levels; ensuring application compatibility and stability across various devices and operating systems; designing effective, multi-channel user support and guidance systems to lower the learning curve; and creating interaction patterns that build confidence and comfort with autonomous technology.

Beyond its standalone application, CBUAMS is conceptualized with the inherent capability for integration into broader MaaS ecosystems. This would enable users to plan, book, and pay for multi-modal journeys that seamlessly integrate CBUAMS with other public and private transportation options (e.g., metro, bus, bike-sharing, and ride-hailing) through a single, unified interface. Such MaaS integration would significantly enhance user convenience and further promote CBUAMS as a key enabler of a truly connected and equitable urban mobility landscape.

## 6 Discussion and conclusions

Urban transportation systems, often designed and optimized primarily for efficiency along high-demand corridors, exhibit significant structural spatial inequity. This leads to pervasive service gaps, particularly the first/last-mile problem, and inadequate mobility access in non-central areas, disproportionately affecting vulnerable populations. While existing solutions such as CBT, shared micromobility, ride-hailing, microtransit, and emerging ASB offer localized or partial remedies, they are individually constrained by limitations related to scale, cost, technological maturity, or, critically, profit-driven biases that prevent them from systematically addressing the root causes of inequity.

To overcome these limitations, this paper proposed and elaborated on the novel framework of CBUAMS, which is designed to advance urban transportation spatial equity by redefining the community as the fundamental unit for mobility planning and operation. It is built upon three interconnected pillars: community-based operations leveraging local resources and governance; ultra-flex service ensuring high responsiveness, broad coverage, and multi-modal integration; and an autonomous mobility

system utilizing community-adapted autonomous vehicles, hybrid cloud-edge computing, and low-cost community-level V2X.

Our analysis demonstrates CBUAMS's significant potential to enhance transportation equity through a synergistic, multi-dimensional strategy. This strategy encompasses: (1) Spatial restructuring via the "Three-Ring Model" (Core, Coordination, External Rings), which prioritizes community-level circulation and local resource access ("community as the smallest equity unit") while ensuring connection to the broader network; (2) Equity-oriented technological innovation, emphasizing that technology must serve social goals, exemplified by the proposed C-ADC, Levels C1-C3, tailored for diverse community contexts and costs, and low-cost, inclusive V2X communication strategies utilizing layered deployment, flexible tech selection, and infrastructure reuse; and (3) Polycentric community governance through a "Government-Enterprise-Community" tripartite model, which clarifies roles, responsibilities, and collaborative mechanisms (including funding, operation, liability, and incentives) to foster local responsiveness and balance diverse stakeholder interests.

The primary contribution of this paper lies in proposing CBUAMS as a system-level, integrated solution framework that explicitly places spatial equity at the heart of urban mobility design. Significantly, CBUAMS is designed to function not in isolation but as an integral and synergistic part of the existing multi-modal transportation ecosystem. By providing efficient community-based services and seamless FMLM connections to established public transportation corridors, CBUAMS enhances the overall accessibility, efficiency, and equity of the entire urban network. By tightly coupling spatial organization, context-aware technological innovation, and multi-stakeholder governance, CBUAMS moves beyond purely technical or market-driven approaches. It offers a theoretical lens and a practical blueprint for developing autonomous mobility solutions that are both efficient and intelligent and fundamentally fair, inclusive, and responsive to diverse community needs. The detailed conceptualization of the Three-Ring Model, C-ADC, equity-oriented V2X strategies, and the tripartite governance structure provides valuable tools for future research, planning, and policy formulation. Furthermore, by emphasizing community participation, CBUAMS envisions transforming residents into active co-creators of their local mobility ecosystem, potentially enhancing community resilience and local identity.

However, realizing the CBUAMS vision faces significant inherent challenges across multiple domains. Technical hurdles include achieving the required reliability and robustness of autonomous driving and V2X communication in complex, unstructured community environments with unpredictable agents, while managing the high costs associated with advanced hardware and ensuring

interoperability. Operational challenges involve developing sophisticated, real-time dispatch algorithms that balance competing efficiency and equity objectives, managing fleet maintenance and energy within communities, and handling volatile demand patterns. Social challenges encompass building user trust in autonomous technology, bridging the digital divide, ensuring usability for all, and addressing potential socio-economic impacts like changes in transportation employment. Governance and management challenges are particularly complex, requiring effective coordination and trust-building among government bodies, private enterprises, and diverse community stakeholders, establishing clear and sustainable financial models, robust liability frameworks for autonomous operations, practical data governance protocols that balance privacy and utility, and effective incentive mechanisms to ensure long-term commitment to equity goals.

Implementing a system as integrated and community-specific as CBUAMS will require a phased, iterative approach, beginning with carefully designed pilot projects. A potential implementation roadmap outlook involves the following:

Phase 1: Foundational validation (Focus: C1 and basic governance): Selecting pilot communities based on criteria like demonstrated mobility needs, favorable community structure, and willingness to participate. Deploying a small fleet of C1-level autonomous vehicles in highly controlled or simpler ODDs within the community (e.g., fixed low-speed routes), focusing on technical validation and establishing the fundamental community-based operational and feedback mechanisms.

Phase 2: Service expansion and system integration (Focus: C2 and platform/coordination): Expanding services to wider community areas and more complex scenarios (C2-level ODD), increasing fleet size, and implementing the Core Ring's on-demand dispatch and the Coordination Ring's resource sharing logic. Refining governance protocols based on lessons learned, including data-sharing agreements and initial joint decision-making processes. Developing and testing more inclusive application interfaces.

Phase 3: Full integration and optimization (Focus: C3 and External Ring/Sustainability): Integrating CBUAMS services with the external macro-transportation network (External Ring connection optimization). Piloting C3-level resilience features in specific challenging scenarios. The comprehensive tripartite governance framework fully operationalized, including detailed financial, liability, and incentive structures. Continuously monitoring, evaluating (using equity and efficiency metrics proposed in Section 3), and optimizing the system for long-term sustainability and scalability.

Throughout these phases, continuous interdisciplinary collaboration, transparent communication with residents, and adaptive management will be essential. While realizing

this vision faces significant hurdles, the potential rewards are substantial: transforming urban transportation from a source of inequity into an engine for equity, social inclusion, and enhanced community well-being. Embracing such holistic, equity-focused approaches is vital for shaping a more sustainable and just urban future.

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