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RESEARCH ARTICLE

Yiping YAN, Kai WANG, Xiaobo QU

Urban air mobility (UAM) and ground transportation integration: A survey

Abstract This study explores urban air mobility (UAM) as a strategy for mitigating escalating traffic congestion in major urban areas as a consequence of a static transportation supply versus dynamic demand growth. It offers an in-depth overview of UAM development, highlighting its present state and the challenges of integration with established urban transport systems. Key areas of focus include the technological advancements and obstacles in electric vertical take-off and landing (eVTOL) aircrafts, which are essential for UAM operation in urban environments. Furthermore, it explores the infrastructure requirements for UAM, including vertiport deployment and the creation of adept air traffic control (ATC) systems. These developments must be integrated into the urban landscape without exacerbating land-use challenges. This paper also examines the regulatory framework for UAM, including existing aviation regulations and the necessity for novel policies specifically designed for urban aerial transport. This study presents a comprehensive perspective for various stakeholders, from policymakers to urban planners, highlighting the need for a thorough understanding of UAM's potential and effective assimilation into urban mobility frameworks.

Keywords urban air mobility, integration, eVTOL, ground transportation, flying car

1 Introduction

Urbanization has accelerated globally, leading to a concentration of economic and social activities in urban areas. As shown in Fig. 1, a significant majority of the population in high-income areas, including Western Europe, the Americas, Australia, Japan, the UK, and the Middle East, comprises more than 80% of the population residing in urban areas. Similarly, in most upper-middle-income nations such as China and South Africa, the urban population exceeds 60%. However, India and South Asia have lagged behind, with only slightly more than 35% of their population living in urban settings. Urban centers provide a wide range of high-quality services, enhancing overall quality of life (Bloom et al., 2008; Ritchie and Roser, 2018). However, this concentration has also brought about challenges such as traffic congestion, environmental degradation, and overpopulation (Rijnders et al., 2001; Carlsten and Rider, 2017; Han et al., 2018). Transportation, a crucial aspect of urban areas, not only consumes land but also exacerbates traffic congestion, leading to significant economic and environmental consequences. According to the congestion report by INRIX (2022), cities such as Chicago, Boston, and New York rank among the highest in the US in terms of congestion effects. The economic effects of these traffic delays have surged, with nationwide congestion costs reaching $81 billion in 2022, a 53% increase from the previous year. However, this figure remains below the peak of $88 billion reached in 2019. These economic setbacks highlight the inherent inefficiencies of urban traffic systems.

According to the "2022 Annual China Urban Traffic Report" released by Baidu Maps (2023), Chongqing surpassed Beijing to become the most congested city in China in 2022. Table 1 reveals that during peak commuting hours, vehicles in Chongqing had an actual driving speed of 29.84 km/h, while in Beijing, it was 31.11 km/h. In terms of commuting time, both Beijing and Chongqing ranked at the top. The report showed that in 2022, Beijing was the only city with an average one-way commute time exceeding 40 min. Cities such as Chongqing, Tianjin, Guangzhou, and Chengdu all had average one-way commuting times of more than 36 min. Additionally, the

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Yiping YAN, Kai WANG, Xiaobo QU (✉)
School of Vehicle and Mobility, Tsinghua University, Beijing 100000, China
E-mail: xiaobo@tsinghua.edu.cn

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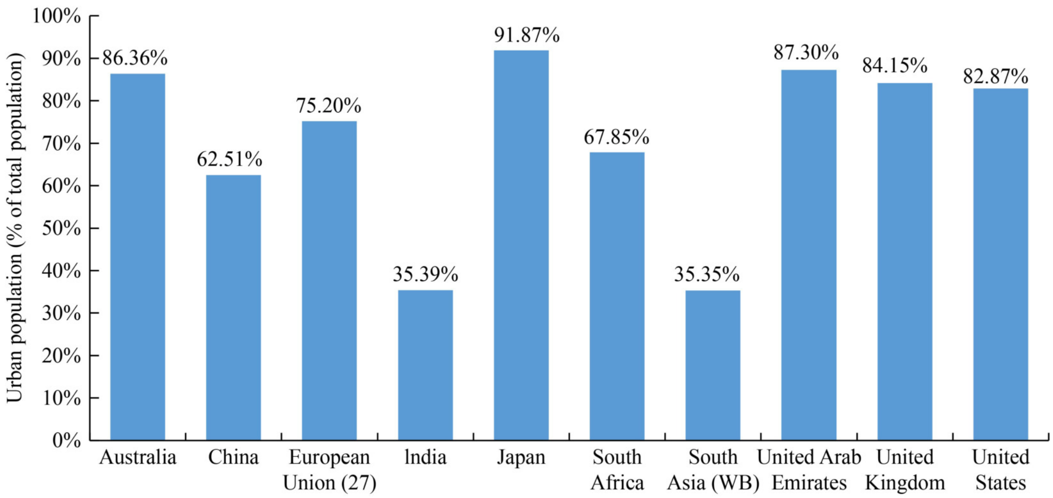

Fig. 1 Global urban population percentage in 2021 (source: UN Population Division (via World Bank)).

Table 1 Traffic congestion rankings of Chinese cities in 2022 (resource: Baidu Maps)

Traffic congestion ranking	City	Congestion index during commuting peak hours in 2022	The actual driving speed during peak hours in 2022 (km/h)	Average commuting time in 2022 (min)
1	Chongqing	1.790	29.84	37.83
2	Beijing	1.769	31.11	42.80
3	Shanghai	1.737	32.16	35.65
4	Hangzhou	1.730	30.33	35.54
5	Changchun	1.706	31.67	37
6	Nanjing	1.695	30.68	35.30
7	Guangzhou	1.677	34.02	36.89
8	Xi’an	1.654	30.60	35
9	Shenyang	1.648	29.16	37
10	Wuhan	1.641	30.16	35.27

report indicates that out of the 44 major Chinese cities surveyed, more than 14 million people endured extreme commutes, 13% of whom had commuted for more than 60 min. In Beijing, 30% of the population had commutes longer than 60 min, making it the city with the highest number of extreme commuters in the country, with a 3-percentage point increase year-on-year. Shanghai closely followed, with 18% of individuals facing commutes exceeding 60 min. Both Tianjin and Chongqing had rates of 17%.

Given these challenges, a compelling argument arises to explore the untapped potential of aerial space as a means to alleviate ground congestion and minimize the need for extensive road infrastructure. As urbanization continues to grow, road congestion in densely populated cities becomes a universal concern. The escalating environmental concerns and land use associated with intensive surface transportation further underline the importance of electric-based urban transport that takes advantage of vertical mobility.

Urban air mobility (UAM) is a promising solution in the context of urban transportation. Originating from early 20th-century visions of ‘flying cars’ and urban aerial transit, UAM has evolved into a sophisticated system that holds the potential for safe, sustainable, and affordable aerial transportation within urban areas (Cohen et al., 2021). By primarily utilizing electric vertical takeoff and landing (eVTOL) vehicles, UAMs represent advancements in electrification, automation, and vertical takeoff and landing (VTOL) technology (Straubinger et al., 2020). As a subset of the broader advanced air mobility (AAM) category, UAM offers numerous benefits, such as reducing urban congestion, decreasing carbon emissions through electric propulsion, and improving urban connectivity (National Aeronautics and Space Administration, 2021). However, the realization of UAM faces various challenges. Historically, helicopters were considered potential urban aerial vehicles but encountered obstacles such as noise pollution, high costs, and safety concerns. Additionally, the production dynamics of airplanes and ground vehicles differ significantly. Airplanes follow a low-volume, scheduled production system, while ground vehicles adhere to a high-volume, rule-based paradigm, affecting their cost structures and public accessibility.

Despite these challenges, technological advancements in battery and propulsion systems have paved the way for innovative VTOL aircraft designs. In conclusion, UAM combines historical precedents with modern innovations to provide a viable solution for redefining urban transportation.

2 Overview of the ground transportation system

In the domain of urban mobility, ground transportation systems have undergone significant evolutions driven by the need for efficiency, environmental sustainability, and user centricity.

Throughout its history, public transportation has played a crucial role in shaping the urban mobility landscape. From simple horse-drawn carriages to today's sophisticated metro systems, public transport has consistently aimed to offer efficient, affordable, and accessible travel options for urban dwellers (Ibrahim, 2003). Buses, trams, subways, and commuter trains form the foundation of public transportation and serve as vital components of urban mobility in cities worldwide. These systems not only provide access to essential services but also help alleviate congestion and reduce environmental harm. Designed for the streamlined transportation of large populations, public transportation systems typically operate on dedicated routes or tracks, minimizing interference from other vehicles. The role of these systems in reducing the number of individual vehicles on the road highlights their significance in tackling congestion and environmental issues.

Simultaneously, the transportation system, characterized by individual vehicles, offers unparalleled flexibility and convenience, allowing individuals to customize their trips according to their schedules. However, this freedom comes at a significant cost. Conventional vehicles, particularly those running on fossil fuels, contribute substantially to greenhouse gas emissions, impacting air quality and hastening global climate change (Carlsten and Rider, 2017). Many cities struggle with outdated or inadequate infrastructure, making it difficult to accommodate the growing number of vehicles and public transport users (Han et al., 2018). As the number of vehicles on the road increases, the risk of accidents also intensifies, and in areas lacking dedicated infrastructure for pedestrians and cyclists, these groups face significant safety challenges (Stoker et al., 2015).

In response to the challenges faced by public transportation, there have been significant innovations and advancements. The trend toward electric vehicles is gaining momentum, as these vehicles emit zero emissions at the tailpipe, greatly reducing the environmental effect of road transport (Becker and Axhausen, 2017; Hu et al., 2021). The emergence of electric buses, contactless payment systems, and real-time tracking technologies are examples of the progress made in modernizing public transport (Ongkittikul and Geerlings, 2006; Camacho et al., 2016; Bakker and Konings, 2018; Lusikka et al., 2020). Self-driving or autonomous vehicles (AVs) have the potential to revolutionize urban transport, improve safety, reduce congestion, and optimize traffic flow (Lin et al., 2023). With the advent of the Internet of Things (IoTs), cities are transitioning to intelligent transportation systems that utilize data analytics and real-time monitoring to manage traffic flow, alleviate congestion, and enhance overall transportation efficiency (Sumalee and Ho, 2018). Mobility as a Service (MaaS) integrates various transportation services into a single accessible platform, enabling users to easily plan and pay for multiple modes of transport (Smith and Hensher, 2020). In regions where urban sprawl covers vast distances, high-speed rail offers a solution for rapid intercity travel, reducing dependence on short-haul flights or long car trips.

While traditional transportation systems have undeniably brought numerous benefits, such as increased travel autonomy and improved accessibility, it is evident that they also pose a set of challenges. These challenges range from strained infrastructure to environmental concerns. Rapid urbanization and population growth have exacerbated issues such as overcrowding, especially during peak hours (Han et al., 2018). Moreover, environmental considerations, the maintenance of infrastructure, and the search for sustainable funding models add complexity to the urban mobility problem. Ensuring comprehensive accessibility, particularly for vulnerable groups such as elderly people and people with disabilities, continues to be an ongoing challenge.

This understanding has paved the way for the emergence of UAM. Recent scholarly literature suggests UAM as a promising solution to the limitations of terrestrial systems. By utilizing aerial routes, UAM has the potential to alleviate congestion, reduce travel times, and introduce a new dimension to urban mobility (Wang and Qu, 2023). In essence, the transformation of ground transportation, along with its inherent challenges, highlights the necessity for innovative solutions such as UAM in the urban mobility landscape.

3 Development of flying cars and the UAM system

The concept of urban air travel has long captured the human imagination, and its history has been characterized by relentless innovation and evolution. It originated at the intersection of aviation and automotive engineering, with the earliest conceptualizations being referred to as "flying cars" or "roadable aircraft"—vehicles designed to navigate both the skies and the roads. This idea traces back to 1841 with pioneers such as William Samuel Henson and John Stringfellow, predating the momentous flight of the Wright brothers (Ballantyne and Pritchard, 1956). By 1917, the concept began to materialize beyond mere drawings when Glenn Hammond Curtis introduced the "Autoplane" at the All-American Air Show in New York (Lally, 2013). This aluminum-fueled device, equipped with fixed wings, marked the beginning of practical UAM. Throughout the 20th century, various iterations, such as Waldo Waterman's "Arrowbile" in 1937 and Robert Fulton's "Airphibian" in 1946, aimed to refine the technology and make it more accessible (Chana, 1996). However, in the late 20th and early 21st centuries, a paradigm shift occurred as conventional flying cars gave way to eVTOLs. Paul Moller's "M400" in 1991 heralded this era, emphasizing the potential for vertical takeoff and landing (Moller, 1998). In subsequent decades, advancements accelerated. Today, global companies, from AeroMobil in Slovakia to XPeng Heitech in China, are not only conceptualizing but also materializing these visions, paving the way for a new phase in the history of urban air travel. As the world seeks more sustainable and efficient transport solutions, eVTOLs are at the forefront of UAM.

eVTOL aircraft represent a transformative evolution in aviation technology, combining elements of drones and conventional airplanes. These advanced vehicles are characterized by their vertical takeoff and landing capabilities, electrified propulsion systems, and automated controls. eVTOLs are designed to revolutionize passenger transportation by serving as air taxis, emergency response vehicles, and leisure crafts while also offering increased capacity for freight transport compared to traditional drones. The rapid development of eVTOLs is driven by advancements in battery and motor technologies, largely fuelled by the automotive industry, as well as progress in drone autopilot systems and lightweight carbon fiber materials. Like helicopters in terms of their vertical takeoff and landing capabilities, eVTOLs differ significantly in terms of flight range and passenger capacity, providing the advantages of reduced noise, lower operating costs, and enhanced safety. The eVTOL sector is attracting a mix of startups and established companies. Startups such as Volocopter (Fig. 2), EHang (Fig. 3), and Joby Aviation (Fig. 4) are pushing boundaries in innovation, while aerospace giants such as Airbus (Fig. 5), Boeing, and Bell Helicopter Textron leverage their existing technologies and supply chains to establish a presence in this evolving mobility services market.

Airbus, in particular, leads the way with its Vahana and City Airbus projects, achieving significant milestones such as successful test flights of these models. Their strategy extends beyond manufacturing to include a broader range of eVTOL-related services. Collaborations with companies such as Voom for air taxi services and Audi for integrated air–land mobility solutions exemplify this comprehensive approach. For instance, their modular "Pop. Up Next" (Fig. 6) concept envisions a seamless transition between air and ground transport. These initiatives highlight the dynamic and rapidly evolving landscape of eVTOL development and promise to reshape urban mobility and air travel in the near future.

The development of eVTOL vehicles, which promise to be quieter, safer, and cheaper, has revived the concept of UAM, utilizing urban airspace for intracity passenger transport. The evolution of UAM has occurred over four distinct stages spanning the past 70 years. Each stage is characterized by its own technological advancements and traffic management characteristics: helicopters in the 1960s, tiltrotors in the 1980s, very light jets and personal air vehicles in the 2000s, and eVTOLs in the 2010s.

The first commercial helicopter airline, New York Airways, was established in 1953 and began transporting passengers to and from New York City's major airports. By 1956, their services expanded to include Manhattan. This innovative effort was soon replicated in Los Angeles, San Francisco, and Chicago, with these carriers primarily

Fig. 2 Volocopter 2X (image source: Wikipedia).

Fig. 3 Ehang 184 (image source: Wikipedia).

Fig. 4 Joby S4 (image source: Wikipedia).

Fig. 5 Airbus CityAirbus (image source: Wikipedia).

offering connections between major airports and nearby city centers. The industry experienced significant growth, with annual passenger numbers increasing from less than 155,000 in 1957 to more than 1.2 million by 1967 (Flight Transportation Laboratory of Massachusetts Institute of Technology 1970). However, the helicopter airline industry in the US faced substantial challenges in the 1960s and 1970s, resulting in the decline of several

Fig. 6 Audi Pop. Up Next (image source: Wikipedia).

companies (Vascik, 2020). Los Angeles Airways and Chicago Helicopter Airways experienced fatal accidents that negatively impacted passenger demand and led to their closures in 1970 and 1965, respectively. Despite steady growth without accidents, San Francisco and Oakland Helicopter Airlines declared bankruptcy in 1970 due to financial difficulties. New York Airways, the largest of these companies, faced fatal accidents and operational challenges, including the 1973 energy crisis and access issues to its main heliport, ultimately leading to its closure in 1979. Boston's Air General also ceased operation in 1969 due to low demand and weather-related service unreliability, despite having no fatal accidents. These events underscore the economic and safety challenges faced by the helicopter airline industry during this era.

The second stage began with the emergence of the civil tiltrotor (CTR) aircraft concept as a promising alternative to helicopters. CTRs offer advantages such as higher cruise speeds and longer ranges. Vertical takeoff and landing, reasonable speed, pressurization with passenger amenities, acceptable safety levels, high reliability, and competitive operating costs were the six essential requirements for the commercial viability of CTRs. In comparison to previous helicopter concepts, the vision of a CTR-based UAM system involved separate air traffic control (ATC) services for conventional flights and the use of 9-40 passenger aircraft (Vascik, 2020). The Small Aircraft Transportation System (SATS), developed by NASA between 2000 and 2005 (Holmes et al., 2004; Viken et al., 2006), aimed to revolutionize personal and business travel by providing on-demand, point-to-point service. This system envisioned the use of small aircraft, specifically 4 to 9 passenger propellers or jet aircrafts, operating across regional, reliever, and general aviation airports or heliports. The SATS concept was based on two new categories of aircraft: very light jets (Trani et al., 2006) and personal air vehicles (Moore, 2003). The fundamental premise of SATS was the optimal utilization of the extensive yet underutilized existing aviation infrastructure, which was already widely accepted for flight operations. SATS prioritized technological advancements to address various challenges identified through experiences with helicopter airlines and CTR aircraft. These challenges included efficient ATC, weather-resilient operations, and network logistics, all of which are critical factors for effectively scaling the system.

There is no clear temporal boundary in Stage Three; however, a significant indicator is the industry's investment in prototypes of eVTOL aircraft. Terms such as UAM, on-demand mobility, and eVTOL have become prevalent in the literature, particularly in the past five years. The first Elevate Summit in 2016 saw Uber's whitepaper redefine and envision urban air transport systems (Holden and Goel, 2016). NASA's "UAM maturity levels" model categorizes the development of UAM into six stages, each addressing specific challenges in vehicle technology, airspace system integration, and community acceptance. This model provides a roadmap for the systematic evolution of UAM in urban areas (Goodrich and Theodore, 2021). In parallel, transportation network companies such as Airbus, Uber, and Blade UAM, Inc., are pioneering aerial ride-sharing and charter services in cities such as São Paulo and New York that integrate new technologies and business models (Haynes and Alerigi, 2016; Uber, 2019). Despite facing challenges such as ATC limitations and community noise complaints, these operations are laying the groundwork for future UAM systems. Additionally, NASA's collaboration with the Federal Aviation Administration (FAA) and its vision of "On-Demand Mobility" have resulted in important research and roadmaps focusing on areas such as electric propulsion, airspace integration, and community acceptance (Federal Aviation Administration, 2018; National

Aeronautics and Space Administration, 2021). By the end of 2019, more than a dozen manufacturers were testing full-scale prototype VTOL or short takeoff and landing aircraft, indicating a move toward more advanced and potentially transformative UAM operations. As autonomous air transport becomes viable and scales up, traditional ATC and aviation rules will need to evolve to accommodate UAM. This phase faces new challenges, including the development of urban low-altitude airspace for UAM, the establishment of flight rules, the construction of infrastructure, and the development of communication and navigation systems.

These stages illustrate the evolving landscape of the UAM system, demonstrating the interplay of technological innovation, regulatory environments, and market dynamics.

4 The vision of the integrated mobility ecosystem

Urban transportation is undergoing a transformative shift, with the UAM paradigm emerging as a symbol of innovation and efficiency. At the core of this transformation was the development of a "flying car" and the integration of UAM with ground mobility. "Flying car" refers to transportation vehicles designed for low-altitude, three-dimensional intelligent transportation; these vehicles primarily include eVTOLs and amphibious cars.

Flying cars, which are a form of low-altitude intelligent transit, are anticipated to play a crucial role in the future of electrified aviation. This progression is a natural result of the electrification and smart advancement of land vehicles. Currently, there is a strong focus on mainstreaming eVTOLs for both cargo and passenger transport (German et al., 2018). In the past, attempts to integrate features of cars and planes resulted in complex designs with limited practicality (Chana, 1996). However, recent advancements in electric and intelligent automotive technologies have paved the way for innovative aircraft designs. The incorporation of smart technology has the potential to address scalability and safety concerns in aviation. Electrified VTOLs, featuring distributed propulsion, offer improved safety, reduced noise, and cost-effectiveness (German et al., 2018). They are poised to make aviation accessible akin to car travel. This trend in eVTOL research has attracted significant attention from both the aviation and automotive industries, as well as from technology startups (Porsche Consulting, 2018; Straubinger et al., 2020; National Aeronautics and Space Administration, 2021). Amphibious flying cars, which are an evolution of eVTOLs, represent a pinnacle in automotive innovation driven by three critical factors: 1) technical feasibility, supported by advances in electrification and intelligent systems enabling autonomous aerial navigation; 2) demand, highlighting the need to address urban congestion by expanding transportation options from land to air; and 3) convenience, emphasizing the ability of these cars to seamlessly transition between land and air (Rajashekara et al., 2016; Luo et al., 2021; Pan and Alouini, 2020).

Modern urban construction already operates in three dimensions, with people residing and working in skyscrapers. However, the existing transportation infrastructure functions in two primary dimensions (Booz Allen Hamilton, 2018). In 2016, Uber released a publication titled "Fast-Forwarding to a Future of On-Demand Urban Air Transportation," which highlights that just as skyscrapers optimize limited urban land, urban aerial transportation can utilize three-dimensional airspace to alleviate ground traffic congestion. The emergence of amphibious flying cars will usher in a transformative phase in human mobility. Cities will transition from their present two-dimensional transport systems to a unified framework that includes both land and air dimensions. This paradigm shift promises increased convenience and safety in travel. Urban and rural development will become more interconnected, optimizing resource utilization and significantly enhancing the overall quality of life for residents.

As illustrated in Table 2, observing a city from an aerial perspective reveals a dynamic world in perpetual motion, driven by the crucial element of mobility. This mobility, essential for the sustenance of urban life, enables the movement of both people and goods. At its core, the urban mobility network consists of robust public transport systems, such as subways, trains, and buses, which transport thousands of individuals daily along predetermined routes. In contrast, private transportation, including private cars and taxis, operates in a more flexible manner, with continuously evolving patterns. This complex interplay of movement becomes further complex with the involvement of trucks responsible for the delivery of goods, waste collection, and other logistical tasks. Moreover, people with softer modes of transportation, such as pedestrians and cyclists, navigate through complex webs, often utilizing shared bikes and scooters.

Table 2 Typical travel distance by mode (Source: Porsche Consulting, 2018)

Mobility mode	Scope	Typical distance by mode (km)
Walking	local	0.5–1.5
Micromobility (bike, e-scooter, etc.)	local	1.5–8
Motorcycle	local	3–15
Car	local	2–400
Bus	local/regional	3–800
Train	local/regional	8–800
eVTOL	local/regional	20–400
Helicopter	regional	20–80
Plane	regional/global	400–1200

Above this bustling terrestrial landscape, helicopters cater to specific emergency and transportation needs, while passenger drones offer more efficient utilization of existing resources by pooling trips and integrating comprehensive mobility platforms. For example, passenger drones, known for their swiftness and on-demand availability, provide an efficient solution for distances exceeding 20 km, particularly considering their minimal infrastructure requirements (Porsche Consulting, 2018). This transformative shift in urban mobility is poised to bring about significant changes. With the advancement of technologies such as autonomy and shared mobility systems, traditional cars will give way to AV and car-sharing platforms, while taxis will evolve into ride-hailing and ride-sharing services (Tafreshian et al., 2020; Mitropoulos et al., 2021; Liu et al., 2023a; Qu et al., 2023). Conventional bicycles will face competition from e-bikes and bike-sharing initiatives, and helicopters will soon share these skies with eVTOL aircraft. The notion of vertical mobility for all is transitioning from mere fantasy to tangible reality, with substantial progress being made on a global scale. Ground-based ride-hailing and ride-sharing services have already been used as innovative methods for more efficient transportation of goods and people (Agatz et al., 2012; Fagnant and Kockelman, 2018). Over the past decade, there have been successful deployments of air taxi applications worldwide. Notably, transportation network companies such as Uber have introduced on-demand UAM services in cities such as São Paulo and New York (Haynes and Alerigi, 2016). Additionally, various helicopter services, including Melbourne CBD Transfers (Microflite, 2020) in Australia, Hiratagakuen (2020) in Japan, Helitaxii (2020) in India, and Helicopter Me (2020) in New Zealand, provide shuttle operations connecting major cities with airports. A significant milestone in this field was reached when EHang's EH216-S, a two-seater autonomous aerial vehicle, obtained the world's first type certificate on October 13, 2023, from the Civil Aviation Administration of China. This certification verified that EH216-S meets safety and airworthiness standards, allowing it to be used commercially for passenger-carrying operations. The business model of these air taxi service companies focuses on providing end-to-end service by integrating both ground and air transportation. This typically involves ground transportation to a vertiport, an eVTOL flight, and a final ride-hailing service to the destination.

While the potential benefits of air taxi helicopter services are widely acknowledged, concerns regarding the sustainability of this business model persist. A primary concern is whether the total time savings offered by these services align with customer expectations for the entire journey (Shah, 2019). The difference between anticipated and actual time savings could significantly impact customer satisfaction and the long-term viability of the business model. Therefore, the success of UAM relies on its seamless integration with existing transportation systems, market size, and accessibility. Its feasibility depends on exploring various future scenarios. Extensive research in this area, as indicated by Nneji et al. (2017), Straubinger et al. (2021), and Vascik and Hansman (2017), has examined multiple application scenarios and business models. These studies cover different types of services (commute and non-commute), market players (private, personal, or commercial), and user groups and assess the suitability of UAM for on-demand services. Creating effective business models for UAM requires a comprehensive understanding of user needs, recognizing that factors driving adoption and usage vary significantly across different scenarios. This highlights the importance of tailoring strategies to each unique context.

The study was conducted by Crown Consulting, which was commissioned by NASA in 2018 (NASA, 2018) and aimed to assess the feasibility of three UAM use cases in 15 cities across the US. These use cases included last mile delivery (unscheduled, real-time delivery of packages from local hubs to a specific receiving vessel, routed immediately as online orders are placed), air metro (an autonomous public transit-style commuter system), and air taxi (an autonomous on-demand ridesharing system) services.

According to the study, almost half of the consumers surveyed expressed an openness to the concept of UAM and its potential applications. However, there were significant concerns raised regarding safety, privacy, job security, environmental effects, noise and visual pollution.

Specifically, in the context of last mile delivery, respondents expressed worries about the potential risks of vehicle malfunctions, package theft, and privacy breaches due to vehicle cameras. On the other hand, in UAM transport scenarios, the primary concerns were the safety of passengers and bystanders, as well as the high operational costs associated with these systems.

To alleviate these concerns and increase consumer confidence in UAM technologies, it is crucial to establish a proven safety record for these systems. Additionally, conducting demonstrations of these technologies in practice can help address any doubts and enhance public acceptance.

Another study conducted by Booz Allen Hamilton (2018), commissioned by NASA in 2018, focused on the UAM market in ten specific urban areas. The study's objective was to assess the market size and barriers, evaluate the feasibility of UAM applications such as airport shuttles, air taxis, and air ambulances, and analyze the societal and environmental effects of UAM. The methodology employed in this study included surveys, focus groups, and stakeholder interviews. The analysis outlined several uncertainties, including technology availability, ATC capabilities, infrastructure development, public acceptance, and legal frameworks. These uncertainties, combined with the emergence of autonomous cars and individual perceptions of travel time, greatly impact the demand for air taxis. It is recommended that future research focus on how emerging technology trends in the transportation sector will influence UAM markets, with an emphasis on environmental sustainability. Furthermore, expanding the scope of the study to include additional urban regions is crucial for accurately assessing market feasibility in different areas and gaining a more precise understanding of the potential scope and effect of UAM. Similarly, Roland Berger identifies three primary future uses for UAM: air taxis for direct on-demand travel, airport shuttles for prebooked scheduled flights, and intercity flights for short distances where regional airlines are not suitable (Baur et al., 2018). They anticipate a phased development timeline beginning with human-piloted, short-range (20–50 km) UAMs for intracity transportation and airport shuttles. From 2025 to 2030, advancements in eVTOL technology are expected to increase the range to 250 km and the passenger capacity to 3–5 persons. This period will witness the global expansion of urban air taxis, including suburban commuting. The final stage involved the introduction of automated passenger drones and small intercity airline services, fully integrating UAM into urban mobility. However, this approach will still be a premium option contingent on meeting several key success criteria.

The UAM business model, which has attracted interest from both academia and industry, was developed by Straubinger et al. (2021) and is based on the innovative passenger UAM models derived from the Osterwalder and Pigneur (2010). These three models, namely, the airport shuttle, company shuttle, and regional public transport shuttle, each offer unique approaches to the implementation of UAM.

Among these models, an airport shuttle operated by airlines leverages existing customer bases but comes with high initial costs and the requirement for seamless integration with airport infrastructure. On the other hand, the company shuttle service model focuses on the efficient transportation of personnel and goods and is executed through a joint venture targeting a consortium of private companies. This approach requires detailed coordination and strikes a balance between exclusive service and broader accessibility.

In contrast, the public transport model aims to connect rural and urban areas, presenting a socially inclusive option. However, challenges related to infrastructure investment and the need to balance operational costs with public service needs are faced. Despite their distinct implementation strategies, these models highlight the multifaceted potential of UAM, taking into account factors such as cost, accessibility, and societal implications.

Importantly, the work of Straubinger et al. underscores the significance of a structured and iterative process for developing UAM business models, which requires empirical data to refine these models over time. This approach provides a comprehensive framework for understanding the complexities of UAM operations and ensures that the models are aligned with specific customer segments, facilitating a more targeted and effective application of UAM services.

Clearly, the implementation of UAM systems requires a comprehensive approach that addresses technological innovation, regulatory frameworks, and societal acceptance. The key to this is the establishment of viable use cases such as air taxis for urban travel, airport shuttles for city-to-airport routes, and regional public transport that connects different areas. These scenarios demonstrate the practicality and benefits of UAM.

In addition, the development and integration of UAM systems must prioritize safety, airworthiness, and minimal environmental effects. It is equally important to address public concerns pertaining to safety, privacy, and ecological considerations to foster societal acceptance. Ultimately, the successful deployment of UAM relies not only on technological breakthroughs but also on its harmonious integration with existing transportation networks, thereby prioritizing accessibility and user convenience. This approach is essential for realizing the transformative potential of UAM for urban and regional mobility.

In conclusion, the concept of an integrated mobility ecosystem, in which aerial vehicles play a pivotal role, represents a promising future for urban transportation. This vision depicts a scenario where the sky seamlessly merges with urban roadways, driven by innovative solutions that enhance efficiency and create a congestion-free, sustainable urban environment (Qu et al., 2022a). Urban aerial mobility offers a unique advantage over traditional transportation systems by connecting various points without the need for extensive physical infrastructure. Unlike linear networks such as roads and rails, aerial mobility functions as a flexible and resilient nodal network, minimizing resource consumption (Wang et al., 2023). As this mode of transportation continues to evolve, its integration will significantly impact the transportation landscape, providing a nodal network that is unrestricted by physical infrastructure. This inherent flexibility contrasts with linear ground transportation networks, which are geographically limited, leave lasting marks on the environment and are susceptible to congestion.

However, UAM has a fair share of challenges. Prominent companies in the aviation sector have highlighted key technological aspects that are vital to the successful implementation of UAM. In its Elevate document (Holden and Goel, 2016), UBER emphasized the importance of batteries, vehicle design, performance, and ATC. Furthermore, considerations related to noise, emissions, efficiency, reliability, and safety were highlighted. Similarly, Airbus (2018) identified automation, communications, and ATC as crucial components for successful

UAM implementation. BOEING (2023) echoed these sentiments, placing significance on ATC, communications, AV, and vehicle performance.

In conclusion, there are three primary layers of challenges to consider. The first layer is the technological layer, which includes various aspects, such as battery technology and propulsion technology. Battery technology plays a pivotal role in directly influencing the range, efficiency, and sustainability of flying cars. Advancements in this field are crucial for ensuring adequate energy storage and optimizing the weight-to-power ratio, which are essential for ensuring the feasibility of UAM. On the other hand, propulsion technology is integral for achieving the necessary thrust and lift, enabling vertical takeoff and landing capabilities, and ensuring the safety and stability of flight.

The second layer of challenges lies in the infrastructural domain. Integrating flying cars into existing airspace requires the support of physical infrastructure and digital infrastructure. For instance, a comprehensive coordination system is needed to manage air traffic, mitigate risks, and address potential conflicts with conventional aircraft. Infrastructure development, including the establishment of vertiports and aerial routes, is crucial for supporting UAM operations and facilitating seamless transitions between aerial and terrestrial transportation modes.

The third critical dimension involves regulatory and policy considerations, taking into account societal and economic factors. The success of UAM relies on its perceived safety, reliability, and affordability. Formulating a robust regulatory framework that addresses concerns such as noise pollution, visual disturbances, and privacy is essential. Gaining community trust and support is integral to this process. Moreover, devising sustainable business models, attracting investments, and understanding the economic ramifications of UAM are vital for the long-term sustainability and growth of the sector.

The following sections provide more details about the challenges and developments related to these three layers.

5 Challenges and advancements in the technology layer

The conceptualization and design of flying cars present a multitude of challenges, more so than those encountered in the design of conventional automobiles or small aircraft. The inherent differences between the design requirements of terrestrial vehicles and aircraft make the integration of these two distinct sets of requirements a daunting task. This integration requires a seamless transition between modes of operation, ensuring smooth transitions from aerial to terrestrial modes and vice versa. Historically, many designs have struggled to strike a balance, often compromising one mode's capabilities for the other (Chana, 1996). Power technology plays a crucial role in determining the payload range of flying cars, thereby impacting their airworthiness and safety (Moller, 1998; Luo et al., 2021). The power system is of significant importance as the "heart" of a flying car. Two predominant energy systems are employed in the propulsion of flying cars: pure electric propulsion for lightweight models and hybrid electric propulsion for medium and heavy variants. Hybrid electric propulsion mainly utilizes engines powered by fuel cells, hydrogen ammonia internal combustion, and hydrogen ammonia. The crucial components of these new energy power systems include motors and batteries, which are undergoing technological advancements and product development driven by the growing demand in the electric vehicle sector. However, the limited power density of these energy systems often leads to constraints in payload capacity and range for flying cars, thereby posing challenges in meeting practical requirements. Additionally, electrical safety, thermal safety, low-altitude weather conditions, and land–air operational conditions further complicate the development of functional flying cars. Consequently, technological advancements in battery technology, autonomous flight mechanisms, detect-and-avoid systems (such as LiDAR and camera vision), electric propulsion, and GPS-independent technologies are crucial for the realization of functional flying cars (Straubinger et al., 2020). UAM vehicles, based on their propulsion mechanisms, can be broadly categorized into two types. First, hybrid vehicles, which are designed for intercity travel, combine traditional fuel systems with electric propulsion. This fusion enables extended ranges and typically higher velocities, with the ability to alternate or merge the two energy sources based on operational demands. Although hybrid power designs are complex and expensive, they offer adaptability, making them a commercially viable option for flying cars. Second, pure electric vehicles, which are suitable for intracity journeys, rely exclusively on electric power. These vehicles are known for their quiet operation, zero emissions, and futuristic design, making them promising options for short-distance urban aerial commutation (Kasliwal et al., 2019). While current battery limitations have limited the focus to intracity or urban travel, expansion to regional and intercity missions is anticipated in the future. As emphasized in a report by Lascara et al. (2018), technological advancements are crucial in the UAM landscape.

Recent advancements in propulsion systems and battery technology have sparked the development of numerous designs and prototypes for personal air transport (Warren et al., 2019). The introduction of electric propulsion in aircrafts opens up new possibilities for distributed electric propulsion. Unlike combustion engines, electric motors maintain consistent efficiency and power density regardless of scale. This enables the use of many small electric motors instead of a few large combustion-based propulsion units, resulting in reduced drag (Sripad and

Viswanathan, 2021). Additionally, electric motors are two to three times more efficient than combustion engines are, leading to higher overall efficiency for electric aircraft. Furthermore, advancements in the specific energy and power of Li-ion batteries have paved the way for eVTOL aircraft designs (Yang et al., 2021). The eVTOL aircraft can be categorized into three main types: multirotor, lift plus cruise, and vectored thrust. Multirotors resemble helicopters but have multiple rotors and lack a fixed wing. Lift plus cruise aircraft use separate rotors for vertical and horizontal flight and typically have a fixed wing. Vectored thrust aircraft utilize a thrust system that adjusts the thrust direction for both vertical and forward flight (SMG Consulting, 2023). The vectored thrust aircrafts can be further divided into tilt rotor, tilt wing, and tilt duct designs. The eVTOL power consumption model outlines the design parameters for various aircraft. The five distinct models in the eVTOL aircraft design space exemplify its diversity (Sripad and Viswanathan, 2021).

One of the models is the "KH Heaviside" by Kitty Hawk Corporation, which is a tilt rotor design tailored for a single passenger. It has a range of 100 miles, a maximum takeoff mass (MTOM) of 395 kg, and an energy consumption below 13 kWh. Another tilt rotor variant, the "Joby 5-seater" by Joby Aviation, can accommodate five passengers, cover 150 miles, and has an MTOM of 2, 180 kg, with energy consumption less than 150 kWh. The Lilium Jet by Lilium GmbH is designed with a tilt duct and can carry seven passengers, traveling 172 miles (150 nautical miles) with an MTOM of 3,175 kg and a battery-specific energy of 330 Wh/kg. Beta Technologies presented the "Beta Alia-250," a lift plus cruise model designed for six passengers, covering 288 miles (250 nautical miles) with an MTOM of 2,730 kg. Finally, the "Archer Maker" by Archer Aviation is a fusion of lift plus cruise and tilt rotor designs built for two passengers, with a range of 60 miles, an MTOM of 1,508 kg, and a 75 kWh battery pack. These designs vary significantly in terms of cruising distance, MTOM, payload capacity, and energy consumption rates.

Batteries, which are crucial for the operation of urban flying cars, have specific requirements in terms of energy density, recharge time, cycle lifespan, and cost (Yang et al., 2021; Bills et al., 2023). An eVTOL trip typically consists of five phases: takeoff, hover, climb, cruise, descent, and landing hover (Figure 7). It is important to note that takeoff and landing hovers consume the most power, determining the battery's peak discharge rate, while the cruise power determines its continuous discharge rate (Luo et al., 2021). The battery performance of flying cars exhibits distinct characteristics during different flight segments. During the vertical climb, the battery reaches its peak power output, which is 1.11 times greater than the power during hovering due to the ducted fan propulsion system counteracting gravity. Conversely, during forward flight, the battery's power output decreases to only 0.21 times the hovering power. This decrease is attributed to the increase in aerodynamic lift as the vehicle velocity increases. The power trend during deceleration is unique, initially dropping and then increasing due to the interaction between the inertial force and air resistance. In the descent segment, the power output mirrors that of takeoff but is slightly reduced, influenced by the direction of air resistance and fan airspeed. The discharge rate of a battery is affected by its output power and internal resistance, with higher internal resistance leading to a higher discharge rate as the state of charge decreases. In terms of current advancements in battery technology, there are several notable battery

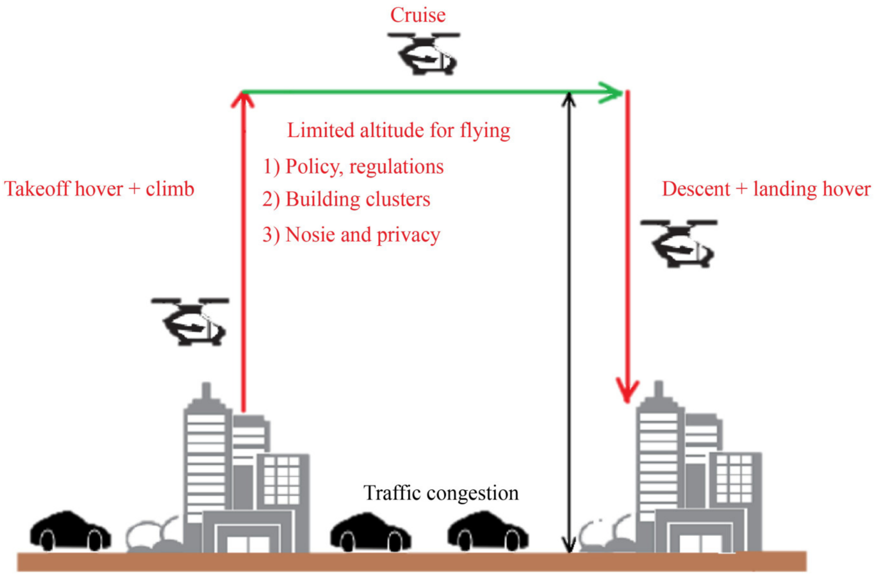

Fig. 7 Operation mode of eVTOLS.

pack performance metrics (Sripad and Viswanathan, 2021; Bills et al., 2023). For example, the Tesla Model S-Long Range battery pack has an estimated power of 493 kW, a specific energy of 165 Wh/kg, and a nominal energy of 109.8 kWh. The Porsche AG Taycan Turbo's battery pack has a power of 460 kW and a specific energy of 136 Wh/kg. The Rimac Automobili Nevera is the leader in power, with an impressive 1,408 kW, a nominal energy of 120 kWh, and a weight of 830 kg. On the other hand, the NASA X-57 Maxwell battery pack is lighter, weighing 350 kg and offering a power of 120 kW. The BYD Auto Co., Ltd. Blade battery pack emphasizes its specific power of 1.5 kW/kg and a specific energy of 140 Wh/kg. Finally, the compact NASA Spacesuit battery pack, weighing just 5 kg, delivers a power of 2.4 kW.

Moreover, advancements in rechargeable battery technology are driving the development of innovative electric UAM aircraft designs. These aircraft have the potential to travel distances of up to 300 miles and carry payloads equivalent to seven passengers (Sripad and Viswanathan, 2021). Depending on their design and use, these new UAM aircraft have energy consumption rates ranging from 130 Wh/passenger-mile to approximately 1,200 Wh/passenger-mile. In comparison, terrestrial electric vehicles are projected to consume more than 220 Wh/passenger-mile, while combustion engine vehicles may consume approximately 1,000 Wh/passenger-mile. It is worth noting that several UAM designs are approaching technological feasibility with current Li-ion battery capabilities, particularly in terms of specific power and energy. However, concerns remain regarding the rechargeability and lifespan of these batteries. Overall, these developments highlight the growing technological maturity of a new transportation sector.

Despite these technological advancements, the electrification of aircraft results in complex interactions between battery size and mission duration and wider implications for infrastructure and energy consumption. Larger batteries enable longer missions due to their increased energy storage capacity (Faunce et al., 2018). However, this advantage is offset by the added weight they introduce to the aircraft, which can potentially inflate acquisition costs. Given the current state of battery technology, eVTOL aircraft will likely require partial or full recharging after each mission. The duration of these recharges, based on existing technology, could limit frequent aircraft usage, especially during periods of high demand. The electricity requirements of a large electric aircraft fleet are significant and pose challenges for the existing electrical grid. Kohlman and Patterson (2018) emphasized the potential strain on electrical infrastructure, highlighting that long charging times may require a substantial number of charging stations at vertiports. This would, in turn, necessitate a significant fleet size to meet the demand for UAM services. The financial implications of upgrading the grid to support UAM operations are also substantial. For example, a report by Black and Veatch highlighted costs ranging from \$75k to \$100k for extending existing service lines and up to \$80 M for new substation banks (Stith, 2020).

Research conducted by German et al. (2018) on cargo operations in the San Francisco Bay Area demonstrated that charging times for eVTOL models could vary between 9.5 and 23.1 min, depending on the charger's capacity. Another study performed by Justin et al. (2017) emphasized the potential effect of UAM operations on the electric grid. Their findings indicated that peak power demands at major airports, such as Boston Logan International, could match the electricity consumption of approximately 1,000 households. They also proposed strategies, such as battery swaps combined with optimized recharging, to reduce peak power demands by approximately 20%. Consequently, the significant power requirements of eVTOL operations necessitate thorough planning, including the optimization of charging station distribution and the consideration of varying electricity costs within different regions. Ultimately, the most suitable battery recharging solution will likely be tailored to meet the specific infrastructural limitations of each individual city.

6 Challenges and advancements at the infrastructure layer

6.1 Physical infrastructure

6.1.1 Vertiport deployment and challenges

As the concept of flying cars becomes a reality, the initial stages of implementation will heavily rely on vertiports for take-off and landing. The strategic placement of these vertiports is crucial for the development of an efficient urban air traffic system for flying cars (Wei et al., 2020). However, determining the optimal locations for these vertiports is a complex task, surpassing the challenges faced in traditional transportation infrastructure decision-making. The dynamic nature of flying car performance, the unpredictable capacity for air traffic, and the variability in travel demand are just a few factors that contribute to this complexity (Kohlman and Patterson, 2018; Robinson et al., 2018; Somers et al., 2019). Therefore, an integrated optimization model is essential for considering the interplay between site selection, operational modalities, traffic capacity, and travel demand (Kai et al., 2022).

In their study, the assumptions for vertiport location modeling considered various factors, such as passenger demand, ground travel duration, passenger pooling mechanism, flight repositioning, battery charging logistics, customer behavior, queue management, and passenger utility considerations. This emphasizes the strategic nature of vertiport planning and advocates for an innovative model to enhance UAM vertiport planning. By considering the unique challenges and dynamics inherent to UAM systems, this model incorporates site selection as the core decision while also incorporating operational and demand models to provide valuable feedback in the creation of an efficient vertiport network. Ultimately, the deployment of vertiports plays a critical role in shaping the capabilities of UAM systems, with design variations directly impacting travel demand, passenger experience, and the overall efficiency of the transportation system.

6.1.2 Corridor design

When incorporating aerial transportation into urban settings, it is crucial to prioritize the establishment of aerial corridors. These corridors are carefully planned routes in the airspace and are designed to facilitate the movement of eVTOL aircraft and other aerial vehicles between designated vertiports or landing zones (Tang et al., 2021). The primary focus of this design is safety, ensuring that aerial vehicles follow specific paths and minimize the risk of collisions. Additionally, these corridors are designed for efficiency, optimizing traffic flow and ensuring punctual arrivals and departures. Several factors influence their design, including altitude levels based on operational requirements, no-fly zones around sensitive areas, adaptability to weather changes, and seamless integration with existing air traffic. Technological advancements play a critical role in enabling dynamic routing, continuous communication between aerial vehicles and traffic management systems, and the use of sensors to enhance safety (Kim et al., 2022). Regulatory aspects, such as airspace classification and mandatory certifications for aerial vehicles, are also integral to the design process. Furthermore, corridors are planned with a focus on minimizing community disturbances, such as noise pollution, and considering the visual implications of frequent aerial movements. As UAM gains momentum, the design framework emphasizes scalability to accommodate a growing number of aerial vehicles and allows for the integration of other modes of transportation for a comprehensive travel experience. This design differs from traditional civil aviation air corridor designs by planning for "roads" for flying cars in a three-dimensional urban space. Compared to their urban counterparts, traditional air corridors for civil aviation lack robustness and flexibility due to the complexities of the urban low-altitude environment, the high volume of flying cars, and susceptibility to weather conditions (Bauranov and Rakas, 2021; Wu and Zhang, 2021).

In summary, the challenge of UAM corridor design combines safety protocols, technological innovation, regulatory compliance, and future adaptability, all of which are essential for the successful integration of UAM into urban landscapes.

6.1.3 Ground infrastructure

Beyond the technological and operational aspects, the analysis of UAM infrastructure extends to ground facilities. The integration of UAM's primary infrastructure components into existing city structures presents a significant challenge. The placement of vertiports, commonly referred to as the "vertiport positioning problem," is crucial to the design of the UAM network. In a study conducted by Maget et al. (2020), a gravity distribution model was utilized to determine demand-driven vertiport networks, with a specific case study conducted in Bavaria, Germany. This approach emphasizes the synergy between the existing traffic network and the proposed UAM system. Additionally, the study highlights the importance of vertiport accessibility and the relationship between vertiport locations and potential UAM travel demand. Venkatesh et al. (2020) developed a formal optimization procedure using mixed-integer programming to identify suitable vertiport locations, with a focus on the South Florida Metro Area. However, there is a gap in the current research, as many studies neglect trajectory-based approaches, fleet planning algorithms, and detailed ground-handling procedures. Sun et al. (2021) provided a comprehensive classification of UAM research areas, emphasizing the need for multicriteria optimization and a deeper exploration of models that assign specific trips to particular vehicles. Another analysis identifies key scaling constraints in UAM, highlighting the significance of ATC scalability, availability of ground infrastructure, and public acceptance.

While some studies have touched on the subject of vertiport placement, practical experience in this area is still limited. The main challenge in developing new infrastructure for VTOL vehicle maneuvers is the availability of space. High-demand areas may face space limitations, particularly if they are located in urban cores. Safety is another crucial concern due to the urban operating environment. Potential sites for VTOL operations include building rooftops, floating docks, highway clearings, and existing land infrastructure. Current helipads and heliports also hold potential as future vertiport options. However, noise and pollution may present societal challenges.

Additionally, the capacity of a vertiport is heavily influenced by the technical specifications and performance of VTOL vehicles. Like how aircraft wake intensity determines aircraft separation at conventional airports, factors such as VTOL vehicle downwash, weight, and pad availability also affect vertiport capacity. Vertiport capacity may be more limited by airspace separations or gate availability rather than by area occupancy duration. While there are existing standards and criteria for heliport/vertiport design, it is uncertain whether vertiports can conform to these standards or if new standards are necessary. Other considerations in vertiport design include charging VTOL vehicles, maintenance, and passenger boarding. The integration of UAM networks with existing transport networks is also a significant issue, not only for accessibility but also for enhancing the effectiveness of the entire transportation system by creating a multimodal network and services. Although current research has focused mainly on time savings, monetary costs, and vertiport reachability, there is a pressing need to investigate the distribution of ground-handling capacities, maintenance facilities, and battery-charging infrastructure in a comprehensive manner.

6.1.4 Communication infrastructure

In the field of UAM development, the UAM maturity level-4 (UML-4) serves as a testament for the thorough development and integration of advanced physical infrastructure components (Deloitte, 2020). These components are vital for ensuring that UAM operations not only meet the demanding requirements of UAM but also maintain high standards of efficiency and safety. One of the crucial elements of this infrastructure is communication pathways. At the UML-4 level, there is a strong focus on seamless communication between fleet operators, providers of services to UAMs (PSUs), and UAMs. This is achieved through three distinct channels: aircraft-to-aircraft, aircraft-to-ground, and ground-to-ground communication. These channels are essential throughout various operational phases, including surface movements, departure/arrival procedures, and en route operations.

In parallel, the navigation systems in UAM incorporate both onboard systems and external aids. The integration of performance-based navigation capabilities into physical infrastructure is particularly noteworthy, as it enables precise trajectory-based operations even under adverse visibility conditions. Surveillance, including both cooperative and noncooperative entities, is also a critical aspect of UAM. The surveillance infrastructure comprises a combination of ground-based, aircraft-borne, and satellite-driven systems, which enhance individual aircraft capabilities and ensure comprehensive situational awareness for heightened safety. Moreover, the control facility infrastructure is specifically designed to provide robust control facilities for PSUs, fleet operators, and other key stakeholders. This infrastructure serves as the backbone for efficient communication links, accurate navigation services, and comprehensive weather surveillance, all of which are vital for maintaining safety and operational efficiency.

In summary, UAM presents a groundbreaking perspective on urban transportation. However, its successful implementation relies heavily on addressing the complex challenges associated with infrastructure. Strategic planning, substantial investment, and collaborative efforts among all stakeholders are essential for overcoming these challenges and fully realizing the potential of UAM.

6.1.5 MRO infrastructure in the UAM industry

Maintenance, repair, and overhaul (MRO) infrastructure, including facilities such as hangars, plays a crucial role in ensuring the longevity and safety of aerial vehicles. In the airline industry, OEM-independent MRO service providers, such as those skilled in Structural Repair (SR) techniques, have established themselves as indispensable entities, offering specialized services for a wide range of aircraft (Airbus, 2018; Baur et al., 2018; Porsche Consulting, 2018). However, the UAM industry currently lacks comparable infrastructure. This gap is understandable considering the early stage of the UAM industry, in which the focus is primarily on vehicle-specific MRO services. It is anticipated that a more universal MRO service provider will emerge once the industry matures further or a dominant design becomes prevalent, as highlighted by Roland Berger in 2020. This evolution will be instrumental in streamlining maintenance processes and establishing standardized safety protocols across the UAM sector.

6.2 Digital infrastructure

6.2.1 Urban air traffic management system

Precise ATC systems are indispensable for ensuring the secure and efficient movement of aircraft in high-altitude airspace. In contrast, a parallel centralized system is essential for the management of urban low-altitude spaces because of its unique set of challenges. Unlike civil aircraft, which operate at altitudes largely unaffected by various meteorological conditions, UAMs operate within urban low-altitude spaces, rendering them highly susceptible to complex weather conditions such as heavy rain, snow, and wind (Somers et al., 2019). These atmospheric elements introduce notable uncertainties into the systems. Urban low-altitude spaces, influenced by the presence of buildings and varying terrains, exhibit complex structural layouts, and the volume of UAM traffic is expected to be significantly greater than that of civil aviation. Furthermore, the substantial traffic flows associated with UAM are bound to generate noise pollution. Hence, in addition to enhancing vehicle-level technologies, corridors designated for urban air traffic must be strategically positioned away from residential areas. All these characteristics necessitate thorough consideration in the design of urban air traffic systems to establish a highly robust, adaptable, and secure centralized ATC system.

6.2.2 Traffic flow management

At the heart of maintaining the smooth operation of an air traffic system lies traffic flow control, a tactical-level technology. In contrast to conventional ground traffic flow management, which relies predominantly on a decentralized approach utilizing traffic lights, the technology for managing urban aerial traffic aligns more closely with the centralized management observed in traditional civil aviation. The challenges associated with overseeing the flow of urban aerial traffic are particularly formidable due to its operation at low altitudes, rendering it highly vulnerable to various meteorological conditions, such as rainfall, snowfall, and strong winds (Federal Aviation Administration, 2019). Additionally, the high volume of traffic and complex airway structure in urban aerial traffic further exacerbate these challenges. Drawing upon the primary technical methodologies of traditional civil aviation flow management, the management of urban aerial traffic flow will employ strategies such as ground-based waiting and acceleration/deceleration, along with adjustments to the direction of travel within the airway to regulate airway capacity. Crucially, the technical advancements in this domain depend on fully accounting for uncertainties and large-scale traffic control.

6.2.3 Conflict resolution

Conflict resolution technology plays a vital role in ensuring the safety of flying cars by preventing conflicts during airway transitions at connecting nodes. Traditional ground traffic conflicts typically occur at intersections and are managed through traffic regulations and signals. In contrast, traditional aviation relies on air traffic caution and collision avoidance systems to assist pilots in avoiding conflicts. Urban aerial traffic, characterized by extensive hovering, introduces significant safety risks compared to traditional ground traffic. The high density of traffic flow in urban aerial traffic necessitates more stringent conflict avoidance technology. To prevent conflicts, intelligent features of flying cars can be leveraged by utilizing sensors and advanced communication technology to anticipate potential conflicts based on the status of various flying cars. Speed control algorithms can then be employed to adjust the speed of different aircraft, thereby altering their arrival times at connecting nodes. Additionally, moderate adjustments to flight direction and altitude control can further reduce conflicts at these nodes.

6.2.4 Separation in flight

The concept of separation in flight is essential for maintaining a safe distance between flying cars during their journey. Unlike traditional ground traffic, where separation is achieved by adhering to fixed safe distances between vehicles, flying cars must consider safe distances in three-dimensional space. Given that the braking capabilities of flying cars in flight are inferior to those of ground vehicles, a more rigorous implementation of flight separation is needed. Furthermore, a smaller urban low-altitude flight space and a larger volume of traffic necessitate precision in flight separation. During the initial phases of urban aerial traffic development, when the traffic volume is lower, static separation strategies can be employed for each flying car.

6.2.5 Trajectory planning

Flight path planning is an essential technology designed specifically for flying cars. This enables these vehicles to navigate aerial routes within a city, starting from any point and reaching any destination (Tang et al., 2021; Kim et al., 2022). This falls under the broader category of navigation systems for flying cars. Unlike traditional ground route planning, aerial transportation in cities requires three-dimensional mapping. This presents unique challenges compared to traditional aviation. The complex layout of urban low-altitude spaces adds complexity to aerial route planning within cities. Specifically, when determining routes for urban aerial transport, it is crucial to consider potential changes in airways at specific nodes and the directional restrictions within those airways. Navigating efficiently in three-dimensional urban spaces to find the best route in real time can be quite daunting. To address this, a hybrid approach of online and offline planning is proposed. This approach involves generating multiple potential routes in advance and selecting the most efficient route in real time based on current traffic and congestion conditions. It is also crucial to diversify the airways used when precharting these routes to avoid potential bottlenecks.

In essence, while physical infrastructure focuses on tangible assets such as vertiports, charging stations, and landing pads, digital infrastructure emphasizes intangible systems and platforms that facilitate seamless operations, coordination, and communication. The full potential of UAM can be realized only when digital and physical infrastructures are seamlessly integrated. For example, vertiports equipped with sensors can provide real-time weather condition, vehicle status, and passenger flow data to centralized data platforms. Charging stations can communicate with UAM vehicles to monitor battery status, ensuring optimal charging and minimizing downtime. Landing pads can be equipped with navigation aids that communicate with UAM vehicles, ensuring precise and safe landing.

6.2.6 Flight operations and ticket distribution

In the rapidly evolving domain of UAM, the ticket distribution plays a crucial role in optimizing the passenger experience. This system includes various components, allowing passengers to purchase or reserve seats on urban air vehicles such as eVTOLs. Booking flights can be performed through dedicated apps, websites, or integrated platforms that merge different transportation modes. The pricing models for these rides may vary, taking into account factors such as distance, demand, or time of day. Seat allocation methods, whether chosen by passengers or assigned automatically or via flight scheduling, are also integral aspects of the ticket distribution system. Additionally, integrating ticket distributions with other transportation modes, such as trains or buses, is a significant aim, aiming to provide a seamless travel experience. Refund and cancellation policies are also essential elements of this framework. Essentially, the ticket distribution for UAM, while resembling airline ticketing, is specifically designed for shorter urban flights with potentially more frequent departures, impacting both the passenger experience and the economic viability of UAM services.

6.2.7 Ground transportation coordination

The success and efficiency of UAM depend not only on advancements in aerial technology but also on smooth coordination with ground transportation systems. In the initial phases of UAM, eVTOL vehicles primarily operate between established vertiports rather than offering door-to-door solutions. This necessitates integrating ground vehicles to facilitate travel from the initial location to departure vertiports (first-mile travel) and from arrival vertiports to final destinations (last-mile travel). A pivotal aspect of this integration is ensuring a seamless intermodal experience that bridges ground commutes with aerial journeys. However, a significant challenge highlighted by recent studies is the potential for traffic congestion around vertiports. As UAM expands, it is expected to generate increased demand for ground transportation, resulting in heightened congestion in vertiport areas (Mayor and Anderson, 2019; Venkatesh et al., 2020; Wu and Zhang, 2021). Addressing these challenges is crucial to fully harnessing the potential of UAM, emphasizing its core advantages: convenience, efficiency, and sustainability.

6.2.8 Autonomous ground vehicles and their role

The domain of autonomous ground vehicles has experienced significant advancements, with some even reaching full demonstration stages or becoming available on the market (Fagnant and Kockelman, 2018; Maget et al., 2020; Garrow et al., 2021). While much has been discussed regarding the implications of autonomous cars for overall mobility, it is important to recognize that many of the challenges and barriers they face can also be applied to flying vehicles (Qu et al., 2022b; Zeng and Qu, 2023). Key technologies, such as control algorithms, play a critical role in enabling not only autonomous flights but also complex maneuvers, such as formation flights and detect-and-avoid strategies (Wu and Qu, 2022; Lin et al., 2023; Liu et al., 2023b).

6.2.9 Communication and navigation in UAM

The integration of unmanned aerial systems (UASs) presents significant challenges that must be addressed for passenger UAMs. Effective communication systems are essential, particularly due to the need for coordination and data sharing among numerous airspace users. The emergence of 5G technology (Ullah et al., 2019) holds great promise, with research focused on its adaptation for aeronautical use and ensuring security in aeronautical communications. An intriguing possibility is the potential role of UAS and UAM vehicles as communication relays, alleviating the shadow effects caused by urban structures. While 5G is already operational, challenges persist, particularly regarding UAV communication in 5G and future wireless systems.

6.3 Infrastructure development for UAM

The emergence of UAM has presented the potential for a revolutionary form of transportation, particularly in urban areas. However, the realization of this vision hinges upon the development of a robust infrastructure capable of accommodating the unique requirements of UAM. This infrastructure includes vertiports; charging or fueling stations; and advanced communication, navigation, surveillance, and IT systems. Initially, the integration of UAM may make use of existing infrastructure, such as helipads. However, as UAM evolves and expands, there will be a crucial need to either repurpose existing infrastructure or invest in new developments specifically designed for UAM operations. Notably, the construction of new vertiports may encounter challenges ranging from local opposition and financial limitations to issues related to multimodal integration. Several service providers, including Lilium, have already begun initiatives to develop vertiport infrastructure, as demonstrated by their announcement of the construction of a vertiport near Orlando International Airport in 2020. A pivotal decision for communities will be the ownership and access of UAM infrastructure. Should infrastructure be exclusive to specific service providers, or should it be open to multiple carriers, similar to traditional airports? While publicly funded infrastructure could promote inclusivity and a broader network, privately funded ventures may expedite the development process. Additionally, when designing UAM infrastructure, urban planners must consider diverse urban contexts, from densely populated city centers to suburban areas. The potential for different facility sizes, such as vertipads and vertihubs, will vary based on operational demands, urban density, and the surrounding environment. Interestingly, regions with access to water resources may explore seaplanes or amphibious aircraft as alternatives, reducing the necessity for new infrastructure. Suburban areas, despite being easily accessible, may lack demand, whereas city centers, teeming with potential, could face military restrictions. Existing urban infrastructure is crucial to air taxi planning; however, the scarcity of suitable infrastructure poses obstacles. Vertiports, envisioned as mini-airport facilities, require a range of amenities, from electricity and water to elevators and waste disposal. Although some advocate for vertiports on top of towering skyscrapers, research suggests that buildings spanning 10 to 20 stories provide optimal conditions to ensure smooth passenger transit.

Innovative vertiport designs propose integration with various infrastructures, including airports, transportation hubs, urban spaces, and industrial zones. Even specialized infrastructures, such as hospitals, can be considered if air taxis serve them. The number of vertiports a city needs depends on factors such as space, capacity, and demand. For example, initial calculations suggest that a city such as Frankfurt could meet the needs of its entire population with 15 vertiports per year (Kreimeier and Stumpf, 2017). However, these projections require further examination due to the complex challenges involved in integrating UAM. Urban planners have several tools available to facilitate UAM integration. For instance, Los Angeles previously included emergency helipads for high-rise buildings in their fire code, and overlay districts and form-based codes can also be used to achieve the desired development standards around vertiports. Furthermore, the synergy between high-density development, mixed-use areas, and public transportation can improve UAM efficiency, especially during unexpected operational delays. It is crucial for communities to consider the entire UAM journey, from booking to arriving at the destination. Tools such as the US Department of Transportation's Mobility on Demand Planning and Implementation guide, as well as NASA's Regional Modeling UAM Planning Tool, provide valuable insights for community integration and vertiport selection.

Energy infrastructure adds another layer of complexity. Establishing a comprehensive network of refueling and charging facilities is essential. For eVTOL aircraft, there is a need for new charging infrastructure and improvements to the existing power grid. Ground battery storage may also be necessary to manage peak demands and stabilize the power grid. Additionally, the adaptation and development of communication, navigation, and surveillance systems are crucial for scaling UAM operations. Transitioning from voice communications to secure data links is vital for efficient interactions between aircraft and ATCs. The development of standards for data architectures and communication systems is crucial. Furthermore, ensuring the cybersecurity of these systems is important for mitigating the risks of cyberattacks that could compromise safety and national security. The radio spectrum, being a finite resource, will also be a point of contention, particularly with the increasing demands from connected and automated vehicles.

In conclusion, while UAM holds promise for urban transportation, its successful implementation necessitates addressing numerous infrastructure challenges. Proactive planning, investment, and collaboration among stakeholders are essential for managing these challenges.

7 Challenges and advancements at regulatory and policy layers

7.1 Regulatory landscape

Table 3 presents an overview of the current regulatory landscape of UAM, highlighting significant developments on a global scale. These developments indicate a strong international movement toward establishing a cohesive regulatory environment for UAM. In 2021, the European Aviation Safety Agency (EASA) introduced the "Design Verification Guide for Special Category Drones," specifically for UAM aircraft design. This initiative is part of Europe's broader efforts, where the EASA has already established a regulatory framework consisting of key regulations such as the Basic Regulation (EU) 2018/1139 and the VTOL Special Condition (SC-VTOL-01). These regulations address important aspects, including unmanned aircraft categorization, VTOL aircraft certification, and vertiport design. Aligning with EASA's standards, the UK manages AAM under existing regulations by adopting a case-by-case approach and actively encouraging close collaboration between manufacturers through initiatives such as regulatory sandboxes and funding for innovation (Gesley and Feikert-Ahalt, 2023).

In 2022, the Civil Aviation Administration of China (CAAC) issued the "14th Five-Year Special Plan for General Aviation Development," aiming to promote the development of passenger unmanned aerial vehicles and urban air transportation. This progress aligns with China's focus on infrastructure development and regulatory frameworks to integrate UAM effectively. Similarly, Japan has initiated the ReAMo project, which focuses on developing evaluation methods and operational management techniques required for next-generation air transportation (Ministry of Land, Infrastructure, Transport and Tourism of Japan, 2023).

In the United States, the emphasis lies in infrastructure development and operational integration, as demonstrated by the AAM Coordination and Leadership Act,S.516 - 117th Congress (2021–2022). This act establishes a task force dedicated to integrating UAM into the existing airspace. The FAA plays a crucial role in leading UAM

Table 3 Recent developments in global regulations in UAM

Year	Regulation and policy	Contribution	Country/ region	Source
August 2018	Basic Regulation (EU) 2018/1139	• Updates EU safety legislation in civil aviation • Includes rules for Unmanned Aircraft Systems (drones) divided into open, specific, and certified categories, with Urban Air Mobility (UAM) falling under the certified category	Europe	The European Union Aviation Safety Agency
July 2019	VTOL Special Condition (SC-VTOL-01)	• Published by EASA to address VTOL-capable aircraft, especially air taxis. • This condition is expected to be the basis for future VTOL certification specifications	Europe	The European Union Aviation Safety Agency
September 2020	The EU-China Bilateral Aviation Safety Agreement (BASA)	• Covers airworthiness certificates and monitoring of civil aeronautical products • Environmental testing and certificates of civil aeronautical products • The certification and monitoring of design and production organizations • The certification and monitoring of maintenance organizations • Personnel licensing and training • Operation of aircraft • Air traffic services and air traffic management	Europe &China	The European Union Aviation Safety Agency and the Civil Aviation Administration of China
April 2021	Guidelines On Design Verification for UAS Operated in the 'Specific' Category	• Explains the process for the design verification of drones, an important element in ensuring safe drone operations in the 'specific' category	Europe	The European Union Aviation Safety Agency
May 2021	Means of Compliance with the Special Condition VTOL (MOC SC-VTOL)	• Provides clarification of VTOL and demonstration of compliance with them	Europe	The European Union Aviation Safety Agency
June 2022	14th Five-Year Special Plan for General Aviation Development	• Focus on infrastructure, regulatory framework, operational efficiency, cost management, talent cultivation, innovation, environmental sustainability, cultural development, governance, and international collaboration • Facilitate the integration of UAM into China's transportation ecosystem, enhancing connectivity and efficiency in urban areas	China	The Civil Aviation Administration of China
March 2022	Prototype Technical Specifications For the Design of VFR Vertiports for Operation with Manned VTOL-Capable Aircraft Certified in the Enhanced Category (PTS-VPT-DSN)	• Published with detailed recommendations for vertiport design, such as a funnel-shaped area above the vertiport and omnidirectional trajectories to vertiports	Europe	The European Union Aviation Safety Agency
June 2022	Notice of Proposed Amendment (NPA)	• Addresses air mobility with manned VTOL-capable aircraft, initial and continuing airworthiness of UAS • Introduces the concept of IAM (Innovative Air Mobility) with UAM as a subcategory, focusing on new-generation technologies and multimodal transportation systems	Europe	The European Union Aviation Safety Agency
June 2022	Special Conditions (SC)-VTOL used by EASA	• The basis for UK certification for new eVTOL aircraft	UK	The UK Civil Aviation Authority
June 2022	Advanced Aviation Infrastructure Modernization (AAIM) Act	• Provides $25 million in grants for planning and building AAM infrastructure	US	The US House of Representatives
September 2022	The Advanced Air Mobility Coordination and Leadership Act	• Plans for and coordinate efforts to integrate advanced air mobility aircraft into the national airspace system, and for other purposes	US	US Congress
September 2022	Engineering Brief No. 105, Vertiport Design	• Provides interim guidance for the design of vertiports for aircraft with VTOL capabilities	US	Federal Aviation Administration
October 2022	Memorandum of Understanding (MOU)	• Development of Regulatory Standards • Strategies for outreach to relevant stakeholders on urban air mobility • Joint organization of conferences, workshops, talks and other activities on urban air mobility	Singapore & The European Union	The Civil Aviation Authority of Singapore & the European Union Aviation Safety Agency
Dec 2022	ToR RMT.0230	• Outlines the proposed regulatory framework for the operation of UAS and UAM in the EU aviation system • Differentiates between three types of operations and aims to harmonize the regulatory framework across Member States	Europe	The European Union Aviation Safety Agency
May 2023	Considerations for Aerodromes and Vertiports planning to operate Vertical Take-off and Landing Aircraft (VTOL)	• Enables current licensed aerodromes to accommodate VTOL aircraft, and • Enables bespoke 'vertiports' to operate VTOL aircraft	UK	The UK Civil Aviation Authority

(*Continued*)

Year	Regulation and policy	Contribution	Country/ region	Source
June 2023	The Third Means of Compliance with the Special Condition for VTOL	• Deals with batteries thermal runaway	Europe	The European Union Aviation Safety Agency
June 2023	Notice of Proposed Rulemaking: Integration of Powered-Lift: Pilot Certification and Operations; Miscellaneous Amendments Related to Rotorcraft and Airplanes	• A proposed regulation that seeks to establish the appropriate rules for certifying the first group of pilots for powered-lift aircraft	US	Federal Aviation Administration
June 2023	Interim Regulations on the Unmanned Aerial Vehicles Flight Management	• Establishes a comprehensive framework for UAV operations • Standardizes UAV flights and related activities • UAVs are defined as pilotless aircraft with their own power systems, classified into micro, light, small, medium, and large based on performance indicators • Outlines specific management principles emphasizing safety, innovation, and regulatory compliance	China	The State Council and The Central Military Commission of the People's Republic of China
July 2023	Guidance for Vertiport Design	• Provides initial guidance in the planning and physical design of vertiports to support the safe and efficient operation of vertical take-off and landing (VTOL) capable aircraft operating with a pilot on board in visual conditions only	Australia	Australia's Civil Aviation Safety Authority
July 2023	Memorandum of Understanding (MoU)	• Cooperation between DGCA and EASA in the areas of development of certification standards and environmental standards and related requirements for the certification and use of unmanned aircraft systems and innovative air mobility operations which includes licensing of personnel, training, air traffic management and infrastructure, including Unmanned Aircraft System Traffic Management (UTM) standards and services	India and Europe	The Directorate General of Civil Aviation India and the European Union Aviation Safety Agency
July 2023	Updated Fact Sheet (2023) on State and Local Regulation of Unmanned Aircraft Systems (UAS)	• Discusses legal considerations applicable to state and local regulation of Unmanned Aircraft Systems ("UAS")	US	The Federal Aviation Administration and the United States Department of Transportation

operations through acts and guidelines that specifically address vertiport design and pilot certification.

Furthermore, the EU collaborates with countries such as Singapore, India, and Australia through Memoranda of Understanding, with a focus on certification standards and infrastructure, including Unmanned Aircraft Systems (UASs) Traffic Management. This collaborative effort highlights the global commitment to creating a safe, efficient, and sustainable UAM environment. Both the EU and the US are adapting their air traffic management systems to accommodate UAM, with programs such as the Digital European Sky and NASA's AAM National Campaign playing pivotal roles (Flight Transportation Laboratory of Massachusetts Institute of Technology, 1970; SESAR Joint Undertaking, 2020). At the local level, governments are actively shaping the future of UAM by addressing important aspects such as zoning, noise, and privacy (Booz Allen Hamilton, 2018). Cities in Europe, including Aachen, Hamburg, Amsterdam, Enschede, Liege, and Malaga, are analyzing frameworks to ensure that they have a decisive say in UAM operations (UAM Initiative Community, 2021). This collaborative effort is dedicated to ensuring the safety, operational efficiency, and environmental sustainability of UAM, paving the way for its integration into global transportation networks. The regulations and agreements underscore the importance of international standardization and cooperation in fostering the worldwide growth and acceptance of UAM technology. As the industry continues to evolve, certification, particularly in design and airworthiness, plays a crucial role in ensuring the safe and efficient integration of UAM into urban environments. Safety remains of significant importance, with experts targeting 2035 as a potential timeframe for unmanned passenger UAM operations and NASA predicting a commercially viable UAM market by 2028 (Booz-Allen Hamilton, 2018; SMG Consulting, 2023).

7.2 Regulatory and policy challenges

Flying cars, as a revolutionary mode of transportation, pose unique regulatory and policy challenges that must be addressed to ensure their successful integration into our transportation systems. These vehicles, seamlessly transitioning between road and air travel, inherently blur the distinctions between traditional motor vehicles and aircraft. From a regulatory perspective, flying cars face the challenge of standard aggregation. While on the ground, they are considered motor vehicles, but upon taking flight, they are classified as aircraft. Consequently, in addition to obtaining a "motor vehicle factory certificate," they must also obtain the "three major airworthiness certification certificates" mandated by the "Civil Aviation Law of the People's Republic of China." This dual nature of flying cars also extends to registration. Registration is required with both the Civil Aviation Administration to obtain a nationality registration certificate and with the public security traffic management department to obtain a car license plate. This results in a "double registration" dilemma that highlights the challenge of standard aggregation.

Moreover, the technical standards for both motor vehicles and aircraft are extensive and diverse. Motor vehicles have 117 mandatory national standards, while aircraft have 18 national standards. Additionally, there are 622 industry standards, 178 technical standards, and 49 special conditions and exemptions, specifically for aircraft. Harmonizing these standards presents a significant challenge, considering their distinct purposes and the technological advancements since their initial formulation. For instance, aircraft standards may prioritize anti-crash measures, whereas motor vehicle standards may focus on frontal collisions.

In regard to operational standards, flying cars must comply with both the "Civil Aviation Law" and the "Road Traffic Safety Law of the People's Republic of China." This dual compliance can lead to potential overlaps and conflicts in regulations. For example, while the Civil Aviation Law mandates adherence to aviation regulations during flight, the Road Traffic Law requires compliance with road traffic rules during terrestrial travel. This dichotomy can result in normative competition, where a single incident, such as a collision, could fall under multiple legal norms, necessitating the selection of one over the other. Another concern is criminal responsibility. As flying cars become more prevalent, there is potential for criminal issues, such as hijacking. A perpetrator hijacking a flying car could be charged with both the hijacking of an aircraft and the hijacking of a motor vehicle, creating a situation of potential competition.

To address these challenges, relying solely on existing policy support and legal interpretations is insufficient. It is essential to accelerate the revision and legislation related to flying cars and incorporate specific provisions for them in relevant laws and regulations. This approach will help resolve the legal gaps and conflicts in their application. Additionally, during the airworthiness certification process, the introduction of a special compliance plan tailored to flying cars can mitigate risks and enhance advanced development. This plan, a specialized compliance management system, will assist enterprises in navigating complex regulatory landscapes, ensuring that flying cars are both safe and compliant.

7.3 Public perception and acceptance

The introduction and potential integration of UAM into urban infrastructures have become subjects of significant academic and policy discussions. Beyond the technological aspects, it is crucial to explore the societal implications of UAM. As a novel urban travel paradigm, public perceptions play a decisive role in shaping the trajectory of UAM. The focus should include not only assessing potential UAM demand but also understanding public reservations, particularly regarding safety and privacy. Exploring the broader societal effect of UAM on urban landscapes requires comprehensive research to understand its nuances and develop adaptive strategies. Central to these discussions is the theme of public acceptance. A study led by Yedavalli and Mooberry (2019) shed light on the public's primary concerns, which mainly revolve around the safety of individuals on the ground, the acoustic footprint of UAM vehicles, their operational schedules, and cruising altitudes. Interestingly, the study revealed a direct relationship between the magnitude of the effect on nonusers and their acceptance levels: the lower the perceived effect was, the greater the acceptance.

While assessing broader public sentiment is undoubtedly important, it is equally essential to have a deep understanding of the concerns of potential users of UAM for its successful entry into the market. This notion has been emphasized by Vascik (2017). As the UAM sector is still in its early stages, there is limited dedicated research on the factors that drive its acceptance. However, insights can be drawn from the literature on AVs, particularly in areas related to the perceived reliability of automation and vehicle safety (Nees, 2016; Adnan et al., 2018; Bennett et al., 2019). It is important to note that there may be certain factors specific to UAM that are not direct analogs according to the AV literature (Fu et al., 2019; Al Haddad et al., 2020; Hwang and Hong, 2023).

Drones, as part of the UAM concept, have been studied in relation to noise pollution (Vascik and Hansman, 2017) and privacy concerns (Lidynia et al., 2017). Al Haddad et al. (2020) took a more comprehensive approach, examining how accepting drivers from other transportation sectors might influence the adoption of UAM. Their findings highlighted the positive role of users' inclination toward modern technological solutions while also pointing out concerns related to data privacy and environmental effects as barriers. A meta-analysis conducted by Straubinger et al. (2020) further emphasized the significance of travel time and cost as primary factors in making urban mode choices. Given UAM's potential to significantly reduce travel times, especially for longer routes, it has the potential to transform urban mobility. Drawing comparisons with commercial aviation, Garrow et al. (2019) suggested that UAM passenger behavior might exhibit unique patterns. They also hypothesized that AVs could emerge as direct competitors to UAM, given the similarities in their service structures. This alignment implies that insights from AV studies could be invaluable in shaping UAM mode choices and strategies. Despite the growing interest in UAM, comprehensive research, especially related to mode choices, is still in its early stages.

In summary, travel time and cost continue to have significant influences on UAM mode choices. However, it is crucial not to underestimate the importance of system efficiency, minimized number of transfers, or strategic market targeting. It will be instrumental to ensuring service transparency and communicating robustly about safety protocols, data privacy, and security measures to foster public and user acceptance. Proactive campaigns promoting automation awareness can also further strengthen UAMs' position in the market. According to preliminary studies, assuming that UAM prices range from 1 €/km to 7 €/km, modal share estimations are projected to be approximately 0.5% (Pukhova et al., 2021). Additionally, the initial exploration of the public perception of UAM has yielded invaluable insights that can significantly influence urban planning, policymaking, and engineering (Kreimeier and Stumpf, 2017; Fu et al., 2019). Established aircraft manufacturers with strong safety records are preferred over new market entrants, and noise mitigation is a crucial factor in UAM acceptance. Geographical nuances in perception are evident, with urban residents showing considerable interest in UAM.

7.4 Future directions

Considering the complexities outlined above, the integration of UAM and ground transportation systems poses multifaceted challenges, including various aspects such as vehicle design, propulsion technology, network design, air traffic management, business models, regulatory frameworks, and public perception. Currently, UAM is still mostly conceptual, with emerging vehicle types such as the "Audi Pop. Up Next."

The next challenge is the necessity of the vertiport infrastructure. This rapid technological evolution calls for a broader vision in future research, particularly in refining demand studies to gain a better understanding of the consumer market and the effects of new flying car types (Zheng et al., 2023). The uncertainties surrounding vehicle performance, market potential, infrastructure needs, community acceptance, and integration with the ground transportation system require an updated approach to assumptions and analyses, especially regarding potential amphibious flying cars.

Additionally, UAM offers a notable advantage in urban transportation by significantly reducing travel times on longer routes through its ability to quickly cover most distances by flying. However, the current operational mode of UAMs, particularly eVTOL aircraft, faces time-consuming challenges in the first and last mile segments, which heavily rely on ground transportation (Straubinger et al., 2021; McKinsey, 2022). Therefore, the effectiveness of UAM is closely tied to the existing urban infrastructure (Pukhova et al., 2021). This issue is especially pronounced in Chinese cities due to higher levels of ground congestion compared to those in the US

While UAM has the potential to alleviate congestion on main roads and highways by facilitating medium- to long-distance commutes, it may inadvertently increase traffic volume on minor roads around vertiports as a result of increased local ground traffic during first- and last-mile travels (Wang et al., 2023). Consequently, while UAM can address congestion on major routes, it can also exacerbate local congestion around vertiports. Several potential solutions to these challenges include enhancing vertiport accessibility, improving local transport efficiency, and advancing eVTOL technology for door-to-door flying services to address first-and-last-mile issues. Moving forward, gaining a detailed understanding of how specific types of flying cars or operational concepts will impact existing transport systems and ground traffic is crucial and should be a primary focus in the evolution of UAM.

Moreover, it is important to recognize that the concept of UAM extends beyond just eVTOL aircraft. While eVTOL technology is a significant development for UAM, it should not be considered the definitive or sole concept for this field. Given the rapid evolution of technology in this area, future research should adopt a broader vision by considering other operational concepts and technologies that may contribute to UAM. By acknowledging and exploring the potential diversity of UAM operations and technologies, research can pave the way for more inclusive and comprehensive UAM solutions. This approach is crucial for ensuring that UAM systems are not only technologically advanced but also versatile and adaptable for meeting the diverse demands of different urban transportation contexts and scenarios. By expanding the focus beyond eVTOL, research in UAM can effectively address various aspects of urban air travel, including infrastructure requirements, regulatory frameworks, public acceptance, and environmental effects.

This research establishes a foundational understanding of how UAM can integrate with ground transport systems, highlighting key developments and challenges in achieving a more cohesive UAM-ground transport system. Future work could offer a substantial scope to expand upon this foundation, enhancing our comprehension of UAM's potential role in evolving urban transportation landscapes.

8 Conclusions

The extensive body of UAM research includes various dimensions, including technological advancements, system design, operational frameworks, market development, and public acceptance. Technologically, UAM has undergone remarkable progress, particularly in propulsion systems and battery storage. Polaczyk et al. (2019) analyzed 44 eVTOL projects, emphasizing battery limitations in energy density and safety. Brelje and Martins (2019) explored various propulsion designs and the role of power electronics and thermal management in aircraft design. Kim et al. (2018) discussed distributed electric propulsion, highlighting its propulsive efficiency, noise reduction, and system resilience, despite integration challenges. Research on system design, such as Bauranov and Rakas (2021), evaluated urban airspace concepts, emphasizing safety, technological complexity, noise, and privacy. Kai et al. (2022) innovatively addressed vertiport infrastructure planning, revealing the sensitivity of UAM profitability to network planning and customer expectations.

Operational frameworks and market studies offer insights into the practical implementation of UAM. The FAA, NASA, SESAR, and Japan's Ministry have developed various ConOps for UAM, focusing on airspace design, fleet management, and regulatory frameworks (Deloitte, 2020; FAA, 2020; SESAR Joint Undertaking., 2020; Ministry of Land, Infrastructure, Transport and Tourism of Japan, 2023; SESAR Joint Undertaking, 2023). Krylova (2022) emphasizes urban planning for UAM infrastructure by considering factors such as location, capacity, and environmental effects. Research in market analysis, including studies by Goyal et al. (2018), Rimjha et al. (2021), and Long et al. (2023), explores market potential, demand estimation, and operational challenges, highlighting the importance of pricing strategies and operational reliability. Public acceptance research, such as that of Al Haddad et al. (2020) and Fu et al. (2019), explores the factors influencing UAM adoption, emphasizing safety, trust, cost, and the role of demographics. Hwang and Hong (2023) study UAM adoption in Republic of Korea, focusing on the Seoul Metropolitan Area and identifying cost and access time as significant factors influencing UAM usage, in addition to individual user characteristics.

Overall, the existing body of research provides a comprehensive understanding of UAM, highlighting its technological, operational, and societal complexities and the interplay between these elements in shaping the future of urban air travel.

In conclusion, the successful implementation of UAM as a promising future for urban transportation relies on overcoming a range of challenges through proactive planning, investment, and collaboration among various stakeholders. The regulatory landscape for UAM is evolving on a global scale, with significant advancements in certification, design, and airworthiness standards to guarantee safe and efficient integration into urban environments. Key challenges include the establishment of standard aggregations for flying cars, the harmonization of technical standards, and navigating adherence to both aviation and road traffic regulations. Additionally, public perception and acceptance play crucial roles in the successful market introduction of UAM. Concerns regarding safety, privacy, and environmental effects are central to ensuring public and user acceptance. This study emphasizes the need for further exploration, collaboration among stakeholders, and strategic initiatives to effectively shape the future trajectory of UAM. The integration of UAM into urban transport systems not only poses technological challenges but also involves addressing societal concerns and regulatory obstacles and ensuring compatibility with existing transportation infrastructures.

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