Urban Air Mobility: History, Ecosystem, Market Potential, and Challenges

Adam P. Cohen, Susan A. Shaheen, and Emily M. Farrar

***Abstract*—Since the early 20th century, inventors have conceptualized "plane cars" and other urban aerial transportation. Emerging innovations in electrification, automation, and other technologies are enabling new opportunities for on-demand air mobility, business models, and aircraft design. Urban air mobility (UAM) envisions a safe, sustainable, affordable, and accessible air transportation system for passenger mobility, goods delivery, and emergency services within or traversing metropolitan areas. This research employed a multi-method approach comprised of 106 interviews with thought leaders and two stakeholder workshops to construct the history, ecosystem, state of the industry, and potential evolution of UAM. The history, current developments, and anticipated milestones of UAM can be classified into six phases: 1) "flying car" concepts from the early 1910s to 1950s, 2) early UAM operations using scheduled helicopter services from the 1950s to 1980s, 3) re-emergence of on-demand services starting in the 2010s, 4) corridor services using vertical take-off and landing (VTOL) envisioned for the 2020s, 5) hub and spoke services, and 6) point-to-point services. In the future, UAM could face several barriers to growth and mainstreaming, such as the existing regulatory environment; community acceptance; and concerns about safety, noise, social equity, and environmental impacts. UAM also could be limited by infrastructure and airspace management needs, as well as business model constraints. The paper concludes with recommendations for future research on sustainability, social and economic impacts, airspace integration, and other topics.**

***Index Terms*—Advanced air mobility (AAM), automation, electrification, flying cars, helicopters, on-demand air mobility, rural air mobility, unmanned aircraft systems (UAS), unmanned aerial vehicles (UAVs), unmanned aircraft (UA), urban air mobility (UAM), vertical take-off and land (VTOL).**

I. Introduction

IN RECENT years, a variety of technological advancements in electrification, automation, and vertical take-off and landing (VTOL) are enabling innovations in urban aviation, including new aircraft designs, services, and business models. These trends are converging to enable new opportunities for on-demand aviation for passenger mobility and goods delivery in urban areas [1]–[4]. Collectively, these innovations are referred to as advanced air mobility (AAM). AAM is a broad concept focusing on emerging aviation markets and use cases for on-demand aviation in urban, suburban, and rural communities. AAM includes local use cases of about a 50-mile radius in rural or urban areas and intraregional use cases of up to a few hundred miles that occur within or between urban and rural areas. Urban air mobility (UAM), which is a subset of AAM, envisions a safe, sustainable, affordable, and accessible air transportation system for passenger mobility, goods delivery, and emergency services within or traversing metropolitan areas. While this paper focuses primarily on UAM (air transportation for passengers and goods in metropolitan areas), there are also applications for on-demand aviation in rural markets, sometimes referred to as rural air mobility (e.g., crop dusting using unmanned aircraft, etc.). Advanced, urban, and rural air mobility concepts are closely related to the thin-haul market. The thin-haul commuter concept refers to an envisioned class of four to nine seat passenger aircraft operating short flights and providing scheduled and on-demand service between smaller airports [5].

This paper provides a history of UAM, the UAM ecosystem, current market developments, and anticipated milestones mapped across a six-phase framework. This paper is organized into six sections. First, the authors describe the methodology. Next, there is an overview of UAM history in North America. The third section introduces contemporary definitions, an on-demand aviation ecosystem, and potential business and operational models. In the fourth section, the authors discuss the state of the industry and projected developments. Challenges and potential barriers to implementation and mainstreaming are described in the fifth section. Finally, the authors conclude with policy considerations and recommendations for additional research.

II. Methodology

This study employed a multi-method approach to researching the ecosystem and definitions, the history and state of the industry, and barriers to UAM adoption. To begin, the authors conducted a comprehensive review of the literature (i.e., market studies, governmental reports, academic research, conference proceedings, and other items). This review was supplemented with an Internet search documenting recent and planned developments. A summary of the published literature and other academic studies, which are categorized by topic area, is shown in Fig. 1. The figure does not include a

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Adam P. Cohen is with the Transportation Sustainability Research Center (TSRC), University of California (UC) at Berkeley, Berkeley, CA 94720 USA (e-mail: apcohen@berkeley.edu).

Susan A. Shaheen is with the Civil and Environmental Engineering Department, University of California (UC) at Berkeley, Berkeley, CA 94720 USA, and also with the Transportation Sustainability Research Center (TSRC), University of California (UC) at Berkeley, Berkeley, CA 94720 USA (e-mail: sshaheen@berkeley.edu).

Emily Farrar is with the Department of Civil and Mineral Engineering, University of Toronto, Toronto, ON M5S, Canada (e-mail: emily.farrar@mail.utoronto.ca).

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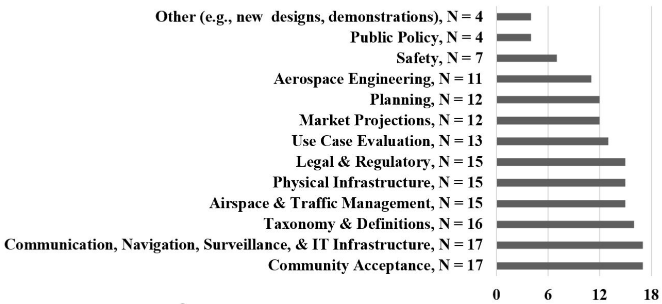

Fig. 1. Distribution of topics reviewed in literature. *Please note a source may be counted in more than one category, if it includes more than one topic.*

breakdown of the Internet materials; they primarily covered industry updates (e.g., new aircraft designs, prototype testing, announcements for planned services). Given this emerging topic and the vast number of planned deployments and industry developments, it is possible that some examples were inadvertently omitted.

In addition to the literature review, the authors developed an interview protocol and conducted more than 50 expert interviews with members of a National Aeronautics and Space Administration (NASA) market study advisory group (SAG) and other thought leaders representing a variety of academic, public, and private sector perspectives between Summer 2017 and Winter 2020. SAG members represented senior leaders and subject matter experts from the Federal Aviation Administration (FAA); NASA; National Transportation Safety Board (NTSB); North Carolina Department of Transportation; New York City; the city of Los Angeles; Los Angeles World Airports; International Civil Aviation Organization (ICAO); and numerous startups, manufacturers, and research institutions. Some of the participating public sector thought leaders included directors for the FAA's Aviation Plans and Policy Office, Office of International Affairs, Unmanned Aircraft Systems (UAS) Integration Office, and a former NTSB chairman. There was notable representation from manufacturers and startups, as this reflected the diverse range of planned airframes with unique operational requirements, such as fixed-wing, rotorcraft, short take-off designs, vertical take-off designs, piloted, and autonomous aircraft.

The authors also facilitated two UAM workshops in April 2018 and January 2020 in Washington, D.C. The first workshop was held as part of a NASA market study. This workshop included over 50 thought leaders representing the public and private sectors. This format included semi-structured discussions around key challenges, such as market feasibility, legal and regulatory barriers, and issues related to societal acceptance from the user and non-user perspectives. The second workshop was held at the 2020 Transportation Research Board Annual Meeting, which included a facilitated dialogue among over 130 participants from public-sector organizations, private companies, non-governmental organizations, and educational institutions. More than two dozen government, industry, and academic experts also presented and participated in panel discussions. Participants discussed opportunities and challenges, planning issues, community acceptance, research, and next steps needed for implementation, emphasizing the future of multimodal UAM [6].

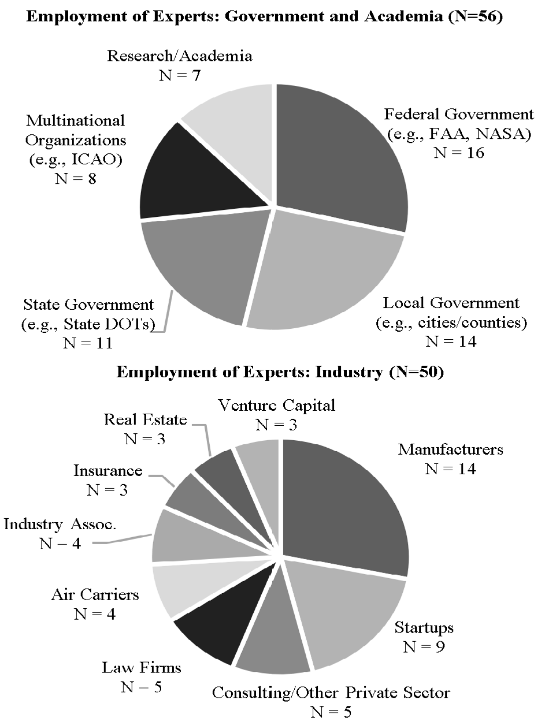

Fig. 2. Employment of experts.

Further, the authors sponsored the SAE International standards JA3163 and J3163, between November 2017 and February 2020, to develop definitions for terms related to UAM, shared mobility, and enabling technologies. As part of this process, the authors engaged 20 experts representing NASA; the General Aviation Manufacturers Association (GAMA); the FAA; and private sector original equipment manufacturers and air carriers as part of three expert panel meetings on UAM.

The expert interviews, both workshops, and the SAE standards development provided a rich understanding of the state of the industry, opportunities and challenges for implementing UAM, and key inputs into the ecosystem. A summary of all of the thought leaders engaged in this outreach and their subject matter expertise is shown in Fig. 2. Overall, the breadth of experts and thought leaders ($N = 106$) engaged covered one of ten key disciplines related to UAM: 1) taxonomy and definitions; 2) aerospace engineering; 3) airspace and air traffic management; 4) legal and regulatory; 5) planning; 6) safety; 7) community acceptance; 8) public policy; 9) market projections; and 10) use case evaluation.

III. UAM History

The concept of urban aviation is not new. Beginning in the early 1900s, inventors began developing "flying car" concepts and by the mid-20th century, early operators began offering scheduled flights using helicopters. This paper describes the history, evolution, and potential future of UAM in six phases (see Fig. 3). This first section provides an overview of UAM's history, described in the two initial phases.

A. Phase One: Flying Car Concepts

The concept of UAM traces its origins to the Autoplane, a functional "flying car" developed by Glenn Curtiss

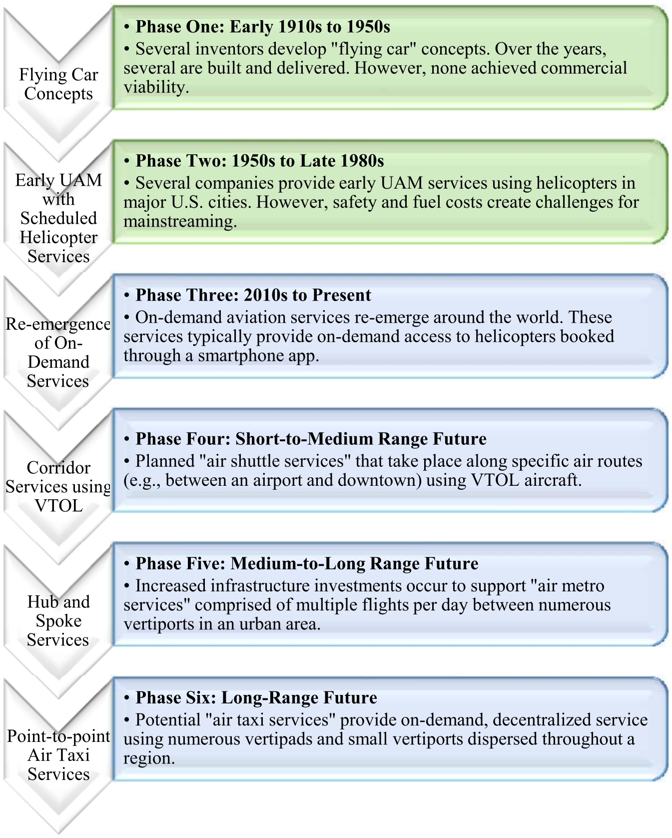

Fig. 3. Six phases of UAM history and anticipated evolution.

around 1917. Over the years, automakers and inventors built and delivered various concepts for flying automobiles. In the 1920s, Henry Ford developed a concept for "plane cars" and began developing single-seat aircraft prototypes. Ford's flying car project ended within a few years following a crash and fatality of their test pilot [7]. In 1937, Waldo Waterman developed the Arrowbile, a hybrid Studebaker-aircraft with detachable wings, but the project dissolved due to a lack of funding [8]. The 1940s was marked by several efforts including the first "flying car" to be approved by the Civil Aeronautics Administration (CAA), the predecessor to the FAA, the Airphibian. Despite the aircraft's technical achievements, it never received investment capital. Inspired by the Airphibian, Moulton "Molt" Taylor developed the Aerocar prototype in 1949 [9]. The flying car was the second and last roadable (i.e., aircraft that can be driven on roadways as vehicles) aircraft to receive CAA approval. Consolidated-Vultee developed the ConvAirCar in 1947, a two-door sedan equipped with a detachable airplane unit. However, the project ended after a crash on its third test flight [9]. In the late 1950s, Ford developed the Levacar Mach I, a vehicle prototype suspended just slightly above the surface by ducted air from three levapads on its underside [7]. The first early VTOL aircraft designed for military use, the Avrocar, was initially funded by the Canadian government but was dropped when it became too expensive. In 1958, the U.S. Army and Air Force took over the project. However, this flying-saucer-shaped aircraft suffered from thrust and stability problems and the project was canceled in 1961 [10]. None of these early concepts achieved commercial viability.

Although inventors, engineers, industrial designers, and technology entrepreneurs have long envisioned a future of "flying cars," there were a number of technical and practical factors that have made this difficult to achieve. As a practical matter, the addition of wings to a traditional vehicle chassis can block driver sight lines and make a vehicle difficult to drive and park on roadways. Because the size, shape, and weight distribution needs are very different between vehicles and aircraft, both have very different regulatory, technical, and safety design considerations that make it difficult to design one vehicle/aircraft that can serve both use cases (e.g., aircraft engines have been designed to take advantage of air cooling whereas car engines are designed to be water cooled to prevent overheating while in traffic). Although there has been a lot of experimentation with flying car concepts, these longstanding practical and technical challenges caused the industry to focus more on improving safety and enhancing economic and operational efficiency of vertical flight.

B. Phase Two: Early UAM Operations With Scheduled Helicopter Services

Between the 1950s and 1980s, several operators began providing early UAM services using helicopters in Los Angeles, New York City, San Francisco (SF Bay Area), and other cities. New York Airways offered passenger service between Manhattan and LaGuardia in the mid-1950s. In the U.S., these early passenger helicopter services were typically enabled through a combination of helicopter subsidies (discontinued in 1966) and airmail revenue [11]. Between 1965 and 1968 (resuming in 1977), Pan Am offered hourly connections between Midtown and JFK's WorldPort, allowing passengers to check in at the Pan American building in Midtown 40 minutes prior to their flight departure at JFK. Over the years, the service offered various promotions, such as "buy one, get one free" that offered international business travelers a free helicopter connection to their flight. The service was discontinued in 1977 when an incident involving metal fatigue of the landing gear caused a rooftop crash killing five people (four people on the roof and one person 59 stories below on the ground) [12]. Helicopter services began to slowly re-emerge in Manhattan in the 1980s. Trump Air offered scheduled service using Sikorsky S-61 helicopters between Wall Street and LaGuardia airport connecting to Trump Shuttle flights. The service was discontinued in the early 1990s when Trump Shuttle was acquired by US Airways [12].

Inventors continued developing flying car and VTOL prototypes during the 1960s and 1970s. Engineer Paul Moller began developing VTOL aircraft in the 1960s, and an early prototype hovered a few feet off of the ground in 1967 [13]. The 1966 Aerocar was able to reach 60 miles per hour (mph) on the ground and 110 mph in the air [8]. Advanced Vehicle Engineers (AVE) created a flying car by combining a Cessna Skymaster and a Ford Pinto; however, a test flight crash ended the project in 1973 [8]. The 1980s also saw several attempts to develop new VTOL aircraft. Boeing invested $6 million US into the Sky Commuter program and developed three VTOL prototypes before the program was canceled [14]. Moller developed the M200X in 1989. The flying-saucer-shaped aircraft reached an altitude of 40 feet and remained airborne for three minutes [15]. The project evolved into the Moller Skycar, which was under development until 2003 [8].

IV. Contemporary UAM Concepts and Definitions

Recent technological developments in electric propulsion, automation, and sensing are contributing to new aircraft configurations. Innovations are also occurring in supporting areas such as infrastructure and air traffic management. Due to these new developments and associated nomenclature, this section introduces readers to current definitions, marketplace ecosystem, and potential business and operational models.

A. Definitions for Urban Air Mobility

UAM encompasses an array of aircraft, with variations in propulsion (i.e., battery electric, hydrogen electric, hybrid, or gas-powered); design; technology; capacity; range; autonomy; and compatibility with existing infrastructure [16]. Table I introduces and defines frequently used terms and key concepts related to contemporary UAM to assist readers in understanding the state of the market and anticipated developments.

B. On-Demand Aviation Ecosystem

The advanced air mobility ecosystem (inclusive of UAM) can be classified according to the following characteristics:

- Design characteristics, such as passenger capacity, propulsion, airframe, or aircraft types (e.g., wingless designs, electric rotorcraft, aircraft that use any of its thrusters for vertical lift and cruise vs. aircraft that use independent thrusters for vertical lift and cruise);
- Operational characteristics, such as VTOL and aircraft that can fly and also be driven on roads (sometimes referred to as roadable aircraft);
- Training and knowledge requirements for pilots and operators;
- Airworthiness certification approaches, based in part or whole on established FAA and international processes;
- Service characteristics or use case (e.g., scheduled service, semi-scheduled service, unscheduled service, passenger mobility, goods delivery, etc.); and
- Distinctions based on piloted, remotely piloted/operated, and levels of aircraft automation (with respect to specific aircraft systems and phases of flight).

Reference [1] developed a taxonomy of five operational models for on-demand and near on-demand passenger use cases, such as UAM. This taxonomy blends characteristics of operational models, approximate number of passengers, operating regulations, and various levels of demand-responsive service (Table II). The operating regulations refer to the U.S. Federal Aviation Regulations (FARs) that govern all aviation activities in the U.S. Part 91 of the FARs provides general operating and flight rules for small non-commercial aircraft within the U.S. Part 107 regulates a broad spectrum of commercial and government uses of sUAS. Part 121 regulates scheduled air carriers (i.e., airlines). Part 135 primarily oversees commuter and on-demand operations. Generally, each of these parts has requirements for pilot licensing, aircraft

TABLE I
Definitions and Common Terms

KEY CONCEPTS	
Rural Air Mobility	Envisions a safe, sustainable, affordable, and accessible air transportation system for passenger mobility, goods delivery, and emergency services within or traversing rural and exurban areas. Rural air mobility may overlap with UAM in cases where flight traverses an urban area and at an altitude low enough to impact communities on the ground.
Urban Air Mobility (UAM)	Envisions a safe, sustainable, affordable, and accessible air transportation system for passenger mobility, goods delivery, and emergency services within or traversing metropolitan areas. UAM may overlap with rural air mobility in cases where flight traverses a rural area and at an altitude low enough to impact communities on the ground.
AIRCRAFT AND AERIAL SYSTEMS	
Short Take-off and Land (STOL)	An aircraft with short runway requirements for take-off and landing.
Small Unmanned Aircraft	An aircraft that weigh less than 55 pounds on takeoff, including everything that is on board or otherwise attached.
Small Unmanned Aircraft System (sUAS)	Small unmanned aircraft and its associated elements (including communication links and the components that control the small unmanned aircraft) that are required for the safe and efficient operation of the small unmanned aircraft in the national airspace system.
Unmanned Aerial Vehicles (UAV)	UAVs are multi-use aircraft with no human pilot aboard, commonly referred to as 'drones.' UAVs can be remotely piloted or fully autonomous. Devices used for cargo delivery typically have four to eight propellers, rechargeable batteries, and attached packages underneath the body of the UAV. Larger UAVs can be used to transport passengers as well. UAVs without a pilot on-board could be capable of carrying passengers who have no ability to intervene in the operation of the aircraft. The term "Unmanned Aircraft Systems" or "UAS" may be used to describe the systems that enable the operation of UAVs, such as ground control, communications, and other support equipment.
Unmanned Aircraft (UA)	An aircraft operated without the possibility of direct human intervention from within or on the aircraft (i.e., no on-board pilot). Unmanned aircraft with no pilot on-board could be capable of carrying passengers who have no ability to intervene in the operation of the aircraft.
Vertical Take-off and Land (VTOL)	An aircraft that can take off, hover, and land vertically.
INFRASTRUCTURE (AERODROMES/SKYPORTS)	
Vertipad	A single landing pad and parking stall intended to accommodate one parked aircraft.
Vertiport	A single landing pad, intended to accommodate two to three parked aircraft.
Vertihub	Two or more landing pads with parking for multiple aircraft.
AIRSPACE AND TRAFFIC MANAGEMENT	
Unmanned Aircraft Systems (UAS) Traffic Management (UTM)	A traffic management system that provides airspace integration requirements, enabling safe low-altitude operations. UTM provides services such as: airspace design, corridors, dynamic geofencing, weather avoidance, and route planning. NASA proposes that UTM systems will not require human operators to monitor every aircraft continuously; rather, the system will provide data to human managers for strategic decisions. UTM has the potential to enable safe visual and beyond visual line-of-sight UAS flights in low-altitude airspace.

TABLE II
TAXONOMY BASED ON OPERATIONAL CHARACTERISTICS (ADAPTED FROM [1])

Operational Model and Description	Approx. Number of Passengers	Operating Regulations
Private Service model is one in which an aircraft serves only one individual or party for a length of time greater than the duration of a single flight.	1-6	Part 91*
Air Taxi is an on-demand service in which a single user or a single group of users reserve an entire aircraft for a flight and determine the flight's origin, destination, and timing.	1-4	Part 135
Air Pooling is a largely on-demand service where multiple individual users are aggregated ("pooled") into a single aircraft for flights. Flight departure times and/or origin-destination pairs may be set by a single user with other users fitting into that schedule, or the operator may adjust all users' desired schedules to enable passenger aggregation.	3-6	Part 135
Semi-Scheduled Commuter is a model where aircraft departure times and/or locations are modified from a baseline schedule based on the preferences of consumers. For example, an aircraft may be scheduled to depart between 8am and 10am each day on a particular route, but the actual departure time will be modified day-to-day based on an aggregation of customers' stated preferences/availability.	6-19	Part 135
Scheduled Commuter provides a near-on-demand service by offering frequent flights along the same route(s) in a regularly scheduled service.	6-19	Part 135 or 121

maintenance, crew duties, insurance, and other requirements that must be met to legally operate in the national airspace system.

This taxonomy provides a baseline for classifying on-demand aviation services from approximately "most" to "least" on-demand and passenger capacity. Generally, higher passenger loads provide additional operational efficiencies and less schedule flexibility. This taxonomy can be used for classifying services based on existing operating regulations, passenger loads, and both frequency and flexibility of flights, but it does not include goods delivery and distinctions between piloted and autonomous aircraft.

There are a wide range of stakeholders involved in, influenced, or affected by AAM. Broadly, these stakeholders include federal, state, and local lawmakers and agencies; infrastructure owners and operators; emergency services; commerce and industry; mobility and app service providers; and the public (both users and non-users). Fig. 4 depicts the on-demand aviation ecosystem and how the aircraft and personnel capabilities influence and are influenced by market and operational objectives. Both on-demand aviation market segments (i.e., urban and rural air mobility), aircraft, operator, and personnel are impacted by a variety of policy, legal, and regulatory factors. There are a number of enablers and challenges that can be broadly categorized into market economics, policies and regulation, community acceptance, infrastructure, and innovative and emerging technologies. The remainder of this paper examines many of the key components of this ecosystem, including the state of the industry, emerging innovations, and potential challenges to deployment and mainstreaming.

V. STATE OF THE INDUSTRY AND EMERGING INNOVATIONS

Current and emerging UAM services include a variety of use cases and business models. However, the vast majority of developments are occurring predominantly in passenger mobility and to some extent goods delivery [16]. The following section describes these developments in the context of Phases Three through Six of UAM's evolution (see Fig. 3).

A. Phase Three: Re-Emergence of On-Demand Services

Recent developments in UAM goods delivery and passenger mobility are discussed below:

1) Goods Delivery: The concept of sUAS for goods delivery first appeared to take hold in the 2010s, and the number of active services has grown rapidly. Current UAS applications around the globe span a wide range of industries including: consumer goods delivery, transport of medical samples and emergency supplies, mapping, and surveillance, among others.

In recent years two areas of industry focus have emphasized the delivery of emergency supplies and consumer goods using small drones. For example, medical facilities are using sUAS to transport emergency medical equipment, medicine, laboratory samples, and/or vaccines. Indeed, there are several operational services internationally. Zipline International delivers blood, vaccinations, and medication in Rwanda and Ghana via UAS. In Switzerland, Matternet and Swiss post have launched a UAS delivery service for lab samples. Examples of emergency delivery undergoing testing include a partnership between DHL and Wingcopter (Tanzania), the MEDRONA project (Belgium), and SwoopAero (Vanuatu).

In the U.S., the FAA's UAS Integration Pilot Program (IPP) has brought state, local, and tribal governments together with private sector entities, such as UAS operators or manufacturers, to accelerate safe drone integration. The IPP has funded nine lead participants that are evaluating a host of operational concepts including: 1) package delivery (for both consumer goods and medical supplies), 2) flights over people and beyond the pilot's line of sight, 3) night operations, 4) detect-and-avoid technologies, and 5) reliability and security of data links between pilot and aircraft [17]. A number of these demonstrations include a variety of delivery use cases. For example, in North Carolina, Matternet and UPS are partnering to deliver medical supplies to a hospital. In April 2021, UPS also announced it was purchasing 10 eVTOL aircraft designed to accommodate shipping containers from Beta Technologies. UPS intends to test the aircraft as part of an express air delivery network, with the option of purchasing 150 additional aircraft. In California, Deloitte and Rady Children's Institute for Genomic Medicine are exploring plans to deliver lab samples via UAS. In the United Kingdom, Royal Mail has begun testing the use of drones to deliver parcels, personal protective equipment, and COVID tests between the mainland and the Isles of Scilly.

Fig. 4. On-Demand aviation marketplace ecosystem.

The use of sUAS for consumer goods delivery has also increased in recent years with a variety of small scale planned and operational demonstrations with Wing, Flirtey, Flytrex, DHL, EHang, Amazon, Uber Eats, and others. In the U.S., many of these operations have received a variety of FAA exemptions, such as approval for beyond visual line-of-sight operations, operations over people, and the ability to operate as sUAS air carriers (i.e. 'drone airlines').

2) Passenger Mobility: In the early 2010s, on-demand, app-based aviation services began entering the marketplace. In New York City, BLADE launched in 2014, providing helicopter services booked through a smartphone app. BLADE uses third-party operators that own, manage, and maintain their aircraft under FAR Part 135. BLADE passengers are required to check-in using valid government identification, and combined weight (passenger and baggage) must fall within permissible limits [18]. BLADE offers a variety of annual

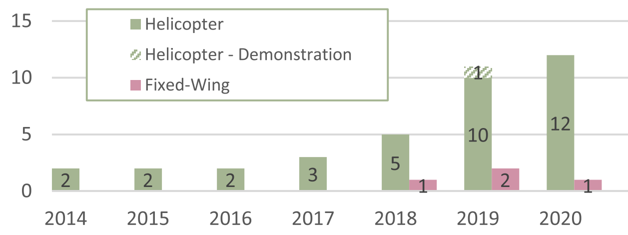

Fig. 5. Cumulative number of global UAM passenger services (2014-2020). *Thirteen services have launched, of which 12 are operational as of March 2020 (N = 13). SkyRyde is counted twice in 2018 and 2019, as it used both fixed-wing aircraft and rotorcraft. SkyRyde stopped flying fixed-wing aircraft in February 2019. In the SF Bay Area, BLADE offered both helicopter and fixed-wing service in 2019 and 2020.*

packages ranging from \$295 to \$795 US, which includes a per flight discount for the primary passenger and a guest. The discount ranges between \$50 to \$100 US per flight for the primary passenger and \$25 to \$50 US for their guest, depending on the package. Before the pandemic, BLADE launched similar on-demand services in the SF Bay Area and Mumbai. In December 2020, Blade announced that it would become publicly listed on the National Association of Securities Dealers Automated Quotations (or NASDAQ) as part of a merger with Experience Investment Corporation. The company also has announced plans to purchase 20 eVTOL aircraft from Beta Technologies. In Los Angeles, SkyRyde links passengers to pilots with privately owned helicopters. The service is currently on hold while it obtains FAA certification under Part 135 [19]. Skyryse, a startup focused on helicopter automation, debuted a demonstration in Summer 2019 shuttling passengers using piloted helicopters between John Wayne Airport and downtown Los Angeles for \$149 US per seat. In New York City, Uber Copter has been testing on-demand helicopter service since 2016. In July 2019, the service expanded its availability to a greater number of Uber users. The service can be booked up to five days in advance on the Uber app and offers eight-minute flights between Manhattan and JFK airport, typically costing \$200 to \$225 per person [20]. In December 2020, Uber Elevate (including the Uber Copter service) was sold to Santa Cruz-based Joby Aviation. As part of the sale, Uber is investing \$75 million US (in addition to \$50 million US previously invested in January 2020) [21]. In March 2020, Oregon Helicopters launched an on-demand rotorcraft service carrying passengers from personalized locations to downtown Portland or PDX International Airport. Internationally, Airbus' Voom operated similar helicopter services in Mexico City, Sao Paulo, and the SF Bay Area. The service ceased operations in April 2020 due to an overall drop in travel demand associated with the global COVID-19 pandemic [22]. Over its four years of operation (2016 to 2020), Voom reported 150,000 active app users, 15,000 helicopter passengers, and a 45% repeat customer rate. Over this period, Voom estimates an average ticket price approximately twice the cost of a private ground taxi with an average travel time savings of 90% [22]. The growth and estimated number of app- and web-based, on-demand UAM passenger services around the world using helicopters and fixed-wing aircraft are shown in Fig. 5 (N = 13). Twelve helicopter services are operational as of March 2020, and one demonstration ended in summer 2019. This excludes pre-arranged charter services from this analysis (as of January 2020, close to 2,000 operators were registered under Part 135 with the FAA).

In recent years, there has been an increase in the number of air charter brokers selling Part 135 on-demand capacity using business models, such as crowdsourcing, membership programs, and smartphone apps [23]. While there are a number of legal and regulatory considerations with this type of business operation, theoretically this model could be applied to UAM to help reduce costs by increasing load factors (similar to how pooled for-hire services help reduce traveler costs when Lyft and Uber trips have higher occupancies).

Other Industry Developments: NASA has established AAM Ecosystem Working Groups to solicit public and private sector expertise. Additionally, NASA has also launched the AAM National Campaign that aims to improve safety and accelerate scalability through demonstrations and ecosystem challenges in the U.S. In March 2020, NASA signed agreements with 17 companies to test the capabilities and readiness of vehicles and systems that could be used for UAM. In April 2020, the U.S. Air Force launched Agility Prime, a program seeking to identify opportunities of vertical flight for military applications prior to civil certification.

B. Phase Four: Corridor Services Using VTOL

It is estimated that in a future phase of UAM evolution (Phase Four) passenger operations will begin using VTOL aircraft. These operations may take the form of regularly scheduled "air shuttle services" that occur along specific air routes (e.g., between an airport and downtown), evolving from Phase Three services (e.g., BLADE, Voom, etc.). A few market studies estimate the potential for scaled operations and profitable services in the late-2020s and early 2030s based on a variety of pre-pandemic market assumptions [2], [3]. A number of service providers anticipate launching in the early- to mid-2020s. At least four companies plan to launch on-demand aviation services with electric VTOLs (eVTOLs) in the next decade including: 1) Volocopter in Singapore in 2021-26; 2) EHang in Linz, Austria in 2021; 3) Vertical Aerospace in London in 2022; and 4) Lilium in Munich, Orlando, and other cities around the world by 2024-25. Despite the recovery from the global pandemic, availability of certified eVTOL aircraft and other factors could impact the previously announced timelines. A few companies with unknown launch timelines include Archer, Joby Aviation (formerly Uber Elevate), Wisk (formerly Kitty Hawk), and Skyryse. Wisk plans to own, operate, and maintain up to 30 eVTOL aircraft that will be deployed on BLADE's platform. Skyryse plans to launch a service with autonomous helicopters vs. VTOLs. In Q1 2021, a number of VTOL manufacturers announced plans to go public. Lilium announced a \$3.3 billion US merger with Qell Acquisition Corporation and its intention to list on NASDAQ. In February 2021, both Joby Aviation and Archer announced plans to go public. Joby Aviation entered into a business agreement valued at \$5.7 billion US with Reinvent Technology Partners. After closing the transaction, Joby Aviation will be publicly listed on the New York Stock Exchange. Archer also announced plans to go public with a \$3.8 billion US valuation. The company has received investments from Stellantis, United Airlines, and Mesa Airlines, among others. Both United and Mesa anticipate acquiring up to 200 aircraft to provide airport shuttle service between smaller communities and hub airports [24]. In addition to Stellantis, other automakers that have announced investments in UAM include: Aston Martin, Audi, Daimler, Geely, General Motors, Hyundai, Porsche, and Toyota. The 2020s may also see a growth in UAS for goods delivery and emergency services to test unmanned traffic management and demonstrate safety. A number of pre-COVID market studies forecast the total market potential for UAS and UAM over the coming decade [2], [3], [25], [26]. These studies estimate a:

- *Total global market* projected between \$74 to \$641 billion US in 2035. The wide variation is due to scope; the \$74 billion US estimate only includes eVTOLs and excludes military applications.
- *Goods delivery market* projected between \$3.1 to \$8 billion US in 2030.
- *Passenger mobility market* - projected between \$2.8 to \$4 billion US in 2030.

However, these projections vary widely due to differences in assumptions (e.g., geographic region, timeline, etc.); methodologies; and the use cases examined. Additionally, the COVID-19 pandemic has the potential to impact the trajectory of the UAM marketplace in a number of ways. In the short term, the experimentation with UAS for new applications, such as social distancing enforcement; emergency medical delivery (i.e., viral tests); and sanitation could increase exposure to innovative aviation use cases, but also raise concerns (e.g., privacy, noise, and safety). The pandemic could accelerate the replacement of rotorcraft with eVTOLs as air carriers seek to reduce their operational costs during the economic downturn. Additionally, while some OEMs and service providers press forward, others are changing business models, capital expenditures, and investments in research and development. The longer-term growth of e-commerce, work-from-home/telework, and potential shifts to suburban/exurban lifestyles could also change the type of UAM uses cases envisioned.

C. Phase Five: Hub and Spoke Services

Phase five may experience increased infrastructure investments to support "air metro services" as the cost of flights decrease and societal adoption might begin to mainstream. These services could be comprised of multiple flights per day between a vertihub (two or more landing pads that each accommodate multiple aircraft) and numerous vertiports (single landing pads that accommodate two to three aircraft) forming hub and spoke operations throughout an urban area. For example, vertihubs may be located in dense commercial centers with vertiports located throughout lower-density residential communities. Flights may be scheduled at regular intervals throughout the day, and more passengers may share a flight, reducing the price per seat. However, land use, demand, and travel patterns could also contribute to directional travel patterns that could result in higher costs and lower load factors due to deadheading (i.e., an aircraft without passengers or goods repositioning to another location). These potential market developments will likely need to be supported by technological improvements, such as dynamic pricing and advanced algorithms to reduce deadheading, improved battery capacity, reduced charging times, and enhancements in UTM.

D. Phase Six: Point-to-Point Air Taxi Services

The most advanced phase culminates with the arrival of "air taxi services" that provide near point-to-point, on-demand service using a variety of infrastructure sizes depending on urban density and flight demand. However, true point-to-point service using aircraft in urban areas may never become technically feasible due to infrastructure and capacity limitations, dependability due to weather, and concerns about noise, safety, air traffic, and other impacts associated with dispersed and scaled operations. These and other challenges to market feasibility are explored in the next section.

VI. Potential Challenges

As an emerging concept, UAM will face many barriers, such as safety and the regulatory environment; air traffic management; noise; community acceptance; weather; environmental impacts; infrastructure; and security. This section discusses a number of potential barriers that could limit UAM growth and adoption and some strategies that could help overcome these challenges.

A. Safety and the Regulatory Environment

Valid concerns about the safety of UAM users, other airspace users, and bystanders (i.e., people flown over on the ground) could present safety risks and barriers to adoption. Aviation safety is supported by a robust policy and regulatory environment governing aircraft and airworthiness; operations (including crew requirements); and access to airspace [27]. Civil aviation authorities have a number of tools, such as certification, operational approvals, airspace access, and others to promote safety. A few key areas include issuing and enforcing regulations, advisories, guidance, means of compliance, and minimum standards:

- Governing the manufacturing, operation, and maintenance of aircraft;
- Certifying pilots, aircrew, maintenance, and other personnel;
- Certifying aviation facilities; and
- Operating a network of air navigation, airspace, and air traffic management facilities, including developing air traffic rules and assigning the use of airspace.

This broad regulatory scope provides a toolbox of approaches that civil aviation authorities can use to manage and promote the safety of all stakeholders [3], [27]–[30]. In addition to national civil aviation authorities, state and local governments can promote safety through land use and zoning, building and fire codes, and law enforcement operations.

Six system-wide, safety-critical risks that will need to be addressed (see [16], [27]) include:

- Flight outside approved airspace;
- Unsafe proximity to people and/or property;
- Critical system failure (e.g., degraded or loss of command and control, GPS; engine failure; etc.);

- Loss of control (e.g., flight control system failure);
- Cybersecurity risks; and
- Hull loss.[1]

Other potential hazards could include weather, avian/birds, air and ground crew human factors (i.e., loss of situational awareness, task saturation, etc.), passenger interference (i.e., disruptions, hijacking, sabotage, etc.), and others.

Under the current regulatory regime only standards exist for on-board piloted operations. The legal, policy, and regulatory environment may present challenges for certifying and authorizing the use of some novel technologies and combinations of features that could be found in UAM aircraft. While this is not an exhaustive list, some of these could include distributed electric propulsion/tilt-wing propulsion, VTOL, autonomy hardware and software, optionally piloted configurations, electric energy storage, and others. While established processes can delay technology deployment as manufacturers, air carriers, and aircrew go through certification and training processes that may delay deployment; these regulatory processes can also be an enabler by providing public assurance that the standard for safety is sufficiently high.

Efforts are underway to identify and address regulatory and safety challenges for emerging aviation technologies, such as:

- *Autonomy and Highly Complex Software:* Machine learning and other algorithms are non-deterministic, which means that even for the same input, the algorithm may exhibit different behaviors on different runs [3], [27].
- *Electric Propulsion and Energy Storage:* Both propulsion and energy storage may pose a variety of challenges. More research is needed to understand a variety of risks associated with aircraft electrification [3], [27].
- *Unmanned and Optionally Piloted Aircraft:* In order for UAM aircraft to operate autonomously, there are a number of operational risks, such as physical security, operational procedures, cybersecurity and unmanned traffic management that will need to be considered as part of airworthiness [3], 27].
- *Ratio of Aircraft to Operators Less Than 1:* Several UAM business models involve a transition period to full autonomy that may include operations centers with remote operators controlling multiple aircraft. The associated operational risks will need to be considered as part of airworthiness certification; airspace access; crew training; certifications; and operational approvals [3], [27].

Waivers, policy changes, and/or additional regulations will likely be needed for the certification and authorized use of many of these operations and technologies. Finally, due to the multi-disciplinary nature of UAM, a number of other regulatory agencies could have formal, informal, and quasi regulatory roles, such as the Federal Communications Commission (FCC) (regulating the radio spectrum); Environmental Protection Agency (regulating emissions); Occupational Health and Safety Administration (OSHA) (regulating workforce safety); and state departments of transportation, insurance, and public utilities commissions.

[1]A hull loss if often the result of a chain of events that leads to a safety incident that damages an aircraft beyond repair. Hull losses typically result in on-board fatalities and may also include fatalities involving people outside of the aircraft.

B. Air Traffic Management

UAM operations are expected to take place at relatively low altitudes and in dense, urban environments. One of the principal challenges with UAM is that it will likely have to interact with commercial aviation and UAS ecosystems in a variety of contexts. Commercial air carriers operate with experienced pilots in controlled airspace where air traffic controllers have the authority to direct air traffic. In recent years, UAS has generally evolved in low-level and uncontrolled airspace using a different set of regulations, often with relatively inexperienced operators. UAM services operating in urban areas (and particularly to/from large and medium airports) will likely fly in both controlled and uncontrolled airspace, and it will also need to ensure safe take-off, approach, and landing alongside drones that typically operate below 400 feet.

The FAA's UAM Concept of Operations (ConOps) v1.0 describes the envisioned operational environment to support the anticipated growth of flight operations in and around these urban areas [31]. The ConOps presents the FAA's air traffic management (ATM) vision to support initial UAM operations in urban and suburban environments. The ConOps envisions that initial UAM operations will be comprised of a small number of low complexity operations and will evolve to mature state operations with a high density and high rate of complex operations. As the operational tempo of UAM increases, the ConOps envisions the establishment of "UAM corridors" where piloted aircraft will have the capability to exchange information with other corridor users in order to deconflict traffic without relying on air traffic control (ATC). In the future, remotely piloted and autonomous aircraft could allow for increasingly complex and higher volume operations; however, the development of new regulations, policies, procedures, guidance materials, and training requirements are needed to enable such operations. The ConOps also envisions the establishment of "Providers of Services for UAM" (PSUs) to support operations planning, operational intent (a technical term describing a UAM flight plan), airspace management, and information exchange during operations. The PSU would process flight requests; evaluate the operational intent for air traffic, space availability, and adverse conditions; and if approved facilitate information sharing with the PSU network. Because it is envisioned that multiple PSUs can provide service within the same geographic area, the PSU network is a collection of PSUs that share data.

The ability for UAM to transition from either uncontrolled Class G airspace and/or UAM corridors to busy controlled airspace (i.e., Class B) without overwhelming ATC represents a key unresolved challenge. Additionally, the ability for UAM aircraft and PSUs to communicate with both commercial and general aviation aircraft (which have a range of sophisticated to basic avionics and communication capabilities, respectively) is also unresolved. Procedures will need to be established for resolving collision avoidance alerts, particularly between UAM and commercial (Part 121) aircraft. As the number of operations increase, collision avoidance, communication, and management systems of both UAM and non-UAM airspace users may need to adapt. To ensure constant communication for operations near buildings (where GPS signals may be blocked), the aviation industry may need to invest in data link, 5G, or other information technology (IT) infrastructure. Governments are also exploring the use of UTM – automated systems that continuously monitor aircraft systems – to manage increased demands for airspace by new users. In March 2020, the FAA released the UTM Concept of Operations 2.0 that seeks to address more complex airspace operations in the U.S. The UTM ConOps 2.0 focuses on UAS operating at or below 400 feet above ground level, but it also addresses increasingly more complex operations within and across controlled and uncontrolled airspace [32].

C. Noise

Aircraft and rotorcraft noise are a frequently cited nuisance in neighborhoods around airports and heliports. In the near future, the high level of rotorcraft noise will likely limit the use of helicopters in urban areas. Reference [33] conducted a general population survey across four locations - Los Angeles, Mexico City, Switzerland, and New Zealand. The study found that the second and third highest factors impacting UAM public perceptions were the type of sound generated by eVTOL aircraft, followed by the volume of sound generated from an aircraft. An exploratory study by [34] included a combination of focus groups in Los Angeles and Washington, D.C. and a general population survey in five U.S. cities. The study found that noise levels could impact support for UAM by the public. Reference [4] estimates that eVTOL aircraft should be one-half as loud as a medium-sized truck passing a house (75 to 80 decibels at 50 feet; approximately 62 decibels at 500 feet altitude) – approximately one-fourth as loud as the smallest four-seat helicopter on the market. As the UAM market matures, noise concerns could be mitigated through technological improvements (i.e., aircraft design and electrification) or persist as the market matures into larger-scale operations (e.g., total ambient aircraft noise from multiple aircraft operating in close proximity). Additionally, as surface transportation electrifies, a potential reduction in ambient urban noise could make aircraft noise more perceptible in the future than it is today.

Under existing law, local governments can plan and mitigate aviation noise primarily by promoting compatible land uses, requiring real estate disclosures, and including noise data in municipal codes. With respect to larger aircraft (e.g., commercial aviation operations), the Airport Noise and Capacity Act (ANCA) of 1990 prohibits local governments from implementing aircraft noise restrictions after October 1990. Although airports can apply to the FAA to impose additional noise restrictions, such as curfews under FAR Part 161, as of April 2020 no airports have successfully received approval [35]. In some cases, communities have closed smaller airports in response to community complaints about noise and quality of life (e.g., Santa Monica airport is now scheduled to close in 2028). Although the FAA and other regulatory bodies have set thresholds for community noise around airports, UAM may need to meet a stricter noise standard due to the nature of low-level flight over highly populated urban areas, coupled with scaled operations [4]. In the future, legislative and regulatory reform may expand policy mechanisms for noise abatement by local communities.

D. Community Acceptance

Negative community perceptions could pose challenges to adoption and mainstreaming. A few key potential concerns include noise (previously discussed); visual pollution and privacy (particularly for flights over residential land uses); social equity (perceptions that UAM is a mode for wealthy households to buy their way out of congestion); and safety and security, among others. Each of these could impact user and non-user community acceptance. Table III summarizes these barriers and includes potential mitigation strategies that could help overcome these challenges.

In particular, social equity may be one of the largest barriers to community acceptance. Current on-demand aviation services have typically averaged $149 to $300 US per seat (although some are considerably more expensive). Today, these price points serve higher-income and business travelers. While proponents compare UAM to early commercial aviation and the eventual democratization of air travel, it took decades for the industry to achieve mass market affordability. Additionally, the business models of intraurban, small aircraft operations are quite different from commercial aviation. Reference [36] estimate eVTOLs will reduce total operating cost per seat mile by about 26% (compared to helicopters currently in use). Porsche Consulting estimates on-demand air taxis will cost $8 to 18 US per minute [24]. McKinsey and Company estimate that an "air metro" type service will cost $30 US per trip in 2030, while air taxis will remain higher, ranging from $131 to $1,912 US per trip (depending on vertiport density) [2]. While aircraft electrification and autonomy may be able to reduce costs, both can raise other types of community concerns, such as range anxiety and the safety of remotely piloted and autonomous aircraft. In summary, there is uncertainty about how much UAM will ultimately cost, how long it will take to become affordable (if ever), and what type of public investment (if any) should support UAM.

While a number of surveys have attempted to understand barriers to community acceptance, the lack of public experience with UAM aircraft and scaled operations represents notable limitations of these studies (i.e., it is difficult for respondents to accurately comment on something they have no direct experience with) [2]–[4], [33], [34], [37]. In November 2019, the Community Air Mobility Initiative (CAMI), a non-profit industry association, was established to educate and provide resources to the public and local, state, and provincial decisionmakers. Community engagement and research are needed to advance understanding of potential societal barriers and policies that serve the public good. In October 2020, the Canadian Air Mobility Consortium (CAAM) was established to support the planning and implementation of UAM in Canada.

E. Weather

Weather could pose a number of critical safety and operational challenges for UAM. First, the safety risks and sensitivity of aircraft and passengers to weather hazards increases with the decreasing size of aircraft. A variety of weather conditions, such as low visibility, icing (snow/ice that accumulate on flight surfaces), wind shear, and thunderstorms could present

TABLE III
POTENTIAL COMMUNITY ACCEPTANCE CHALLENGES AND MITIGATION STRATEGIES

Community Acceptance Challenge	Potential Mitigation Strategies
Noise, Visual Pollution, and Privacy • Individual aircraft and scaled operational noise • Aesthetic impacts of low-level aircraft on views and/or the natural environment • The use of cameras or sensors to take to take photos, videos, or other surveillance without someone's knowledge or consent • Data privacy including the collection, storage, management, and sharing of user, financial, location, and trip data	• Visual simulations of UAM operations for communities • Flight operations at higher altitudes • Flight path deviations to avoid sensitive areas • Time of day flight restrictions • Flight paths over existing transportation corridors (i.e., highways, sea lanes, and air routes) • Incorporate potential community concerns into vertiport planning (e.g., siting, ground access, approach paths) • Limits on aircraft density (i.e., limiting the number of aircraft and/or flights) • Restrict the use of photo- and video-graphic equipment on aircraft • Establish national and state legislation, regulation, and standards for how UAM service providers handle and protect consumer data (e.g., requiring consent for data sharing, anonymizing data collected, providing data breach notifications, allowing travelers to know what data are being collected, the ability to opt-in or out of data collection, and enabling consumers to request the deletion of personal information)
Social Equity • Accessibility for people with disabilities • Mass market affordability for all users	• Consider Americans with Disabilities (ADA) access as part of all planning and implementation processes • Ensure fair treatment and meaningful involvement through community engagement of all people (UAM users, non-users, and other airspace users) in planning process • Expand access through special pricing models, subsidies, and other programs that expand access to low-income and marginalized communities
Personal Safety • Personal safety from other passengers	• Passenger background checks • No-fly lists for people convicted of certain criminal offenses • Passenger rating systems • Emergency dispatch buttons • Individual passenger compartments within an aircraft
Operational Safety and Security • Public concerns about operational safety (new propulsion types, range anxiety, autonomy) • Cyber and physical security threats, such as sabotage and terrorism	• Build public trust through demonstration programs and independent evaluations • Public education and outreach about certification, airworthiness, and other regulatory processes intended to protect public safety • Personnel and passenger background checks • Evaluate potential strategies for communication, surveillance, and navigation to provide system redundancy • Develop data sharing, security, and emergency response protocols for pre-, mid-, and post- flight

a number of safety, operational, and reliability challenges for UAM. Some of these challenges could be greater for UAM due to low-altitude operations over urbanized areas and an additional critical phase of flight (i.e., the transition from vertical to horizontal flight for VTOL operations). Strategies that are typically used in commercial aviation to overcome adverse weather conditions, such as delaying and rerouting flights to alternate airports are not particularly viable strategies because the value proposition of UAM is premised on convenience and time savings over other transportation modes. Additionally, a number of proposed technologies for autonomous flight operations degrade in low visibility conditions (i.e., lidar).

An exploratory UAM climatology analysis, representing ten U.S. cities with a variety of typologies and weather patterns, found the most favorable weather in the Pacific region of the U.S. (e.g., California and Hawaii), with much less favorable conditions along the Northeastern Seaboard (e.g., New York City) and Rocky Mountain regions (e.g., Denver) [38]. Average weather conditions were found to be less favorable conditions for UAM operations in most seasons along the Eastern Seaboard and the Southwest regions due to higher frequencies of non-visual flight rules conditions, high winds, and vertical wind shear [3]. The study also found that UAM could face critical weather challenges in the Rocky Mountain region due to lower temperatures, strong winds, and thunderstorms [38]. However, it is difficult to estimate the precise impacts of weather on UAM operations due to a variety of climates and aircraft under development (each with different performance limitations). The ability for UAM to scale operations may be highly dependent on the ability to provide dependable and consistent service with minimal delays. The integration of UAM into mobility on demand and mobility-as-a-service platforms could help to improve traveler reliability and minimize delays by automatically routing a traveler's journey around travel disruptions, such as weather [39]. This could include shifting trips from UAM to other modes at the onset of adverse weather.

In summary, weather could be an important factor for why UAM may succeed in some markets and not others. UAM air carriers and aircraft manufacturers may be able to consider mixed fleets of aircraft with different performance capabilities suited for a variety of weather conditions and climates.

F. Environmental Impacts

Interest in UAM has been closely linked to the development of electric-powered aircraft. UAM proponents suggest that the shared use of electric aircraft could result in emission savings (in contrast to gas-powered vehicles, small aircraft, and helicopters). Reference [40] modelled the environmental impact of eVTOLs using 2020 estimates for average U.S. electric generation emissions. The study estimates that an eVTOL with one occupant (i.e., a pilot and no other passengers) resulted in 35% lower greenhouse gas emissions than a single occupant gas-powered vehicle, but 28% higher emissions than a battery electric vehicle (BEV) with the same occupancy. However, this study estimates that an eVTOL carrying three passengers' results in lower emissions than conventional vehicles and BEVs with an average occupancy of 1.54. However, it is likely that in early years of operation, UAM will rely on helicopters and VTOLs powered by non-renewable sources. Battery technology has yet to realize the range needed to make passenger UAM competitive. Similarly, pooled flights (with multiple passengers) will be important for achieving emission savings and maximizing the sustainability of urban flight. Reference [40] did not factor life cycle emissions, such as aircraft production and end-of-life due to the lack of standardization in design, production processes, and materials.

UAM also has the potential to induce demand due to reduced travel times and costs (the latter if autonomy, electrification, and load factors can reduce prices and increase affordability). More research is needed that factors these considerations into environmental assessments.

G. Infrastructure

Successful deployment of passenger UAM will require extensive infrastructure such as a network of vertiports; charging/fueling stations; and communications, navigation, surveillance, and IT infrastructure. Initially, air carriers may be able to make use of existing helipads. As UAM evolves and scales, infrastructure and service providers will need to identify existing infrastructure and better understand how it can be repurposed with minimal physical modification, renovated and adapted, or replaced and redeveloped for UAM. However, constructing new vertiports could face a variety of challenges, such as local opposition, cost, and multimodal integration.

A number of service providers have announced plans to develop new vertiport infrastructure. For example, Lilium announced plans to construct a vertiport in Lake Nona near Orlando International Airport in November 2020 [41]. As service providers prepare to build their infrastructure networks, communities may need to decide whether UAM infrastructure should be exclusive to a single service provider; preferential use for some service providers but open access to all; or open to multiple air carriers (e.g., similar to airports). Publicly funded infrastructure could ensure vertiport access for multiple air carriers and allow for a greater network of connections, whereas privately funded infrastructure may be faster to fund and construct. Communities may also need to tailor planning considerations, land use policy, and infrastructure to an array of urban contexts (i.e., urban, suburban, edge city, exurban, rural). A variety of different sized facilities (i.e., vertipads, vertiports, and vertihubs) could evolve based on operational tempo, traveler demand, urban density, and the surrounding built environments. Communities with water resources could also potentially use seaplanes and amphibious aircraft to reduce the need for new infrastructure.

Urban planners have access to a variety of tools that could support community integration. For example, in Los Angeles, the city previously required the construction of emergency helipads for high-rise buildings as part of their fire code. Further, the use of overlay districts could provide an additional level of development standards around vertiports or limit building heights to preserve airspace access to a facility. Form-based code is another tool that can be used to achieve a desired built environment in the vicinity of vertiports. Higher density and mixed-use development could also create synergies with public transportation and provide alternatives in the event of inclement weather or other operational delays. Communities will likely need to consider the ‘complete UAM trip’ that accounts for every step in a traveler’s journey, such as booking, first- and last- mile connections to a network of vertiports, and arrival at a traveler’s destination [39]. The U.S. Department of Transportation has developed a Mobility on Demand Planning and Implementation guide intended to aid local, regional, and state governments to prepare for mobility innovations, such as UAM/AAM and automated vehicles [39]. NASA is developing a Regional Modeling UAM Planning Tool to aid communities in vertiport selection and decision-making processes [42]. Ohio is proposing a statewide AAM planning framework for metropolitan planning organizations.

Additionally, energy infrastructure could represent another UAM challenge. Ensuring a network refueling facilities (e.g., aviation fuel, hydrogen, and other alternative and/or biofuels); charging infrastructure; and battery swapping could create a variety of logistical, operational, and technical challenges. For eVTOL, new charging infrastructure and power grid improvements will be necessary. Supportive infrastructure, such as ground battery storage, may be needed to manage peak use and flatten demand on the power grid.

Finally, some challenges exist to adapting and building communications, navigation, surveillance, and other IT infrastructure for scaled UAM operations. Reliance on voice communications has a number of challenges such as responding to transmissions, difficulty hearing transmissions, etc. Both scaled operations and aircraft autonomy will require secure data links (or another type of technology) to send information between aircraft and air traffic control [6], [16]. Standards will need to be developed for data architectures, communications, navigation, and surveillance [16]. Adapting legacy systems, implementing new technologies, upgrading systems, and ensuring cybersecurity of all shared airspace users represent key challenges [16]. Cyberattacks, such as the injection of false flight data and jamming ATC and aircraft communications, present notable safety and national security risks that could create significant disruptions for the national airspace system. In some cases, the same or similar digital infrastructure used by connected and automated vehicles could be applied to or communicate with UAS and UAM. However, this could also create competing demands for the radio spectrum, which is a finite natural resource needed to manage and maximize safety, economic development, and the social good. All of these physical, energy, and IT infrastructure challenges have the potential to impact UAM’s development.

H. Security

Ensuring personal, personnel, physical, and cybersecurity of all aspects of UAM will be critical to maintaining safety and public confidence. During the exploratory focus groups conducted by [34], participants raised numerous concerns about the personal security of the passengers during booking, boarding, and on-board the aircraft from departure to arrival. Some concerns identified include hijacking, people pointing lasers at passengers on take-off and final approach, and violence against passengers (particularly in an autonomous scenario without any aircrew on-board). Advanced technologies, such as biometrics, passenger rating systems, and trusted traveler programs (similar to the Transportation Security Administration’s PreCheck that offers reduced passenger screening for passengers that have completed a vetting process) are a few strategies that could be employed to enhance personal security for a passenger’s journey. Additionally, regulators, air carriers, and ancillary service providers will need a system of policies and procedures to mitigate the risk of insiders (i.e., workers, contractors, vendors, etc.) from exploiting their legitimate access to UAM infrastructure and services for unauthorized purposes. Moreover, the physical security of the vertiports, aircraft, charging/refueling, other physical infrastructure, and cargo will also need to be ensured. Finally, cybersecurity of all the enabling IT systems, including but not limited to ticketing/booking, air traffic management, communications, navigation, surveillance, and autonomous aircraft systems will be critical. Close coordination among private sector stakeholders, law enforcement, and national security agencies is necessary to establish security standards and emergency plans for an array of scenarios.

VII. Conclusion

While UAM is not new, the concept and technology are evolving. This paper summarizes the on-demand aviation ecosystem and proposes six phases of historical and anticipated evolution. Ongoing discussion is needed to further develop industry terms, concepts, and policy.

Despite UAM's goals of providing safe, sustainable, affordable, and accessible mobility, it faces some challenges including: public acceptance regarding noise, safety, and societal equity. Demonstration projects and operational standards, such as flight restrictions over residential areas, at night, and during poor weather conditions; and zero emission standards could help to ease UAM's introduction. Furthermore, early VTOL operations will likely require substantial coordination and investment from industry and the public sector to develop infrastructure and scale operations.

Around the world, cities are experimenting with sUAS to respond the COVID-19 pandemic, such as: 1) social distancing and protective equipment reminders, monitoring, and enforcement; 2) virus detection; 3) delivery of goods and essential equipment; and 4) sanitation or disinfecting of public spaces. While the global pandemic has the potential to increase public familiarity with sUAS, some have raised concerns about privacy, civil liberties, and efficacy achieving desired health and policy goals. It remains to be seen whether the increasing use of sUAS during the pandemic translates into increased public awareness, acceptance, or apprehension for UAM and AAM more broadly.

The global pandemic is impacting both the AAM ecosystem and travel and consumer behavior more broadly. It is likely shifting the overall industry trajectory. The pandemic has the potential to accelerate the transition from passenger rotorcraft to eVTOLs as air carriers seek to cut costs during the economic recession. Additionally, some OEMs and service providers may change their business models, capital expenditures, and investments in research and development as the pandemic changes business goals and priorities. Finally, the growth of e-commerce and UAS for pandemic use cases could cause the private sector to focus more heavily on logistics, aeromedical, and disaster response than passenger mobility for early adoption.

More research is needed to better understand the opportunities and challenges of UAM, such as early use cases to aid in evacuation and recovery efforts (e.g., wildfires, floods, etc.). Furthermore, research is needed to understand the environmental, travel behavior, lifecycle, and network effects of UAM. Efforts should also be made to analyze the social and economic impacts of UAM on communities and to address concerns of inequality (i.e., income divide). Additional research could include: 1) integrating UAM and sUAS in the same airspace through UTM testing; 2) safety and health impacts; 3) identification of data needs (e.g., data metrics, data formats, and standards for sharing); 4) UAM public perception; and 5) best practices for multimodal integration and vertiport design. These topics were raised during stakeholder engagement sessions informing this paper. Moving forward, ongoing research, thoughtful planning and implementation, and study of UAM impacts are needed to balance commercial interests, technology innovation, and the public good.

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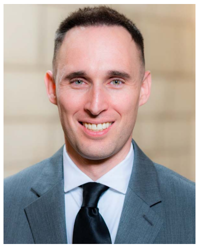

Adam P. Cohen received the M.C.R.P. degree in city and regional planning and the M.S. degree in international affairs from the Georgia Institute of Technology, Atlanta, GA, in 2008. He is currently the Senior Research Manager of the Transportation Sustainability Research Center, University of California at Berkeley, Berkeley. Since joining the group in 2004, his research has focused on innovative mobility strategies, including urban air mobility, shared mobility, last-mile delivery, automated vehicles, smart cities, and other emerging technologies. He has also worked for the Federal Emergency Management Agency (FEMA) and the Information Technology and Telecommunications Laboratory (ITTL), Georgia Tech Research Institute (GTRI). He has coauthored numerous articles and reports on innovative mobility, including a NASA Market study for Urban Air Mobility. He serves as the Vice Chair for SAE International's Shared and Digital Mobility Committee and the Co-Chair for TRB's Standing Subcommittee on Equity of Innovative Mobility Services and Technologies. His unique multi-disciplinary background gives him unique insight into both landside and airside aviation issues, including the potential impacts of innovative and disruptive technologies.

Susan A. Shaheen is currently a Professor with the Department of Civil Engineering and the Co-Director of the Transportation Sustainability Research Center, University of California at Berkeley, Berkeley. She has authored 76 journal articles, more than 125 reports and proceedings articles, 19 book chapters, and co-edited two books. In May 2019, she received the Most Influential Paper Award from the World Conference on Transportation Research. She was named as the "Faculty of the Year" by the Institute of Transportation Studies, Berkeley, in December 2018, and received the 2017 Roy W. Crum Award from the Transportation Research Board (TRB) for her distinguished achievements in transportation research. In May 2016, she was named one of the top ten academic thought leaders in transportation by the Eno Transportation Foundation. In 2021, she became the Chair of the TRB Executive Committee. She was the Founding Chair of the subcommittee for Shared-Use Vehicle Public Transport Systems of TRB (phased out in 2020) and served as the Chair of its Parent Committee on Emerging and Innovative Public Transport and Technologies Committee (AP020) for seven years. She is also a member of the Mobile Source Technical Review Subcommittee to the U.S. Environmental Protection Agency's Clean Air Act Advisory Committee and a Former Member of the ITS Program Advisory Committee of the U.S. Department of Transportation.

Emily M. Farrar received the M.S. degree in civil engineering from the University of California at Berkeley (UC Berkeley), CA, USA, in 2018. She is currently pursuing the Ph.D. degree with the Department of Civil and Mineral Engineering, University of Toronto. From 2018 to 2020, she has worked as a Research Associate with the Transportation Sustainability Research Center, UC Berkeley. Her research interests include urban air mobility, shared micromobility, and the environmental impacts of emerging mobility services.