A Proposed Taxonomy for Advanced Air Mobility

Laurie A. Garrow,[1] Brian J. German,[2] Noah T. Schwab,[3]
Georgia Institute of Technology, Atlanta, GA, 30332, U.S.A.

Michael D. Patterson,[4] Nancy L. Mendonca,[5] Yuri O. Gawdiak,[6] and James R. Murphy[7]
National Aeronautics and Space Administration, U.S.A.

There has been a large growth in interest of utilizing new technologies—most notably electrified propulsion and automation—as well as new business models to bring aviation services into the daily lives of a greater segment of society. Generally, these services are envisioned to augment existing ground modes of transportation or to enable new operating capabilities for shorter-range aviation missions. These services, which have become known as advanced air mobility (AAM), include passenger transportation, cargo transportation, and aerial work missions, such as aerial photography. In this paper we describe advanced air mobility and provide a framework based on demand and supply concepts that can be used for developing a taxonomy for AAM with a focus on passenger applications. This taxonomy is intended to facilitate the nascent AAM stakeholder community in adopting a common terminology and to enable better coordination among disparate AAM research and development activities.

I. Introduction

In recent years there has been a growing interest in regularly transporting passengers and cargo in small aircraft over distances that have historically been served by ground transportation modes. Although the general concept of flying a small aircraft for transportation is not new, over approximately the past decade there have been advancements in technologies and societal changes that may make these operations become a practical part of the average person's typical experience. Notably, the convergence of new technologies, such as electric propulsion and autonomy, as well as new business models, such as mobile application-based ride sharing and network-enabled on-demand services, are generating the potential for new aviation markets to emerge. These new aviation markets are becoming collectively known as advanced air mobility (AAM).

AAM aims to reinvent the idea of air travel. While the current commercial air transportation system is distinct from other modes of transportation because it has a monopoly on long-distance, high-speed journeys, AAM systems

---

[1] Professor of Civil and Environmental Engineering and Co-Director of Center for Urban and Regional Air Mobility, AIAA Member.
[2] Associate Professor of Aerospace Engineering and Co-Director of Center for Urban and Regional Air Mobility, AIAA Associate Fellow.
[3] Undergraduate Aerospace Engineering Student, AIAA Member.
[4] Emerging Applications & Technologies Group Lead, Aeronautics Systems Analysis Branch, NASA Langley Research Center, 1 N. Dryden St. MS 442, AIAA Senior Member.
[5] Deputy AAM Mission Integration Manager, NASA Headquarters, 300 E St SW, Washington, DC 20546.
[6] Airspace Operations & Safety Program Associate Program Director, NASA Headquarters, 300 E St SW, Washington, DC 20546, AIAA Senior Member.
[7] AAM Mission System Architect, NASA Ames Research Center, MS: 243-1, Moffett Field, CA 94035, AIAA Associate Fellow.

have been envisioned to become an integrated part of a city's or region's transportation system and, therefore, everyday life. AAM would work cohesively with ground-based modes as a segment of a customer's multimodal journey to take advantage of high travel speeds and ground traffic avoidance. For instance, customers might start their journey via a car ride-hailing service to arrive at a vertiport where they then board an AAM aircraft. This aircraft could then cruise to and land at a multimodal transit hub across town where the customers can board a subway train to their final destination.

Because the AAM field is revolutionary, has grown quickly, and has stakeholders from historically disparate domains, the body of research has many divergent visions. The diversity of visions has resulted in the creation of many new terms and uses of terms across domains that are often inconsistent. The current body of AAM publications is problematic in that different publications use distinct terminologies to describe similar concepts or use the same terminologies with different assumptions and meanings. Further, for AAM to become an integrated part of a multimodal transportation system, it is important that these new operational terminologies have a level of compatibility with previously defined concepts for ground-based modes. There is a need for standardization and cohesion across the body of AAM literature to foster coordination across the academic, business, and regulatory AAM visionaries and stakeholders. The creation of a common taxonomy will improve the communication and synergy amongst future AAM researchers. Consequently, the major purpose of this paper is to lay out a proposed taxonomy of AAM with a focus on passenger applications based on a survey of related terminology from the existing literature.

We begin the paper with a brief description of AAM and a succinct discussion of the history behind AAM. Next, we provide an overview of literature related to AAM with a specific emphasis on the high-level concepts and market evolution considerations. Then, we present the proposed taxonomy, which is focused on passenger-carrying AAM missions and is built around a supply and demand framework. Within the framework, only a subset of potential terms is defined, focusing on areas that have novel considerations specific to AAM. Within these sections we discuss interactions between the demand and supply sides of the AAM market.

II. A Brief Description of Advanced Air Mobility

NASA defines AAM as *safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions*. As such, AAM is a broad term that covers an array of missions that may be performed in different types of aircraft flying between and over many different locations, including bringing aviation capabilities to areas that are not currently served by aviation. AAM can encompass passenger transport, the movement of cargo or goods, and aerial work missions. The general sentiment behind AAM is bringing aviation into the ordinary experiences of average people, which implies that AAM involves using smaller aircraft for shorter-range and/or shorter-endurance missions than have been typical historically. An artistic depiction of multiple advanced air mobility missions is provided in Figure 1.

The first key component of the AAM definition is that the mission must be transformational—i.e., there must be a substantive change to aviation's role in the mobility landscape. This change could be realized in one or many different dimensions, including the cost to perform the mission, the locations from which the aircraft takes off or lands, the number of flight operations observed, the ease of use, and so forth. Ultimately, truly transformational changes will have demonstrable improvements on how society operates.

A second critical distinguishing characteristic of AAM missions is that they are either "local" or "intraregional," meaning these missions cover relatively short ranges. Local missions occur within a local area, such as a metropolitan statistical area, whereas intraregional missions occur within a region, such as a US state. Although there is no clear "bright line" to delineate the mission ranges, generally speaking, local missions are those of up to approximately 50 to 75 miles and "intraregional" missions are those up to approximately 500 miles. These mission distances help distinguish AAM from much of traditional aviation, which typically involves flights of greater distances.

The adjectives *safe*, *sustainable*, *affordable*, and *accessible* are included in the definition of AAM to highlight features of these new aviation missions in several important axes. Although elements of these terms are important for virtually any aviation capability to be successful in the marketplace, their inclusion collectively in the definition of AAM is intended to convey the sentiment that AAM will enable more people to practically utilize aviation than ever before and to make aviation a more common part of individuals' regular experiences. In this sense, they help identify key aspects that can classify missions as transformational compared to prior aviation missions and markets.

At the time of writing this paper, a more in-depth description of AAM, including more detailed descriptions of each of the adjectives in the AAM definition, is being written and is planned for publication by NASA by the summer of 2022. For the sake of keeping the discussion here more concise and avoid duplicating the other publication, we will only briefly describe what is perhaps the least clear of the adjectives in the AAM definition: *accessible*. Accessible here refers to the ability of end users to conveniently access the aerial service. Accessibility includes (but is not limited to) consideration of the requesting/booking of the service, the proximity of takeoff and landing locations to the ultimate desired origin and destination, the integration with other transportation services, the training required for utilizing the service, and the ability of individuals with disabilities to easily utilize the service. Although there are no strict requirements on any of these parameters, in order to provide a transformational capability, AAM must be more accessible than historic aviation. One of the most notable increases in accessibility of many proposed AAM services is their on-demand nature—i.e., customers will have access to AAM services more closely to when and where they want them than has been achieved historically.

Figure 1: An artistic depiction of various AAM missions.

There are generally three broad application categories within AAM: urban air mobility (UAM), regional air mobility (RAM), and low altitude mobility (LAM) [1]. We call these application categories because there are many specific potential missions within each of these categories. UAM is "a safe, efficient, convenient, affordable, and accessible air transportation system for passengers and cargo…around metropolitan areas" [2]. Most envision UAM missions with small, electric vertical takeoff and landing (eVTOL) aircraft flying passengers across town, including from rooftops. Many immediately think of UAM when thinking of AAM, but UAM is only a subset of AAM. RAM is another part of AAM that "focuses on building upon existing airport infrastructure to transport people and goods using innovative aircraft that offer a huge improvement in efficiency, affordability, and community-friendly integration over existing regional transportation options" for trips of approximately 50-500 miles [3]. As such, RAM represents the longer-range "intraregional" missions within the AAM umbrella. LAM is a newly proposed term for very low-altitude operations that principally occur within the Unmanned[8] Aircraft System (UAS) Traffic Management (UTM) environment [4]. Many refer to LAM as small UAS (sUAS) operations, which are operations of aircraft that weigh less than 55 lb, but the FAA's UTM Concept of Operations version 2.0 does not limit larger UAS (i.e., those above 55 lb) from utilizing UTM; furthermore, the LAM term provides parallelism with UAM and RAM, focusing on the key attribute of these missions: flying entirely at lower altitudes than historical aviation—typically under 400 ft above ground level.

A. A Brief History of AAM

The term "advanced air mobility" in its present usage is relatively new. The first known use of the term with its current meaning was in the name of the NASA AAM Project that was first publicly mentioned in the fiscal year 2020

[8] Recently there have been proposals to change the term "unmanned" to the gender-neutral term "uncrewed." We use the historical term "unmanned" here but acknowledge that this term may shift in the near future.

President's Budget Request for NASA [5], which was released on March 11, 2019 [6]. However, the authors are unaware of anyone using this term directly to describe a set of missions until the National Academies of Sciences, Engineering, and Medicine published its report "Advancing Aerial Mobility – A National Blueprint" [7] in February 2020 [8]. Although this report substituted "aerial" for "air" in AAM, we view these terms as synonymous for our purposes here. Shortly after the publication of National Academies report, NASA began utilizing the term more broadly than just for its AAM Project, including changing the name of the UAM Grand Challenge to the AAM National Campaign, and the definition for AAM presented above was first provided publicly during a workshop in March of 2020 [9].

Despite the relative newness of the AAM term, there has been interest in missions similar to the modern concept of AAM for at least multiple decades, and AAM is generally a convergence of the UAS and general aviation communities. Notions similar to the AAM concept in the general aviation community can be traced back to at least the early 2000s [10], and the modern civil UAS community grew in prominence in the mid- to late-2000s [11].

The general aviation side of AAM grew primarily out of the on-demand mobility (ODM) concept [12, 13, 14, 15, 16], and Patterson et al. provide a more detailed discussion of the history of ODM with an emphasis on UAM [17]. One of the key technological drivers behind the ODM and AAM concepts is electric propulsion, which was practically demonstrated in passenger-carrying scale aircraft in the mid- to late-2000s, including Electravia's BL1E Electra [18], Yuneec International's E340 [19], Boeing's Fuel Cell Demonstrator [20], and Pipistrel's Taurus Electro [21]. By 2011, NASA's Green Flight Challenge [22] showcased several electric aircraft, and the successful flights that occurred during the challenge led NASA's Chief Technologist to remark, "Today we've shown that electric aircraft have moved beyond science fiction and are now in the realm of practice" [23].

Much of the energy in AAM around UAS has grown from the sUAS community and the UTM concept, which emerged in the mid-2010s [24]. Earlier civil UAS applications were generally focused on UAS that were larger and flew at higher altitudes than sUAS, but technical and regulatory challenges have inhibited the growth of these operations. The pathway to airspace access provided by the UTM concept, along with continued cost reductions for sUAS, led to a large growth in the sUAS market in the latter half of the 2010s. These sUAS are now generally envisioned to be the pathway through which initial regulatory approvals can occur with lessons-learned being applied to larger UAS flying at higher altitudes.

III. Literature Review

Since 2015, the number of scholarly publications related to UAM and AAM has increased dramatically. As shown in Figure 2, the number of publications world-wide, as determined from a search of the Scopus and AIAA databases, has grown from six in 2015 to 259 as of September 1, 2021. As part of prior research [25], Garrow et al. classified UAM and AAM[9] articles published from January 2015 to June 2020 into several categories, shown in Figure 3. Their analysis showed that about half of the research was related to aircraft technology whereas the other half was related to quantifying the market for AAM and designing AAM operations.

Given AAM research has grown so fast over the last few years, combined with the fact that there are many different characteristics of AAM that have been explored by researchers, it should not be surprising that there are different visions of AAM – and more importantly, different terminologies that are being used to describe these visions. The lack of a common and precise terminology can be problematic, particularly when different fields are using distinct terminologies to describe similar concepts or when the same terms are used in different contexts with a differing set of underlying assumptions.

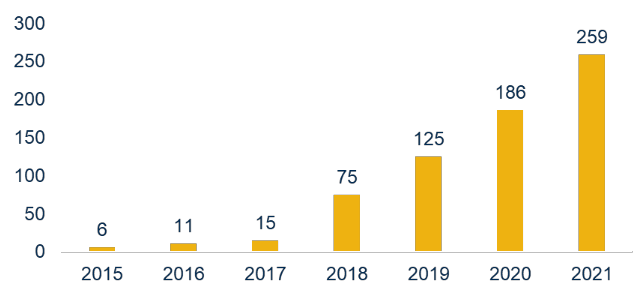
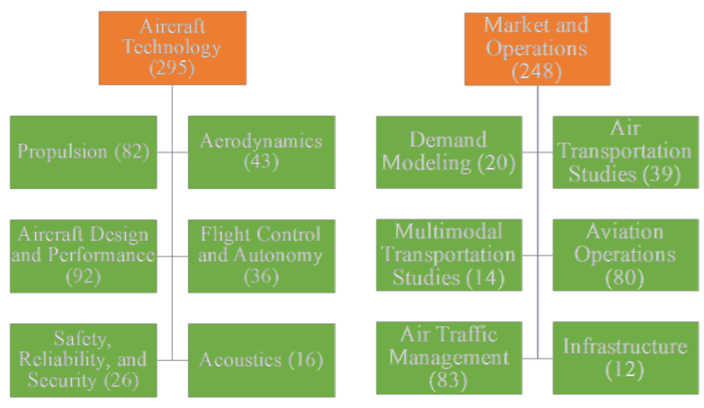


Figure 2: Number of UAM and AAM publications.

Illustrating this issue, we performed a literature review of 60 AAM publications and reports to analyze the currently used terminology and operational concepts. It became immediately evident that the aircraft technology branch of terminology was more consistent and developed across the literature. To target the under-developed attributes of

[9] As explained earlier, over this period the new term of AAM emerged. In this section, we refer to UAM and AAM as AAM with the caveat that the search included both terms.

AAM, we initially searched the market and operations side, finding publications relating to demand, market evolution, sustainability, infrastructure, and trip definition. A total of 106 articles aligned with these topics from a Scopus and AIAA database search and were initially selected for further review. Next, nine attributes were specified in order to succinctly define the concept of operations for the AAM model(s) depicted in each publication. These attributes are shown in Table 1. Papers were categorized through the lens of these attributes.



Source: [25].

Figure 3: Themes in UAM, and AAM Publications from Jan 2015 - June 2020.

Many articles either were unclear on specific operational details of their chosen AAM model(s) or lacked focus on specific models. Articles that failed to provide enough details of their specific concept(s) to categorize them in a majority of the nine dimensions were removed from consideration. In final, 60 AAM publications were selected and successfully categorized.

A result of this categorization was creating groupings of articles based on similar operational models, removing the inconsistency brought about by the current terminologies. The categorization established what specific operational concepts publications were referring to when using AAM buzzwords like "Intra-city Trip," "Air Taxi," "On-Demand Aviation," and "Autonomous Flight Control." These commonly used terms had a broad range of meanings.

Table 1: Attribute of AAM operational concepts considered in literature search

Attribute
Payload Type Transported
Propulsion Energy Source
Piloting
Service Type
Trip Distance
Vertiport/Airport Type
Trip Purpose
Ownership
Capacity

For example, there are many subtle distinctions related to "on-demand" service reported in the AAM literature. In most cases, this term refers to using a smartphone app to summon a flight in real time. However, depending on the trip purpose, the time at which a flight is summoned may differ. A contrasting case involves individuals who desire to book an AAM trip to the airport in advance of their mainline commercial flight. Within the ground literature, on-demand services are usually distinguished by the amount of advance notice that is provided – be it real time, an hour, or a day. This is one instance of how, through the creation of a precise terminology, we can not only help clarify the important dimensions of a particular concept (in this case "on-demand") but also link the terminology to other fields, thereby facilitating inter-disciplinary research. Given that many proposed passenger journeys for AAM are multimodal in nature, relating operations to other transportation types is a necessity.

As a second example, we see little clarity on trip distance definitions in the literature. Many articles refer to missions as intra-city or inter-city, but given the different sizes of cities, the physical range (in miles for instance) of an intra-city mission can be quite large and/or overlap with that of an inter-city mission. Prior research has provided a taxonomy of operational models [17] but given its relatively narrow scope and how fast the field is moving, it would be beneficial to revisit this taxonomy to ensure that definitions align with the aircraft technologies and market segments that are frequently discussed in the literature or are envisioned to be part of a longer-term vision for AAM.

This categorization helped scope the operational characteristics that needed to be refined or redefined, as well as how a new taxonomy could supplement the mission classification progress already made in scholarly literature. An effective taxonomy will provide a clear and consistent terminology for describing operational concepts while acting as a scaffolding that stays relevant as the proposed AAM mission models and characteristics evolve over time.

We anticipate that this work will complement ongoing research efforts. One of these efforts that is occurring is part of the DLR German Aerospace Center's HorizonUAM project [26]. As part of the HorizonUAM project, a consortium of ten German universities are collaborating to explore a variety of topics related to UAM and AAM. In particular, they define five use cases: Intra-City, Mega-City, Airport-Shuttle, Sub-Urban and Inter-City. For each use case, they define technology scenarios, mission profiles, concepts of operation, vehicle configurations, and infrastructure [27]. The HorizonUAM project has a stronger focus on UAM specifically, and there are areas where operational capabilities between the United States and Europe may differ in important ways. In addition, we hope that this work will complement parallel efforts that are working to define a taxonomy for AAM, including the Federal Aviation Administration's UAM concept of operations [28] and SAE International's standard [29] that has focused on defining a taxonomy for on-demand and shared mobility for ground, aviation, and marine modes.

IV. Taxonomy

We used the conceptual framework shown in Figure 4 to organize a taxonomy for AAM passenger operations. The framework includes demand-side factors (passenger and trip characteristics) and supply-side factors (aircraft, infrastructure, operational, and service characteristics). We do not outline a taxonomy for all potential areas; for example, we do not focus on community-related issues, such as zoning and noise ordinances. In organizing the taxonomy, we focus on terms and concepts that describe (1) how AAM differs from other modes and (2) how demand-side factors influence supply-side factors, or vice-versa. Feedback loops between demand and supply capture nuances of how definitions associated with AAM passenger operations will evolve over time.

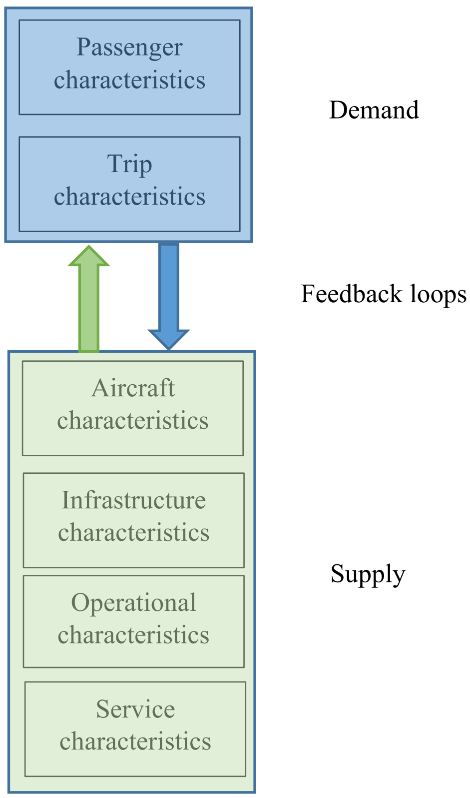


Figure 4: A Conceptual Framework for Classifying a Taxonomy for AAM Passenger Missions

A. Passenger Characteristics

Passenger characteristics and preferences influence demand for AAM. By modeling AAM demand as a function of customer preferences, researchers and policy-makers can gain insights into the sensitivity of AAM demand to various characteristics, including aircraft performance, vertiport placements, and pricing.

Travel demand models are "used to predict travel behavior and resulting demand for a specific future time frame, based on assumptions dealing with land use, the number and character of trip makers, and the nature of the transportation system" [30]. Travel demand models seek/strive to capture how potential passengers with different socio-demographic and socio-economic (SED) characteristics would make travel decisions and the relative importance they give to different trip characteristics. This understanding of travel behavior provides valuable insights for a wide range of AAM applications, including aircraft and service design, infrastructure investments, pricing and profitability analyses, marketing and informational campaigns, etc. [31].

Passenger characteristics include a variety of SED factors including but not limited to age, gender, ethnicity, household size and composition, annual household income, highest educational attainment level, employment and student statuses (e.g., employed full-time, part-time student, retired), occupation, and home ownership status. Several SED characteristics have been shown to influence interest in and intent to use new transportation alternatives. For example, several studies have found that interest in electric ground vehicles (EVs), autonomous ground vehicles (AVs), shared mobility modes, and/or AAM is associated more with individuals who are younger, more educated, have higher incomes, and are male (e.g., see [32,33,34,35,36,37,38,39,40,41,42]).

Passenger characteristics also include access to different modes and prior experience with different modes. Prior experience with ride-hailing service, public transportation, and commercial air travel have been found to influence willingness to use AAM, i.e., individuals who frequently use ride-hailing services and/or transit and/or frequently travel by commercial airlines are more likely to express interest in using AAM (e.g., see [42,43]).

Geospatial attributes associated with the individual, such as her residential and work locations, can influence interest in AAM. *A priori*, we would expect that as the distance and/or ground travel times between the home and work location increase, so too does interest in using AAM.

Passenger characteristics also include individuals' attitudes, beliefs, or opinions about a variety of topics. For example, in the context of new transportation modes such as shared mobility, individuals' opinions about the trustworthiness of drivers and other passengers may influence their willingness to use transportation network companies (TNCs) such as Uber and Lyft. Prior literature has shown that individuals who are early adopters of new technologies and have positive attitudes towards technology and/or automation are more likely to show interest in using EVs, AVs, shared mobility modes, and/or AAM (e.g., see [37,43,44,45,46,47,48,49,50,51]).

It is often easier to use SED and geospatial characteristics for short-term and long-term demand predictions than individuals' attitudes. Many SED and geospatial characteristics are available free of charge through government sources such as the Census or can be purchased from companies that specialize in aggregating location-based data from mobile devices that can be used to model transportation demand. Long-term prediction models of demand adjust passenger characteristics by taking into account how the spatial and temporal distribution of ages in the population is changing (e.g., through births, deaths, changes in life expectancies, immigration, migration, etc.) as well as how residential and work locations are expected to change as transportation networks and land use evolve over time (e.g., see [52] for an example within AAM).

One of the largest benefits that is typically associated with a new or enhanced transportation service is travel time savings. Given that "the value of travel time is a critical factor in evaluating the benefits of transportation infrastructure investment," the US Department of Transportation (DOT) has established procedures that all of the administrations within the US DOT must use in all cost-benefit of cost-effectiveness analyses to evaluate travel time increases or decreases associated with proposed transportation projects [53]. This is important in the context of AAM as – depending on the source of funds that are used to build vertiports or other AAM infrastructure – the benefits associated with a proposed design may need to be quantified and justified using the value of travel time savings (VTTS) set by the US DOT. Within the AAM literature, VTTS are often referred to as door-to-door travel time savings. To date, numerous studies have been conducted that have examined potential door-to-door travel time savings that a new AAM mode could offer and examined the sensitivity of these travel time savings to different parameters, such as access and egress times and aircraft cruise speeds [54,55,56,57,58].

Given a general overview of passenger characteristics and how they may influence interest in and use of AAM, we define two terms that are particularly relevant for modeling interactions between AAM supply and demand.

A.1 Preferences refer to certain characteristics any consumer wants to have in a good or service to make the good or service preferable to her. Preferences are the main factors that influence consumer demand (adapted from [59]).

A.2. The value of travel time savings (VTTS) refers to the benefits from reduced travel time, including waiting as well as actual travel (adapted from [60]).

In summary, the terminology used to describe passenger characteristics is standard across different disciplines, with the key difference related to terminology used to describe value of travel time savings.

B. Trip Characteristics

Demand for UAM and AAM will also be influenced by both the existing transportation system and characteristics of the new mode. Demand for UAM and AAM is also a function of trip characteristics. Passengers generally prefer trips that have shorter door-to-door travel times, fewer transfers and stops, are less expensive, have high levels of reliability, and depart and/or arrive close to preferred departure and arrival times. UAM and AAM are generally envisioned to save time, but may come at the expense of more transfers, stops, and higher costs. It remains to be seen how tradeoffs among these trip characteristics will influence overall AAM demand.

The terminology used to describe passenger and cargo movements on the transportation network differs for ground and air networks, but the fundamental concepts are the same. For example, within commercial airlines, a trip is often referred to as an itinerary that contains one or more flight legs. Given the terminology used to describe trip characteristics is arguably one that varies most across different disciplines, in this section we compile a taxonomy that can be used for UAM applications. Given that the vision for AAM is for longer-distance trips that would be similar in spirit to those served by commercial airlines today, we focus here on defining trip characteristics for UAM. A second motivation for this focus is that there are many subtle differences between the ground and air definitions for shorter trips (e.g., the definition of "stops"), so defining precise terminology for this application will arguably be more critical in the near-term.

Here, we define a *trip* as travel between a *trip origin* and *trip destination*. The trip occurs on one or more *modes* and includes one or more *legs*. A *multimodal* trip occurs on two or more modes (and includes at least two legs). Figure 5 helps us visualize these concepts by depicting five exemplar trips. Trip 1 represents travel from an origin to a destination in a ground vehicle (e.g., an auto owned by the individual). The individual leaves the origin and travels directly to the destination. The trip involves a single *leg*, representing the travel between the origin and destination (without stopping). Trip 2 occurs between the same origin and destination as Trip 1, but Trip 2 is *multimodal* and has three legs and three distinct modes. Leg 1 occurs in a ground vehicle (e.g., an auto owned by the individual) from the trip origin to the *origin (or departure) vertiport*. Leg 2 occurs in an aircraft from the *origin vertiport* to the *destination (or arrival) vertiport*. Leg 3 occurs in a ride-hailing ground vehicle from the destination vertiport to the final trip destination.

Different definitions can be used to divide a trip into individual legs. For UAM and AAM applications, we use the concepts of transfers and connections to distinguish the legs of the trip. In Trip 2, individual legs occur when passenger makes a *transfer* or *connection* between two distinct modes. Trip 3 shows an example of how individual legs occur when a passenger makes a transfer or connection on the same mode, specifically when the passenger physically moves from one eVTOL aircraft to another eVTOL aircraft. A *transfer* (or *connection*) is distinct from a *stop*. In a transfer, the passenger physically moves from one mode to the other or physically moves from one vehicle to another vehicle on the same mode. In a stop, the passenger or vehicle the passenger is taking temporarily stops in order to fulfill a purpose that is not associated with the *primary trip* purpose, i.e., the motivation for traveling between the trip origin and trip destination.

For example, in Trip 4, the passenger makes a stop in order to fulfill a certain purpose (e.g., to get gas, drop off dry cleaning, drop off or pick up children at school, etc.). Importantly, the purpose for the stop is not associated with the primary trip purpose, and the passenger does not change vehicles or modes.

In Trip 5, the vehicle (and passengers in the vehicle) makes a stop (e.g., to pick up additional passengers); no fueling or maintenance repairs are conducted at this stop (to be consistent with the FAA definition of a vertistop as discussed in the next section). Consistent with Trip 4, the purpose for the stop is not associated with the primary trip purpose, and the passenger does not change vehicles (as was the case for the transfer in Trip 3).

Given a general overview of trip and leg characteristics, we propose the terminology for describing trips on UAM and competing modes:

B.1. A trip is defined as travel between a trip origin and trip destination on a specific mode or sequence of modes.

B.2 Trip departure time is the time passenger(s) leave the trip origin.

B.3 Trip arrival time is the time passenger(s) arrive at the trip destination.

B.4 Trip distance is the distance from the trip origin to trip destination as traveled by the passenger(s) across all modes. Trip distance is a function of the transportation network and may differ across modes, e.g., the distance to travel on surface streets may be longer than the distance to travel by air.

B.5. A trip leg is a portion of a trip between two points (i.e., a leg origin and a leg destination) that is taken with a single mode.

B.6 A transfer occurs when the passenger changes modes or vehicles between two consecutive legs.

B.7 A stop occurs when the ground or air vehicle in which the passenger is traveling ceases movement in order to fulfill a purpose that is not associated with the primary trip purpose. A passenger does not change modes or vehicles while on a stop but may briefly exit the vehicle.

B.8 Transfer time is the time to complete a transfer, which is the difference between the departure time of the second leg (or leg l) and the arrival time of the first leg (*or leg* l-1)

B.9 Door-to-door travel time is the difference between the arrival time at the trip destination and the departure time at the trip origin. Note that door-to-door travel times will vary across modes, departure times of the day, departure days of the week, and potentially by seasonality.

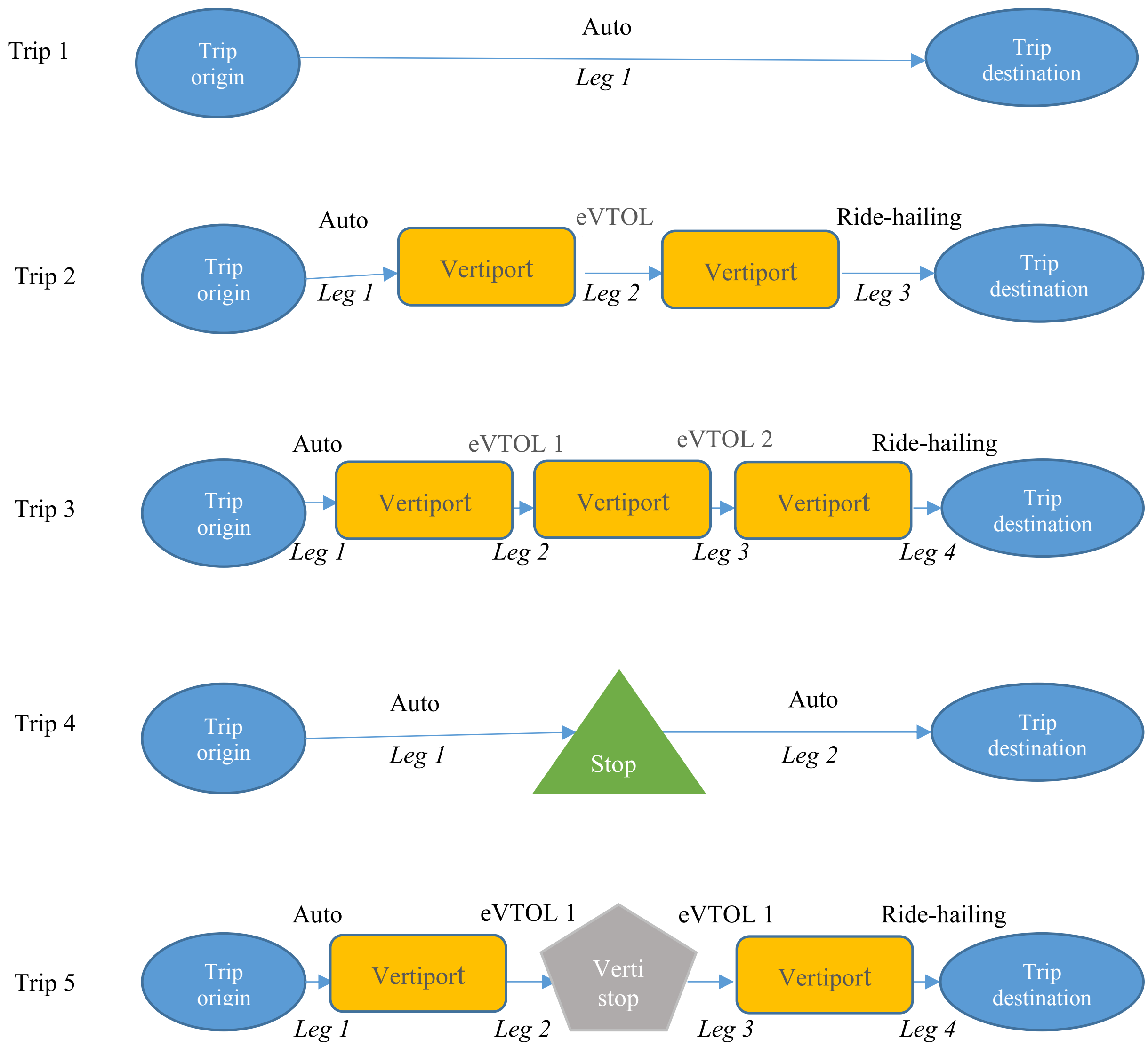


Figure 5: Relationships among Trips, Legs, Modes, Transfers, and Stops for UAM

In summary, the terminology used to describe trip characteristics differs slightly between the ground and air literature, but at a fundamental level describes the components of traveling from an origin to a destination via one or more modes at a specific time of day.

C. Aircraft Characteristics

Maturing technologies, most notably advancements in electric propulsion and automation, are creating the possibilities for new aircraft that many believe can help enable AAM. These novel aircraft could look to the casual observer either very similar to or very different than existing small, fixed wing airplanes or helicopters. However, the capabilities these aircraft are anticipated to provide could lead to significantly lower operating costs, greatly reduced noise levels, and significantly lower environmental impacts than traditional aircraft.

Although these aircraft themselves may be novel, they will ultimately still perform the same basic functions that aircraft have historically: lifting some form of payload into the air to perform a mission. Consequently, many of the historic metrics defining an aircraft's utility will remain important in AAM. Perhaps most notably, the payload weight carried by the aircraft, the speeds at which the aircraft flies, and the range or endurance of the aircraft. These terms' definitions remain unchanged in the AAM context; however, additional nuances exist in some cases.

Below we provide three main characteristics of aircraft and the operation of individual aircraft that are important to understanding the AAM domain: electrification, piloting and automation, and takeoff and landing characteristics.

1. Electrification

One of the chief characteristics of essentially all novel AAM aircraft is an electrification of the propulsion system, which can enable more efficient aircraft designs and potentially also directly reduce energy costs. Electrification refers to a propulsion system architecture that relies at least in part on electric motors to produce thrust for the aircraft [61]. There are a variety of different specific propulsion system architectures that fit under the "electrified" title [62]. A large number of proposed aircraft are fully electric, relying on batteries to store electricity and then distribute this energy to electric motors that drive some form of propulsor, which could be any number of devices including propellers, ducted fans, and rotors. There are a number of different hybrid-electric or turboelectric architectures that rely on some form of fuel-burning engine to produce electrical power, which is often flowed through a battery prior to being distributed to the electric motors. Some of these hybrid-electric or turboelectric systems generate thrust from the engine or shaft spun by the engine directly in addition to creating electrical power, while others solely produce electricity. Other electrified propulsion systems rely on fuel cells—be they hydrogen fuel cells [63], solid oxide fuel cells [64], or some other fuel cell type—for electricity generation.

C.1 An ***electrified aircraft*** is an aircraft that relies on electric motors to provide some or all of its thrust (adapted from Ref. [61])

The means of energy storage can have implications on the range and endurance of electrified aircraft. Most notably, current battery chemistries tend to experience a degradation of capacity with time, which implies a reduction of the maximum range and endurance of the aircraft as the battery ages. Exactly how to specify the range and endurance of full or partial battery-electric aircraft is still a topic of discussion. The General Aviation Manufacturer's Association has published some recommendations for reporting the range capabilities of these aircraft [65]. Particularly in the near-term, electric aircraft are likely to have limited range or endurance capabilities, which will impact the routes they can practically serve. Such route limitations are likely to constrain the potential demand for early electric AAM services. A consideration for hydrogen, and potentially other novel fuels, is that some of the fuel can boil off and leak from storage tanks, which can have implications on the range and endurance capabilities of these aircraft, particularly if they remain parked for a long period of time.

This electrification can enable a wide variety of new aircraft configurations that can be more efficient than traditional aircraft [66,67,68,69]. Many AAM aircraft distribute propulsors over the aircraft to achieve synergistic propulsion-airframe interactions that increase the efficiency of the aircraft. Although these beneficial interactions have been well known for many years [70], electric motors enable more flexible placement of propulsors than conventional engines historically have due to the relative ease of transmitting electric power compared to mechanical power and the nearly scale-invariant nature of electric motor's efficiency and specific power. There are hundreds of new proposed designs in the AAM space [71], some of which look quite different from traditional aircraft. Although electrification enables these new designs, it is unclear how the general public may react to such novel aircraft; some consumers may be hesitant to ride on these aircraft due to their novelty or perceived danger while others may excitedly board.

Electrification is likely to lead to changes in the energy sources for aircraft, which will have implications on the required infrastructure and the emissions produced by the aircraft. All-electric aircraft and some hybrid-electric aircraft will require charging infrastructure, which may limit the practical locations from which these aircraft can operate. Other hybrid-electric aircraft will require conventional fuels while others will explore different types of fuels, such as sustainable aviation fuels. Perhaps most notable of these alternate fuel sources is the desire by some to power aircraft with hydrogen, which would require vastly expanding hydrogen supply chains, including new production, distribution, storage, and refueling infrastructure. The need for any new fuel-related infrastructure is another potential limit on the number of practical operating locations for these aircraft, which will have impacts on the demand for AAM services. Another important aspect of electrification is the potential for more environmentally sustainable operations. In addition to offering the potential for aircraft that use less energy to perform a given mission, there are at least theoretical pathways to achieving very low emissions from electrified aircraft. The ultimate "greenness" of any aircraft that relies on energy from the electric grid or an alternative fuel (such as hydrogen) will depend on the environmental friendliness of the production and distribution of that energy source. Consumer's viewpoints on environmental sustainability and how AAM aircraft and their energy sources are perceived may impact ultimate demand for AAM services.

2. Piloting and Automation

A second important characteristic of most AAM aircraft is an increased level of automation in the piloting functions of the aircraft compared to their most analogous historical counterparts. Automation can be defined as "[t]he automatically controlled operation of an apparatus, process, or system by mechanical or electronic devices that take the place of human labor" [72]. Increased levels of automation are envisioned to reduce costs and help ensure the safety of operations by assisting or potentially even replacing the traditional human pilot. Additionally, in some cases, high levels of automation are essentially required due to the complexity of novel aircraft designs, particularly those with large numbers of propulsors and control effectors.

There are a wide variety of concepts for how AAM aircraft may be "piloted," ranging from the historical onboard expert human pilot to a fully autonomous aircraft. Concepts that fall between these extremes can be referred to as "hybrid piloting" architectures in which there are a range of functional allocations among humans, automation, and the locations at which humans or various automated capabilities reside. From the highest level, these concepts can be broken into two categories: either manned or unmanned[10] aircraft. Manned aircraft require a human onboard the aircraft to perform at least some of the "piloting" functions, whereas unmanned aircraft do not have a human "pilot" onboard at all.

Within the manned aircraft category, the most prominent proposal for AAM aircraft with increased automation is the simplified vehicle operations (SVO) concept.

C.2 Simplified vehicle operations (SVO) is "the use of automation coupled with human factors best practices to reduce the quantity of trained skills and knowledge that the pilot or operator of an aircraft must acquire to operate the system at the required level of operational safety" [73].

SVO can refer to a variety of specific implementations, but the general premise is to allow the role of the human in piloting an aircraft to be reduced while increasing the responsibilities of the automation [74]. Because the role of the human in piloting the aircraft is modified, the human "pilot" in an SVO concept is referred to as an "aircraft operator" [2].

C.3 An ***aircraft operator*** is a human, who may be onboard or offboard the aircraft, that is partially responsible for the safe flight of a single aircraft, sharing this responsibility with automated systems.

Note that the "aircraft operator" term is broader than just for manned aircraft or the SVO concept and can include aircraft operators located remotely.

Whereas increasing the level of automation onboard an aircraft historically has increased pilot training requirements due to the need for the pilot to be the "backstop" in case of automation failure, the SVO concept is based on the premise that the aircraft operator (i.e., human "pilot") need never be responsible for the functions that the automation handles. Proponents of the SVO concept view it as a means to practically and gradually introduce increased levels of automation and to design systems in a way that maximizes the advantages that both humans and machines provide.

Unmanned operations have several prominent concepts for piloting being discussed by those in the AAM ecosystem. First, remotely piloted operations rely on an expert human pilot to fly the aircraft from a ground control station. Typically, remote pilots perform nearly all the same functions that an expert human pilot onboard an aircraft traditionally would (with a prime exception being the ability to "see and avoid" other air traffic). On the other extreme end of the spectrum of unmanned operations, some envision fully autonomous aircraft that have no direct human involvement in the piloting of the aircraft.

The precise meaning of "autonomous" or "autonomy" varies. The NASA Autonomous Systems Capability Leadership Team defines autonomy as "the ability of a system to achieve goals while operating independently of external control" [75], and ASTM International's Administrative Committee 377 defines autonomous flight as "a flight that does not require human decision making and instead relies on automation that can independently determine a new course of action in the absence of a predefined plan to execute management or operational control of a flight" [76]. We here propose that a "fully autonomous aircraft" is an aircraft that is able to perform all necessary piloting functions, including in off-nominal and contingency situations, totally independent of any human involvement. This

---

[10] We again acknowledge that there are proposals to formally change the terms "manned" and "unmanned" to "crewed" and "uncrewed," respectively. We are using the historical terms here, but will modify these terms if there is an official acceptance of the new gender-neutral terminology by the FAA.

does not mean that humans will be totally uninvolved; for example, the general mission the aircraft will perform is likely to be generated by a human. However, it does imply that safety can be maintained in aircraft operations even in the absence of any human oversight.

C.4 A ***fully autonomous aircraft*** is an aircraft that can perform all necessary piloting functions, which includes determining a new course of action in the absence of a predefined plan, while operating independently of any external control, including control from a human pilot, aircraft operator, and/or multi-aircraft supervisor (adapted from Refs [75,76]).

On the spectrum between remotely piloted and fully autonomous aircraft are a number of different schemes that rely on varying levels of automation. Perhaps the most prominent concept in this spectrum is called remote supervisory operations (RSO) [74,77]. In RSO, some number of human "multi-aircraft supervisors," often numbered as "m," remotely supervise multiple aircraft, often numbered as "N." Consequently, RSO is also referred to as m:N operations, and, to effectively reduce costs, m is envisioned to be notably less than N (i.e., the number of human multi-aircraft supervisors is less than the number of aircraft). There are varying terms used for the multi-aircraft supervisor, but we select this term because (1) the role of the remote human "pilot" in RSO is very different from that of a traditional expert pilot as well as an onboard aircraft operator in a SVO paradigm, (2) the human has responsibility for more than one aircraft, and (3) the human's role is at a higher-level of oversight or supervision than in many other piloting paradigms, including an onboard aircraft operator in SVO.

C.5 A ***multi-aircraft supervisor*** is a remotely located human that is partially responsible for the safe flight of multiple aircraft, sharing this responsibility with automated systems and potentially also other multi-aircraft supervisors.

C.6 Remote Supervisory Operations (RSO) is an operational paradigm in which one or multiple remote multi-aircraft supervisors oversee(s) the operations of multiple, highly automated aircraft.

It is likely that RSO will not be the first step in the evolution of unmanned operations toward increasingly automated operations. Prior to achieving RSO, it is generally believed that there will be remote aircraft operators with responsibility for a single aircraft. Such a remote aircraft operator, like the aircraft operator in SVO, shares responsibility for piloting the aircraft with automated systems; however, unlike SVO, a remote aircraft operator is not located onboard the aircraft.

As the level of automation in aircraft increases, there are several dynamics that may affect the demand for automated AAM services. First, if automation can indeed lead to reduced costs as is desired, then demand for services is likely to increase as more individuals will be able to practically afford the AAM services. Similarly, if automation can effectively increase safety, demand may also increase, since some are hesitant to ride on small aircraft today due to safety concerns. On the other hand, the consumer acceptance of increased levels of automation is an open question; if the general public does not widely accept increased levels of automation, demand for automated AAM aircraft will be limited.

3. *Takeoff and Landing Characteristics*

One of the key means of distinguishing among various AAM aircraft and operational types are how they takeoff and land. Some aircraft will be able to takeoff and land without any ground roll, performing a vertical takeoff and landing (VTOL). Other AAM aircraft are likely to be similar to conventional airplanes that require thousands of feet of runway to become airborne and safely land. These aircraft are termed conventional takeoff and landing (CTOL) aircraft, and there is not a specific takeoff or landing distance that explicitly defines a CTOL aircraft; the specific runway length required for a CTOL aircraft varies with many factors, perhaps most prominently the aircraft's weight, thrust capabilities, and lift coefficient. Aircraft that require some ground roll for takeoff and landing but less than a typical CTOL aircraft of the same general category and class are called short takeoff and landing (STOL) aircraft. Again, there is no specific, well-defined runway length requirement for such aircraft, and there are some AAM aircraft that are proposed with STOL capabilities.

A new category of aircraft that have what we term super-short takeoff and landing (SSTOL) capabilities have entered the discussion around AAM in relatively recent years. These SSTOL aircraft could be considered simply STOL aircraft, but the added "super" modifier denotes that these aircraft require incredibly short distances—on the order of only 100-500 feet of runway for takeoff and landing. The terminology around these aircraft is not fully settled. Some describe them as extremely short takeoff and landing (ESTOL) aircraft [78] while others term them ultra-short takeoff and landing (USTOL) aircraft [79]. We have elected the SSTOL terminology for at least three reasons: (1) to differentiate from the term electric short takeoff and landing (eSTOL), which is now fairly common [80]; (2) to differentiate from previous NASA ESTOL activities in the early 2000s, which were focused on larger 50-150 passenger aircraft with less than 2000 ft takeoff and landing distances [81]; and (3) for consistency with other literature [82,83,84].

C.7 Super-short takeoff and landing (SSTOL) is the takeoff and landing of an aircraft in distances of more than zero but less than 500 feet.

Among the VTOL, SSTOL, STOL, and CTOL aircraft types, VTOL aircraft will generally have the greatest operational flexibility in terms of takeoff and landing locations because they do not require ground rolls to takeoff or land. This flexibility should generally act to increase the demand for these aircraft, due to fewer time penalties for AAM travelers in reaching takeoff and landing locations. However, the ability to fly vertically comes with weight penalties that result in these aircraft generally costing more to operate, being able to carry less payload, flying shorter ranges, and/or generating more noise than their non-VTOL counterparts with similar technologies. These penalties will act to constrain the demand for VTOL services relative to other aircraft with other takeoff and landing characteristics.

Proponents of SSTOL aircraft argue that these aircraft can reach nearly all, if not all, the same locations that VTOL aircraft can reach with fewer weight penalties, enabling them to achieve improved performance; however, these claims have yet to be proven with a functional SSTOL aircraft. If such claims cannot be proven, then demand for services with SSTOL aircraft will be constrained by the number of locations from which they can operate. If these capabilities can be proven, then these aircraft will not be constrained by takeoff and landing locations any more than other aircraft, but there will almost certainly still be weight penalties relative to CTOL or potentially also other STOL aircraft. These weight penalties will generally constrain demand for SSTOL services relative to CTOL aircraft for longer range and/or higher payload missions.

CTOL aircraft are likely to have the lowest operating costs and greatest range of all aircraft takeoff and landing types. These characteristics will generally act to increase the demand for CTOL-aircraft-based services. However, CTOL aircraft will be the most constrained in the locations from which they can operate of all takeoff and landing types, likely being relegated to traditional airports with multiple thousand-foot runways. This limit on operating locations will tend to decrease demand for CTOL aircraft-based services due to the generally increased time required to access these services. Ultimately, a variety of takeoff and landing types are expected within AAM that balance the benefits and penalties of each.

D. Infrastructure Characteristics

Infrastructure includes the readily identifiable landing facilities and the sensors, communications and support equipment, and utilities that are required for the facilities' efficient operation. Not surprisingly, most of the current aviation infrastructure terms will remain the same when referring to AAM-specific operations. Current terms, such as air and ground side, runway, taxiway, ground support equipment (GSE), passenger and cargo terminal, facility, final approach and takeoff area (FATO), touchdown and lift-off surface (TLOF), and gate, will continue to describe the objects or features that will perform similar functions for AAM though there may be some expansion of these terms to encompass new features present in AAM operations. For example, ground support equipment may evolve to use different propulsion and become more automated, but it will still be referred to as GSE. Consequently, many characteristics currently used for demand modeling and other analysis related to infrastructure planning can be treated much as they are today.

New AAM infrastructure taxonomy will be challenging due to overlapping specialties caused by the tight integration of aviation within local communities and other transportation modes. For example, from an aviation perspective, the term vertiport would be used, but the vertiport could be referred to as a public transportation hub from a local planners' perspective or a commercial transportation facility from a zoning perspective. While each of these terms refers to the same building, they could each imply different regulatory, environmental, or approval requirements. This paper is looking at nomenclature from primarily an aviation perspective.

Even umbrella terms will likely not evolve significantly such as airport or aerodrome, heliport or vertiport. These terms are typically codified in regulation with specific definitions, and while they allow for multiple differentiating features, the broad inclusion in the term allows for the application of regulations without attempting to codify every characteristic. It also provides the user with a commonly recognizable term to use in general conversations, much like the term highway can refer to specific instantiations such as freeway, motorway, turnpike, parkway and expressway. A specific example of a defined umbrella term is a vertiport.

D.1 Vertiport is “an area of land or a structure, used or intended to be used, for” vertical takeoffs and landings or super short takeoffs and landings in all-electric, hybrid-electric, turboelectric, and hydrogen-fueled aircraft “and includes associated buildings and facilities” (adapted from Ref. [85]).

Note that the draft engineering brief from the FAA on vertiport design released in 2022 [85] was limited to vertical takeoffs and landings, but we have extended the definition to also include super short takeoffs and landings, which would be accomplished with an extended touchdown and lift-off surface (TLOF). The now-canceled previous Vertiport Design Advisory Circular included considerations for elongated TLOFs that could allow tiltrotor aircraft to perform rolling takeoffs [86]. Additionally, there is interest in SSTOL aircraft operating to and from vertiports. For these reasons, we have chosen to include SSTOL aircraft operations into the vertiport definition, but we acknowledge that this is an area of ongoing discussion within the AAM ecosystem.

Much like the example of highway above, ambiguity is introduced as terms are utilized as word abbreviations to capture specific characteristics. These abbreviated terms capture characteristics that could be functional, e.g., general aviation vs jet; could indicate a level of performance or design feature, e.g., jet vs turbofan/turboprop; or indicate a capability, e.g., airplane vs rotorcraft. These abbreviations frequently include qualifiers such as jumbo, regional, or business to indicate a characteristic of a jet relevant to the specific conversation. In the case of vertiports, two qualifiers are achieving more frequent usage. The first of these terms below is defined in FAA documents, and the second was introduced recently. The definitions and their sources are:

D.2 Vertistop is “an area similar to a vertiport, except that no charging, fueling, defueling, maintenance, repairs, or storage of aircraft are permitted” [85].

D.3 Vertiplex refers to multiple vertiports within a geographic area whose arrival and departure operations are highly interdependent [adapted from 87].

Other infrastructure characteristics have terms that reflect much less maturity or are yet to have common recognition across the AAM ecosystem. One of these areas is how FATOs and TLOFs will be differentiated. For example, one “level” or “type” of FATO/TLOF will be able to be used by some vehicles but not by others; the U.S. Navy uses Level and Class for this purpose [88]. Other terms may emerge to reflect specific characteristics, such as a term to describe a fully versus partially automated vertiport or a term for a vertiport that only handles cargo versus one that services both passengers and cargo. Another area of potential need for specificity in infrastructure characteristics is whether the vertiport is a consumer of energy, as opposed to one that stores energy, such as electrical storge during non-peak periods, or is capable of energy generation. Other emerging areas that could also develop specific characteristics include if vertiports have different terms depending on the weather in which they can operate, whether the ownership model is public, private or another model, such as mixed, or if they are in an area that in the future requires greater specificity such as a vertiport located at an airport.

Another type of characteristic that touches on infrastructure is weather, which is included here as the weather sensors are infrastructure. The new terms being more commonly used include *qualify*, *microweather,* and *hyperlocal*. Qualify has not yet been specifically defined but has been used in reference to UAM services. Services that are required to be used by UAM operators due to FAA regulation or for a direct connection to FAA systems must be *qualified* and approved by the FAA [28]. *Microweather* leverages the dictionary definition for microclimate: the climate of a very small or restricted area, especially when this differs from the climate of the surrounding area. *Hyperlocal* is typically defined as relating to or focusing on matters concerning a small community or geographical area. The term appears to have originated relative to news content capturing both geographical and time characteristics and is currently also being used in conjunction with GPS, mobile applications, and Internet of Things devices, such as when a company utilizes the location of a mobile device to send a banner ad for a restaurant within 100 yards of the device.

Some terms have been proposed and have already been superseded. The term, aerodrome was used in the FAA’s UAM ConOps v1.0 [28] but was not used in the recent FAA Vertiport Engineering Brief No. 105 [85]. The term vertiplace was proposed as an umbrella term that could include vertihub, vertiport and vertistop, though it appears that the ecosystem has become comfortable with utilizing vertiport as this umbrella term.

Infrastructure characteristics reflected in a vertiport taxonomy are important for comparability across demand models. The taxonomy indicates likely transfer times, e.g., a vertistop will likely have a shorter transfer time than a vertihub and potentially trip leg lengths where the deconflicting of traffic at a vertiplex could result in a longer leg length than a leg between two vertistops. A vertiport integrated with another mode hub, multimodal integration, could increase demand by reducing transfer times along with leg times and thus trip lengths. Additionally, the need for any new infrastructure is another potential limit on the number of practical operating locations for these aircraft, which will have impacts on the demand for AAM services.

E. Air Operations Characteristics

There are a wide range of operation types related to the AAM ecosystem, including but not limited to air operations, ground operations, passenger operations, and multimodal operations. For the purposes of this document, we focus on the classification of AAM air operations and how the management of AAM air traffic impacts the demand for AAM services. For example, if the number of air operations a system can support for a given AAM mission is limited by airspace management constraints, it is expected that either prices for those services or delays to passengers will increase, either could lead to a decrease in demand.

The short duration and distance of local AAM mission flights (i.e., up to 50-75 miles) influence several operational characteristics. The expected flight altitudes are considerably lower than typical commercial air traffic, with aircraft anticipated to routinely cruise at altitudes between 500’ and 5000’ above ground level at speeds up to 150 knots (though speeds up to 200 knots would be permitted) [89,90]. At these altitudes and depending on the meteorological conditions and aircraft equipage, vehicles will currently fly under visual flight rules (VFR) or instrument flight rules (IFR).

E.1 Digital flight is a proposed flight operations capability, enabled by a set of cooperative procedures and digital technologies, in which flight operators ensure flight-path safety through automated separation and flight path management in lieu of visual procedures and air traffic control separation services (quoted directly from [91]).

E.2 Separator is the agent responsible for separation provision for a conflict and can be either the airspace user or a separation provision service provider (quoted directly from [92]).

The introduction of digital flight is intended to enable increased AAM operations by providing aircraft a mechanism to use automation technologies in support of safe and efficient flight in a variety of meteorological conditions. Digital flight is being developed to add a third set of flight rules, compatible with the existing visual and instrument flight rules [91]. One of the tasks for developing digital flight is defining the separator for digital flight aircraft and the rules for interaction with the pilot/separator for aircraft flying under VFR and the air traffic control/separator for IFR flights [91].

These lower altitudes may also be a factor in aircraft route design and placement of airports or vertiports. Procedures for deconflicting AAM and traditional aircraft at and around existing airports will need to be developed. This includes procedures for interacting with existing classes of airspace, e.g., Class B, C, and D terminal airspaces. In addition, the acoustic noise signatures of the AAM aircraft at lower altitudes may be a distraction to the public and also influence the development of acceptable flight and approach paths, particularly in urban areas [93].

E.3 Airspace constructs refer to novel airspace design elements used to support the safe management of AAM aircraft through a defined airspace in which aircraft abide by rules, procedures, and performance requirements specific to the airspace construct. Examples include corridors, UAM operating environments, etc. (adapted from [94] and [28]).

In order for industry to meet the anticipated passenger demand associated with AAM missions, the frequency and reliability of AAM air operations will need to be increased. An increase in overall air traffic in a given area increases the likelihood that airspace capacities will need to be managed, both along popular and convenient air routes, as well as at airports and vertiports. One of the underlying principles of UAM is “airspace management will be structured where necessary and flexible when possible” [28]. New airspace constructs in the form of corridors are being considered to support the management of UAM operations. These corridors are intended to reduce operational complexity by providing “structure” to the airspace [28].

The unique features of eVTOL aircraft, which are being considered by many for local AAM missions, have traffic management implications. Due to the disproportional amount of the available energy many eVTOL aircraft require during landing, routine air traffic management procedures may be impacted [95]. For instance, a missed approach may put these aircraft into critical situation, depending on how much energy was expended during the attempt. The flight may need priority landing for their go around or immediately go to their alternate landing location. Depending on the cruise configuration of the aircraft (i.e., whether it flies on a wing), holding aircraft while in flight may also be difficult for the AAM aircraft to do for extended periods of time.

E.4 3rd party service providers are public or private entities that provide traffic management and flight safety services under rules and regulations established by the governing civil aviation authority (CAA). Services provided may include routing, traffic deconfliction, operational constraints, operational modifications, airspace notifications, wind and weather, and other information (adapted from [2]).

Air traffic "flexibility" comes from the use of 3rd party service providers to support the management of traffic in those new airspace constructs under the authority of the governing CAA. Services provided by these 3rd parties are intended to reduce ATC workload by providing a mechanism to manage the AAM traffic through the sharing of data with AAM operators and other airspace providers [95]. In addition, services like tactical separation services within the AAM airspace constructs will not be provided by air traffic control but allocated to AAM operators, "pilots," and the 3rd party service providers. The procedures for using these services to enable AAM operations are developed cooperatively by industry and the appropriate CAA [28].

E.5 Cooperative Operating Procedures (COPs), augment AAM-driven regulations to establish the expectations of AAM operators and 3rd Party Service Providers. COPs are developed by industry based on FAA guidelines and require FAA approval to address elements covered by FAA authority (e.g., safety, demand/capacity balancing, equitable access to airspace, security) (adapted from [28], where they were referred to as Community Based Rules (CBRs)).

Cooperative Operating Procedures, or COPs, define the rules by which AAM operations will be managed safely and efficiently, particularly within an AAM airspace construct. These rules are designed to be developed specifically for the unique characteristics of the AAM aircraft and their operational characteristics, providing industry with optional solutions to traffic management. For example, in order to mitigate the need to use holding to manage eVTOL arriving at a busy vertiport optional COPs could be:

1.) to provide more "slack" in the system, which would reduce the need to hold aircraft but tend to reduce the capacity of the airspace and the number of supported operations, or
2.) to require improved navigation performance for aircraft flying in AAM airspace, reducing the need to add as much slack.

Both options could reduce the number of times eVTOL aircraft fly holding patterns, for instance, but improving navigation performance may have greater impact, providing additional flexibility for passengers (i.e., more time slots for flying).

Each of the airspace management considerations described above are intended to maximize passenger demand for AAM services by improving air operations efficiency while maintaining the safety of the overall system. However, this leads to a final consideration: the reliable availability of the system. Flights that are routinely delayed or outages that occur during marginal weather conditions will discourage passengers from using AAM services when time is critical. Examples include using AAM to get to the airport for a traditional flight and commuting to/from work. If AAM is unable to transport the passenger to the airport on time and the passenger misses their long-range flight or if an individual is able to get to work via AAM, but unable to ride on the AAM aircraft back home, the passenger may never trust the AAM mode again, reducing overall demand.

E.6 Operational Resiliency is the ability to provide or resume necessary services in a timely fashion when operations are disrupted (e.g., due to weather events, crew unavailability, customer misconnections, maintenance requirements, etc.)

There will always be disruptions to the AAM services. The goal is to minimize impact and enable passengers to complete their primary mobility objective: to get from one place to another. Some solutions rely on technology to help better manage the airspace, like the improvement of aircraft flight path and timing accuracy or improved weather and wind prediction models/products. Others are more procedural, including several discussed above (e.g., COPs, digital flight, and airspace construct). The final guard against disruptions may be more aligned with brute force, including but not limited to the availability of weather-tolerant aircraft, additional aircraft to handle short term demand spikes, getting the passenger close enough to their final destination, or integrating with other modes of transport all together.

F. Service Characteristics

For many members of the public, perceptions of aviation are related to travel experiences with airlines. Airlines offer scheduled service with flights between specified city pairs at specified times. Customers are familiar with this air travel experience and are accustomed to sharing a flight with many other members of the traveling public. In contrast, the passenger experience with AAM will likely be very different, combining aspects of the experience associated with ground transportation and with general aviation. In this section, we discuss characteristics that describe the experience of an AAM service in terms of the passenger's ability to select "where" (origin and destination), "when" (flight time and reservation time), and "with whom" (sharing with other passengers) to travel. We use the term "AAM operator" for the service provider, analogous to the term "airline" for scheduled commercial flights.

In June of 2021, SAE International released *A Taxonomy of On-Demand and Shared Mobility: Ground, Aviation, and Marine* that included several shared ground service definitions and shared aviation service definitions [29]. In this section, we review the shared ground service taxonomy proposed by SAE International and expand upon their shared aviation service definitions for AAM. Before defining service characteristics for AAM, it is useful to review the SAE definitions, which arguably are taken from the operator and/or vehicle perspective. One of the key distinctions between ground and air transportation is that for the latter, individuals are accustomed to traveling with others who are not members of the same household. Thus, when the AAM literature uses the term "air taxi service," many authors are referring to a concurrent sharing situation. That is, the phrase "I took a taxi to the airport," is more likely to connote the image of a sequential sharing situation in which the passenger does not share the cab with anyone else whereas "I took a helicopter (or air taxi) from Manhattan to JFK airport" is more likely to connote the image of sharing the aircraft with other passengers.

The following definitions are provided by SAE and enhanced where appropriate with a discussion based on FAA terminology.

F.1 On-demand is "the ability to reserve or dispatch a service upon request by users" (taken directly from [29]).

The key distinction of on-demand service is the customer's ability to select the origin and destination locations and a window of time in which the trip takes place. For aviation, on-demand operations are defined in the U.S. Federal Aviation Regulations as, "…any operations in which the departure time, departure location, and arrival location are specifically negotiated with the customer or the customer's representative…." [96].

F.2 Concurrent sharing is "sharing of the same transportation vehicle, device, or service by travelers from different households and/or different traveling parties in a simultaneous manner" (taken directly from [29]).

F.3 Sequential sharing is the "sharing of the same transportation vehicle, design, or service by travelers from different households and/or different traveling parties one after the other (i.e., in a sequential manner)" (taken directly from [30]).

F.4 Transportation Network Company (TNC)/Ridehailing/Ridesourcing is "a service that provides the traveler with pre-arranged and/or on-demand access to a ride for fee using a digitally enabled application or platform (e.g.., smartphone apps) to connect traveler with drivers using their personal, rented, or leased motor vehicles. Digital enabled applications are typically used for booking, electronic payment, and ratings" (taken directly from [29]).

F.5 Ridesplitting/ridepooling is a concurrently shared commercial ride service in a vehicle where the traveler is matched with other riders traveling along a similar or identical route (adapted slightly from [29]).

Given these and other subtle differences in shared transportation for air taxis, we propose the following definitions for AAM service characteristics that are centered more on the passenger perspective.

F.6 A Per-seat On-demand[11] service is one in which passengers reserve and pay for individual seats on an aircraft.

F.7 Per-vehicle On-demand service occurs when an individual reserves and pays for all seats on an aircraft.

F.8 Per-vehicle On-demand with Resale is a service in which a passenger reserves and pays for all seats on an aircraft but retains the right to resell the extra seats that the passenger does not intend to use or to allow the AAM operator to attempt to resell the extra seats.

---

[11] We thank Bruce Holmes for his suggestions to use "per-seat" and "per-plane" terminologies to distinguish between

The purpose of on-demand service with resale is to allow a passenger to book a flight time, origin, and destination on a multi-passenger aircraft that might not otherwise have been offered by the operator via per-seat on demand service for economic reasons. In this service, the passenger, not the operator, assumes the risk that the remaining seats may not be sold.

F.9 Air Pooling is "an on-demand service in which multiple individual users share an aircraft" (taken directly from [97]).

Air pooling may be implemented by an AAM operator who offers per-seat on-demand service by negotiating the departure time, origin, and destination with the customers to achieve multiple bookings into a single flight. Air pooling is a form of demand aggregation. Air pooling is the aviation equivalent to ridesplitting/ridepooling and concurrent sharing in ground transportation, as defined in [29].

F.10 Scheduled Service consists of flights in which departure times, origins, and destinations have been pre-planned by the operator. The flight schedule is made available to customers at the time of booking to allow customers to select available flights that best meet their trip requirements.

Scheduled service is the most common type of service offered via large commercial aircraft through 14 CFR Part 121 operations [98]. In the context of AAM scheduled service, the frequency of flight operations may be expected to be increased considerably compared to Part 121 operations, with multiple flights scheduled daily or even hourly between origin-destination pairs with high demand. As discussed in [97], the potential for high flight frequency in scheduled AAM service might enable customers to select flights with enough flexibility to effectively mimic the customer experience of on-demand service.

F.11 Advance Reservation Notice is the amount of time before the flight that customers reserve the service.

Passenger preferences for advance reservations will vary by trip purpose and other attributes, e.g., passengers may prefer to reserve an AAM flight to an airport a day or two in advance of departure, whereas passengers may prefer to reserve an AAM flight for commuting purposes only a few minutes before departure.

G. Interactions between Demand and Supply

There are many ways in which demand can influence supply and supply can influence demand – both now and over time. This section focuses on discussing longer-term influences between demand and supply. Potential demand for AAM is influenced by consumer preferences for a variety of characteristics, including but not limited to cost, travel time, travel time reliability, on-time performance, number of transfers, safety features, vehicle design and comfort, and ride quality. Consumer preferences vary across the population and are a function of passenger and trip characteristics. For example, many individuals who want to take an eVTOL from a vertiport near their home to a local airport may place a higher priority on making a reservation in advance for the eVTOL flight and having scheduled departure and arrival times. This helps to reduce uncertainty associated with eVTOL flights not being available and airport arrival times. However, consumer preferences for advance reservations and fixed schedules may not be as important (or even relevant) for other trip purposes, such as regular work commuting. This is one example of how demand-side consumer preferences can influence supply-side service characteristics.

Consumer preferences evolve over time, particularly as consumers learn about and experience using a new mode of transportation. For example, in commercial aviation, significant flight delays and cancellations can affect long-term customer retention – that is, a bad customer experience with one airline may lead the customer not to travel with that airline in the future. This is one example of how a service characteristic that is highly valued by a consumer can influence demand via a feedback loop.

Demand and supply characteristics can interact in more subtle ways as well. As AAM enters the market, it will provide travel time savings over existing modes and may facilitate residential location changes. Some individuals may decide to move further from their work locations in order to take advantage of lower housing costs and better schools while simultaneously maintaining their current commute times (only now taking an AAM aircraft versus ground vehicle). In turn, this would increase the average commute distance (a passenger characteristic). Similarly, as battery technologies advance, new AAM aircraft will emerge that can fly longer distances (an aircraft characteristic). This will increase the catchment areas for AAM and resulting demand.

AAM has been and will continue to be shaped by several major trends and feedback loops for the foreseeable future:

1. Increasing climate change impacts are driving the need to shift to zero emission operations enabled by ongoing investments and improvements in battery technologies, in particular increased power density and faster recharging capabilities.
2. Increasing climate change impacts will also drive the need for more physical transportation multimodal integration where the advantages of each mode can be fully leveraged to maximize the overall physical trip efficiencies. This capability is being driven by network-enabled coordination and operations which will continue to improve with advanced information technology and artificial intelligence technologies. Multimodal integration will increase the flexibility and convenience of all modes of transportation.
3. As telepresence capabilities and autonomous delivery systems mature and supplant daily commuting and logistics trips by humans, the population will be able to afford higher quality transportation modes for those times when they do travel physically.
4. Improvements in telepresence has also enabled employees to live further from work which will increase demand for longer range commutes to the office for those occasions when physical presence is needed in the workplace.
5. Maturity of autonomous systems driven by multiple industries will decrease operating costs of physical transportation systems, as well as making them more efficient overall, especially when combined with network-enabled services enabling an ever-larger portion of the population to take advantage of the AAM services.

V. Conclusions

In this paper, we have proposed a taxonomy that describes characteristics of Advanced Air Mobility (AAM) for passenger transportation. The purpose of the taxonomy is to continue the development of a lingua franca for AAM that bridges between historical terminologies of the air transportation and ground transportation research communities. Although the paper makes progress in this direction, we must acknowledge that the taxonomy is incomplete in certain respects. For example, whereas we discussed air operations characteristics, we did not comprehensively define other operational characteristics of AAM, such as multimodal operations and ground-side operations in passenger terminals. Additionally, our focus was on passenger transportation missions, and future work is needed to expand the taxonomy to include cargo transport and aerial work AAM missions. Finally, we recognize that AAM is in its infancy, with few if any operations yet in service, and the conceptualization of AAM by both researchers and business leaders is evolving rapidly. For these reasons, the taxonomy presented in this paper must be viewed as a snapshot in time, with needs for updates in the future to overcome our failures of imagination at present.

Acknowledgments

The material is based upon work supported by NASA's Aeronautics Research Mission Directorate, including under contract award number 80LARC17C0004, activity number 202071.

References

[1] Patterson, M. P. "Advanced Air Mobility (AAM): An Overview and Brief History," *Transportation Engineering and Safety Conference*, 10 Dec 2021. https://ntrs.nasa.gov/citations/20210024608.

[2] Hill, B. P., DeCarme, D., Metcalfe, M., Griffin, C., Wiggins, S., Metts, C., Bastedo, B., Patterson, M. D., and Mendonca, N. L. *UAM Vision Concept of Operations (ConOps) UAM Maturity Level (UML) 4*, 2020. https://ntrs.nasa.gov/citations/20205011091

[3] Antcliff, K., Borer, N., Sartorius, S., Saleh, P., Rose, R., Gariel, M., Oldham, J., Courtin, C., Bradley, M., Roy, S., Lynch, B., Guiang, A., Stith, P., Sun, D., Ying, S., Patterson, M., Schultz, V., Ganzarski, R., Noertker, K., Combs, C., and Oullette, R. *Regional Air Mobility: Leveraging Our National Investments to Energize the American Travel Experience*, 2021. https://ntrs.nasa.gov/citations/20210014033.

[4] Federal Aviation Administration (FAA). "Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Concept of Operations v2.0: Foundational Principles," 2020. https://www.faa.gov/uas/research_development/traffic_management/media/UTM_ConOps_v2.pdf.

[5] National Aeronautics and Space Administration (NASA), *Fiscal Year 2020 Explore Budget Estimates (Congressional Justification),* 2019. https://www.nasa.gov/sites/default/files/atoms/files/fy_2020_congressional_justification.pdf.

[6] Dunbar, B. "FY 2020 Budget Request." NASA webpage last updated 22 March 2021. https://www.nasa.gov/content/fy-2020-budget-request.

[7] National Academies of Sciences, Engineering, and Medicine. *Advancing Aerial Mobility: A National Blueprint*. The National Academies Press, 2020. https://doi.org/10.17226/25646.

[8] "NASA, Teamed with FAA, Industry, and Academia, Should Research Effects of Increased Drone Traffic on Privacy, the Environment, and Cybersecurity." *Nationalacademies.org*, National Academy of Sciences, 19 Feb. 2020, https://www.nationalacademies.org/news/2020/02/nasa-teamed-with-faa-industry-and-academia-should-research-effects-of-increased-drone-traffic-on-privacy-the-environment-and-cybersecurity. Accessed 2 Nov 2021.

[9] eVTOL Editorial Staff. "NASA Rebrands UAM Grand Challenge to Embrace 'Advanced Air Mobility'." *Evtol.com*, Evtol.com, 24 Mar. 2020, https://evtol.com/news/nasa-advanced-air-mobility-national-campaign/. Accessed 2 Nov 2021.

[10] Moore, M. "21st Century Personal Air Vehicle Research." In *AIAA International Air and Space Symposium and Exposition: The Next 100 Years*, American Institute of Aeronautics and Astronautics. https://arc.aiaa.org/doi/pdf/10.2514/6.2003-2646.

[11] Wolfe, J., Bauer, J., Bixby, C. J., Lauderdale, T., Shively, J., Griner, J., and Hayhurst, K. *Meeting of Experts on NASA's Unmanned Aircraft System (UAS) Integration in the National Airspace Systems (NAS) Project*. 2010. https://ntrs.nasa.gov/citations/20100027484.

[12] Moore, M. "Aviation Frontiers - On Demand Aircraft". In *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, American Institute of Aeronautics and Astronautics, 2010. https://arc.aiaa.org/doi/abs/10.2514/6.2010-9343.

[13] Gawdiak, Y., Holmes, B., Sawhill, B., Herriot, J., Ballard, D., Creedon, J., Eckhause, J., Long, D., Hemm, R., Murphy, C., Thompson, T., Wieland, F., Price, G., Marcolini, M., Moore, M., and Alcabin, M. "Air Transportation Strategic Trade Space Modeling and Assessment Through Analysis of On-Demand Air Mobility with Electric Aircraft." In *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, American Institute of Aeronautics and Astronautics. https://arc.aiaa.org/doi/abs/10.2514/6.2012-5594.

[14] Moore, M. D., Goodrich, K., Viken, J., Smith, J., Fredericks, B., Trani, T., Barraclough, J., German, B., and Patterson, M. "High Speed Mobility Through On-Demand Aviation." In *AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Los Angeles, CA, 2013. https://ntrs.nasa.gov/citations/20140002448.

[15] Moore, M., Goodrich, K., and Patterson, M. "NASA Aeronautics Research Mission Directorate ODM Technical Roadmap Report Out." In *Transformative Vertical Flight Workshop*, 29 September 2016. http://www.nianet.org/ODM/September/1%20Hartford%20Intro%20Slides%20Goodrich.pdf

[16] Holmes, B. J., Parker, R. A., Stanley, D., McHugh, P., Garrow, L., Masson, P. M., Olcott, J. "NASA Strategic Framework for On-Demand Air Mobility", 2017. http://www.nianet.org/ODM/reports/ODM%20Strategic%20Framework%20-%20Final%20170308.pdf. Accessed 19 April 2022.

[17] Patterson, M. D., Antcliff, K. R., and Kohlman, L. W. "A Proposed Approach to Studying Urban Air Mobility Missions Including an Initial Exploration of Mission Requirements." Presented at the AHS Annual Forum and Technology Display, Phoenix, AZ, 2018. https://ntrs.nasa.gov/citations/20190000991.

[18] Bremmer, C. "Air Travel Switches to Electricity." *The Times*. 3 January 2008. https://web.archive.org/web/20130601111600/http://www.electravia.fr/DOCUMENTS/Presse_Prototypes/TheTimes030108.jpg

[19] Drone Nodes. "Demonstration of integrated hydrogen fuel cell in Yuneec Tornado H920 at Inter Drone Las Vegas," *YouTube Video*, 17 September 2016. https://www.youtube.com/watch?v=cj-xU4tmQWc.

[20] Lapeña-Rey, N., Mosquera, J., Bataller, E. and Ortí, F. "The Boeing Fuel Cell Demonstrator Airplane." SAE Technical Paper 2007-01-3906, 2007, https://doi.org/10.4271/2007-01-3906.
[21] Pipistrel. "History." https://www.pipistrel-aircraft.com/about-us/history/. Accessed 18 April 2022.
[22] Wells, D. NASA "Green Flight Challenge: Conceptual Design Approaches and Technologies to Enable 200 Passenger Miles per Gallon." In *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, American Institute of Aeronautics and Astronautics. https://arc.aiaa.org/doi/abs/10.2514/6.2011-7021.
[23] Steitz, D. E., "NASA Awards Historic Green Aviation Prize," Press Release 11-334, NASA Headquarters, Oct 3 2011.
[24] Prevot, T., Rios, J., Kopardekar, P., III, J. E. R., Johnson, M., and Jung, J. "UAS Traffic Management (UTM) Concept of Operations to Safely Enable Low Altitude Flight Operations." In *16th AIAA Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics. https://arc.aiaa.org/doi/abs/10.2514/6.2016-3292.
[25] Garrow, L.A., German, B.J. and Leonard, C.E. (2021). "Urban air mobility: A comprehensive review and comparative analysis with autonomous and electric ground transportation." *Transportation Research Part C,* 132: 103377. https://doi.org/10.1016/j.trc.2021.103377.
[26] Schuchardt, B.I., Becker, D., Becker, R.-G., et al. (2021). "Urban air mobility research at the DLR German Aerospace Center – Getting the HorizonUAM project started." AIAA Aviation Forum. https://doi.org/10.2514/6.2021-3197.
[27] Asmer, L., Pak, H., Prakasha, P.S., et al. (2021). "Urban air mobility use cases, missions and technology scenarios for the HorizonUAM project." AIAA Aviation Forum. https://doi.org/10.2514/6.2021-3198.
[28] Federal Aviation Administration (FAA) (2000). "Urban Air Mobility (UAM) Concept of Operations v1.0." Available online at https://nari.arc.nasa.gov/sites/default/files/attachments/UAM_ConOps_v1.0.pdf. Accessed March 29, 2022.
[29] SAE International (2021). "Taxonomy of On-Demand and Shared Mobility: Ground, Aviation, and Marine." Report number JA3136_202106. Available online at https://www.sae.org/standards/content/ja3163_202106/. Accessed March 29, 2022.
[30] Connecticut Department of Transportation. "Travel Demand Forecasting." https://portal.ct.gov/DOT/PP_SysInfo/Travel-Demand-Forecasting#:~:text=Travel%20Demand%20Forecasting%20is%20the,nature%20of%20the%20transportation%20system.. Accessed April 18, 2020.
[31] Wedel, M. and Kamakura, W.A. *Market Segmentation: Conceptual and Methodological Foundations, Second Edition.* Part of the International Series in Quantitative Marketing (ISQM, Volume 8). 2000.
[32] Dong, G., Ma, J., Wei, R., Haycox, J. 2019. "Electric vehicle charging point placement optimisation by exploiting spatial statistics and maximal coverage location models." Transportation Research Part D: Transport and Environment 67, 77–88. https://doi.org/10.1016/j.trd.2018.11.005
[33] Hudson, J., Orviska, M., Hunady, J., 2019. "People's attitudes to autonomous vehicles." Transportation Research Part A: Policy and Practice 121, 164–176. https://doi.org/10.1016/j.tra.2018.08.018
[34] Kopp, J., Gerike, R., Axhausen, K.W., 2015. "Do sharing people behave differently? An empirical evaluation of the distinctive mobility patterns of free-floating car-sharing members." Transportation 42(3), 449–469. https://doi.org/10.1007/s11116-015-9606-1
[35] Liu, P., Guo, Q., Ren, F., Wang, L., Xu, Z., 2019. "Willingness to pay for self-driving vehicles: Influences of demographic and psychological factors." Transportation Research Part C: Emerging Technologies 100, 306–317. https://doi.org/10.1016/j.trc.2019.01.022
[36] Nordstrom, W. "Optimal Locations for Air Mobility Vertiports," Community Integration AAM Ecosystem Working Group Meeting, 25 Jan 2022, https://aam-cms.marqui.tech/uploads/aam-portal-cms/originals/78f26bc3-ac73-4809-b972-24eec371ab17.pdf

[37] Potoglou, D., Whittle, C., Tsouros, I., Whitmarsh, L., 2020. "Consumer intentions for alternative fuelled and autonomous vehicles: A segmentation analysis across six countries." Transportation Research Part D: Transport and Environment 79, 102243. https://doi.org/10.1016/j.trd.2020.102243

[38] Shabanpour, R., Golshani, N., Shamshiripour, A., Mohammadian, A. (Kouros), 2018. "Eliciting preferences for adoption of fully automated vehicles using best-worst analysis." Transportation Research Part C: Emerging Technologies 93, 463–478. https://doi.org/10.1016/j.trc.2018.06.014

[39] Spurlock, C.A., Sears, J., Wong-Parodi, G., Walker, V., Jin, L., Taylor, M., Duvall, A., Gopal, A., and Todd, A. "Describing the users: Understanding adoption of and interest in shared, electrified, and automated transportation in the San Francisco Bay Area." *Transportation Research Part D: Transport and Environment* 71, 283–301, 2019. https://doi.org/10.1016/j.trd.2019.01.014

[40] Vij, A., Ryan, S., Sampson, S., Harris, S., 2020. "Consumer preferences for on-demand transport in Australia." Transportation Research Part A: Policy and Practice 132, 823–839. https://doi.org/10.1016/j.tra.2019.12.026

[41] Wang, S., Zhao, J., 2019. "Risk preference and adoption of autonomous vehicles." Transportation Research Part A: Policy and Practice 126, 215–229. https://doi.org/10.1016/j.tra.2019.06.007

[42] Yedavalli, P., Mooberry, J., n.d. "An assessment of public perception of urban air mobility (UAM)." Airbus UTM: Defining Future Skies. Available online at https://storage.googleapis.com/blueprint/AirbusUTM_Full_Community_PerceptionStudy.pdf. Accessed September 21, 2020.

[43] Axsen, J., Goldberg, S., Bailey, J. (2016). "How might potential future plug-in electric vehicle buyers differ from current 'Pioneer' owners?" Transportation Research Part D: Transport and Environment 47, 357–370. https://doi.org/10.1016/j.trd.2016.05.015

[44] Reiche, C., Goyal, R., Cohen, A., Serrao, J., Kimmel, S., Fernando, C., Shaheen, S. (2018). "Urban Air Mobility Market Study." National Aeronautics and Space Administration (NASA). http://dx.doi.org/10.7922/G2ZS2TRG. Available online at https://escholarship.org/uc/item/0fz0x1s2#main. Accessed June 10, 2021.

[45] Bennett, R., Vijaygopal, R., Kottasz, R. (2019). "Attitudes towards autonomous vehicles among people with physical disabilities." Transportation Research Part A: Policy and Practice 127, 1–17. https://doi.org/10.1016/j.tra.2019.07.002

[46] Biresselioglu, M.E., Demirbag Kaplan, M., Yilmaz, B.K. (2018). "Electric mobility in Europe: A comprehensive review of motivators and barriers in decision making processes." Transportation Research Part A: Policy and Practice 109, 1–13. https://doi.org/10.1016/j.tra.2018.01.017

[47] Kim, S.H., Circella, G., Mokhtarian, P.L. (2019). "Identifying latent mode-use propensity segments in an all-AV era." Transportation Research Part A: Policy and Practice 130, 192–207. https://doi.org/10.1016/j.tra.2019.09.015

[48] Lane, B.W., Dumortier, J., Carley, S., Siddiki, S., Clark-Sutton, K., Graham, J.D. (2018). "All plug-in electric vehicles are not the same: Predictors of preference for a plug-in hybrid versus a battery-electric vehicle." Transportation Research Part D: Transport and Environment 65, 1–13. https://doi.org/10.1016/j.trd.2018.07.019

[49] Sweet, M.N., Laidlaw, K. (2019). "No longer in the driver's seat: How do affective motivations impact consumer interest in automated vehicles?" Transportation 47, 2601–2634. https://doi.org/10.1007/s11116-019-10035-5

[50] Tsouros, I., Polydoropoulou, A. (2020). "Who will buy alternative fueled or automated vehicles: A modular, behavioral modeling approach." Transportation Research Part A: Policy and Practice 132, 214–225. https://doi.org/10.1016/j.tra.2019.11.013

[51] Wang, Y., Wang, S., Wang, J., Wei, J., Wang, C. (2020). "An empirical study of consumers' intention to use ride-sharing services: Using an extended technology acceptance model." Transportation 47(1), 397–415. https://doi.org/10.1007/s11116-018-9893-4

[52] Straubinger, A., Verhoef, E.T., and de Groot, H.L.F. (2021). "Will urban air mobility fly? The efficiency and distributional impacts of UAMin different urban spatial structures." Transportation Research Part C: 127, 103124. https://doi.org/10.1016/j.trc.2021.103124

[53] US Department of Transportation (2015). "2015 Revised Value of Travel Time Guidance." Available online at https://www.transportation.gov/resources/2015-revised-value-of-travel-time-guidance. Accessed March 29, 2022.

[54] Akhter et al., 2020 Akhter, M.Z., Raza, M., Iftikhar, S.H., Raza, M. (2020) "Temporal and economic benefits of vertical take-off and landing vehicles in urban transport." *2020 Advances in Science and Engineering Technology International Conferences (ASET)*, pp. 1–6. https://doi.org/10.1109/ASET48392.2020.9118256.

[55] Antcliff, K.R., Moore, M.D., Goodrich, K.H. (2016). "Silicon Valley as an early adopter for on-demand civil VTOL operations." In *16th AIAA Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics, Washington, DC, June 13–17. https://doi.org/10.2514/6.2016-3466.

[56] Kreimeier, M., Stumpf, E., Gottschalk, D. (2016). "Economical assessment of air mobility on demand concepts with focus on Germany." In *16th AIAA Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics, Washington, DC, June 13–17. https://doi.org/10.2514/6.2016-3304.

[57] Roland Berger (2018). "Urban Air Mobility: The Rise of a New Mode of Transportation." (video) Available online: https://www.rolandberger.com/en/Publications/Passenger-drones-ready-for-take-off.html#:~:text=As%20the%20Roland%20Berger%2Dstudy,ease%20the%20existing%20traffic%20situation. Accessed September 2, 2020.

[58] Roy, S., Kotwicz Herniczek, M.T., Leonard, C., Jha, A., Wang, N., German, B., Garrow, L. (2020). "A multi-commodity network flow approach for optimal flight schedules for an airport shuttle air taxi service." *AIAA Scitech 2020 Forum*, Orlando, FL, January 6. https://doi.org/10.2514/6.2020-0975.

[59] The Economic Times (2022). "Definition of 'preferences'." Available online at https://economictimes.indiatimes.com/definition/preferences. Accessed March 29, 2022.

[60] Victoria Transport Policy Institute. (2009). "Transportation Cost and Benefit Analysis II – Travel Time Costs." Available online at http://cruz511.org/wp-content/uploads/2014/09/tca0502-TravelTime.pdf. Accessed May 29, 2022.

[61] Jansen, R. "Overview of NASA Electrified Aircraft Propulsion Activities." Presented at the Energy Optimized Aircraft (EOA) Meeting, 2017. https://ntrs.nasa.gov/citations/20180000593.

[62] National Academies of Sciences, Engineering, and Medicine. *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*. 2016. https://nap.nationalacademies.org/catalog/23490/commercial-aircraft-propulsion-and-energy-systems-research-reducing-global-carbon.

[63] Datta, A. *PEM Fuel Cell MODEL for Conceptual Design of Hydrogen EVTOL Aircraft*. 2021. https://ntrs.nasa.gov/citations/20210000284.

[64] Borer, N. K., Geuther, S. C., Litherland, B. L., and Kohlman, L. "Design and Performance of a Hybrid-Electric Fuel Cell Flight Demonstration Concept." In *AIAA Aviation*, Atlanta, GA, 2018. https://ntrs.nasa.gov/citations/20190033418.

[65] "Hybrid & Electric Propulsion Performance Measurement." GAMA Publication No. 16. *General Aviation Manufacturers Association.* Washington, DC USA. 2017. https://gama.aero/wp-content/uploads/GAMA-Publication-No-16-Hybrid-and-Electric-Propulsion-Performance-Measurement-1.pdf.

[66] Moore, M. D., and Fredericks, B. "Misconceptions of Electric Propulsion Aircraft and Their Emergent Aviation Markets." In *AIAA Aerospace Sciences Meeting*, National Harbor, MD, 2014. https://ntrs.nasa.gov/citations/20140011913.

[67] Stoll, A. M., and Mikic, G. V. "Design Studies of Thin-Haul Commuter Aircraft with Distributed Electric Propulsion." In *16th AIAA Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics. https://arc.aiaa.org/doi/abs/10.2514/6.2016-3765.

[68] Borer, N. K., Patterson, M. D., Viken, J. K., Moore, M. D., Bevirt, J., Stoll, A. M., and Gibson, A. R. "Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator." In *16th AIAA Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics. https://arc.aiaa.org/doi/abs/10.2514/6.2016-3920.

[69] Patterson, M. D. "Conceptual Design of High-Lift Propeller Systems for Small Electric Aircraft." 2016. https://smartech.gatech.edu/handle/1853/55569.

[70] Yaros, S. F., Sexstone, M. G., Huebner, L. D., Lamar, J. E., McKinley, R. E., Torres, A. O., Burley, C. L., Scott, R. C., and Small, W. J. *Synergistic Airframe-Propulsion Interactions and Integrations: A White Paper Prepared by the 1996-1997 Langley Aeronautics Technical Committee*. Publication L–17723. 1998. https://ntrs.nasa.gov/citations/19980055126.

[71] eVTOL News. "eVTOL Aircraft Directory." https://evtol.news/aircraft. Accessed 18 April 2022.

[72] Jones, C. A., Stafford, M. A., Latorella, K., Bard, C., Dorelli, J., Rodgers, E., Pensado, A., Benjamin, G., Lewis, S., Patrick, A., Hay, J., Stafford, M. A., Latorella, K., Bard, C., Dorelli, J., Rodgers, E., Pensado, A., Benjamin, G., Lewis, S., Patrick, A., and Hay, J. "Recommendations to Advance Space Trusted Autonomy." In *AIAA Ascend*, 2021. https://ntrs.nasa.gov/citations/20210017228.

[73] "A Rational Construct for Simplified Vehicle Operations (SVO)." GAMA EPIC SVO Subcommittee Whitepaper. *General Aviation Manufacturers Association.* Washington, DC USA. May 20, 2019. https://gama.aero/documents/svo-whitepaper-a-rationale-construct-for-simplified-vehicle-operations-svo-version-1-0-may2019/.

[74] Wing, D. J., Chancey, E. T., Politowicz, M., Ballin, M. G., Chancey, E. T., Politowicz, M., and Ballin, M. G. "Achieving Resilient In-Flight Performance for Advanced Air Mobility through Simplified Vehicle Operations." In *AIAA AVIATION 2020 Forum*, American Institute of Aeronautics and Astronautics, 2020. https://ntrs.nasa.gov/citations/20205000771.

[75] Fong, T. W., Frank, J. D., Badger, J. M., Nesnas, I. A., and Feary, M. S. "Autonomous Systems Taxonomy." May 14, 2018. https://ntrs.nasa.gov/citations/20180003082.

[76] ASTM International, "Autonomy Design and Operations in Aviation: Terminology and Requirements Framework" (West Conshohocken, PA: ASTM International, 2019), https://doi.org/10.1520/TR1-EB

[77] Holbrook, J., Prinzel, L. J., Chancey, E. T., Shively, R. J., Feary, M., Dao, Q., Ballin, M. G., and Teubert, C. "Enabling Urban Air Mobility: Human-Autonomy Teaming Research Challenges and Recommendations." In *AIAA AVIATION 2020 Forum*, American Institute of Aeronautics and Astronautics, 2020. https://arc.aiaa.org/doi/10.2514/6.2020-3250.

[78] Seeley, B. A. "Regional Sky Transit." In *15th AIAA Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics. https://arc.aiaa.org/doi/abs/10.2514/6.2015-3184.

[79] Ullman, D. G., Homer, V., Horgan, P., Ouellette, R. "Comparing Electric Sky Taxi Visions." June 2017. https://www.davidullman.com/_files/ugd/20f020_0a6311be71f245e29c588d9122c64d05.pdf.

[80] Courtin, C., Mahseredjian, A., Dewald, A. J., Drela, M., and Hansman, J. "A Performance Comparison of ESTOL and EVTOL Aircraft." In *AIAA AVIATION 2021 FORUM*, American Institute of Aeronautics and Astronautics, 2021. https://arc.aiaa.org/doi/10.2514/6.2021-3220.

[81] Zuk, J., and Wardwell, D. A. "Summary of NASA's Extreme Short Take-Off and Landing (ESTOL) Vehicle Sector Activities." *SAE Transactions*, Vol. 114, 2005, pp. 674–687. https://www.jstor.org/stable/44682764.

[82] DeLaurentis, D., Kang, T., Lim, C. (Samson), Mavris, D., and Schrage, D. "System of Systems Modeling for Personal Air Vehicles." In *9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, American Institute of Aeronautics and Astronautics, 2002. https://arc.aiaa.org/doi/10.2514/6.2002-5620.

[83] Lechniak, J. A., Salazar, M., Abbigail, W., Morello, J., and Papathakis, K. "Nano-Electro Fuel Energy Economy and Powered Aircraft Operations." In *AIAA Scitech 2020 Forum*, American Institute of Aeronautics and Astronautics, 2020. https://arc.aiaa.org/doi/10.2514/6.2020-0117.

[84] Courtin, C., Hansman, R. J., and Drela, M. "Flight Test Results of a Subscale Super-STOL Aircraft." In *AIAA Scitech 2020 Forum*, American Institute of Aeronautics and Astronautics, 2020. https://arc.aiaa.org/doi/10.2514/6.2020-0977.

[85] Federal Aviation Administration (FAA). *Draft Engineering Brief 105 Vertiport Design.* 2022. https://www.faa.gov/airports/engineering/engineering_briefs/drafts/media/eb-105-vertiport-design-industry-draft.pdf. Accessed 18 April 2022.

[86] Federal Aviation Administration (FAA). *Advisory Circular 150/5390-3: Vertiport Design (Cancelled).* 31 May 1991 (cancelled 28 July 2010).

[87] Northeast UAS Airspace Integration Research Alliance. "High-Density Automated Vertiport Concept of Operations." Contractor Report. *National Aeronautics and Space Administration.* 2021. https://ntrs.nasa.gov/citations/20210016168

[88] "Joint Shipboard Helicopter and Tiltrotor Aircraft Operations." Joint Publication 3-04. *Joint Chiefs of Staff.* December 6, 2012. https://irp.fas.org/doddir/dod/jp3_04.pdf.

[89] Lascara, B., Lacher, A., DeGarmo, M., Maroney, D., Niles, R., & Vempati, L. (2019). "Urban Air Mobility Airspace Integration Concepts: Operational Concepts and Exploration Approaches." MITRE CORP MCLEAN VA. https://www.mitre.org/sites/default/files/publications/pr-19-00667-9-urban-air-mobility-airspace-integration.pdf.

[90] "91.117 Aircraft Speed." Code of Federal Regulations, Title 14. *National Archives and Records Administration.* 2022. https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-B/subject-group-ECFRe4c59b5f5506932/section-91.117.

[91] Wing, D. J., Cotton, W. B., Maris, J., and Vajda, P. (2022). "Applicability of Digital Flight to the Operations of Self-Piloted Unmanned Aircraft Systems in the National Airspace System," NASA/TM-20210025961. NASA, Washington D.C. https://ntrs.nasa.gov/citations/20210025961.

[92] International Civil Aviation Organization (2005). "Global air traffic management operational concept (No. 9854)." Montreal, Canada. https://www.icao.int/Meetings/anconf12/Document%20Archive/9854_cons_en[1].pdf

[93] Code of Federal Regulations, Title 14 Aeronautics and Space, Part 150 Airport Noise Compatibility Planning. (14 CFR Part 150). https://www.ecfr.gov/current/title-14/chapter-I/subchapter-I/part-150. Accessed 18 April 2022.

[94] Levitt, I., Phojanamongkolkij, N., Witzberger, K., et al. (2021). "UAM Airspace Research Roadmap." NASA/TM-20210019876. NASA, Washington D.C. https://ntrs.nasa.gov/citations/20210019876.

[95] Yang, S.-G., Liu, T., Ge, S., Rountee, E., and Wang, C.-Y. "Challenges and key requirements of batteries for electric vertical takeoff and landing aircraft," *Joule* 5(7): 1644-1659, 2021).https://doi.org/10.1016/j.joule.2021.05.001

[96] Code of Federal Regulations, Title 14 Aeronautics and Space, Part 110 General Requirements, Section 110.2 Definitions. (14 CFR Part 110, § 110.2). https://www.ecfr.gov/current/title-14/chapter-I/subchapter-G/part-110/section-110.2. Accessed 18 April 2022.

[97] Cohen, A., & Shaheen, S. (2021). "Urban Air Mobility: Opportunities and Obstacles." In International Encyclopedia of Transportation. UC Berkeley: Transportation Sustainability Research Center. http://dx.doi.org/10.1016/B978-0-08-102671-7.10764-X. Retrieved from https://escholarship.org/uc/item/0r23p1gm

[98] Code of Federal Regulations, Title 14 Aeronautics and Space, Part 121 Operating Requirements: domestic, Flag, and Supplemental Operations. (14 CFR Part 121). https://www.ecfr.gov/current/title-14/chapter-I/subchapter-G/part-121?toc=1. Accessed 18 April 2022.