A Proposed Approach to Studying Urban Air Mobility Missions Including an Initial Exploration of Mission Requirements

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ABSTRACT

Urban air mobility (UAM) is an emerging aviation market that seeks to revolutionize mobility around metropolitan areas via a safe, efficient, and accessible on-demand air transportation system for passengers and cargo. In this paper we describe our three-pronged approach to studying passenger-carrying UAM missions, and we detail the first phase of this approach, which consists of defining an initial set of requirements for multiple exemplar UAM missions. The development of these mission requirements provides justifiable assumptions that feed the second phase of the approach, which is performing aircraft conceptual design studies. Vehicle design is not included in this paper, but the work described here will define sizing missions for follow-on design and sizing studies. The aircraft that emerge from the design studies can then feed the third phase of our UAM analysis approach, which involves simulating an entire UAM network over a metropolitan area to study transportation-system level characteristics. Iteration between each of the three phases of the UAM analysis approach will be necessary to propagate lessons learned as our research progresses and as the UAM community coalesces on a more unified vision for UAM. Therefore, we anticipate that the mission requirements set forth in this paper will be modified over time as the urban air mobility concept matures.

INTRODUCTION

In recent years, there has been a growing interest around the field of "on-demand mobility" (ODM). ODM is a multi-modal transportation capability in which individuals have access to immediate and flexible high-speed transportation, which can incorporate air travel, to take them safely and efficiently from one location to another over ranges from approximately 10 to 500 miles. In the words of Holmes et al., full realization of ODM would enable "anyone to fly from here to there, anytime, anywhere" (Ref. 1). ODM missions may include trip segments in conventional takeoff and landing (CTOL) aircraft, vertical takeoff and landing (VTOL) aircraft, or anything in between (e.g., short takeoff and landing aircraft). The benefits of moving from the ground to the air for at least portions of a trip include more direct routing, increased speeds, and moving to a node-based instead of a path-based transportation system. These benefits can ultimately lead to faster door-to-door trip times with less variability in the total travel time than is currently experienced in today's transportation system (Refs. 2, 3).

Large investments in road infrastructure have been made over the years to obtain high-speed mobility, but, particularly within large metropolitan areas, traffic congestion has become a major problem. Although some propose building more roads to alleviate this issue, Duranton and Turner (Ref. 4) argue that there is a "fundamental law of road congestion," which suggests no matter how many more lanes on existing major roads or new major roads in urban areas are added, they will eventually become congested as well. To potentially help alleviate this congestion or at least provide a new means of high-speed mobility, Moore casts a vision for how air travel could be revolutionized to provide true on-demand mobility (Refs. 2, 5).

Since Moore's initial vision, several application studies have been published that discuss the potential benefits and challenges of realizing ODM. Moore et al. (Ref. 6) describe a notional ODM system consisting of easily-rentable and highly-automated electric aircraft (Refs. 6–9). Melton et al. (Ref. 10) envision 6-, 15-, and 30-passenger electric VTOL vehicles suitable for aerial mass transit. Antcliff et al. (Ref. 3) depict a highly-distributed system of vertiports (i.e., takeoff and landing locations for VTOL aircraft with supporting ground equipment and passenger access) placed throughout the Silicon Valley area and determine that two to three times lower door-to-door trip times could be achieved with aviation-enabled ODM. Other systems studies have also been performed for such a VTOL ODM system, including estimating demand (Ref. 11) and identifying system-level challenges associated with realizing the implementation of such a system (Ref. 12).

In addition to these studies, NASA led a series of ODM Roadmapping Workshops (Refs. 13, 14) in collaboration with

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the Federal Aviation Administration (FAA) in 2015 and 2016. One of the goals of these workshops was to identify and bring together a community of interest around ODM, including operators, aircraft manufacturers, suppliers, universities, and other government agencies. Approximately 120 organizations from around the world participated in these workshops, demonstrating a strong and growing interest in the ODM realm. Another primary goal of these workshops was to identify technical and regulatory barriers to achieving ODM. Four working groups developed technology roadmaps aimed at identifying potential solutions to these challenges (Ref. 13). Perhaps one of the more significant outcomes of these workshops was that, as the workshops progressed, the interest in utilizing VTOL aircraft for short-range missions within a single city or small region grew markedly, as evidenced by the emergence of efforts such as A^3's Vahana (Ref. 15) and Uber's Elevate program (Ref. 16). This strong community growth, coupled with the potential benefits of realizing a short-range VTOL ODM capability, has led to the emergence of a new field termed "urban air mobility" (UAM), which is effectively a subset of ODM that focuses specifically on short-range transportation around a single metropolitan area. Ultimately, the urban air mobility concept seeks to revolutionize mobility around urban areas by providing a safe, efficient, and accessible on-demand air transportation system for passengers and cargo.

NASA has begun to fund new research in the UAM realm to build upon prior NASA-funded studies such as (Refs. 3, 10–12). Most of these previous studies considered the broader transportation system at a high level. We seek to build on these studies by adding appropriate detail and incorporating lessons learned. In this paper, we outline our approach to studying the UAM mission space, which consists of three phases: requirements definition for exemplar UAM missions, vehicle design studies, and full UAM network simulations. We also detail the first phase of this approach by defining a proposed set of mission requirements for multiple passenger-carrying UAM missions. We anticipate that the mission requirements proposed here will be modified over time as the UAM community continues advancing closer to truly enabling the urban air mobility vision.

AN OVERVIEW OF PROPOSED PASSENGER-CARRYING UAM MISSIONS

Many different urban air mobility missions have been proposed in the past. These proposals range from presenting purely notional or aspirational capabilities to detailed design studies or the development of actual flight vehicles. Publicly stated missions in the UAM space include:

1. commutes to/from work or other routine trips around a city (Refs. 3, 11, 12),
2. airport shuttles to provide faster connectivity for airline passengers to/from existing airports (from close to their origin or to near their final destination) (Ref. 17),
3. end-to-end city transfer allowing passengers to bypass city traffic and quickly move from one side of town to another (Ref. 17), and
4. "metro-like" services to connect passengers to other existing forms of mass transit (Ref. 10).

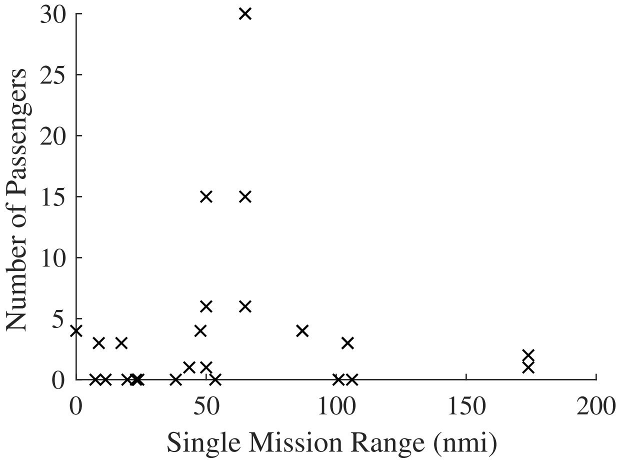

Fig. 1. Compilation of proposed passenger sizes and ranges for UAM-like missions found in the literature (where a value of 0 represents an unspecified parameter).

The reader is cautioned that this list is not intended to be exhaustive. In fact, there are a very large number of potential missions for these aircraft, many of which have yet to be described publicly.

A summary of desired mission capabilities found in the literature for passenger-carrying "UAM-like" aircraft is shown in Fig. 1. A value of zero for the number of passengers or range indicates that there was no value specified for that parameter. We use the term "UAM-like" because the term "UAM" has only been used extensively since approximately mid-2017. Many of the references represented in Fig. 1 predate the use of the UAM term, and we acknowledge that not every mission shown in the figure may necessarily be applicable to the current notion of urban air mobility. The missions represented in Fig. 1 were drawn from Antcliff et al. (Ref. 3), Melton et al. (Ref. 10), Syed et al. (Ref. 11), Holden and Goel (Ref. 16), McDonald and German (Ref. 18), Badalamenti and Peterson (Ref. 19), Vascik (Ref. 12), Moore and Goodrich (Ref. 20), Duffy et al. (Refs. 21, 22), Lovering (Ref. 23), Bower (Ref. 24), and Johnson et al. (Ref. 25).

As can be seen in Fig. 1, the majority of proposed missions have ranges of less than 100 nautical miles with nine or fewer passengers. The longest-range missions, i.e., those at 174 nautical miles (nmi) or 200 statue miles, are primarily aspirational in nature, aiming for connectivity between the center of a metropolitan area and its surrounding suburban/rural areas or between suburbs. Only three missions have more than nine passengers. Two of these missions were proposed by Melton et al. (Ref. 10), who were considering VTOL aircraft for a mass transit system for the San Francisco Bay Area. The third was proposed by Johnson et al. (Ref. 25) for use as one of multiple reference missions that "span the space" of the missions being proposed. One reason most proposed missions have nine or fewer passengers is that the nine-passenger level is a "break point" in the current Federal Aviation Regulations (FARs). Specifically, Part 23, which will be used (at least in part) for the certification of many novel UAM aircraft, has more stringent requirements for aircraft above nine passenger seats than for aircraft with seven to nine passenger seats.[1] Additionally, an aircraft can only be operated with a single pilot under Part 135 if the aircraft has nine or fewer passenger seats.[2] Finally, any aircraft can be flown in both an on-demand or commuter operation if there are nine or fewer passenger seats.[3]

A Taxonomy of Operational Models

When reviewing missions that have been proposed, we have observed approximately five different operational models for "on-demand" or "near-on-demand" passenger-carrying aviation missions, which are described below. Not all of these operational models have been proposed explicitly for the UAM domain, but such operations have been considered for other on-demand missions. The ordering of these operational models is roughly from the "most" to the "least" on-demand. Typical characteristics of the various operational models are shown in Table 1.

1. Private Operations: The private operations model is one in which a vehicle serves only one individual or party for a length of time greater than the duration of a single flight. Specifically, this model has a defining characteristic that the aircraft is dedicated to the service of the individual or party and does not serve other customers between missions. One implication of this model is that the vehicle will require space to park. Examples of this operational model include private vehicle ownership, fractional ownership, and rental. Such a model is similar to how most general aviation aircraft are operated today.
2. Air Taxi: The air taxi model is a truly on-demand service in which a single user or a single group of users reserve an entire aircraft for a flight and determine the flight's origin, destination, and timing. There are several examples of this operational model in the literature or in service today, including Refs. 6, 26, and 27.
3. Air Pooling: The air pooling model is a largely on-demand service where multiple individual users are aggregated ("pooled") into a single vehicle for flights. Flight departure times and/or origin-destination pairs may be set by a single user with other users fitting into that schedule, or the operator may adjust all users' desired schedules to enable aggregation of passengers. A few examples of this model can be found in Refs. 16, 28, and 29.
4. Semi-Scheduled Commuter: In the semi-scheduled commuter model, aircraft departure times and/or locations are modified from a baseline schedule based on the preferences of consumers. For example, an aircraft may be scheduled to depart between 8am and 10am each day on a particular route, but the actual departure time will be modified day-to-day based on an aggregation of customers' stated preferences/availability.
5. Scheduled Commuter: The scheduled commuter model provides a near-on-demand service by offering frequent flights along the same route(s) in a regularly scheduled service. Examples of this type of operation can be found in Refs. 10 and 30.

Table 1. Typical characteristics of the different operational models

Operational Model	Approx Number of Passengers	Operating Regulations
Private Service	1-6	Part 91
Air Taxi	1-4	Part 135
Air Pooling	3-6	Part 135
Semi-Scheduled Commuter	6-19	Part 135
Scheduled Commuter	6-19	Part 135 or 121

These operational models are not inherently tied to any one of the specific example missions that were listed previously. Many missions could be performed with any of the five operational models; however, certain missions will be limited to a subset of the operational models. For example, an airport shuttle mission could theoretically be performed under any of the five operational models. However, a "metro-like" mass transit mission is incompatible with the private ownership and air taxi models.

In our terminology, we will refer to a distinct "use case" as a particular mission paired with a specific operational model. For example, a scheduled commuter airport shuttle and an air taxi airport shuttle are two separate use cases, where each use case has the same base mission but is performed under a different operational model.

An Observation About Proposed Aircraft

Despite the variation in payload and range capabilities proposed for the UAM-like missions described above, there is one common thread among the proposed *vehicles* in these studies: electrification of the propulsion system. Many of these studies advocate for a fully-electric propulsion system, including Refs. 16 and 21, whereas others consider hybrid-electric or turboelectric systems[4] (Ref. 25). Because these vehicles rely on some form of electric propulsion system, the

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[1] See 14 CFR §23.2005

[2] See 14 CFR §135.99

[3] Commuter Operations are prohibited for airplanes with ten or more passenger seats. See 14 CFR §110.2, which defines commuter and on-demand operations, and 14 CFR §135.411, which describes rules for maintenance, preventive maintenance, and alterations. It should be noted that rotorcraft can be flown in either on-demand or commuter operations regardless of the number of seats per current regulations.

[4] Hybrid-electric vehicles use a combination of fuel and another form of energy storage system such as battery, while turboelectric systems store all of the mission energy as fuel and convert this to electricity

community has begun to call these vehicles electric vertical takeoff and landing (eVTOL) aircraft.

Although there is no definitive requirement that UAM vehicles have some form of electric propulsion system, there are several reasons why eVTOL aircraft are viewed as an enabler for UAM missions. First, electric propulsion expands the design space by enabling power to be distributed over the airframe with relatively few penalties. Such design freedom allows many concepts that were unsuccessful in the past, such as many of those found on the V/STOL Aircraft and Propulsion Concepts "wheel" (Ref. 31), to be revisited and improved. These new configurations can provide increased cruise efficiency and higher speeds than typical rotorcraft. Second, the operating costs of eVTOL aircraft can be reduced, as compared to conventionally powered aircraft. Energy costs can be lowered because the cost of electricity is typically less than that of conventional fuels and the vehicles can be designed to consume less energy per flight. Additionally, electric motors contain far fewer moving parts and produce less vibration than conventional engines, which may lead to significantly lower maintenance costs. Because UAM aircraft will most directly compete with cars or other forms of ground transportation for ridership, the operating cost of UAM aircraft is of greater importance than in other aviation applications. The reader is referred to Refs. 21, 22, 16, and 32 for more information about the potential benefits of electric propulsion technologies for UAM and ODM aircraft.

APPROACH TO STUDYING UAM MISSIONS

With the large amount of uncertainty that surrounds the UAM market and the wide spectrum of missions that have been proposed in the past, we do not anticipate that we will adequately and accurately define all the mission requirements for UAM operations in our first attempt in this paper. Therefore, we have developed a strategy for helping us to systematically study the UAM mission space.

This approach begins with the work that will be described in the following sections of this paper where we define multiple sets of mission requirements and sizing missions. We believe these are appropriate for the desired capabilities being sought in the UAM arena and would result in aircraft that can be safely operated. Requirements for the following three missions will be presented in this paper:

1. a long-range, small-payload mission,
2. a short-range, large-payload mission, and
3. a long-range, large-payload mission, which combines the most constraining elements of the previous two missions.

The second phase of this strategy is to design multiple reference aircraft that conform to the mission requirements developed in the first phase. These aircraft will include fully-electric, hybrid-electric, and conventionally-powered versions so that the relative merits and drawbacks of each design can be studied and assessed.

The third phase of our approach is to model the as-designed reference aircraft in an UAM network across a single metropolitan area, which we refer to as a "city-wide simulation." This city-wide simulation will be capable of modeling many distinct aircraft, landing locations, and use cases. As such, it will provide information about many high-level, "system-of-systems" considerations for UAM networks (such as the number of aircraft required to meet a specified demand, average load factors on aircraft, total energy costs, etc.). Multiple distinct city-wide simulations can also be performed to analyze a mission case

After the preceding three steps have been taken, we can then begin an exploratory process where we modify mission requirements and/or vehicle designs and/or operational parameters for city-wide UAM networks and analyze the impacts of these changes. Ultimately, we anticipate this to be a highly iterative process in which inputs from across NASA, industry, academia, the FAA, and other government agencies will be incorporated over time to refine individual models and assumptions. To help further describe why we believe this strategy is necessary, in the remainder of this section we provide several examples of how we may implement this process and studies we plan to perform.

Motivating Example 1

Even solely from the four example missions and five different operational models listed above, one can ascertain that distinct use cases (i.e., a mission flown under a specific operational model) may impose noticeably different requirements on the aircraft. For example, a person commuting to work for the day will likely only carry a few pounds of baggage with them that occupies a small volume, whereas an airport transfer service would require larger volumes and weight capabilities for airline passengers who may carry several large bags, including oversized items (e.g., sporting equipment, musical instruments, etc.). Similarly, the vehicle for commuting to work will likely only require room for a single passenger whereas an airport shuttle requires multiple passenger seats to allow small groups of travelers to remain together. Furthermore, an aircraft designed/optimized for the daily work commuting mission may have greatly varying requirements if it is operated as a privately-owned vehicle as opposed to an air taxi. A privately-owned vehicle could be designed with a shorter range capability and would have little need for a very rapid turnaround time capability (which imposes requirements on refueling/recharging), whereas an air taxi aircraft would likely need longer range and rapid refueling/recharging capabilities to reposition and perform as many missions as possible in a "rush hour" period to maximize profitability.

These examples indicate that UAM operators may wish to have a single aircraft that is capable of handling the most stringent requirements for all desired missions or multiple aircraft that are optimized to a subset of use cases. Ultimately, which of these general approaches is most optimal depends on the operational scenario(s). Therefore, it is necessary to consider at least one city-wide simulation in which each of these operational scenarios can be compared and contrasted under different input assumptions. It is possible that in certain scenarios it may be optimal from a system-of-systems perspective to operate a single vehicle for all use cases, whereas in other scenarios having multiple distinct vehicles would provide improved overall UAM network performance.

To provide us with the ability to perform such studies, we present both a longer- and shorter-range sizing mission below. In future studies we will size aircraft to each of these missions and simulate multiple UAM networks consisting of various use cases.

Motivating Example 2

Many in the eVTOL community are advocating for reserve requirements that are reduced from those specified in the existing FARs. Current regulations require between 20 min[5] and 45 min[6] of reserve fuel, in addition to fuel for a flight to an alternate airport under instrument flight rules (IFR).

The logic for reducing these fuel (or, more generically, energy) reserves is based on the fact that UAM missions are significantly shorter in both duration and distance than traditional aviation missions and suitable landing locations (i.e., vertiports) will be much closer together than typical airports or heliports. An entire UAM flight could very well be less than 20 min in total duration and the aircraft could be within a couple of minutes of a landing area throughout the entire flight. Additionally, weather does not typically change drastically in manners that were not forecast over such short time scales. Therefore, it seems unnecessarily burdensome for a UAM aircraft to carry more reserve energy than is required for the entire nominal flight.

Although there is some potentially sound logic behind these efforts to reduce reserve requirements, the authors have not seen any information published in the literature with modeling and simulation to support the claim that reductions in reserve requirements are, in fact, safe. The approach described above will provide us with the necessary tools to perform simulations that can help determine what levels of reduced reserve requirements may still provide safe operations.

METROPOLITAN AREA SELECTION AND CHARACTERISTICS

Before proposed mission requirements for UAM missions can be developed, locations where UAM missions may be performed must first be selected. The characteristics of these locations—weather, geography, population distribution, etc.—will dictate the requirements to which UAM aircraft should be designed. For our study, we selected 28 metropolitan areas in the United States with generally large populations, problematic ground congestion,[7] and high volumes of existing commercial air traffic.[8] Specifically, we have included the top 10 most populous Metropolitan Statistical Areas (MSA) (Ref. 34), as well as those that are home to the FAA's "Core 30" airports, excluding Memphis, TN.[9] We also ensured that the selected areas provided a good geographic diversity, and we included metropolitan areas that have large numbers of "super-commuters," i.e., people who work in the heart of a metropolitan area but travel very long distances to work (typically only one or two times per week) from their homes outside of the boundaries of that metropolitan area (Ref. 35). The twenty-eight metropolitan areas are: Atlanta, GA; Boston, MA; Charlotte, NC; Chicago, IL; Cincinnati, OH; Dallas, TX; Denver, CO; Detroit, MI; Honolulu, HI; Houston, TX; Las Vegas, NV; Los Angeles, CA; Miami, FL; Minneapolis, MN; Nashville, TN; New York City, NY; Orlando, FL; Philadelphia, PA; Phoenix, AZ; Pittsburgh, PA; Portland, OR; Salt Lake City, UT; San Antonio, TX; San Diego, CA; San Francisco, CA; Seattle, WA; St Louis, MO; and Washington, DC. Each of these areas and some of their characteristics are listed in Table 2 of Appendix A.

Weather Characteristics of Metropolitan Areas

The weather characteristics of the chosen locations will drive some requirements for the vehicles that operate there. For our initial study we consider the density altitude and winds in these locations to specify the altitude and wind conditions at which the vehicles must be capable of operating.

Density Altitude To determine the altitude above mean sea level (MSL) from which aircraft will be assumed to operate in the sizing missions, we analyzed historical meteorological data for the selected metropolitan areas to calculate the density altitude. We then analyzed these historical trends to determine an appropriate takeoff and landing elevation.

Meteorological Terminal Aviation Routine (METAR) weather report data were obtained at the airports reported in Appendix A from Iowa State University (Ref. 36). Where possible, 50 years worth of data (from February 26, 1968 to February 26, 2018) were collected. Density altitude was calculated as follows:

- The METAR data provides the altimeter setting based on local atmospheric conditions. This altimeter setting was transformed into a barometric pressure (p) at the airport based on a 1976 standard atmosphere assumption.
- Tetëns' formula, $p_s = (610.78)10^{(7.5t_d)/(237.3+t_d)}$, was used to calculate the saturation pressure of water (p_s, in Pascals) at the local dewpoint (t_d, where t_d is expressed in degrees Celsius) (Ref. 37)
- The partial vapor pressure of water present (p_v) was calculated from the saturation pressure (p_s) and the relative humidity (RH) as $p_v = p_s RH$ (Pascals), where $RH = 0.5$ for 50% relative humidity.
- The partial pressure of air (p_a) was found from the local barometric pressure (p) and the partial pressure of water as $p_a = p - p_v$.

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[5] for rotorcraft in visual flight rules (VFR)—see 14 CFR §91.151

[6] for aircraft other than helicopters in instrument flight rules—see 14 CFR §91.167

[7] as evidenced by the Travel Time Index, which is a ratio of travel time during peak periods to the travel time with no traffic (Ref. 33)

[8] High volumes of commercial air traffic indicate a general public acceptance of flight and that there is a large market for airport shuttle missions.

[9] Much more cargo than passengers are transported through the Memphis airport and the Memphis MSA ranks low in population.

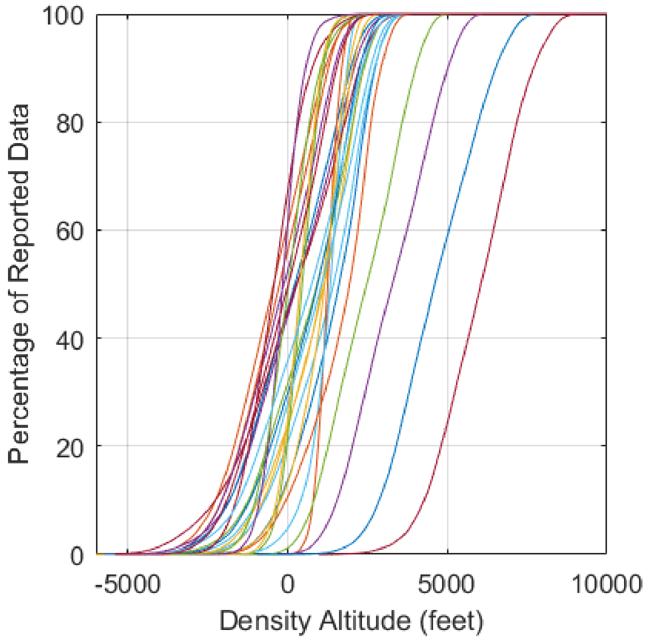

Fig. 2. Cumulative Distribution Function (CDF) of Density Altitude (feet) for 28 selected metropolitan areas.

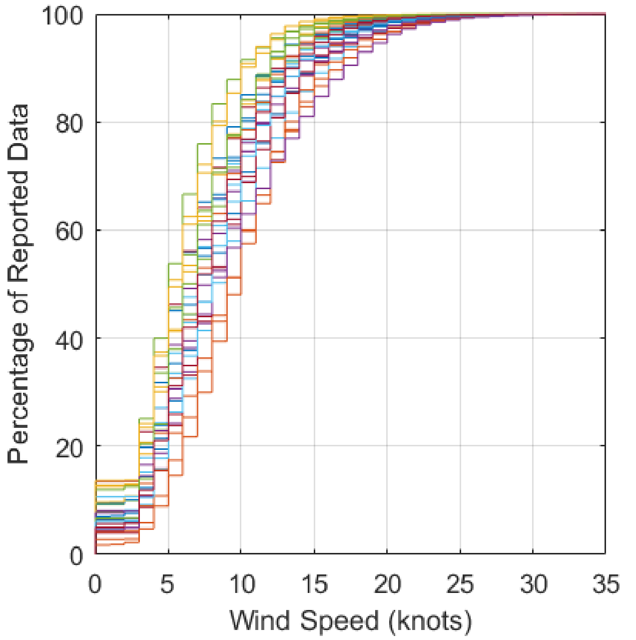

Fig. 3. Cumulative Distribution Function (CDF) of Wind Speed (knots) for 28 selected metropolitan areas.

- The temperature and partial pressures were used to calculate density (ρ) from $\rho = p_a/(RT) + p_v/(R_v T)$, where R is the air gas constant (287 J/kg-K), T is the local temperature in Kelvin, and R_v is the water vapor gas constant (461.5 J/kg-K) (Ref. 38).
- The standard atmosphere was used to convert density to density altitude.

The cumulative distribution function (CDF) for density altitude at each of the airports is shown in Fig. 2. A more detailed comparison of density altitude data is presented in Appendix B.

The location with the highest density altitude is Denver, which is represented by the rightmost magenta curve in Fig. 2. The next three highest density altitude areas are Salt Lake City (shown in blue), Las Vegas (shown in purple), and Phoenix (shown in green). The remaining locations experience somewhat lower density altitudes, and there is far less variation among them than there is among the other four cities.

Based on this data, we propose a takeoff and landing altitude requirement of 6,000 ft MSL for vehicle design missions. This selection allows operation on

- an average day in all locations, and
- the 99th percentile day in all but 2 cities (Denver, Salt Lake City).

Note that if operations year round are desired in Denver and Salt Lake City, reduced payloads and/or range capabilities will result from this altitude requirement. However, we deem this limitation to be acceptable because their populations are not as widely distributed as other locations and, therefore, missions in these metropolitan areas will generally be shorter.[10]

If an operator desired to provide UAM service in a reduced set of metropolitan areas, a case could be made for an alternative altitude requirement of 3,200 ft MSL. With a 3,200 ft base altitude, operations could occur on the 95th percentile day in all but four of the studied metropolitan areas (i.e., Denver, Salt Lake City, Las Vegas, and Phoenix).

Winds The METAR data was also processed to extract wind speed and wind gust data. The CDF of wind speed for all 28 cities is shown in Fig. 3, and a comparison of wind speed for all 28 cities is provided in Appendix B.

Based on the wind speed data, a vehicle design capable of maintaining six degrees-of-freedom control in a sustained wind of 20 knots will be able to operate in any of the 28 cities a minimum of 95% of the time.

Based on the data shown in Fig. 3, we propose a headwind requirement of 10 knots for the sizing mission, which ensures that aircraft will be able to operate for the desired ranges at least 50% of the time. A higher headwind requirement is unnecessary because not all flights will be directly into a headwind, and, as is often done in aircraft design, reserve requirements will account for some of the uncertainty in wind speeds.

The CDF of wind gusts for all 28 cities is shown in Fig. 4, and a comparison of wind gusts in all 28 cities is shown in Appendix B.

Based on wind gust data, a vehicle capable of stable control in wind gusts up to 35 knots will be able to operate 95% of the

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[10] The population distribution of all the selected cities is described below.

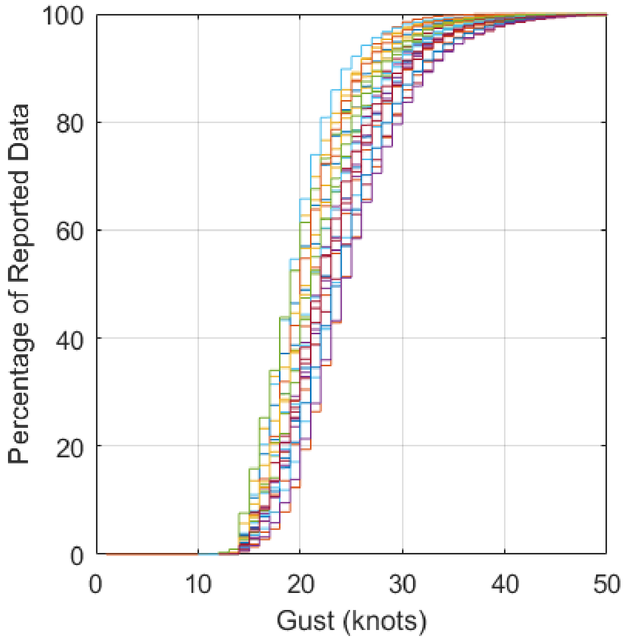

Fig. 4. Cumulative Distribution Function (CDF) of wind gust (knots) for 28 selected metropolitan areas.

time that gusts are reported in all but two cities. (The 95th percentile levels for Denver and San Francisco are slightly higher than 35 knot gusts.)

Generic City Representation

A generic representation of the vertiport locations in a city has proven helpful for our modeling of UAM networks and for identifying a sizing mission, including reserve requirements. This generic city model resulted from our observation that many of the cities of interest consist of a "wheel-and-spoke" configuration of a beltway and highways. In general, interstate highways radiate out from the city center toward surrounding (smaller) communities while a concentric beltway(s) circumferentially connects the smaller communities and provides alternative routes for bypassing traffic. Many cities have between four and eight major "spokes" that connect the smaller communities with the urban core and typically one beltway surrounding the city center. A generic model of vertiport placement to achieve similar mobility around the city can be envisioned to be a hexagon with a seventh vertiport in the center, forming six equilateral triangles. The model can be extended by placing additional equilateral triangles or individual vertiports around the inner hexagon. In this way, a large portion of the metropolitan area is connected similar to its highway system, a "vertiport beltway" is formed, and the model is simple because the distance from any vertiport to the next nearest one is equal.

This hexagonal model will be used with the analysis of population distribution to determine the length "L" of each equilateral triangle side. An example of this generic hexagonal model overlaid on the Atlanta metropolitan area with an L distance of 18.75 nmi[11] is shown in Fig. 5. With this simple extended hexagonal model, much of the Atlanta metropolitan area can be connected with vertiports.

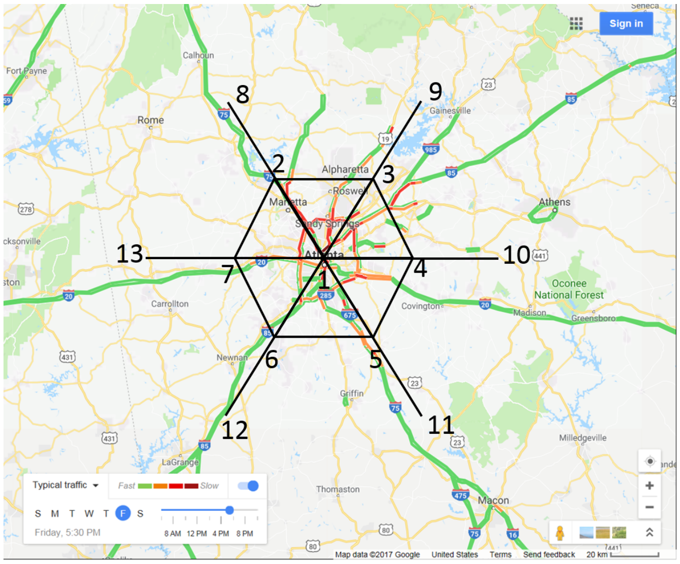

Fig. 5. Simple extended hexagon model shown overlaid with map of Atlanta where numbers denote vertiport locations.

Another example of the hexagonal model is shown in Fig. 6, with an L distance of 18.75 nmi. This figure shows a full second-order hexagonal model, i.e., one in which the inner hexagon is surrounded by equilateral triangles forming an outer hexagon. This second-order model produces two separate vertiport beltways that mirror the two separate beltway-like routes around the Houston area, although they are placed at a greater distance out. Another second-order hexagonal model example is provided in Appendix A.

We acknowledge that this generic hexagonal model does not mirror all metropolitan areas in an ideal manner. There are cities, such as Boston, San Francisco, Miami, and Salt Lake City, that developed around geographic constraints such as bodies of water and mountains. In such geographically constrained cities, the full hexagonal generic city model is inappropriate. However, in many of these areas a modified hexagonal model in which certain vertiports are eliminated can still provide a reasonable representation of the area. An example of the generic vertiport model applied to a geographically constrained area is shown in Appendix A.

GENERAL MISSION PROFILE

Each of the missions defined below are assumed to follow the same general mission profile, i.e., each mission will consist of the same segments. These mission segments are illustrated in Fig. 7, and we describe these segments along with their associated constraints in this section.

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[11] this distance is significant based on work that will be described below

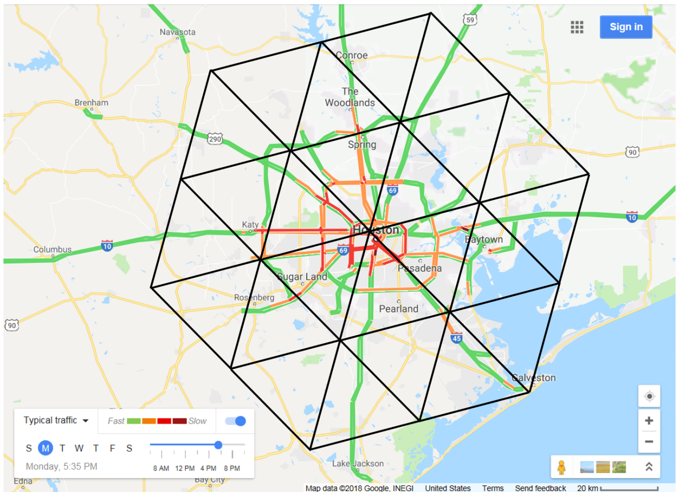

Fig. 6. Full second-order hexagonal model shown overlaid with map of Houston.

The general mission profile begins with a taxi segment, which could be performed in several ways. The vehicles could hover, power themselves while rolling on wheels, or there could be some form of ground-based infrastructure that could move the vehicle from a parking/loading area to the takeoff pad. We propose that each vehicle should be capable of taxiing on its own wheels and, therefore, must carry fuel/energy to conduct 15 seconds of taxi at 10% of its cruise power.

After taxi, the vehicle must take off vertically, climbing vertically to 50 ft above ground level (AGL) at a rate of 100 ft/min. This represents a slow climb rate that should be comfortable to passengers. We acknowledge that some in the UAM community are proposing operations from small "air parks" with extremely short takeoff and landing aircraft. However, we are limiting our scope to pure VTOL aircraft because we assume that operations will occur in densely populated areas where there is little land available and land costs are high. It should be noted that this 50 ft vertical takeoff requirement implies that the aircraft must be able to safely perform such a maneuver, which is not the case for some VTOL aircraft.

After the 50 ft vertical takeoff, the aircraft will transition and move into climbing flight. For conventional helicopters, this transition is effectively instantaneous, but for many eVTOL aircraft (e.g., a tiltwing) there is a finite period where the aircraft undergoes a configuration change from vertical to horizontal flight. The details of this transition can be highly complex and are configuration-dependent. In the lack of sufficiently detailed information about transition, a sizing mission should contain a 10 second segment at maximum power for transitioning aircraft.

After transition, the aircraft will enter a climb up to the cruising altitude. To help ensure that the aircraft can quickly gain altitude and move away from the takeoff area, we specify a climb rate for the aircraft of 900 ft/min at the beginning of the climb. If such a climb rate is maintained, the aircraft would reach an altitude of 500 ft AGL, which will place it above airspace in which UAVs may be operating, approximately 1 minute after takeoff.[12]

After climbing to the desired altitude, which will be specified in the following subsection, the aircraft will then enter cruise flight. The length of the cruise segment will be specified in the following sections for each mission. Range credit should be given for the climb segment so that the actual distance spent at the cruise altitude will be less than the specified range. We elect not to dictate a specific cruise speed, but rather allow each vehicle to fly at the speed that maximizes its range.[13] To ensure sufficient maneuverability of the vehicle and the ability to fly higher if required (e.g., for potential airspace integration needs), the aircraft must be capable of at least a 500 ft/min rate of climb in the cruise segment.

As opposed to specifying a particular descent segment profile, we specify that aircraft should be designed to fly in the cruise segment until reaching the desired range from the takeoff location. Assuming such a no-credit descent is a common, conservative approach often employed in aircraft design. After descent, the aircraft will enter a transition segment similar to that described previously with the exception that in this case the aircraft must transition to vertical flight.

Next, aircraft must perform a 30 second hover out of ground effect before performing a vertical descent from 50 ft AGL at 100 ft/min to land. The 30 second hover segment is added to allow for final pre-landing clearances, which may require a short hold, and to position the aircraft appropriately for landing. When this hover segment is coupled with the vertical descent from 50 ft, there is one minute of "hover-like" power levels required for landing. After landing, a final taxi segment, which has the same requirements as described above, must be performed.

Finally, we require that aircraft complete the general mission profile with 20 minutes of additional cruise added as a reserve. This segment is subject to all the same constraints as the main cruise segment in the mission. This reserve is based on existing regulations for rotorcraft operating under visual flight rules (VFR), which are specified in 14 CFR §91.151. Rotorcraft regulations are assumed because the aircraft that perform this mission will be capable of vertical landings like rotorcraft today. This VTOL capability greatly increases the number of suitable locations for an emergency landing in the event of an off-nominal situation in which the aircraft could not find a normal, designated landing location. VFR is assumed because early UAM operations will be performed under VFR. Additionally, typical UAM mission are likely on the order of 20 minutes, which implies that such a reserve will enable the

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[12] 30 sec to climb vertically to 50 ft and an additional 30 seconds to climb the remaining 450 ft. This ignores any time for transition, but it is likely the transition will occur as a smooth blending of the vertical and horizontal climbing segments.

[13] UAM network economics may dictate minimum cruise speeds for aircraft to help ensure that vehicles can perform many missions during "rush hour" periods. Ultimately iteration between this speed requirement, vehicle design, and the economics of the UAM network as determined through the city-wide simulations described previously will be required to determine appropriate minimum cruise speeds.

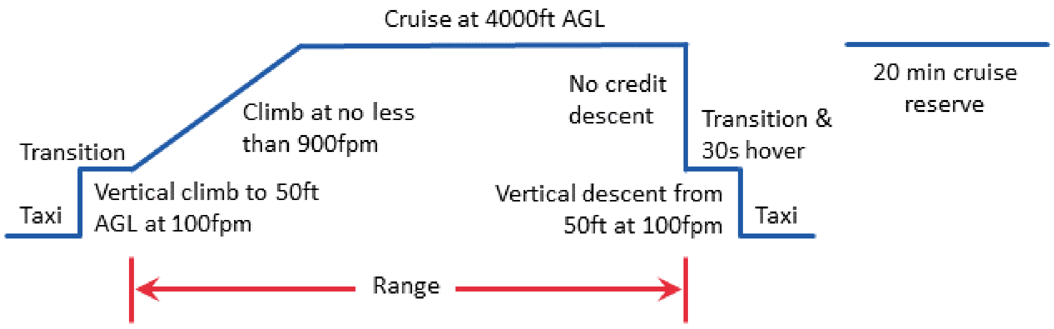

Fig. 7. General mission profile shown in blue with relevant constraints listed.

aircraft to fly to an alternate vertiport.[14]

Determining Flight Altitude Above Ground Level

Due to their short duration, UAM missions will likely be flown at relatively low altitudes—on the order of one to a few thousand feet above ground level (AGL). From a performance perspective, it is optimal for these aircraft to fly as close to the ground as is safe and practical to avoid wasting energy in a climb. However, other considerations such as airspace management and community integration (e.g., noise) will likely dictate that aircraft fly higher than the absolute minimum required for safety.

In selecting a cruising altitude requirement, the existing FARs, which dictate minimum safe altitudes in 14 CFR §91.119, must be considered. This regulation has multiple components, but for the purposes of UAM missions, which will be flown over congested areas, the rule states in 14 CFR §91.119(b) that an aircraft must fly at least 1,000 ft above the highest obstacle within a 2,000 ft horizontal distance of the aircraft. The rule does provide an exception for helicopters to be operated at lower altitudes, as long as the helicopter operator "complies with any routes or altitudes specifically prescribed for helicopters by the FAA." Although initial UAM operations will take advantage of these helicopter routes, it is unclear if the FAA will specifically prescribe new helicopter routes in every location where UAM aircraft will operate. Even if new routes are designated, it is unlikely that there will be a sufficient density of routes to enable fairly direct routing, which may be necessary for UAM services to maintain a sufficient speed advantage over competing ground transportation modes (e.g., cars). Furthermore, it is unclear if novel eVTOL aircraft that cruise with lift provided by wings rather than rotors will be treated as "helicopters" for the purposes of this rule. Therefore, we define a sizing mission cruise altitude in height above ground level based on the regulations prescribed in 14 CFR §91.119(b).

To determine an appropriate altitude based on minimum safe altitude requirements, we must ascertain the height of obstacles over potential areas where UAM aircraft could operate.

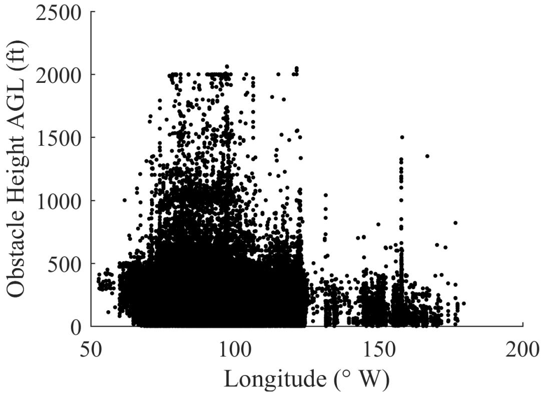

Fig. 8. Man-made obstacle heights above ground level over the United States.

The FAA maintains an obstacle database that documents the height of man-made objects above 499 ft AGL.[15] Specifically, we obtained data from the Digital Obstacle File that was updated in September of 2017 (Ref. 41). The height of all obstacles, excluding balloons, is shown in Fig. 8. Balloons are excluded from this figure because none of these are in or very near any metropolitan areas of interest. Some also extend to over 15,000 ft AGL, which would be impractical to fly over.

From Fig. 8, it is clear that nearly every man-made obstacle is below 2,000 ft AGL. There are only five obstacles above 2,000 ft AGL and each of these is less than 2,064 ft. Therefore, to maintain the 1,000 ft vertical clearance over all known man-made obstacles, an aircraft would have to fly above 3,064 ft AGL. For the purposes of specifying mission requirements, we will round this value and dictate that aircraft must cruise at or above 3,000 ft AGL.[16] Note that for most operations aircraft will not fly within 2,000 ft of obstacles that are near the 2,000 ft AGL height. Therefore, the minimum safe altitudes will generally be lower than 3,000 ft, which makes the 3,000 ft AGL altitude conservative.

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[14] Although such logic could potentially justify reduced reserves, we believe that initial operations must conform to existing FAA regulations.

[15] As described in 14 CFR §77. See specifically §77.17

[16] Of the five obstacles over 2,000 ft AGL, only three are near major metropolitan areas. One is approximately 50 miles north of downtown Dallas, TX at 2,008 ft and the other two are effectively co-located approximately 20 miles south of Sacramento, CA at 2,049 ft and 2,030 ft.

Finally, to enable many aircraft to safely integrate into the airspace around metropolitan areas, we specify that an additional 1,000 ft of altitude be added to the conservative estimate of the minimum safe altitude of 3,000 ft AGL, which results in a cruise altitude requirement of 4,000 ft AGL. The 1,000 ft buffer is based on current regulations for VFR cruising altitudes found in 14 CFR §91.159, which separate eastbound and westbound traffic by 1,000 ft.

MISSION 1: LONG-RANGE, SMALL-PAYLOAD MISSION

The first sizing mission we propose is a long-range mission with a small payload weight. Such a mission is representative of the daily commute to and from work. Commuting is a common hassle in many urban areas; in 2014, 3.6 million Americans spent 90 minutes or more traveling to work one way. These commuters, in one year, spend the equivalent of an entire month traveling to and from work (Ref. 39). This substantial problem has historically been a driving force and an enticing market for ODM.

For this mission, a typical commute was assumed to involve a single person with little baggage. Many commuters will travel from the outskirts of a given metropolitan area to the city center in the morning, then return back to the outskirts in the evening. Many others will commute to areas around the existing beltway(s) and/or vertiport beltway from the city center, suburbs, or another location around the beltway(s), returning back to their origin in the evening. Since commuter missions will be concentrated during "rush hour" windows, the aircraft should be able to fly at least two "hops" without having to recharge or refuel, which allows for more rapid turnaround times. Additionally, requiring the vehicle to perform multiple flights reduces the burden on vertiport infrastructure because not all locations would inherently be required to include refueling/recharging stations. The most constraining multiple-hop case is flying from one extreme suburb to the city center and back; therefore, we will consider this case in developing the requirements for the commuting sizing mission.

Range Calculations

The population densities of the 28 metropolitan statistical areas (MSAs) selected for this study were examined to determine the range that would best capture the majority of commuters in these urban areas. Using the generic city representation as an example for a given commute, the traveler would fly a distance of 2L into the city, then return via an additional 2L distance.[17] Thus, the range is determined by the percentage of the total population of a MSA captured by a distance of 4L spanning the metropolitan area.

To span a given urban area, the center of that area must be defined. The center of the largest city within the MSA was chosen for 24 of the 28 metropolitan areas. For the remaining four urban areas (San Francisco, Miami, Dallas, and Los Angeles), a center was chosen between the several large cities within that MSA, to capture typical routes within these large cities. As an example, a map of the population density of the San Francisco Bay Area is given with concentric circles around this point in Fig. 9.

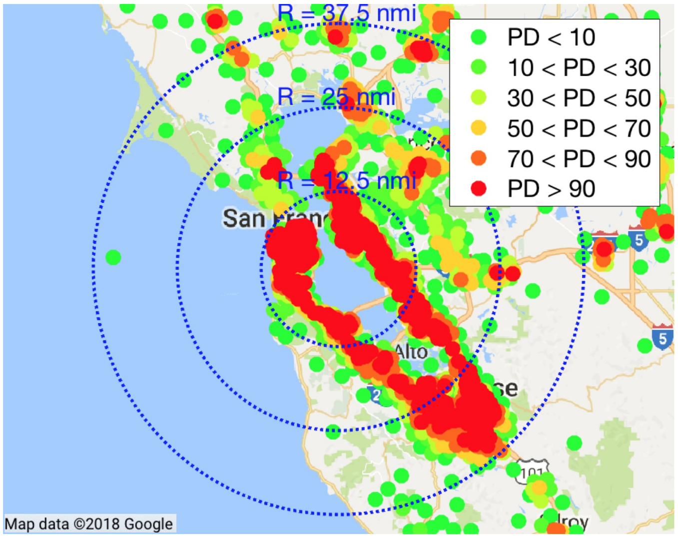

Fig. 9. A map of the population density (PD, Population/100 sq. mi.) of the San Francisco Bay Area with potential range considerations for a commuting mission.

Based on population density data like that shown in the map in Fig. 9, a cumulative distribution function (CDF) was generated to determine the distance of the population from the center of each of the metropolitan areas. The aggregation of all the CDFs for each of the 28 metropolitan areas is given in Fig. 10, where the distances shown represent the distance of the population from the center point. Based on this combined CDF, a design range of 75 nmi was chosen for the long-range commuting mission, where this total 75 nmi will be achieved with two independent flights, each of 37.5 nmi, representing, for example, a trip into the city and back out. This range allows commutes from beyond the extreme edge of the average MSA to the center and back. Additionally, 75% of the population of the most expansive MSA can be captured by a 37.5 nmi trip from the city center, and all of the population of the most expansive MSA could perform a one-way commute to the city center with this range. It is worth noting that, because this mission consists of two independent flights of 37.5 nmi each with its own takeoff, landing, and cruise segments, aircraft sized for this mission will be capable of flying one-segment missions with distances longer than 75 nmi.

We acknowledge that the use of MSAs will not capture true commuting patterns perfectly because, in many cases, there are often commutes that occur between multiple MSAs. An example is that the San Francisco-Oakland-Hayward MSA is distinct from the San Jose-Sunnyvale-Santa Clara MSA. Because we are not including trips between MSAs in the analysis above, our range estimates are likely somewhat lower than what may be ideal. However, the aggregation of 28 distinct metropolitan areas effectively captures a generic city and re-

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[17] An example of such a mission in Fig. 5 would be traveling from Vertiport 8 to Vertiport 1 and then from Vertiport 1 to Vertiport 8.

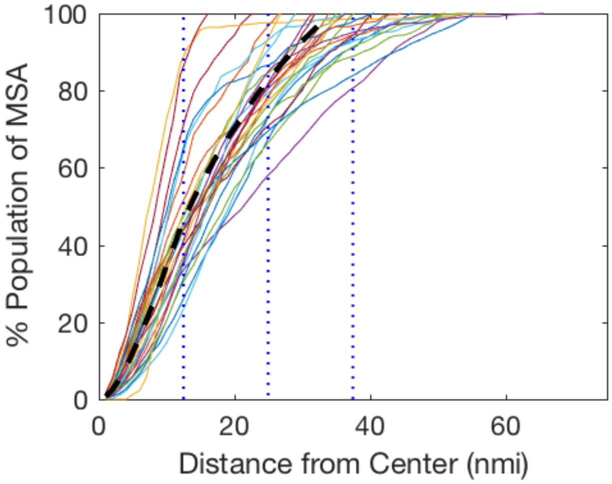

Fig. 10. A combined cumulative distribution function for 28 MSAs showing the percentage of the MSA population less than the given distance from the center. Blue dotted lines are shown as an indication of 12.5, 25, and 37.5 nmi.

sults in a range that is still longer than the majority of current UAM vehicle specifications, including that proposed by Uber (Ref. 18).

Mission Profile

The mission profile for the "two hop" long-range commuting mission is shown in Fig. 11. This profile is formed by combining two of the generic mission profiles described previously in Fig. 7, where only one reserve segment is kept. The new mission profile in Fig. 11 exhibits compelling characteristics in regards to reserves. First, this profile allows the first hop up to 37.5 nmi to be completed with existing IFR (helicopter) reserve requirements met. Second, if reserves are not used on the first 37.5 nmi flight, the second mission can be completed while meeting VFR rotorcraft reserve requirements as described above.

Existing IFR reserves are described in 14 CFR §91.167 and require an aircraft to fly to its intended destination, then fly to an alternate airport, and then cruise for an additional 30 minutes if a helicopter or 45 minutes otherwise. The first flight can meet these requirements for helicopters because, per the generic hexagonal city model, there would be an alternate landing site no more than 18.75 nmi away, and the second flight can be considered a reserve for the first hop. The 18.75 nmi flight to an alternate landing site is satisfied with the second hop and there is an additional 18.75 nmi of cruise as extra reserve. If the aircraft flies at 112.5 knots or less in cruise, then there is at least 10 minutes of reserve from the extra 18.75 nmi of cruise in the second flight. When this 10 (or more) minutes is added to the explicit 20 minutes of reserve, the required 30 minutes of reserve is achieved.

If aircraft fly faster than 112.5 knots, the profile given in Fig. 11 will not satisfy existing IFR helicopter reserve requirements. For such aircraft, additional cruise reserve time should be added to the 20 minutes specified at the end of the mission profile. This additional reserve time can be found as $10-(18.75/V)60$ min, where V is the cruise speed in knots.[18] We elect to require IFR reserves for the first hop of this long-range mission to enable aircraft to begin operations under current regulations and because it will have minimal to no impact on the aircraft sizes.

As a brief aside, it is evident from this mission profile how penalizing existing IFR reserve requirements are to UAM aircraft whose missions are much shorter than conventional aircraft. Current IFR reserves effectively equate to an entire additional mission for UAM aircraft, whereas with conventional aircraft that fly longer ranges the requirements are a substantially smaller portion of the vehicle's range capability.

Payload

Because today the majority of daily commutes to and from work are performed with a single person, we assume this trend will continue for UAM aircraft that perform commuting missions. To determine a payload weight, we assume that the aircraft should be capable of carrying virtually any person along with a small bag. The 95th percentile male in the United States aged 20 and over is 275 lb (124.9 kg) (Ref. 40). If we assume that this person flies with 15 lbs of baggage, then there is a total payload requirement of 290 lb for this mission.

There are also payload volume issues that must be considered. For sizing our passenger compartments, we will consider the 95th percentile male, which is 74.1 inches in height and has a 51 inch waist circumference (Ref. 40). For the baggage compartment, we will accommodate a standard airline carry-on item, which has dimensions of approximately 9 x 14 x 22 inches.

MISSION 2: SHORT-RANGE, LARGE-PAYLOAD MISSION

It is common for both business and leisure travelers to use a taxi service or other ride-hailing alternative to travel between an airport and an urban center. This mission typically involves several people and a large amount of luggage traveling a shorter distance than many commuting trips.

Range Calculations

For the short-range mission, a similar approach to the commuting range calculation was used, but for an exemplar short range mission: an airport transfer. For this mission, the largest airport for a given urban area was chosen as the center. Then, in lieu of the population of the metropolitan statistical area, the population of the largest city was selected to determine range requirements. This approach assumes that many of these airport transfer missions will connect airline passengers

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[18] For cruise speeds of 125 knots, 150 knots, and 175 knots, this additional reserve time is 1 min, 2.5 min, and 3.6 min, respectively.

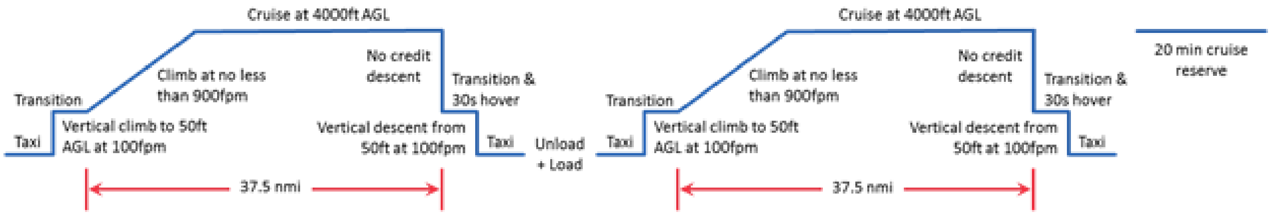

Fig. 11. Mission profile for the long-range mission.

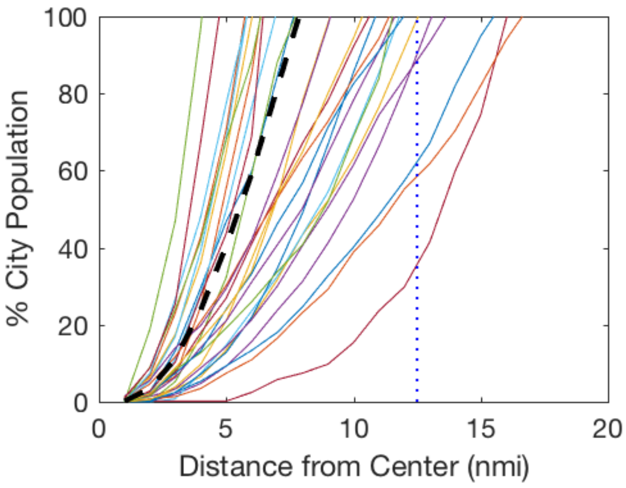

Fig. 12. A combined cumulative distribution function of 28 cities showing the percentage of the city population less than the given distance from the center for a short-range airport transfer mission. A blue dotted line is shown as an indication of 12.5 nautical miles.

to their final destinations in the city to which they have traveled, and that their final destination is likely within the urban core. Next, the data from the 28 cities were aggregated into a combined cumulative distribution function as shown in Fig. 12. As an aside, the assumptions proved to produce expected results as the longest ranges were in Denver, New York City, and Houston where the airport is outside of the urban core.

Based on the aggregation of data from all metropolitan areas, the average MSA, in terms of the population distance from the airport, requires a range of 15 nmi to capture 100% of the city population. The largest distance to reach 100% of the population is 34 nautical miles. Based on these results, a range of 37.5 nmi (or half of the commuting range) was chosen to capture 100% of the intra-city air transfer demand across all urban areas examined. It is convenient to specify this range because it is consistent with the long-range commuting mission and the generic hexagonal city model associated with the previous mission, which has an L of 18.75 nmi.

Similar to the long range commuting mission, we propose that this total 37.5 nmi distance be split into two individual missions, each of 18.75 nmi in length. This enables a flight both from and back to the airport (or some other centralized "hub") to be taken across all cities studied. The mission profile for this mission consists of combining two of the generic mission profiles described previously in Fig. 7, where only one reserve segment is kept and the range is set to 18.75 nmi for each flight.

Payload

Airline transfer missions will often have groups (e.g., a family) traveling together. To help select a reasonable payload, we will consider different sizes of individuals in addition to the 95th percentile male. Specifically, the 50th and 75th percentile male are 189 lb and 219 lb, respectively (Ref. 40).

We must also consider the potentially large amounts of luggage that these airline transfer passengers will bring with them. Most commercial airlines have policies that allow passengers to check bags of up to 50 lb, while luggage any larger is deemed "oversized." Additionally, carry-on bags are on the order of 25 lb in weight. Therefore, we assume it is unlikely that most passengers will carry more than 75 lbs of luggage each. If an UAM aircraft carried four 75th percentile males each with 70 lb of luggage each, the total payload weight would be 1,176 lb. With this example in mind, we propose a payload weight of 1,200 lb.

This 1,200 lb payload weight will allow the following groups of passengers onboard the aircraft:

1. six 50th percentile males each with 11 lb of baggage,
2. five 50th percentile males each with 51 lb of baggage,
3. four 75th percentile males each with 81 lb of baggage,
4. five 75th percentile males each with 21 lb of baggage, or
5. four 95th percentile males each with 25 lb of baggage.

These passenger capacities are consistent with the multiple 4-6 passenger sizes proposed in previous studies as shown above in Fig. 1, as well as many other general aviation aircraft and helicopters.

For cabin layout and cargo volume, we consider the five scenarios described just above. These scenarios impose a requirement that the cabin must contain six passenger seats. For determining the cargo volume requirement, we allow the option of placing some carry-on size or smaller luggage in unoccupied passenger seats. With this assumption, a dedicated cargo volume for four large bags and two carry-on bags or five large bags is sufficient. Such volume can hold the six small bags implied by Scenario 1, the five large bags of Scenario 2, five carry-on bags implied by Scenario 4, and the four carry-on bags from Scenario 5. The third scenario implies four large bags as well as four carry-on bags, which cannot all be held in the dedicated cargo area. The two unoccupied passenger seats can be used to hold the extra two carry-on bags for this scenario.

The dimensions of large bags are not standardized, but a brief survey of large suitcases shows that the maximum dimension is typically between 30 and 36 inches. Commercial airlines usually dictate that the maximum linear dimension of checked luggage[19] should be less than approximately 62 inches, which implies other bag dimensions on the order of 10 to 20 inches each.

In addition to the requirements for dedicated cargo volume above, there must also be sufficient space to hold at least one oversized item, such as a pair of snow skis, which are approximately 75 inches long. It is acceptable for this size payload to only be carried when there are four passenger seats occupied.

MISSION 3: MOST CONSTRAINING MISSION

In addition to the two missions as described in the preceding two sections, we also will specify a third set of mission requirements that consists of the most constraining requirements of each of these missions. If the only vehicles developed were to the specifications of the previous two missions, an operator could not carry a large payload over a long distance. Such missions may be desired, for example, to transport an entire family from one end of a metropolitan area to another.

This third mission follows the same profile shown in Fig. 11 with all the same constraints on these segments. Therefore, this mission allows for an unrefueld/unrecharged range of 75 nmi consisting of two separate hops, each of 37.5 nmi in length. As with the second mission, a payload weight of 1,200 lb with six passenger seats is required. This configuration allows a fairly wide variety of groups to travel over long distances, where six passengers can weigh up to 200 lb on average.

OTHER CONSTRAINTS

Although the above missions define the required nominal performance of UAM aircraft, there are off-nominal situations that may impact the design of vehicles and must also be considered. In this section we discuss a few of these scenarios and their implications on the vehicle design.

Holding Pattern

In an ideal world, UAM aircraft would be able to fly from their point of origin to their destination where they could land immediately upon arriving. However, it is unlikely that aircraft will be able to fly in such an ideal manner due to real-world constraints and uncertainties that will affect the sequencing and spacing of aircraft both into and out of a vertiport. Uncertainties may arise in mission flight time due to weather or other air traffic. Passenger loading and unloading times are subject to fairly wide variation, which will impact when vehicles will be ready to depart. Limitations on available takeoff and landing pads will also likely lead to conflicts where multiple aircraft could ideally each be occupying the pad simultaneously. Additionally, off-nominal situations, such as a person walking onto a landing pad or an accident closing a landing pad, may cause delays in the ideal landing time.

All of these issues imply that aircraft may not be able to land at the desired time. Therefore, there must be some consideration for how a UAM aircraft can loiter in close proximity to the final landing area. One approach would be for the aircraft to hover. However, dictating that aircraft hover for an extended period of time may impose an unnecessary burden on the vehicle energy requirements and, therefore, size (i.e., gross weight), which will decrease the efficiency of the aircraft throughout all phases of its mission.

A preferred approach is to prescribe a holding pattern in which aircraft can maintain forward flight to reduce energy consumption and noise. Conventional instrument approach procedures specify holding patterns for similar reasons as those listed above and represent a starting point for defining a potential UAM holding pattern. However, typical holding patterns occupy more space and take longer to complete than is practical for UAM aircraft. A normal holding pattern (Ref. 42) is a "racetrack" shape consisting of two, 180° turns with straight segments flown between these turns. These straight segments are typically one minute in duration. The turns are flown at a "standard rate" of 3° per second, which makes a single lap in the racetrack pattern four minutes in duration. Although four minutes is a short amount of time relative to a typical IFR flight in a conventional airplane, this timeframe could represent a fairly large percentage of a UAM flight. For example, one loop in a typical holding pattern would be 20% of the length of a 20 minute UAM flight.

There is no set speed at which such patterns are to be flown, but maximum speeds are defined. If aircraft are flying at altitudes less than 6000 ft (MSL), the maximum speed is set to 200 knots (Ref. 42). If the straight leg of a standard instrument holding pattern is flown at 200 knots, this leg would last for over 3.3 nmi, which is likely longer than the distance between adjacent vertiports in a future, fully-developed UAM system. Similarly, flight at even just 100 knots would represent a straight leg distance of approximately 1.7 nmi, which may be approximately equivalent to the distance between vertiports.

As a first estimate of what the distance between future vertiports may be, we refer back to the work of Antcliff et al. (Ref. 3) who proposed a UAM system in the Silicon Valley area of California. They found that substantial door-to-door time savings could be achieved with a UAM system where there were 0.71 vertiports per square (statute) mile. On aver-

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[19] The linear dimension is the length plus width plus height.

age, this implies that vertiports would be approximately 1 nmi apart.

We propose a new holding pattern for UAM aircraft that requires less space than traditional holding patterns. Specifically, we suggest that UAM holding patterns be flown as circles using a standard rate turn. This implies that a complete lap in the holding pattern would last 2 minutes. Furthermore, if we assume that two aircraft in holding patterns for adjacent vertiports must be 500 ft apart at closest approach[20] and take the conservative assumption that adjacent vertiports will have holding patterns at the same altitude, this implies that the holding pattern should be of a diameter no greater than 0.95 nmi (5766 ft). For an aircraft to make a constant altitude turn at a standard rate that has a diameter of no more than 0.95 nmi, the maximum airspeed at which the aircraft can fly is just over 89 knots.[21] Therefore, we will require in our design studies that aircraft which depend on wings for lift in forward flight are capable of performing a constant altitude turn at 89 knots. The energy required for these holding patterns will be accounted for in the reserves of the sizing mission.

"Engine" Inoperative Scenarios

UAM aircraft will be operated over potentially very densely populated areas; therefore, it is critical that any UAM aircraft be designed in such a manner that it is capable of safely landing (ideally at a designated vertiport, but potentially at another suitable location away from people and structures on the ground) in the event of at least the single most critical failure of the power train/propulsion system. In a conventional aircraft this single most critical failure is typically an engine failure, but in an electric aircraft or hybrid-electric aircraft, there are different critical failures, such as a loss of a battery pack/bus.

SUMMARY

In this paper, we have outlined a three-phased approach to studying urban air mobility (UAM) missions and provided details on the first phase of this approach. This approach consists of (1) defining mission requirements for multiple exemplar UAM missions, (2) designing aircraft that conform to these requirements, and (3) simulating an entire UAM network or multiple UAM networks. This approach is iterative; lessons learned from each phase as well as feedback from the UAM community can be incorporated to revise previous steps.

We have described the first phase of this approach by defining three sets of proposed initial requirements for sizing urban air mobility (UAM) aircraft for passenger-carrying operations. We view these requirements as a starting point for conversations with the community and for simulations of city-wide UAM networks. These three requirement sets are motivated by two distinct potential UAM missions: a long-range daily commuting mission and an airport transfer service. The third requirement set is derived from the most stringent requirements of these two missions.

We believe that, in order to fully understand the operations of and design requirements for UAM aircraft, we must perform simulations of the entire UAM network over a metropolitan area. We can then perform studies to better inform the system-level economic implications of changes in design parameters such as varying payloads. Additionally, such studies can help answer many other research questions such as assessing the potential safety implications of modifying reserve requirements. To help us model a metropolitan area simply, we have proposed a generic representation of the vertiport locations in a city that is based on the general layout of major highways around cities. This model places one vertiport in the center of the city with six vertiports arranged in a hexagonal shape placed outside of it. This hexagonal city representation has a distance between a vertiport and its nearest neighbor(s) of length L.

Several key assumptions common across each of the proposed sizing missions are as follows:

1. Missions modeled as two separate flights of equal lengths to reach the ultimate desired unrefueled/unrecharged range
2. A takeoff and landing altitude of 6,000 ft ISA and cruise altitude above ground level of 4,000 ft
3. Purely vertical climb and descent segments enforce true VTOL capability and imply safety requirements
4. Headwind of 10 knots
5. Reserves consistent with existing VFR rotorcraft requirements

Key differences in the sizing missions are in range and payload requirements. The payload for the long-range commuting mission is set to 290 lb, whereas the short-range airport transfer mission payload is specified as 1,200 lb. The long-range mission requires 75 nmi unrefueled/unrecharged range performed in two hops of 37.5 nmi each, whereas the short-range mission requires 37.5 nmi unrefueled/unrecharged range performed in two hops of 18.75 nmi. These ranges allow us to generate a generic hexagonal city model for city-wide simulations where L (i.e., shortest distance between two vertiports) is 18.75 nmi and the longest distance between any two vertiports is a distance of 4L or 75 nmi.

Future studies will size aircraft to these three missions and explore sensitivities of the vehicle designs to varying technology assumptions and modifications to mission requirements. Additional studies will analyze the economic characteristics of entire UAM networks with different fleet mixes. These studies will also shed light on other system-level parameters such as required vehicle fleet sizes to meet demand, passenger wait times, and power requirements at vertiports (for electric vehicles to charge).

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[20] A 500 ft distance appears in other regulations such as minimum safe altitudes and is the vertical distance between VFR and IFR cruising altitudes

[21] This turn would imply a 13.8° bank angle at a load factor of 1.03, which should be comfortable for the passengers on the aircraft

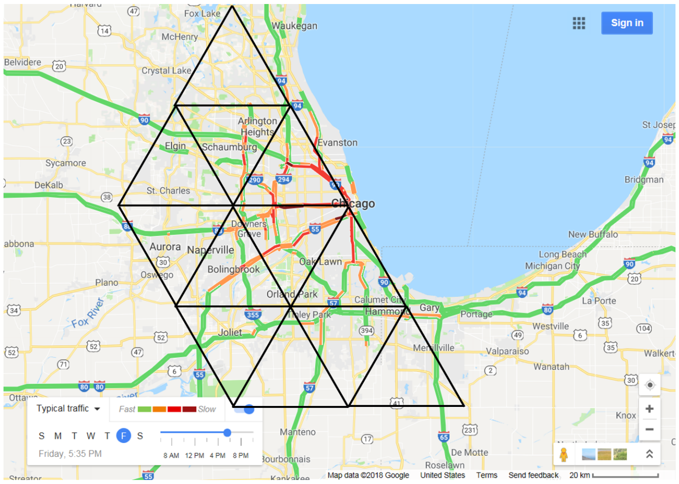

Fig. 13. A modified second-order hexagonal model for a geographically-constrained metropolitan area shown overlaid with map of Chicago.

APPENDIX A: METROPOLITAN AREA CHARACTERISTICS

In this appendix we provide more information about the characteristics of the metropolitan areas selected for our work and additional examples of the generic hexagonal city model.

Table 2 provides a list of the metropolitan areas considered in our study along with characteristics of these areas, including the major airport used for weather data, the 2015 travel time index, MSA population from the 2010 census, population of the largest city in the MSA from the 2010 census, and the centroid for the calculations of range described above for both the long-range and short-range missions.

An example of how the hexagonal city model can be modified to fit a geographically constrained metropolitan area is shown in Fig. 13. Here, we see that the Chicago area can be represented fairly well by eliminating a few vertiports that fall over the water from the simple hexagonal model. The L distance in this figure is 18.75 nmi.

Finally, another example of a full second-order hexagonal model where L is 18.75 nmi is shown in Fig. 14 overlaid on a map of Philadelphia.

APPENDIX B: WEATHER DATA

In this appendix we provide more details on the meteorological data collected at all the airports listed in Table 2. Fig. 15 summarizes the density altitudes for each of the metropolitan areas selected. The blue bar in these figures denotes the mean value, the "whiskers" show one standard deviation around the mean, and the 95th percentile of the data is denoted with a diamond.

Fig. 16 summarizes the wind speeds, and Fig. 17 summarizes the wind gust data for each of the metropolitan areas selected. These figures are formatted in the same manner as Fig. 15.

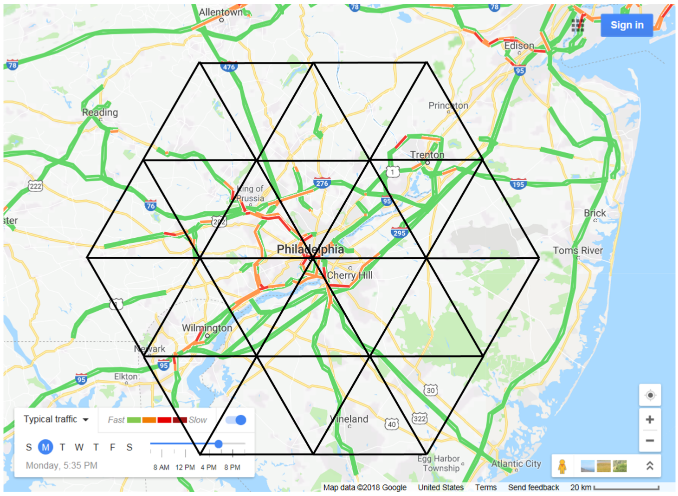

Fig. 14. Full second-order hexagonal model shown overlaid with map of Philadelphia.

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Table 2. Metropolitan area characteristics

Largest City in MSA	Airport	2015 Travel Time Index[a]	City Population[b]	MSA Population[b]	Long-Range Mission Centroid		Short-Range Mission Centroid	
					Latitude	Longitude	Latitude	Longitude
Atlanta	KATL	1.24	420,003	5,286,728	33.74900	-84.38842	33.63670	-84.42786
Boston	KBOS	1.29	617,594	4,552,402	42.35973	-71.05927	42.36294	-71.00639
Charlotte	KCLT	1.23	731,424	2,217,012	35.22832	-80.84395	35.21375	-80.94906
Chicago	KORD	1.31	2,695,598	9,461,105	41.87810	-87.62944	41.97732	-87.90801
Cincinnati	KCVG	1.18	296,943	2,114,580	39.10270	-84.51225	39.04884	-84.66782
Dallas	KDFW	1.27	1,197,816	6,426,214	32.79034	-97.02272	32.89723	-97.03769
Denver	KDEN	1.30	600,158	2,543,482	39.73959	-104.98971	39.86167	-104.67317
Detroit	KDTW	1.24	713,777	4,296,250	42.33144	-83.04565	42.21242	-83.35339
Honolulu	PHNL	1.37	2,100,263	953,207	29.76020	-95.36921	29.98444	-95.34144
Houston	KIAH	1.33	583,756	5,920,416	36.16972	-115.14000	36.08006	-115.15225
Las Vegas	KLAS	1.26	3,792,621	1,951,269	33.92142	-118.11742	33.94249	-118.40805
Los Angeles	KLAX	1.43	399,457	12,828,837	26.12240	-80.13732	25.79536	-80.29011
Miami	KMIA	1.29	382,578	5,564,635	44.97765	-93.26423	44.88197	-93.22178
Minneapolis	KMSP	1.26	601,222	3,348,859	36.16256	-86.78130	36.12447	-86.67817
Nashville	KBNA	1.21	8,175,133	1,670,890	40.71275	-74.00586	40.63993	-73.77870
New York	KJFK	1.34	238,300	19,567,410	28.53808	-81.37896	28.42939	-81.30900
Orlando	KMCO	1.21	1,526,006	2,134,411	39.95248	-75.16464	39.87208	-75.24066
Philadelphia	KPHL	1.24	1,445,632	5,965,343	33.44818	-112.07372	33.43428	-112.01158
Phoenix	KPHX	1.27	305,704	4,192,887	40.44048	-79.99578	40.49142	-80.23269
Pittsburgh	KPIT	1.19	583,776	2,356,285	45.52304	-122.67648	45.58871	-122.59687
Portland	KPDX	1.35	186,440	2,226,009	40.76078	-111.89113	40.78839	-111.97777
Salt Lake City	KSLC	1.18	1,327,407	1,087,873	29.42392	-98.49338	29.53396	-98.46906
San Antonio	KSAT	1.25	1,307,402	2,142,508	32.71583	-117.16099	32.73356	-117.18967
San Diego	KSAN	1.24	805,235	3,095,313	37.69660	-122.29684	37.61881	-122.37542
San Francisco	KSFO	1.41	608,660	4,335,391	47.60613	-122.33205	47.44989	-122.31178
Seattle	KSEA	1.38	319,294	3,439,809	38.62696	-90.19949	38.74870	-90.37003
St Louis	KSTL	1.16	335,709	2,787,701	27.95050	-82.45698	27.97547	-82.53325
Washington DC	KDCA	1.34	601,723	5,636,232	38.90715	-77.03655	38.85144	-77.03772

[a] From (Ref. 33)

[b] From 2010 Census

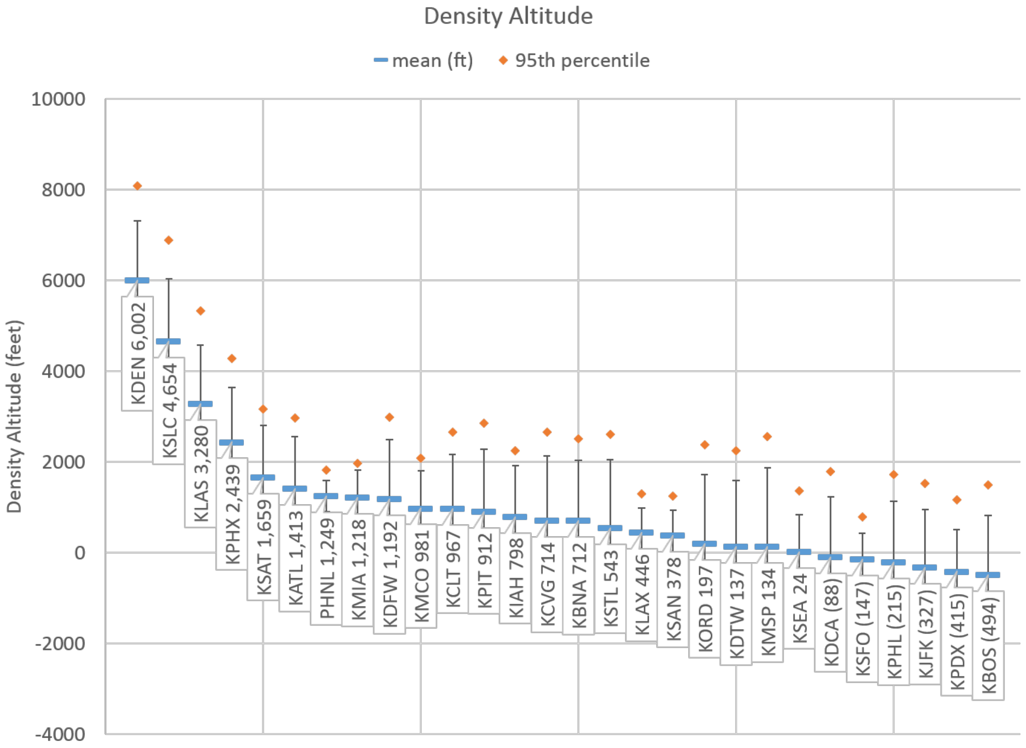

Fig. 15. Density altitude (feet) for all 28 selected metropolitan areas.

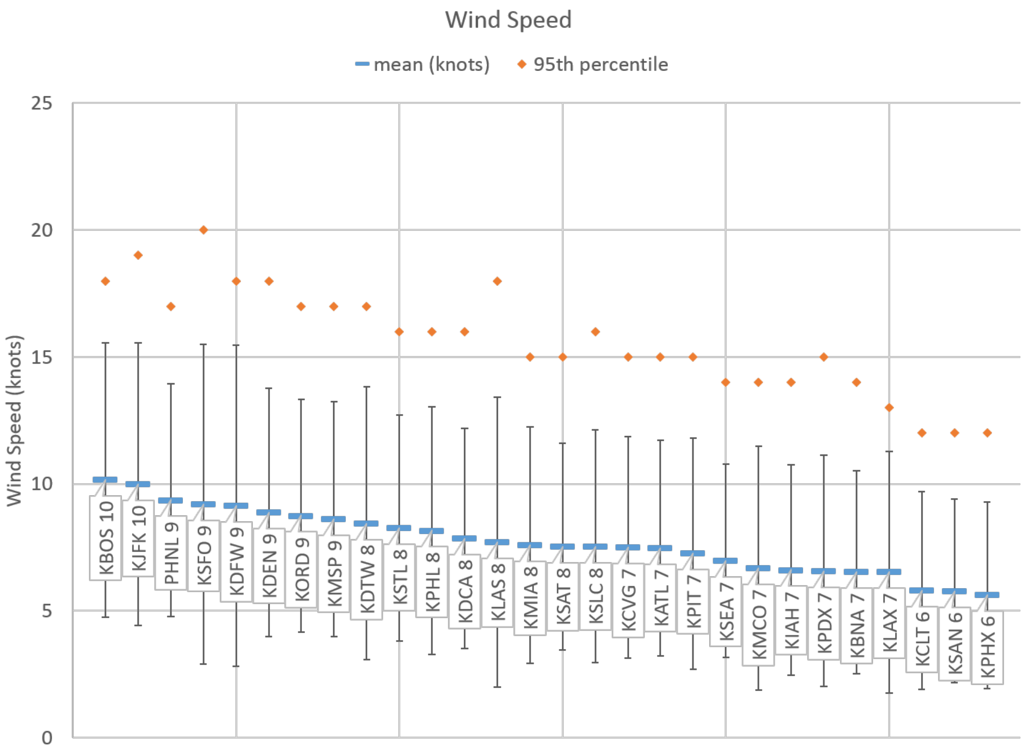

Fig. 16. Wind speed (knots) for all 28 selected metropolitan areas.

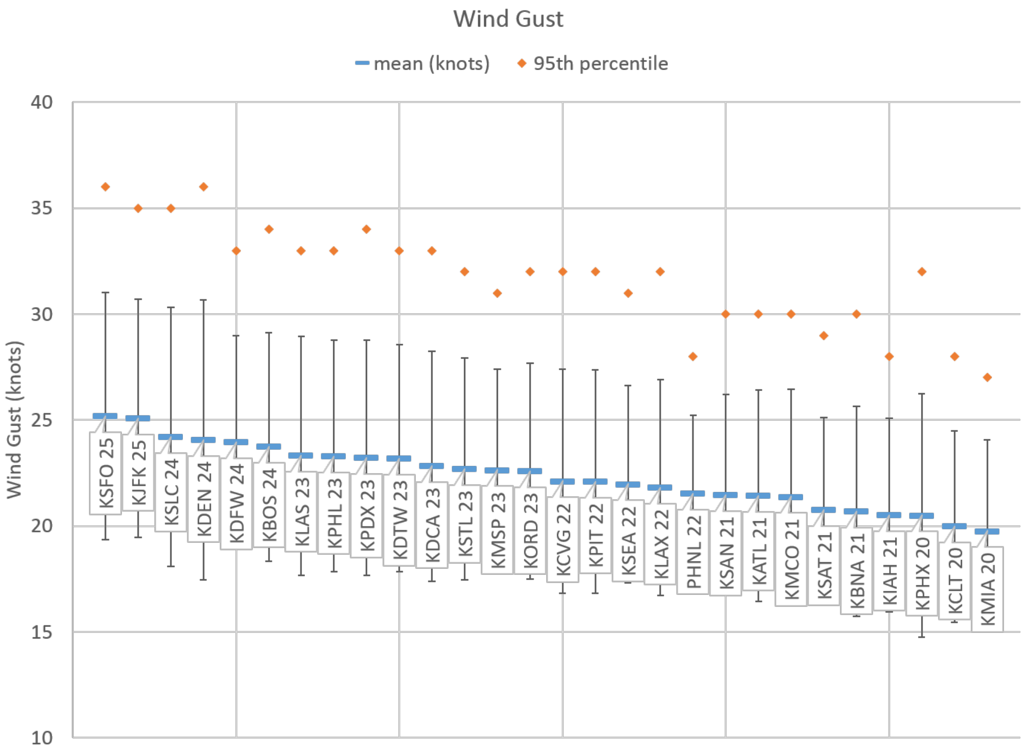

Fig. 17. Wind gust (knots) for all 28 selected metropolitan areas.

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